DEVELOPMENT AND EVALUATION OF SEMI-CONTINUOUS MICROWAVE CONVECTIVE DRYER FOR FOOD PRODUCTS

By
Er. Alfiya P V
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TAVANUR P. O. – 679573

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DECLARATION

I, hereby declare that this thesis entitled **“DEVELOPMENT AND EVALUATION OF SEMI-CONTINUOUS MICROWAVE CONVECTIVE DRYER FOR FOOD PRODUCTS”** is a bonafide record of work done by me during the course of project work and that it has not previously formed the basis for the award to me for any degree/diploma, associateship, fellowship or other or other similar title of any other University or Society.

Place: Tavanur **Er. Alfiya P V**

Date: **(2019.28.2021)**

CERTIFICATE

Certified that this thesis entitled **"DEVELOPMENT AND EVALUATION OF SEMI-CONTINUOUS MICROWAVE CONVECTIVE DRYER FOR FOOD PRODUCTS"** is a record of project work done independently by Er. Alfiya P V under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to her.

Place : Tavanur
Date :

Dr. Rajesh G. K.
(Major Advisor, Advisory Committee)
Assistant Professor
Department of Processing and Food Engineering
KCAET, Tavanur

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(*Alfiya P V*)

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NOTATIONS

A	:	area of cross section, m^2
a	:	constant used in drying equation
A_c	:	surface area of solar collector, m^2
SD	:	solar drying
P	:	microwave power level
a_w	:	water activity
DT	:	drying time, h
RR	:	rehydration ratio
m	:	metre
ρ	:	bulk density in kg/m
ρ_T	:	true density in kg/m^3
μ	:	coefficient of friction
F	:	frictional force
N	:	normal force
θ	:	angle of repose
h	:	altitude of pile, m
d	:	diameter, m
Q	:	rate of heat transfer, W
K	:	thermal conductivity, W/mK
A	:	surface area of heat transfer, m^2
dt/dx	:	temperature gradient, °C/m
M_w	:	mass of water, g
MW	:	microwave
HAMW	:	hot air assisted microwave drying
C_p	:	specific heat of air at constant pressure, kJ/kgK
T_i	:	inlet air temperature, °C
T_f	:	final air temperature, °C
M_i	:	initial moisture content (% w. b)
M_f	:	final moisture content (% w. b)

W_i	:	initial weight of the sample, g
M_w	:	mass of water evaporated, g
L	:	latent heat of vaporization, kJ/kg
V_a	:	volumetric flow rate of air, m^3/s
V	:	air velocity, m/s
n	:	number of air passage ducts
W_d	:	bone dry weight of product, kg
C_{pp}	:	product specific heat, kJ/kg°C (shrimp - 3.65 kJ/kg°C, mushroom – 0.9 kJ/kg°C)
$\frac{\delta M}{\delta t}$	:	change in moisture content with respect to time
MR	:	moisture ratio
D_{eff}	:	effective diffusivity, m^2/s
M	:	moisture content at time (t=t)
M_o	:	moisture content at time (t=o))
M_e	:	equilibrium moisture content (%)
MC (d.b)	:	moisture content dry basis (%)
E_{lpg}	:	energy supplied by LPG, W
E_{sc}	:	energy supplied by solar collector, W
E_{pb}	:	energy supplied by pumps and blowers, W
E_T	:	total energy, kWh
WVTR	:	water vapour transmission rate (g/cm^2/24 h at 38 ^{0}C & 90% RH)
OTR	:	oxygen transmission rate (cc/cm^2/24 h/atmos)
a*, a_0	:	redness/greenness of dried and raw samples respectively
b*, b_0	:	yellowness/blueness of dried and raw samples respectively
$D_{initial}$	:	initial diameter of the sample before drying (m)
D_{final}	:	final diameter of the sample after drying (m)
ΔE	:	total color change
η	:	efficiency (%)
L*, L_0	:	lightness value of dried and raw samples respectively
E_{pb}	:	energy supplied by pump and blower (W)
E_{sc}	:	energy supplied by LPG solar collector (W)

I	:	average incident solar radiation (W/m^2)
m_w	:	mass flow rate of water (kg/h)
MDA	:	melonaldehyde
TBARS	:	thiobarbituric acid (N/100g)
TMA	:	trimethyl amine (N/100g)
TVBN	:	total volatile base nitrogen (mg malonaldehyde/kg of lipid)
TPC	:	total plate count
TPA	:	total plate count agar
T_{ci}	:	temperature of water in the inlet of collector (K)
T_{co}	:	temperature of water in the outlet of collector (K)
RH	:	relative humidity (%)

SYMBOLS

°C	-	degree centigrade
et al.,	-	and others
hp	-	horse power
h	-	hour
m	-	metre
K	-	Kelvin
kg	-	kilo gram
kWh	-	kilo watt hour
min	-	minutes
MT	-	metric tonnes
mol	-	moles
mm	-	milli metre
ml	-	milli litre
N	-	Newton
Pa	-	Pascals
₹	-	Indian currency, Rupees
s	-	seconds
%	-	percentage

Introduction

CHAPTER I

INTRODUCTION

Agriculture has a pivotal role in Indian economy and currently contributes to 15% of the national GDP (India Stat, 2023). Globally, India ranks first position in the production of milk, tea, jute, pulses and many more; apart from being second in total food production (Sati, 2023). In contrary to this scenario, food worth Rs. 92,651 crore is lost in India due to post-harvest loss before it has reached the consumer (Beriya, 2021). This monetary value is approximately 40% of the total produce in India, making it one of the few countries to have higher post-harvest loss. One of the complementary solutions to mitigate post-harvest loss is to adopt a dry chain in food supply. Dry chain refers to the drying of perishable commodities soon after harvest and storing them in moisture proof containers during transit and storage (Bradford *et al*, 2020).

Drying is one of the most ancient and pre-eminent physical methods of food preservation. (Moses *et al*, 2014). Food drying is a process by which moisture is removed from the products by sublimation or vaporization, thereby reducing the availability of water for microbial, chemical or enzymatic degradation (Rafaiane *et al*, 2018). Apart from extending the shelf life of food commodities, drying also reduces the costs involved in handling, packaging, transportation, storage and distribution. Drying is also a suitable alternative for management of post-harvest loss of agricultural products. According to Grabowski *et al*. (2003), around 20% of world's perishable crops are dried for safe storage and consumption. It is a highly energy intensive unit operation consuming about 12-20% of the total energy in food processing industries (Raghavan *et al*., 2005). Drying uses energy in form of heat to vaporize water present in foods and for its subsequent removal. Hence, it involves simultaneous transfer of heat, mass and momentum in which heat penetrates into the product and moisture is removed by evaporation into an unsaturated gas phase (Mujumdar *et al.,* 2008).

Water present in food materials is of two types – free water and bound water. Free water denotes the liquid fraction in excess of equilibrium moisture content at a given temperature and humidity, that is removed during drying by vapor pressure gradient between product and atmosphere. Bound water is the fraction of liquid that exerts a vapor pressure less than that of the free moisture at the given temperature. Drying involves vaporization of water from a free surface by liquid diffusion, vapor diffusion, Knudsen diffusion, hydrostatic pressure difference and surface diffusion (Mujumdar and Devahasthin, 2000). Rate of drying depends upon the rate of heat transfer from the drying medium to the wet solid which can be a result of convection, conduction, radiation or a combination of them. The objectives of drying include preservation of perishables, preventing the seasonal glut in market and reduction in volume for convenient and economic storage.

Based on the mode of application of heat, dryers are classified as direct (convection), indirect (conduction or contact) and radiation dryers. Vega-Mercado *et al*. (2001) classified dryers into four generations: first generation (kiln, tray, rotary, conveyor, tunnel dryers); second generation (spray and drum dryers); third generation (freeze drying and osmotic dehydration) and fourth generation (microwave and radio frequency dryers). Presently, over 85% of the industrial food drying systems works on the principle of convective drying, where hot air or flue gas acts as a medium to remove water from foods (Zarein *et al.,* 2015).

In convective drying, thermal energy is transferred from surface of the material to the inside by temperature gradients resulting in lower drying rates and longer drying times especially in falling rate period of drying. The major drawbacks associated with these drying systems are higher drying times that affect the quality of final dried products. Higher drying temperatures and longer drying times during convective drying of food causes development of hard shell or crust on the surface of food being dried (Miraei *et al*., 2022). This phenomenon called case hardening prevents adequate removal of water from within the foods. Case hardening affects the moisture transport within the foods during drying and ultimately affects the material shrinkage (Grabowski *et al*., 2003). In this phenomenon, outer surface of food dries at a faster rate than inside and enters into a glassy state (Ratti, 1994). This results in development of an intensified stress field at the glassy-rubbery interface leading to stress cracking and rupture of material (Inazu *et al*., 2005). Thus, a major challenge in drying of perishable crops is to lower the moisture contents into a predetermined level while maintaining the quality attributes such as color, texture and chemical components (Khraisheh *et al*., 2004).

Dielectric drying can mitigate these problems by increasing diffusion rate and supplying moisture to the surface. Dielectric drying is an advanced drying technology consisting of microwaves and radio frequency waves that renders higher drying rates with minimal losses in nutritional and sensory qualities of dried products (Zhang *et al*., 2006). The frequency applied in radiofrequency and microwave drying are in range of 10 – 300 MHz and 300 MHz - 300 GHz respectively. According to United States Federal Communications Commission (UNFCC, 2008), the responsible regulatory agency for the out-of-band emissions from domestic, industrial, scientific and medical (ISM) applications, the allocated frequencies for industrial applications are as follows: 915 MHz ± 25 MHz, 2450 MHz ± 50 MHz, 5800

MHz ± 75 MHz and 24125 MHz ± 125 MHz for microwave processing and 13.56 MHz ± 6.68 MHz, 27.12 MHz ± 160.00 kHz, 40.68 MHz ± 20.00 kHz for radiofrequency heating.

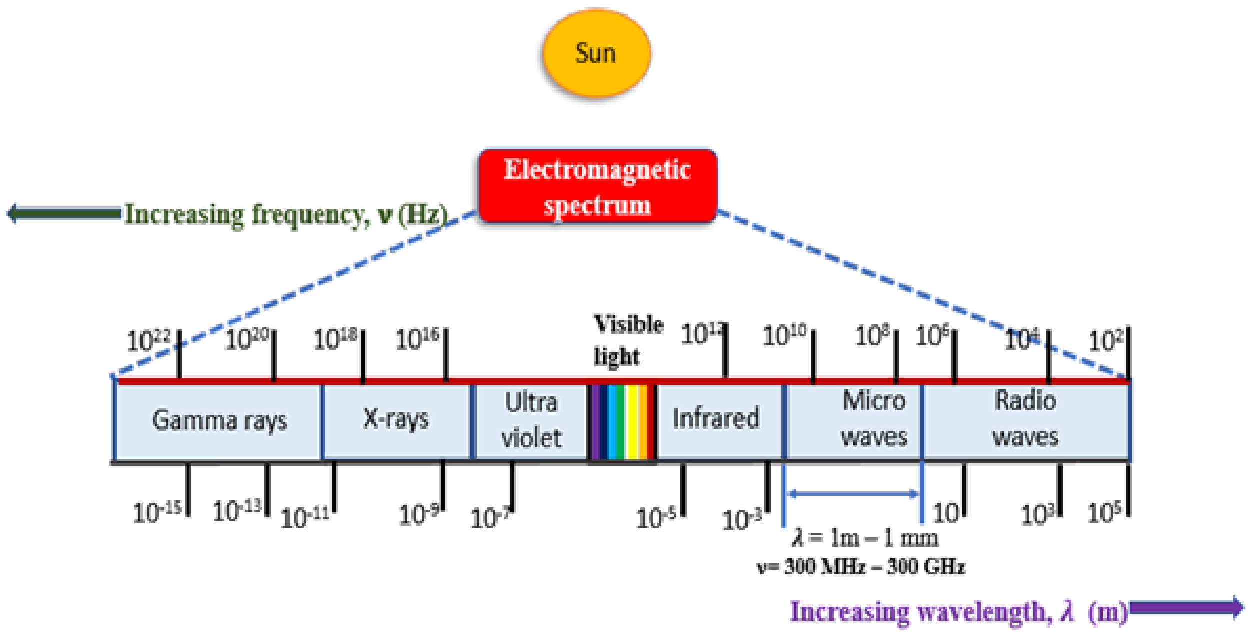


Fig. 1.1 Allocation of wavelengths and frequencies of radiations in the electromagnetic spectrum (Source: Zamanian and Hardiman, 2005)

Microwaves are non-ionizing electromagnetic radiation in the frequency range of 300-300 GHz with a wavelength of 1 mm – 1 m (Banik *et al.*, 2003). Microwaves penetrate the material and heats up volumetrically, facilitating higher diffusion rate and pressure gradient to expel moisture from inside of material (Turner and Jolly, 1991). Microwave heating is based on two mechanisms – dipole rotation and ionic interaction. Water molecules present in food are dipolar in nature and try to orient in the direction of electric field which alternates at a frequency of 2.45 billion cycles/second, making the dipoles move with it. Dipole rotation refers to the rotation of molecules that produces friction and generates heat inside the food material. In ionic polarization, the ions, particularly in salty foods, migrate under the influence of electric filed migrate and generate heat (Kumar *et al.*, 2014). Microwave drying system consists of microwave generator (magnetron), wave applicator, handling devices and control systems. Although numerous studies have been conducted on microwave heating, most of them were done in domestic microwave oven and a single-mode cavity with stationary materials (Rattanadecho *et al.*, 2007).

However, the major downsides of convective/hot air drying are the lower energy efficiencies and longer drying times involved in the process (Orikassa *et al.*, 2014). Microwave (MW) drying is said to address these drawbacks thereby making the process more effective

(Rodrigues *et al*., 2016). In MW drying, the internal pressure of products reaches higher levels with the increase in internal temperature of materials to a level closer to boiling point (Swain *et al*., 2012). The increase in vapor pressure facilitates migration of water molecules towards the surface of materials, resulting in faster drying rate than that produced by the convective drying, where heat is transferred from the surface towards the inner core of materials (Song *et al*., 2017). However, the moisture brought up to the surface needed to be carried away by an air flow system. Since cold air has a very low water absorption capacity, hot air at desired temperatures is used. Hence hot air assisted MW drying overcomes the problems related to traditional convective and dielectric only drying systems (Mirzabeighi *et al*., 2016).

Fish, being a highly perishable product, is subjected to immediate spoilage soon after harvest. The post-harvest loss in fisheries sector of India is 5.23-10.52% which is crucial requiring immediate attention. Drying of fish is an important strategy adopted towards reducing the post-harvest loss. But the existing drying systems for fish often results in inferior product quality due to long drying time requirement and non-uniform drying. Shrimp belongs to the phylum arthropod with extended abdomen and is one of the most important commercial sea foods in the world (Oosterveer, 2006). India is the world’s second largest producer of shrimp with an annual production of 4,00,000 tonnes in 2021 as per the reports from Marine Products Export and Development Agency (Durai *et al*., 2022). It makes around 67% of India’s sea food exports. Shrimps contain nearly 20% protein (w.b.) with adequate amount of amino acids and other micronutrients such as calcium and selenium (Yanar and Celik, 2006). Lipids in shrimps are largely made up of highly unsaturated fatty acids such as eicosapentanoic (20:5n3, EPA) and decosahexanoic (22:6n3, DHA) acids that are essential for human health (Feliz *et al*., 2002). They are rich in vitamin B12 and asthaxanthin, a fat soluble carotenoid with anti-oxidant properties (Venugopal, 2008). Owing to the high moisture and protein content of shrimps, they are subjected to rapid deterioration soon after harvest. Dried shrimps are popular worldwide for their delicacy and flavor and a major production of shrimp (%) are dried for domestic and export market. Natural sun drying is practiced as an economic method for drying of fish and shrimps. This method has several disadvantages such as longer drying time, weather uncertainties, infestation by birds and insects and uncontrolled rate of drying (Jain and Pathare, 2007). Hence convective hot air dryers are generally used for commercial hygienic production of dried shrimps.

The existing convective drying systems for shrimp often result in inferior product quality due to longer drying time requirement and non-uniform drying. Microwave drying technique is a promising alternative to reduce drying time and enhance energy efficiency

(Soysal *et al*., 2006). Microwave drying of shrimp increased drying efficiencies to about 22.54% and reduced specific energy consumption to about 28.94% when microwave power was increased from 200 to 500 W (Farhang *et al*., 2011). Darvishi *et al*. (2013) studied the effect of microwave and hot air (MWHA) combination on the rate of drying, effective moisture diffusivity (EMD), and energy for drying Sardine fish at four varying MW powers of 200 W, 300 W, 400 W, and 500 W and at constant air velocity. The moisture content of the samples was reduced to 0.01 (dry basis) with a reduction in drying time (9.5 to 4.25 min) as power increased. Wu and Mao, (2008) investigated the influence of hot air (HA) and MW drying on the nutritional properties of grass carp (*Ctenopharyngodon idellus*) fillets. Microwave drying showed an increase in protein contents since it had less effect on the amino acid composition of grass carp fillets. Mohd and Ng, (2010) reported that drying time for catfish slices was reduced to 75% using the microwave as compared to hot air (HA) drying.

Microwave drying of shrimp increased drying efficiencies to about 22.54% and reduced specific energy consumption to about 28.94%, by increasing MW power from 200 to 500 W (Farhang *et al*., 2011). Drying under the microwave (MW) was found to lower drying time and enhance energy efficiency (Soysal *et al*., 2006). Ikrang *et al.* (2019) optimized the process conditions for drying of catfish using an electrical dryer using RSM. Temperature (50–70 °C), thickness of sample (10–20 mm), salt concentration (0–20%) and drying time (480–600 min.) were the independent parameters. The moisture content of the dried products under optimized conditions (Temperature = 63.43 °C, thickness = 14.81 mm, salt concentration = 9.07% and drying time = 600 min) was 2.64% w.b. Optimum conditions for horse mackerel (*Trachurus japonicus*) drying using RSM under heat pump drying technique were: drying air temperature 30 °C, drying air velocity 1.5 m/s and NaCl content in the osmotic solution 9.9% (Shi *et al*., 2008).

Mycoproteins are considered to be a substitute for meat proteins making them one of the most sustainable sources of proteins. Oyster mushroom (*Pleurotus ostreatus*) is an edible fungus that contains 20-25% protein, 37-48% fat, 4-5% carbohydrates, 37-48% moisture and 86-87% moisture (Silva *et al*. 2002). Mushrooms are also rich in minerals such as calcium (3 mg/100g), copper (0.24 mg/100 g), iron (1.33 mg/100 g), magnesium (18 mg/100g), manganese (0.11 mg/100g), phosphorous (120 m/100 g), potassium (420 mg/100 g), selenium (2.6 µg/100 g), sodium (18 mg/100 g) and zinc (0.77 mg/100g) (Raman et al, 2020). Vitamins like thiamin (0.125 mg/100 g), riboflavin (0.35 mg/100 g), niacin (4.96 mg/100 g), pantothenic acid (1.29 mg/100 g), Vitamin E (7.23 mg/100 g) and vitamin C (0.363 mg/100 g) are also present (Adeboyo and Oloke, 2017). They are also rich in amino acids such as glutamic acid, cysteine, aspartic acid and lysine (Patil *et al*., 2014). According to the reports of Bijla (2023), the annual production of mushrooms in India is around 1.29 MT, of which 70% share is button mushroom, 16% by oyster mushroom and remaining is constituted by milky mushroom and other types. Kerala produces over 500 MT of oyster mushroom and 300 MT of milky mushrooms. Owing to their high respiration rates (60 ml O_2/hr.kg) and moisture contents (75-85%), oyster mushrooms are susceptible to deterioration making them shelf stable for 2-5 days. Shelf-life of fresh mushrooms is very limited, being 1–3 days at ambient temperature, and 4–7 d at 4°C. This quick deterioration is mainly caused by high metabolic activity, respiration rate and dehydration (Ares *et al*., 2007). The absence of cuticle in the dermal tissues makes them prone to damages, microbial attack and water loss (Martine *et al*., 2000). They require low storage temperatures (0 - 2 ^{0}C), low O_2 concentration (1-2%), relatively high CO_2 concentration (8-15%) and high relative humidity (90-98%) for storage life (Thompson *et al*, 2018). However, drying is the best known and economically feasible method for processing oyster mushrooms for shelf-life extension.

It is also suitable for consumption by patients with diabetes or cardiac diseases, and offers various valuable biological effects, including antitumor, anti-aromatase, antimicrobial, immuno-modulatory, anti-inflammatory and antioxidant activities (Walde *et al*., 2006). Of all mushrooms produced around the world, 40–50% is consumed as fresh. After being harvested, mushrooms can be stored only for 1–7 days because of their high moisture (approximately 90% w.b.) and enzyme content (Naik *et al*., 2006). Furthermore, rapid loss of quality is observed throughout the storage process. Enzymatic browning, dehydration and reduction in protein and glucose contents are among the primary problems encountered, restricting consumption of fresh edible mushrooms (Jiang *et al*., 2011). Due to these reasons, mushrooms are generally processed and canned, or offered for consumption in frozen or dried forms. The drying method is relatively more economical compared to other preservation methods, enabling the storage of dried mushrooms in airtight packages for more than 1 year (Rama and John, 2000). Dried mushrooms can be used as a raw material for the instant soup and pizza industries, or as an auxiliary material for various sauce products and baby formulas, or processed to mushroom flour (Arumuganathan *et al*., 2009).

Drying also prevents the different types of spoilage including enzymatic or nonenzymatic browning and microbial growth by reducing the moisture content to a level for safe storage. Dried mushrooms have a characteristic flavor and are often used in various food recipes or as additives in a mixture of different dried vegetable snack products for supplementing the protein requirement. Several reports are available on drying of mushrooms (Seyhan and Evranuz, 2000; Kar and Gupta, 2001; Torringa *et al*., 2001; a, 2007; Jambrak *et al*., 2007; Shukla and Singh, 2007). However, convective air drying is still the most adopted technique worldwide due to its practical utility and easiness of operation. Kotwaliwale *et al*. (2007) reported deterioration in the structure of hot air-dried mushrooms due to its prolonged drying times. However, as microwave drying was found suitable for heat sensitive products, investigations were done on microwave based drying of mushrooms (Zhang *et al*., 2006; Heindl and Muller, 2011).

Microwave drying of mushrooms at a lower microwave power intensity in combination with heated air has resulted in improved rehydration rates, moisture diffusivity, and flavour retention (Giri and Prasad, 2006). Colour and texture serves as the important attributes that influences consumer acceptance. Furthermore, the rehydration ability of the dried product is the rehydration characteristics closely related the porosity of dried products and is considered to be a critical parameter, indicating the measure of the damage to the material caused by physicochemical treatments (Krokida et al., 2003).

The response surface methodology (RSM) is used as a tool for the optimization of process conditions that govern the effect of each variable and its interactions. It involves an experimental approach, mathematical procedures, and statistical implication which offers the user to make an efficient empirical exploration of the targeted unit (Murali *et al*., 2017).

Drying involves complex mass, heat and momentum transport followed by intermolecular transformation (Kudra and Mujumdar, 2002). Hence, drying process needs to be effectively designed and optimized. This can be achieved by mathematical modelling using thin layer drying equations that are practical and give adequately fair results on prediction of drying time. Moisture removal during drying can be projected by modelling of drying kinetics (Alfiya *et al*., 2019). Drying kinetics describe the changes in moisture regime in the product with time. Various models defining the drying rate curve are proposed based on the factors that affects the drying process (Pacheco *et al*., 2015).

The combination of hot air and microwave is an innovative method to improve the effectiveness of drying with better retention of the quality of products. Microwave drying results in lesser energy consumption and quality dried products (Andres *et al*., 2004). In microwave heating, due to faster rate of mass transfer, removal of moisture from the product is difficult and leads to condensation of steam inside the container (Sharma *et al.,* 2009). To overcome this difficulty, microwaves are generally combined with hot air drying, freeze drying, vacuum drying, spouted bed drying and osmotic drying. As vacuum and freeze drying involve higher capital and operating cost, hot air drying is most widely combined with microwaves.

Combining microwaves with hot air drying can significantly shorten drying time thereby improving energy efficiency and product quality. Heat generated by the microwaves increase the pressure within the pores and expels moisture to the surface. The convective air flow aids in removal of the moisture from the surface. Hybrid drying offers many advantages over conventional drying in terms of reduced drying time, reduced energy usage and improved product quality. Furthermore, most of the existing drying techniques are utilizing high energy or leading to carbon emissions. Microwave assisted hot air drying (MWHA) technology has been successfully employed to dry banana, spinach, garlic, peeled longan, American ginseng and other agricultural produces (Sharma *et al*., 2009, Maskan, 2000; Varith *et al*., 2007). Studies on adoption of this technology for Shrimp and mushrooms are limited. Hence it is contemplated to develop technologies which are green, clean and affordable to MSMEs and farmers. Thus, this work on development and evaluation of semi-continuous hot air assisted microwave dryer for shrimp and mushrooms is planned with the following objectives:

1. To develop a semicontinuous type microwave convective dryer for shrimp and mushroom.
2. To optimize the drying process parameters based on drying characteristics and quality parameters of dried products.
3. To execute performance evaluation of the prototype based on thermal efficiency and specific energy consumption.
4. To perform storage studies on dried products under various packaging techniques and packaging materials.

Review of Literature

CHAPTER II
REVIEW OF LITERATURE

This chapter deals with the literature reviews on development of microwave dryer, drying kinetics, modelling, quality evaluation and storage studies of shrimp and oyster mushroom.

2.1 Development of microwave dryer

Manickavasagan *et al.* (2006) published that microwave drying exerts notable reduction in time and the amount of energy consumed and worked on electromagnetic field distribution inside microwave cavity as simulated by Maxwell's equations. The design comprised of rectangular wave guide for maximum transmission of electromagnetic energy. The cavity volume was assumed based on Design-Expert 10 data. This software was used to statistically analyze the effect of different factors on non-uniform heating. The design comprised of two magnetrons located on the opposite transverse lateral faces. However, the volumes considered were not sufficient to meet industry demand.

Radoiu (2020) opined that the quatum energy of electromagnetic radiation is h x f, where h is Planck's constant (i.e. 6.60 × 10−34 J s). For microwaves that have a frequency of 2450 × 106 Hz or 915 × 106 Hz, the quantum energy equals 16.17 × 10-25 J (1.01 × 10-5 eV) and 6.039 × 10-25 J (3.76 × 10-6 eV), respectively. In comparison with radiation burns caused by ionizing radiation, where the dominant mechanism of tissue damage is internal cell damage caused by free radicals, the primary damage mechanism of microwave radiation is by heat.

Junior *et al.* (2019) developed an industrial scale microwave dryer. The equipment has been tested in real conditions of operation, using mass flow rates between 250 and 750 kg/h and organic initial contents of 7.5, 10 and 12.5%. The specific energy ranged during the operation was between 0.12 and 0.34 kWh/kg.

Malafronte *et al.* (2012) applied physical and mathematical models to establish the influence of the main process variables on the final product quality, in order to apply an effective production control. The drying equipment was a straight aluminum waveguide fitted with an air-cooled magnetron. The waveguide has standard sizes 86 × 43 mm with an adjustable length in which the drying cavity was situated. The magnetron works at the frequency of 2.45 GHz in the range of power 300–600 W.

Uprit and Mishra (2003) used a modified programmable domestic microwave oven (IBM, Model Electron), with a maximum output of 625W at 2450MHz and cavity (drying chamber) dimensions of 300 × 240 × 210 mm for soy-fortified paneer drying. Moisture loss in the sample was measured by on-line weight recording at 3 min interval. The temperature and relative humidity of the exhaust air were measured periodically using a digital hygrometer (ALMEMO, Germany).

Ahrné *et al.* (2007) The drying experiments were performed in a dryer specially designed in the framework of the European Union project ICA4-CT-2002-10034 by P.O. Risman in collaboration with SIK and constructed by TIVOX machine AB (TIVOX Maskin AB, Sweden). It can be operated with a temperature of 40--800C and air velocity of 0.3-0.8m/s.

Kowalski *et al.* (2010) used a microwave oven with cavity dimensions 300 × 400 × 450 which can supply maximum power of 600W. They found that temperature was higher in the middle of the sample. In their setup, air with 220C was supplied with installed mechanical ventilation system. However, it is not clear where the ventilation system was placed and how efficiently it worked. Air flow is important because reduced airflow may results moisture accumulation at the surface of the sample which reduces drying rate and degrades sample texture for food application.

Funebo and Ohlsson (1998) designed microwave drying system with applicators constructed to give a horizontal magnetic field with a large incidence angle of the microwaves. The polarisation of an electromagnetic wave with a large incidence angle gives an electric field component which is almost vertical. Most of the long edges in foods intended for microwave heating are horizontal (flat foods), which makes the electric field from the applicators perpendicular to the horizontal edges, making it possible to avoid overheating of these edges. A large incidence angle of transverse magnetic waves reduced the amount of reflected energy from the surface of the food. A reduced amount of reflected energy increases the electrical efficiency of the process.

2.2 Microwave drying of fish and fishery products

Mounir *et al.* (2020) reported that MW power level of 24 W/g yielded the most effective drying performance when 90% of moisture was removed in 10 min, with organoleptic quality attributes and structural properties better than those of conventionally dried shrimp. Intermittent microwave drying with active time of 30 s and tempering time of 60 s followed DIC-texturing of blanched shrimp samples (30 g cubes of 1 cm^3). The MW density power levels tested were 6, 12, and 24 W/g wb (wet basis). The airflow condition was fixed at 3.2 m/s, 20 °C, and 276 Pa water vapor pressure. Drying performance along with the organoleptic, structural, and functional quality parameters was measured for the dried product.

Lee *et al.* (2021) investigated on the microwave-assisted induction heating (MAIH) system that provided comprehensive heating by combining microwave heating (with 1300 W of power and 2450 MHz of frequency) in the top part and induction heating (with 1800 W of power) in the bottom part.

Microwave heating of seafood has the potential to reduce the time and save energy via its rapid penetration and heating. Fish and shell fishes have high moisture content (64–92%), compared to other food products which make them more convenient for microwave applications. However, MH has not been yet utilized to its complete potential considering the development of hot spots depending on time of treatment, product geometry and microwave frequency (Jiang *et al*., 2018).

A combination or hybrid mode of technology has been proposed to overcome the challenges in microwave heating (Ekezie and Cheng, 2017). Many reviews are available pertaining to application of microwave for food processing which discusses mostly on fruits and vegetable, herbs, grains, milk and meat processes (Chandrasekaran et al., 2013; Ekezie *et al*., 2017; Guo *et al*., 2017; Guzik *et al*., 2022; Raghavan *et al.*, 2005).

In contrast to conventional heating methods where heat energy is transferred to the food by conduction, convection or radiation, heat is produced within the material during microwave heating. It is a dielectric processing in which heat is produced by molecular friction caused during the realignment of polar molecules (mainly water molecule) from their equilibrium positions under an oscillating electric field (Meda *et al*., 2017).

The efficiency of a food material to generate heat under microwave energy is regulated by its dielectric properties and ionic mechanism (Chandrasekaran *et al*., 2013) and the ability to absorb, transmit or reflect electromagnetic energy (Puligundla *et al*., 2013). The dielectric property of a food material is described by its dielectric constant (ϵ’-the real part of dielectric properties which refer to a material’s ability to store electric energy) and dielectric loss (ϵ''-the imaginary part of dielectric properties which refer to its ability to convert electric energy to heat).

Water is the chief food component that interacts with microwave and generates heat due to its dipolar rotation and friction. In addition, heat is also generated during migration of positively or negatively charged ions under an electric field, towards the oppositely charged areas of electric field. This movement causes ionic collisions and disruption of hydrogen bonds in water, leading to heat generation (Venkatesh & Raghavan, 2004).

In microwave processing, the dielectric properties of food are primarily influenced by microwave frequency and operating temperature apart from moisture content, salt content and other ionic constituents (Puligundla *et al*., 2013). In addition to dielectric properties of the food material, the heat generation is affected by many other factors such as configuration of oven, shape, size and density of food, location of food inside the oven etc. (Icier & Baysal, 2004).

Though dielectric properties of various food materials including fruits, vegetables, meats, starches and other food products have been investigated thoroughly, reports on dielectric properties of seafood are limited. The dielectric properties such as dielectric constant (ϵ') and the loss factor (ϵ″) are influenced by compositional and structural differences within a fish muscle (Wang *et al.*, 2007).

Wang *et al.* (2019) carried out a detailed investigation on the dielectric properties of different sections of salmon fillet (anterior, middle, tail and belly) at different temperatures (20–120 °C) and at frequencies ranging from 27 to 1800 MHz (radio frequency (RF) and microwave (MW) pasteurization). The dielectric loss factor exhibited a similar trend for all four sections of salmon fillet as a function of temperature at 27 and 915 MHz. However, the fat rich belly portions of salmon fillet had lower dielectric loss factor and dielectric constant than other parts.

Al-Holya *et al*. (2005) measured the dielectric properties of salmon and sturgeon caviar at RF and MW frequencies. They observed a large increase in ϵ' and ϵ″ with increase in temperature and salt content however, both the properties were lower at MW frequencies compared to RF frequency. Power penetration depth increased with increase in salt content but decreased with increase in temperature.

Liu *et al.* (2012) studied the dielectric properties of raw and preheated meat of yellowtail, red sea bream and Atlantic salmon over the frequency range of 200–3660 MHz and at temperatures of 10–90 ◦C. Raw and preheated fish meat samples behaved differently with respect to dielectric properties as the ϵ' of the raw samples decreased markedly than that of the preheated samples.

Changes in protein structure caused by protein denaturation had no effect on dielectric properties of fish, pointing moisture as the single most important factor affecting dielectric properties. A recent study investigated dielectric properties of white shrimp and Antarctic krill during microwave thawing and heating (Yang *et al.*, 2017). Presence of salt had a significant impact on the dielectric properties at microwave frequencies of 300–3000 MHz. During microwave assisted thawing, dielectric properties increased continuously with a rise in temperature especially within the temperature range of − 5 to 0 ◦C.

Li *et al.* (2019) studied the effect of temperature, frequency, and composition on dielectric properties and penetration depth in freshwater and salt water fishes at different temperatures (− 20 ◦C–100 ◦C) and frequencies (1–2500 MHz). The difference in composition led to major differences in dielectric properties and the moisture and fat content of fishes had the major impact.

In hot air assisted microwave drying, the air evaporates moisture from the surface, making a porous structure which restricts the shrinkage in addition to develop a crispy texture in the final product (Guzik *et al.*, 2021). Many reports point out that increase in microwave power reduces the drying time significantly. Microwave drying at different powers (200, 400 and 600 W) was employed to dry tilapia fish fillets by Duan et al. (2011) and the results indicated that final moisture content of the samples decreased with increasing power.

Modelling of microwave drying technique carried out by Darvishi *et al.* (2013) demonstrated Midilli model of drying as the best model for describing the thin layer drying characteristics of sardine fillet by microwave drying. The effective moisture diffusivity varied from 7.158 × 10− 8 to 3.408.1 × 10− 8 m2 /s over the microwave powers tested (200, 300, 400 and 500 W) with minimum specific energy consumption at 500 W (3.78 MJ/kg water). Agreeing to this finding, Kipcak and Ismail (2021) in their research reported a reduction in drying time with increasing power. The authors further confirmed Midilli model for describing the drying behaviour of microwave drying appropriately. In a latest study,

Wei *et al.* (2020) compared the effects of hot air drying, microwave drying and hot air-microwave drying on the color, texture, microstructure, rehydration ability etc. of tilapia fillets. Thermal efficiency of hot air-microwave drying was increased by 5-fold compared to hot air drying and the process improved the color, chewiness and elasticity of dried fillets apart from increasing its rehydration and recovery ratios.

Wang *et al.* (2018) studied drying of Tilapia fillets in microwave oven at 400 W for microwave drying and at 10 W/g and 0.09 MPa for vacuum microwave drying. Osmotic-MVD reduced the drying time by 99% compared to the traditional drying method (HAD). Rehydration rate of HAD was more than double the rates of O-MD and O-VMD.

Microwave heating has extensive applications in drying technologies. Drying is an important preservation technique for fish. Microwave energy offers wide opportunities to get over the disadvantages of conventional drying method such as hot air drying. Heat transfer efficiency of traditional drying method is poor as it takes longer time to reach equilibrium and often result in overheating of the product. On contrary, microwave heating is volumetric; the product gets heated throughout and removes water with greater efficiency (Erle, 2005).

Liu *et al.* (2012) investigated the effect of different microwave power densities, microwave gap ratios (MGR), time of drying and vacuum levels on the quality of tilapia fillet dehydrated by vacuum microwave drying after osmosis. Moisture content of the fillets reduced significantly with increasing power density, time of drying and degree of vacuum and the authors suggested the optimum process parameters as power density = 20 W/g, MGR = 2, vacuum degree = 0.08 MPa and microwave time = 10 min for producing a high-quality product. Some of the recent studies investigated the physicochemical characteristics of microwave vacuum dried fish products.

Liu *et al.* (2018) studied drying of Tilapia fillets at different microwave gap ratios (MGR: 1, 2, 3, 4, and 5), microwave times (4, 6, 8, 10, and 12 min), power densities (10, 15, 20, 25, and 30 W/ g) and degrees of vacuum (0, 0.02, 0.04, 0.06, and 0.08 MPa). Moisture value of fillets was decreased with the increased drying time, power density and vacuum degree. optimum process parameters were MGR = 2, microwave time = 10 min, power density = 20 W/g, and vacuum degree = 0.08 MP.

Viji *et al.* (2019) dried Indian mackerel in microwave vacuum oven at 600 W and 600 Hgmm MVD sample was superior to HAD samples in terms of sensory attributes, rehydration properties and texture. Wei et al (2020) Hot air drying, microwave drying and hot air microwave combined drying Hot air microwave drying was superior to MD as HAMCD improved the hardness, chewiness, and elasticity values, and can obtain crispy tilapia fillets.

Qin *et al.* (2020) studied drying of grass carp Drying in microwave oven at 385 W power for different time (2, 4, 6, 8, 10 min) followed by hot air drying at 65 ◦C Grass carp fillets dried by microwave hot-air combined drying had better qualities compared with single hot-air drying. 6-min microwave drying time followed by HAD given the optimum results.

Pankyamma *et al.* (2019) studied drying of squid shreds in microwave vacuum oven (700 W) and sun drying and hot air-drying Shrinkage and muscle toughness were less with MVD samples. Browning of squid shreds was controlled by microwave drying. Pankyamma et al (2021) dried tuna chunks in microwave vacuum oven at different powers (600, 650 and 700 W) for 2 h Increasing microwave power resulted in reduced moisture content and water activity in dried tuna chunks. Protein denaturation and lipid oxidation increased with microwave power.

2.2.1 Response surface methodology in food drying

Ikrang and Umani (2019) used CCRD of response surface methodology involving thirty experiments to optimize drying conditions for catfish. It consisted of for each of the four drying process factors with 4 axial points and 6 replications at the centre points. Coded values of the independent variables (−1, 0, 1) were used, the coded values −1, 0 and 1 represent the lowest, medium and highest levels respectively. The independent process variables for the drying process were temperature (50–70 ◦C), product thickness (10–20 mm), salt concentration (0–20%) and drying time (480–600 min.). Two factorial interaction (2FI) regression model describing the effects of independent drying process variables on the moisture content was developed.

Ramesh *et al.* (2018) prepared fish crackers by blending lean fish (*Nemipterus japonicus*) along with tapioca, corn and sago in the proportion 40:60 (cooked fish: starch) to optimize the gelatinization conditions in order to improve the expansion and crispiness using Response Surface Methodology (RSM). The process variables were steaming time (20, 40, 60 min), gel setting time (12, 18, 24 h) and drying temperature (40, 50, 60 °C). The responses taken were linear expansion, bulk density and crispiness. The optimum condition predicted by RSM to have high linear expansion of products was at a steaming time of 40 min, a gel setting time of 24 h and a drying temperature of 40 °C.

The chemical properties (moisture content and crude protein), microbial properties, and the panellist’s preferences for *Sardinella lemuru* fish products after the addition of chitosan was determined using RSM. Optimization analysis using Response Surface Methodology showed that the temperature acquired was 60.93˚C. The chitosan concentration amounted to 3.51%, resulting in a water content of 23.47% and protein content of 49.91%. The number of microbial colonies in all treatments did not exceed the maximum limit of salted fish category product, based on SNI 8273 – 2016, but the fungal growth was found in samples with a temperature of 53 and 55˚C on the 20th day (Afghani *et al.*, 2023)

Akpan *et al.* (2022) optimized the process parameters for drying of prawns to get minimum moisture content using RSM. The drying process was influenced by three level of temperatures (50, 60, and 70 °C), prawn thickness (10, 15, and 20 mm), salt concentration (0, 10, and 20 percent), and drying duration (480, 520, and 600 minutes). The impacts of independent drying factors on moisture levels were described using a two factorial interaction (2FI) regression model. For MC, the influence of temperature and drying time were stronger than those of thickness and salt concentration. Drying duration of 600 minutes, prawn thickness of 14.17 mm, temperature of 62.82 °C, and salt concentration of 9.03 percent were found to be the optimal. Moisture content was found to be 2.56 percent w.b. at these optimum conditions. The correlation coefficient (R2) for the model equation was determined to be R2 = 0.992, indicating that the experimental results were validated with the empirical model.

Majdi *et al*. (2019) applied RSM to state an optimized system for convective drying of apple slices using desirability function. The interaction of the independent parameters including air temperature (T = 70–90 °C), air velocity (V = 4–5 m/s), and apple slice geometry (G = circle, square, and triangle) with the dependent variables consist of drying time, energy consumption, and shrinkage is determined. Minimum drying time, energy consumption and shrinkage is regarded as the optimizing drying conditions of apple slices. Experimental results are adapted by a second-order polynomial model where analysis of variance is utilized to define model compatibility and optimal drying conditions. The optimal conditions of combined optimized responses were 90 °C inlet temperature, 5 m/s inlet velocity, and square geometry which designated by maximum desirability function (D = 0.781).

Erbay and Icier (2009) used response surface methodology to optimize operating conditions of the drying of olive leaves in a tray drier and desirability function used as the methodology for the optimization. Optimization factors were air temperature (40–60 °C), air velocity (0.5–1.5 m/s) and process time (240–480 min) while investigated responses were total phenolic content (*PC*) and antioxidant activity loss (*AC*), final moisture content (*MC*), and exergetic efficiency (η).

Sumic *et al.* (2016) applied Box–Behnken experimental design with response surface methodology for optimization of drying process in terms of physical (moisture content, water activity, total color change, firmness and rehydratation power) and chemical (total phenols, total flavonoids, monomeric anthocyanins and ascorbic acid content and antioxidant activity) properties of dried samples. Temperature (48–78 °C), pressure (30–330 mbar) and drying time (8–16 h) were investigated as independent variables. Experimental results were fitted to a second-order polynomial model where regression analysis and analysis of variance were used to determine model fitness and optimal drying conditions.

Response surface methodology was used to optimize the drying conditions based on specific energy consumption and quality of dried okra. The drying experiments were performed using a central composite rotatable design for three variables: air temperature (40–70 °C), air velocity (1–2 m/s) and microwave power level (0.5–2.5 W/g). The quality of dried okra was determined in terms of color change, rehydration ratio and hardness of texture. A second-order polynomial model was well fitted to all responses and high R^2 values (>0.8) were observed in all cases. The drying conditions of 1.51 m/s air velocity, 52.09 °C air temperature and 2.41 W/g microwave power were found optimum for product quality and minimum energy consumption for microwave-convective drying of okra (Kumar *et al*., 2014).

Giri and Prasad (2007) applied a rotatable central composite design was used to develop models for the responses to optimize drying of button mushrooms. Analysis of variance showed that a second-order polynomial model predicted well the experimental data. Optimum drying conditions of 202 W microwave power level, 6.5 kPa pressure, and 7.7 mm slice thickness were established for microwave vacuum drying of button mushrooms. Separate validation experiment was conducted at the derived optimum conditions to verify the predictions and adequacy of the models.

Han *et al*. (2010) used predictive regression models were developed by using an orthogonal rotatable central composite design. The influences of various variables and their interactions on response variables were analyzed using a response surface method, and tridimensional response surfaces were plotted. The optimal conditions were determined to be 12.0 W/g microwave power, 0.089 MPa vacuum level, and 0.692 kg/kg db initial moisture content. A separate validation experiment was conducted at the derived optimum conditions to verify the prediction and adequacy of the models.

Moisture diffusivity is a transport property related to drying of solid foods or rehydration phenomena. The accurate of moisture diffusivity prediction can lead to optimization of drying process (Jain and Pathare, 2007). Fish drying process is a mass transfer phenomenon. It involves simultaneous reduction in volume or shrinkage during drying process which is undesirable in dried products. The reduction in volume is due to moisture transfer from dried fish products. Shrinkage may be due to heat transfer into fish fillets and mass transfer from the inside to the surroundings which negatively affects the dimensions and shape of the dried products (Mayor and Sereno, 2004).

Response surface methodology (RSM) is a statistical and mathematical method that has been developed and successfully used to improve and optimize drying processes in food research and industry. RSM has been used to reduce in the number of experimental trials needed to evaluate multiple parameters and their interactions, thus, requiring less time and labour. RSM has been widely used to improve product quality in the drying process and in new product development, as well as improving existing product design (Kumar et al., 2009). Several studies have been carried on the use of RSM in food drying process optimization such as optimization of dried fish to improve product quality (Shih et al., 2009).

2.2.2 Drying kinetics and modelling

Several research works have been done on drying kinetic of fish. Drying kinetics is an important phenomenon which is used to predict and determine the drying behaviour of food materials as well as in optimization of food drying parameters. In determining drying kinetics, a good understanding moisture diffusivity as well as mass transfer coefficients of different food materials are needed (Vega-Gálvez et al., 2011; Prasad and Sharma, 2006).

Darvishi *et al*. (2012) investigated on microwave drying of shrimp and showed that the times taken for drying of shrimp from the initial moisture contents of 3.103% (d.b.) to final moisture content of around 0.01% (d.b.) were 11.75, 7, 4.75 and 4 min in 200, 300, 400 and 500W, respectively. The drying data were fitted to 7 thin-layer drying models. The performances of these models were compared using the determination of coefficient (R2), reduced chi-square (χ^2) and root mean square error (RMSE) between the observed and predicted moisture ratios. The results showed that Midilli model was found to satisfactorily describe the microwave drying curves of shrimp. The activation energy for moisture diffusion was found to be 12.834W/g.

Farhang *et al. (*2011) used a laboratory microwave oven was used to dry the shrimp, applying microwave power in the four levels of 200, 300, 400 and 500W. Results indicated that drying took place in the falling rate period. The drying rate increased with drying microwave power, but decreased with moisture content. The effective diffusivity varied from 1.54×10^{-10} to 1.43×10^{-9} m^2 /s. About 22.54% increase in drying efficiency and about 28.94% (0.937MJ/kgH_2O) decrease in specific energy consumption could be obtainable by increasing the microwave power from 200 to 500W.

Drying kinetics explains the moisture removal process and how it relates to process variables and therefore important in developing drying model (Gupta and Patil, 2014). There are different drying models for thin layer drying and three models; theoretical, semi theoretical and empirical models have been described (Khazaei and Daneshmandi, 2007).

Fick's second law of diffusion is an example of the commonly used theoretical model. Among the shortcomings of the theoretical models are as follows: it generates erroneous results and complex for practical applications. Hence, in food drying semi-theoretical models have been developed as a better model to fit the drying data of fish fillets to be dried (Hadrich *et al*., 2008; Konishi *et al*., 2001; Vega-Gálvez *et al.*, 2009). Handerson and Pabis model has been used for model drying of corn, but due to inaccuracy and high degree of temperature difference between corn seeds and air, the model could not be fitted during the first 1 or 2 h of drying.

Air temperature has been found as a crucial factor affecting drying kinetics during food drying. It has been observed by Krokida *et al*., (2003), that the drying constant, equilibrium moisture content and moisture diffusivity as a direct relationship with drying temperature. Several studies have been carried out on effects of air temperature on the drying kinetics. Abano *et al*., (2011) used three empirical models namely Page, Logarithmic and Henderson and Pabis model to explain the drying kinetics.

Different air temperatures were used for drying of tomato slices and observed inconsistency in drying high temperatures which show the importance of diffusion as an important physical mechanism for moisture removal. In another study on the effects of sample size and the conditions of air on the drying kinetics of produce Krokida *et al*., (2003) observed that the first-order drying kinetics predicted the drying kinetics of the samples at two ambient temperature and elevated temperatures. They also observed that there was a direct relationship between temperature of the air and loss of moisture and an inverse relationship with the moisture equilibrium of the sample. Time of drying according to Tzempelikos *et al*., (2014) has been observed to be influenced by the air temperatures and air velocities of drying. They also observed that drying time was inversely related to air velocity drying temperature.

Influence of shape on the drying kinetics has been studied by Borges *et al*., (2011). Disk and cylindrical shapes cut produce were dried in a tray drier and observed that drying rate was significantly higher with disk shaped produce when compared to the cylindrical shaped produce. They also observed that temperature has positive effect on the produce and that the effect of blanching could be seen on the produce. Also, air velocity and air temperature were observed to have profound effect on the drying time.

Pre-treatments are procedures undertaken to enhance the quality of produce and drying process. It is done on produce before drying to reduce the drying time, improve taste, structure, to conserve the flavour and to maintain the nutrition of produce. Pre-treatment reduces the initial moisture content and modify the tissue of the produce which helps to fasten the drying rate (Omolola *et al*., 2015).

Relative humidity is the amount of moisture in the air at a particular time. It has serious influence on drying rate and drying kinetic of fish fillets Various drying temperature and relative humidity at a constant air velocity were used. They found that a two-term model was more fitted to the drying kinetics more accurately than the rest of the models used in the experiment. They also observed that the drying time as inverse relationship with the temperature at constant air humidity. And that relative humidity of the air had an insignificant influence on the drying curve due to the initial moisture content of the produce (Azzouz *et al*., 2002).

Duan *et al.* (2011) dried tilapia fish in hot air drying for 4 h followed by drying in a laboratory microwave drying oven for different times (2, 4, 6, 8, 10 min) at different microwave powers (200, 400, 600 W). The shrinkage ratio and rehydration ratio increased as the microwave power increased. Final moisture content reduced with an increase in microwave power. Wan *et al.* (2013) dried salted grass carp fillet in vacuum microwave dryer at 95 kPa (absolute pressure), and microwave intensities were 1, 4, and 7 W/g. Vacuum microwave drying significantly increased effective moisture diffusivity. The vacuum microwave dried fillets were lighter, whereas the hot air dried grass carp fillets were darker and more yellowish. Darwishi *et al*. (2013) dried sardine under Microwave oven drying at 200, 300, 400 and 500 W microwave power levels Drying time of the samples significantly reduced as the power input increased. The effective diffusivity varied from 7.158×10^{-7} to 3.408×10^{-8} over the microwave power range.

Wang *et al*. (2013) designed pilot-scale microwave vacuum dryer at 2.1 kW and 95 kPa, power level and vacuum degree, respectively for silver carp fish. MVD products rehydrated faster and had higher rehydration ratio as well as lower WHC, hardness, springiness, cohesiveness, and chewiness than others. Chen et al (2013) dried squid cubes in microwave dryer at 2100 W and 4.2 W/ g power density. MD sample showed high rehydration ratio with a puffing phenomenon. Microwave drying was advantageous to air drying in terms of drying rate, shrinkage percentage, and rehydration ratio.

Kipcak and Ismail (2021) dried salmon in microwave oven at four power levels of 90, 180, 270 and360 W. Logarithmic and Midilli models were considered the best models to represent the microwave drying kinetics. The effective moisture diffusivity values varied from 31.74 × 10-7 and 16.4 × 10-7 m2 /s. Energy efficiency has increased with the increase of microwave drying power. Fu *et al*. (2015) dried silver carp under microwaves and observed reduction in drying time and lipid oxidation. The TBARS decreased with power intensity during microwave drying but increased with the vacuum during MV drying.

Darvishi *et al*. (2013) studied drying characteristics of sardine under microwave drying. The effect of microwave drying on drying rate, effective diffusivity, and energy consumption of sardine fish was examined at four different microwave powers (200, 300, 400 and 500 W). It was found that the moisture content was reduced from 2.76 to 0.01 (dry basis) and drying time of the samples was significantly reduced from 9.5 to 4.25 min as the power input increased. Five thin layer drying models were fitted to drying data. The Midilli model was selected as the best according to R^2, χ^2 and RMSE. The drying of fish samples took place in the falling rate period and was governed by moisture diffusion. The effective diffusivity varied from 7.158×10^{-8} to 3.408×10^{-7} m^2/s over the microwave power range. No significant differences were observed between the specific energy consumption of microwave-dried sardine fish ($\alpha = 0.05$). However, minimum specific energy consumption (3.78 MJ/kg water) was obtained at 500 W microwave levels.

Kipack (2017) studied the microwave power levels (90, 180, 360, 600 and 800 W) were applied to *Mytilus edulis* to determine their effect on drying kinetics, rehydration characteristics and energy consumptions. The optimal drying times of 16, 5 and 2 min were determined for microwave power levels of 90, 180 and 360 W, respectively. However, at the microwave power levels of 600 and 800 W, the optimal drying times were 80 and 60 s, respectively. The experimental results indicate that the drying kinetics, rehydration characteristics and energy consumptions are slightly affected by the change in microwave power levels. Seven different thin-layer drying models that are widely used in the literature were applied to the experimental data. The results showed that the Weibull model best fits the experimental data (R^2: 0.998135–0.999929, χ^2: 0.000029–0.000401, and RMSE: 0.004172–0.018733) of the drying kinetics of *Mytilus edulis*. The effective moisture diffusivity was determined to be between 2.74×10^{-8} and 4.79×10^{-7} m^2/s. Using a modified Arrhenius-type equation, the activation energy was found to be 95.131 kW/kg. The microwave power level of 360 W was found to be the most effective, considering the minimum energy consumption.

2.2.3 Quality evaluation of dried fish and fishery products

Nuray (2016) studied the changes in biochemical and sensory attributes of Turk-ish traditional salted dried fish products "çiroz" during storage packaged by oxygen absorber and vacuum were investigated. For this purpose, total volatile basic nitro-gen (TVB-N), trimethylamine nitrogen (TMA-N), TBA index values (TBA-i), free fatty acids value (FFA) and peroxide value (PV), sensory attributes and micro-biological analyses were carried monthly during storage.

Niamuy *et al.* (2007) Small shrimp (350 to 360 shrimp/kg) and large shrimp (150 to 160 shrimp/kg) were boiled and then dried until their moisture content was around 25% (d.b.). It was found that the degree of color changes, toughness, and shrinkage of shrimp increased while the rehydration ability decreased with an increase in the concentration of salt solution and boiling time. Size of shrimp and drying temperature significantly affected all quality attributes of dried shrimp. The conditions that gave the highest hedonic scores of sensory evaluations for small dried shrimp are the concentration of salt solution of 2% (w/v), boiling time of 7 min, and drying air temperature of 120 ◦C. On the other hand, the conditions that gave the highest hedonic scores of sensory evaluations for large dried shrimp are the concentration of salt solution of 4% (w/v), boiling time of 7 min, and drying air temperature of 100 ◦C. The quality attributes of dried shrimp measured by instruments correlated well with the sensory attributes, especially the color of dried shrimp

Lee *et al.* (2021) reported that longer heating times decrease the APC levels, but increase the cook loss, color values (lightness, redness, and whiteness), and texture (hardness, cohesiveness and chewiness) of the white shrimp samples. In particular, the white shrimp is fully cooked and gains a completely red appearance, along with no APC detected after heating in the MAIH system at 130 °C for at least 80 s or at 90 °C for at least 100 s. In summary, to achieve a good appearance, no APC detected, and low cook loss, the following heating conditions are recommended for cooking white shrimp in the MAIH system: heating at 130 °C for 80 s or at 90 °C for 100 s. This novel MAIH technology allows food to be heated and sterilized after being packed, thereby eliminating the post-pollution issue.

Effective moisture diffusivity is the movement of moisture in fish products which is dependent on drying rate (Azzouz *et al.,* 2002; Aghbashlo *et al*., 2008). Effective moisture diffusivity differs from drying rate in that effective moisture diffusivity is related to moisture velocity within the material, while drying rate is the moisture vaporizing rate to air which is directly related to the pressure gradient that exists between the material and the air as a result of temperature gradient (Azzouz et al., 2002; Aghbashlo *et al.*, 2008).

Effective moisture diffusivity is used to determine the drying rate of fish products and an indicator to determine an appropriate drying technique that could be used to extend the products shelf-life. Effective moisture diffusivity has been found to be a function of material moisture content, temperature and material structure (Aghbashlo *et al*., 2008). Moisture diffusivities have been found to be directly related to oven temperature according to Omolola *et al.,* (2015). Several researchers Aghbashlo et al., (2008); Caglar et al., (2009); Doymaz and Ismail, (2011) have also reported similar findings.

Colour is a very important quality characteristic of dehydrated fish fillets to almost every consumer. Colour is one of determinant factors and an indicator of the intrinsic good qualities of dried fish (Doymaz *et al.,* 2006). The surface characteristics of fish has been found to be changed by drying operation parameters which also affects colour and reflectivity of dried fish (Fellows, 2009). The colour of fish products is a very important quality parameter that affects consumer acceptance of dried fish products. L (lightness), a (redness), b (yellowness) colour values of the fresh and dried fish fillets can be measured using a spectral photometer or a colorimeter before and after drying.

Bulk density can be described as the ratio of the mass of fish to its total volume. Bulk density of fish could be measured by using a measuring cylinder by filling the fish fillets in a cylinder of known volume and then weighing with a balance to determine the difference (Akpinar and Bicer, 2005).

Shrinkage is an important physical change in the product during drying which alters the shape and volume of the product and the quality of the food material (Pinto and Tobinaga, 2006).

Quantity analysis findings showed that boiling significantly enhanced the total content of volatile compounds from 193.62 ng/g to 387.65 ng/g in shrimp. In boiled shrimp, 1-octene-3-ol, octanal, and hexanal were identified as aroma-active compounds. Trimethylamine and pyrazines were mainly produced during the drying period, and pyrazines considerably increased by 47.16 ng/g in the later drying period. 2-Ethyl-5-methyl-pyrazine, octanal, trimethylamine, 1-octene-3-ol, and hexanal majorly contributed to the flavor of dried shrimp. These results indicate that the boiling and later drying periods are vital stages for enhancing flavor quality (Hu *et al*., 2021).

Akonor *et al.* (2016) studied the influence of different drying methods on physical and nutritional properties of shrimp meat was investigated in this study. Peeled shrimps were dried separately using an air-oven dryer and a tunnel solar dryer. The drying profile of shrimp meat was determined in the two drying systems by monitoring moisture loss over the drying period. Changes in colour, proximate composition, and rehydration capacity were assessed. The rate of moisture removal during solar drying was faster than the air-oven drying. The development of red colour during drying was comparable among the two methods, but solar-dried shrimps appeared darker () than the air-oven-dried. Chemical analysis indicated that protein and fat made up nearly 20% and 2% (w.b.) of the shrimp meat, respectively. Protein and ash content of shrimp meat dried under the two dryer types were comparable but fat was significantly higher in oven-dried meat (2.1%), compared to solar-dried meat (1.5%). Although rehydration behaviour of shrimp from the two drying systems followed a similar pattern, solar-dried shrimp absorbed moisture more rapidly. The results have demonstrated that different approaches to drying may affect the physical and nutritional quality of shrimp meat differently.

Thermal treatments given to seafood during processing alter the biochemical composition which imposes a great influence on nutritional value and technological characteristics. Contrasting results of microwave heating are reported in literature because of difference in power, time, design of oven employed.

Effects of microwave cooking on fatty acid profile of fish have been studied extensively. In their experiment, Stephen *et al*. (2010) evaluated the chemical changes in skip jack tuna induced by different cooking methods such as cooking, frying, canning and microwaving. The loss in major fatty acids after microwave heating was lower than canning and frying, but higher than cooking. Reduction of C20:5 (EPA) was 20–25% whereas loss of C22:6 (DHA) was 55%. Another investigation on fatty acid profile affected by different cooking method indicated an increase in PUFA especially EPA and DHA of crevalle jack (Caranx hippos) and red drum (Sciaenops ocellatus) after cooking in microwave oven (Castro-Gonzalez *et al*., 2015).

Fatty acid profile of red mullet affected by different cooking methods was examined by Koubaa *et al.* (2012). The result indicated a protective effect of microwave cooking on total fat and PUFA content with a suitable ω6/ω3 ratio. This finding is in agreement with Asghari *et al.* (2013) as they observed the highest ω3/ω6 ratio in microwave cooked rainbow trout compared to boiled and fried samples. Microwave process altered the PUFA content of mussels cooked for 3 min at 750 W (Biandolino *et al.*, 2021). However, the process reduced the content of unfavourable n6 fatty acids, presenting a best method for cooking. Though n3/n6 ratio was within the recommended value, orange spotted grouper cooked by microwave had the highest Atherogenicity index (AI value), indicating a poor lipid quality as reported by Momenzadeh *et al*. (2016).

Lipid oxidation changes during microwave heating are of great interest to the researchers. A good amount of polyunsaturated fatty acids in fish render them more liable to oxidation during microwave processing. While examining the effects of different cooking methods on carp fish cutlet, Talab (2014) observed a reduction of primary and secondary oxidation products by microwave heating. The authors assume that a reduction in PV and TBARS of microwaved samples could be due to further breakdown of peroxides and interaction of secondary oxidation products with proteins, respectively.

Fu *et al*. (2015) demonstrated a low degree of lipid oxidation in microwave dried silver carp slices compared to its hot air -dried counterparts. More interestingly, the TBARS value decreased with power intensity, but increase in vacuum didn't protect lipid from oxidation. In contrary, Viji *et al.* (2019) observed higher degree of lipid oxidation in microwave vacuum dried mackerel compared to hot-air dried mackerel. Similar results are reported by Pankyamma *et al.* (2021) in MVD tuna chunks.

Solubility of water soluble and salt soluble nitrogen fractions of microwave vacuum dried mackerel were significantly lower to hot air-dried mackerel, caused by structural alterations (Viji *et al.,* 2019). In similar research, Pankyamma *et al.* (2019) examined FTIR spectra of dried squid shreds prepared by microwave vacuum drying technique and conventional drying methods. In MVD samples, the amide I band, a reliable indicator of protein secondary structure was shifted to lower amplitude than that noticed in sun dried and air-dried samples.

Compared to conventional heating, MH improved the β-sheet content up to 26.85%. Secondary structure of protein in shrimp affected by microwave processing (1000 W for 5–15 min) was studied by Dong *et al.* (2021). The results show that intensity of tropomyosin, an allergen of shrimp was reduced with the time and temperature of treatment results in some loss of vitamins and minerals of fish muscle.

Asghari *et al.* (2013) shows that the amount of macro (Na, K, Ca, Mg and P) and micro (Zn and Fe) minerals increased significantly after microwave cooking at 400 W power for 12 min. According to the observations of Momenzadeh *et al*. (2017), microwave cooking of orange spotted grouper significantly increased vitamins A and D than raw fish, but the amount of vitamin B1 and B3 was lower to the later. The macro minerals like Na, Ca and Mg showed a reduction after microwaving whereas P and K contents were reduced, the authors report. When microwave cooking of grass carp increased Vitamins A and B3 contents, the amount of vitamin D was found to be lower than steamed and poached samples (Golgolipour *et al*., 2019). Moreover, microwave cooked samples presented the highest Na, K, Mg, Mn, Zn and Ca values while the amount of P was lower compared to its counterparts cooked by other methods.

Duan *et al.* (2011) reported that rehydration ratio of sardine samples dried at 200W, 400W and 600W of microwave power for 4min after pre-drying at 50 ◦C, were 72%, 75% and 82%, respectively. So, the effect of the microwave power on the rehydration ratio was closely related to the temperature of pre-drying. The lower the temperature of pre-drying, the more rapid the increase in rehydration ratio.

Shrinkage of dried sardine was highest during the first 2min and then seems to be relatively constant. The shrinkage ratio of samples dried at 200W, 400W and 600W of microwave power for 2min after pre-drying at 40 ◦C, were 54%, 62% and 65%, respectively (Duan *et al*., 2011).

2.3 Solar drying of fish and fishery products

Chavan *et al.* (2008) Eight trials were conducted for drying mackerel by a solar biomass hybrid cabinet dryer (S-BHCD) and open sun drying (OSD) at air temperatures of 32.39–57.69°C, relative humidity 23.9–85.8%, and air flow rate of 0.20–0.60 m/s. The solar radiation ranged between 287 and 898 W/m^2 during the time of experimentation. At nighttime, drying was carried out by combusting biomass. The initial moisture content of the processed mackerel was 72.50±0.44% (w.b.) and was reduced to the final moisture content of 16.67±0.52% (w.b.) in S-BHCD and 16.92±0.54% (w.b.) in OSD. Eleven drying models were used and the coefficients of determination (R^2) and constants were evaluated by nonlinear regression to estimate the drying curves of dried mackerels. The *Midilli* model was found to more satisfactorily describe the drying process of mackerel in S-BHCD with R^2 of 0.9999, χ^2 of 0.0000374, and *RMSE* of 0.0057. In the OSD, a two-term drying model satisfactorily described the drying process with R^2 of 0.9996, χ^2 of 0.0000519, and *RMSE* of 0.0072.

Marine food contains highly sensitive tissues which require optimum drying conditions to ensure the effective drying and maximum retention of quality of the product. Fresh fish is a highly perishable commodity and contains about 80% of water. Upon drying, the moisture content of the final product must be reduced to less than 20-25% (on a wet weight basis) to arrest the growth of microbes, the action of enzymes, and other autolytic chemical reactions. However, it is recommended to reduce the moisture content of the marine product below 15% (on a wet weight basis) if the product was not treated with salt and other preservatives to prevent further mould growth during storage (Rahman, 2008). Traditional methods followed for the immediate preservation of fishery products after harvest and storage were fish salting or brining, open sun drying, and smoking. Among the methods, Open sun drying (OSD) is commonly followed by fisher-folks in developing countries to dry marine products. In this method, fish is directly exposed to the natural sunshine and movement of the wind. This method of drying is cheap and easy to operate; however, it often results in inferior quality of product due to its dependence on weather conditions and vulnerability to the attack of dust, rains, insects, pests, and microorganisms (Okoroigwe *et al.,* 2013). A study reports that losses occurring in OSD due to the activities of animals, insects, and weather conditions were 30-40% of total dry fish production (Hollick, 1999). The marine industry is one of the major sectors in which solar energy can play an important role in the processing and drying of fish. Hence, solar drying can be considered as an alternative to sun drying that is clean, green, and affordable (Sablani *et al*., 2003). It is an advanced form of sun-drying in which a simple structure is used to enhance the effect of incident solar radiation and convective power of the natural wind. This method of drying generates higher air temperature and lower relative humidity, which results in improved drying rates and lower moisture content of the final product (Bala and Mondol, 2001). Solar dried products ensure a reasonably longer storage life. However, the solar drying system should not be introduced for fishery products in isolation. Hence, the solar drying process for fish should be complemented with improved salting, better packaging, and storage techniques with proper sanitary measures.

2.3.1 Solar drying of fish

Dried fish supplies vital animal protein to humans and is consumed as a key dish or used as a flavoring agent in other foods and has a huge demand during the fishing ban period in India (Das *et al.,* 2013). Various types of solar dryers have been designed and evaluated with different fish species for its performance, drying kinetics, and quality characteristics of dried products. Bala and Mondol (2001) designed a low-cost solar tunnel dryer for drying silver jew fishes. The maximum temperature of 52.2°C was observed in the solar collector outlet during the drying experiments. The salt-treated jewfish (67% (w.b.)) was reduced to a final moisture content of 16.23% (w.b.) and 30.62% (w.b.) in solar tunnel dryer and open sun drying method in 5 days, respectively. They reported that the fish samples in the dryer received maximum energy from the solar thermal unit whereas a significant amount of energy has been lost to the environment in open sun drying. The proximate analysis of the salted treated dried fish revealed that the fish dried in the solar tunnel dryer was uniformly dried with low moisture content.

Fudholi *et al.* (2013) studied the energy consumption of a solar hybrid dryer integrated with a backup diesel burner for drying salted silver jewfish. They reported that the solar collector efficiency varied from 30 to 68%. Out of the total energy required for drying of silver jewfish, solar thermal collector supplied 66% and the remaining energy was met from diesel burner heat backup (29%). The dryer required about 8 h to remove the moisture content of silver jewfish from 64% to 10% (wb). The complete drying was achieved with lesser drying time due to the continuous supply of heat through the diesel burner. The specific energy consumption and drying efficiency of the solar dryer was about 2.92 kWh/kg and 23%, respectively.

Sablani *et al*. (2003) developed three variants of solar-based drying system namely rack (OR), convection cabinet (CC), and multi-rack dome (MD) dryer, and evaluated the performance using sardines. The final moisture contents obtained at the end of drying were 16.65 % and 10.10 % for the open rack (OR) and cabinet (CC) dryers, respectively. The final moisture contents of fish samples dried in the top and bottom layer of the multi-rack dome

(MD) dryer were found to be 17.53 and 18.56 % due to variations in temperature and relative humidity inside the drying chamber. The microbial quality of the sardine obtained under the MD unit was poor due to lower drying temperatures between 11℃ and 37℃. They reported that the sardines dried under a cabinet dryer produced the best product with lower microbial load, moisture content, and fat oxidation.

Murali *et al.* (2020) evaluated the performance of a solar-electrical hybrid dryer (S-EHD) using Indian mackerel (*Rastrelliger kanagurta*) and compared it with open sun drying (OSD). The salt-treated mackerel (61.5% w.b.) was dried under for S-EHD for 8 h to obtain the final product with the moisture content of 31.8% (w.b.) whereas open sun drying took about 32 h to attain the similar final moisture content of 30.25% (w.b). They observed the drying efficiency of 23.81% for salted Indian mackerel drying due to maximum utilization of incident solar radiation by the dryer. Biochemical analysis (TVB-N, TMA, and TBA) of dried samples revealed that the mackerel dried under S-EHD was better than OSD. Also, sensory evaluation conveyed that solar-electrical hybrid dryer produces good quality dry fish with a higher overall acceptability score.

A solar dryer integrated with a biomass heat backup system was experimented with using queenfish by Hamdani *et al*. (2018). The photograph of a hybrid solar dryer assisted with a biomass-based air heating system. The drying experiments were carried out from 9.00 am to 4.00 pm with the incident solar insolation and from 4.00 pm to till 6.00 am the next day with a biomass burner while maintaining the drying air temperature in the range of 40-67℃. The initial moisture content of the queenfish was 50.5% (on a wet basis) which was reduced to a final moisture content of 12% in 23 h. The financial analysis revealed that the total cost of the developed solar hybrid dryer was 1870 USD with a break-even point of 2.6 years.

A mixed-mode solar tent dryer of 5 kg capacity was developed for drying Bombay duck fish by Mehta *et al.* (2018). The maximum solar collector outlet temperature of 75°C and average drying chamber temperatures of 65°C was observed in the study. The initial moisture content was about 89% (w.b) and that was dried to 10% (w.b.) in 18 h in the solar dryer and it consumed 38 h open sun drying method. The drying efficiency of the developed solar tent dryer was determined to be 25.42%. The authors observed that a solar tent dryer of small size would be of great help for the coastal communities in the hygienic and quality drying of marine products.

Patterson *et al.* (2018) studied the effect of sun and solar drying on the effect of drying method on the quality of Indian anchovies. The proximate composition and sensory assessment of the samples revealed significant differences due to the method of drying.

Samples dried under solar setup have shown a good organoleptic score compared to the open-air sun-dried samples. The study indicated that the overall quality of fishes dried under the solar dryer was better than the traditionally sundried fish, thus the study concluded that solar drying can be used as an eco-friendly technique for small-scale seafood industries.

2.3.2. Solar drying of shrimp/prawns

Shrimp, a high-value seafood product in the world, is reported to contain about 20% of protein with essential amino acids and other micronutrients. It is an extremely perishable commodity and requires immediate preservation upon harvest. Drying is one such low-cost technique that can be considered for the preservation of shrimps (Tapaneyasin *et al*. 2005). The desirable quality characteristics of the dried shrimp are lower shrinkage, higher rehydration rate, reddish color, and about 20% of moisture content (Niamnuy *et al*. 2007). Before drying, shrimp is commonly pretreated by boiling in saltwater to reduce the microbial load and further dried at controlled conditions to obtain the quality product. Dried shrimp is widely consumed as a main dish and utilized as a major ingredient in sauces and soups for their pleasant taste and flavor (Akonor *et al.* 2016). Oosterveer (2006) reported that solar drying system is economical and easy to operate besides producing a superior quality dried product. Solar and hot air drying of shrimp was investigated by Akonor *et al.* (2016). They observed that the rate of moisture removal during solar drying was faster than the air-oven drying and solar dried shrimp had dark color with a higher rehydration rate.

Mohod *et al.* (2014) designed and fabricated a semi-cylindrical walk-in type natural convection solar dryer for prawn (*Parapaeneopsis stylifera*) drying. They conducted the experiments under no load and fish-loaded conditions to evaluate the performance of the solar tunnel dryer. About 11.24℃ and 18.29℃ improvements in temperature inside the solar tunnel dryer were observed under the no-load test in winter and summer, respectively. The average drying efficiency of 19 % was reported with 28 % savings in drying time over open sun drying. The economic analysis of prawn drying revealed that the payback period is only 2.84 years.

A drying experiment was conducted by Nagori *et al.* (2014) to evaluate the drying efficiency of an ICAR-CIFT solar–electrical tray dryer using prawns. Before drying, prawns were hot blanched in 2% brine solution for 30 seconds at 85°C to reduce microbial load and to attain better color and texture. The average drying chamber temperature of 49°C was noticed at full load conditions with an electrical backup system. The prawns were dried to the required moisture content of 8.7% in 8 h in the solar - electrical hybrid dryer. The solar collector efficiency of 82% was observed during the experiments. They reported that a solar dryer assisted by electrical heat backup ensured uniformly dried prawns.

A solar dryer with a thermal energy storage system assisted by LPG heater backup was designed by Murali *et al.* (2020). The performance of the solar-LPG hybrid dryer was evaluated using shrimps (*Metapenaeus dobsoni*). The moisture content of fresh shrimp was reduced from 76.71% (w.b) to 15.38% (w.b) within 6 h of drying. The maximum water temperature at the collector outlet was 73.5°C during the experiments. They reported that the solar system supplied 73.93% of heat energy and the remaining energy was supplied by an LPG heater. The maximum collector and drying efficiency obtained for shrimp drying were 42.37% and 37.09%, respectively. Another study by Murali et al. (2021) assessed the quality characteristics of shrimp (*Metapenaeus dobsoni*) under a solar-LPG hybrid dryer. Before drying, the shrimps were pre-treated with 3% salt solution at 80°C for 3 mins. It was observed that the proximate and biochemical aspects of the dried shrimps were not significantly affected by drying conditions. The total plate count of dried shrimp was found to be within the acceptable limit (10^4 CFU/g). They reported that dried shrimp had a shrinkage rate of 13.28% and a rehydration ratio of 2.48. The colour attribute received a significantly higher sensory score.

2.3.3 Solar drying of cephalopods

Cephalopods - mainly cuttlefish, squid, and octopus are abundant in this group. Remya *et al.* (2014) carried out a study on the comparative evaluation of squid rings dried in the open sun and solar drying. The moisture content of the samples was reduced from 82 % to 24% in both modes of drying. They observed that the drying time of squid rings in solar drying (12 h) was three times lower than sun drying (36 h). The microbial count of the sun-dried sample was 4.54 log cfu/g which is not within the acceptable limit whereas samples dried under a solar dryer had 3.12 log cfu/g. Solar dried samples were superior in texture, colour, and appearance. Also, the rehydration capacity of the solar-dried samples was 6% higher than sun-dried samples. The shrinkage percentage was also within the acceptable limit.

Kouhila *et al.* (2020) studied the drying characteristics of Mediterranean mussels under a forced convection solar dryer. This study investigated the convective drying kinetics and modeling of Mediterranean mussels (*Mytilus galloprovincilis*) drying in the forced convection solar dryer at the air temperatures of 50, 60, and 70 °C, and air flow rates of 300 and 150 m^3/h. Mytilus Galloprovincilis was dried from the initial moisture content of 2.30 to 2.81% (d.b) to the final moisture content of 0.36 and 0.46% (d.b) at the drying air temperature of 70 °C. The increase in drying air temperature significantly increased the drying rate of the products. During the Modelling of the drying behaviour of mussels, the logarithmic model was found to accurately predict the drying behaviour of mussels. The study obtained an effective diffusion coefficient value (D_{eff}) between 1.14 $\times 10^{-9}$ to 3.61 $\times 10^{-9}$ m^2/s for mussels drying.

2.4 Packaging and storage studies on dried fish and fishery products

Packaging and storage studies of salted and dried lizard fish *(Sawida* sp.) have been conducted using different synthetic films like low density polyethylene (LDPE) of different gauges, high density polyethylene (HDPE) of 200 gauge, polyvinylidene chloride (PVDC) coated 400 MXXT cellophane, 100 gauge polypropylene (PP) and paper laminate of 100 gauge polythene. The films found most effective in the preliminary studies were subsequently used for packaging and storage of dried fish at atmospheric and lower temperature and humidity conditions for confirming their suitability under these conditions. Polyethylene films of higher gauges showed better results under both sets of conditions. PVDC coated cellophane film also performed satisfactorily under the latter conditions which under the former condition got easily attacked by insects. Lower temperature and humidity conditions in general enhanced the storage life of the dried product (Solanki, 2019).

Michel *et al*. (2015) developed three composite packaging materials; Paper-Polyethylene (PaPe,), Polyethylene-Paper **(**PePa) Polyethylene-Paper-Polyethylene (PePaPe) for packaging of dried fish samples with Polyethylene used as control. Some engineering properties (thickness, water and oil absorption rates) were determined using standard methods. Smoked dried catfish were stored in the three composite packing materials and in polyethylene for six months. The composite materials'thicknesses ranged from 0.23 to 0.31 mm while that of control was 0.27 mm. The water and oil absorption rates ranged from 1.73 to 10.00 g/cm2/min and 2.50 to 10.86 g/cm2/min respectively for the composite materials and 0.36 and 0.28 g/cm2/min respectively for the control.

Olayemi *et al*. (2015) tested Six different composite packaging materials for storing smoked catfish for a period of six months. The thickness of the packaging materials ranges from 0.23 to 046 mm with water and oil absorption rates of the packaging materials varies from 0.23 to 10.00 and 0.28 to 10.857 glcm2/mm respectively. The impact resistance weight also varies from 25 to 50 gm. It was observed that the physical properties of the packaging materials are related to the keeping quality of the stored catfish. The two packaging with better engineering properties offered better barrier functionality that gave better keeping quality for the catfish.

Plahar *et al.* (1991) studied on samples of freshly smoked herring (Sardinella eba) at 140g kg moisture were stored for a maximum period of 6 months usingfive diferent storage methods: in polyethylene bags at ambient temperature with and without desiccant, frozen (-20"C), as well as the traditional and a modijied oven storage technique. Their relative efectiveness in preserving the quality of the fish was evaluated in terms of storage losses, sensory changes and decomposition. Next to frozen storage, the most effective method was the modijied procedure which gave storage yields of 97% and high sensory scores. Proteolytic and lipolytic deterioration was negligible. Although the traditional storage retained high sensory and chemical properties, over 30% storage losses were recorded. Storage in polyethylene bags at ambient temperature was ineffective, while inclusion of desiccant only delayed total decomposition beyond one month.

Daramola *et al.* (2007) assessed the comparative changes in the physical and chemical components of five different species of smoked freshwater fish: Bony tongue, *Heterotis niloticus*, African carp, *Labeo coubie*, Snake fish, *Parachanna obscura*, Nile Tilapia, *Oreochromis niloticus* and African mud catfish, *Clarias gariepinus* during storage. The fish were smoke-dried to average moisture content of 10.41 ± 0.02% and stored. Fish were packaged in black polythene bags and kept in perforated plastic containers. The fish were left in the plastic baskets for 56 days at ambient temperature (25-32ºC).

2.5 Drying studies on oyster mushroom

Gothandpani *et al*. (2007) made investigations to extend shelf life of oyster mushrooms by different methods of drying viz., sun diving, fluidized bed drying and thin layer drying with potassium metabisulphite (KMS) and blanching was done. The quality of mushroom dried in fluidized bed condition at 50°C for 80-120 minutes with 0.5 KMS was found to be superior to other drying methods. Rehydration ratio was also maximum in KMS treated mushroom and no significant difference at higher concentration. The treatment with KMS and blanching reduces the nutritive quality but improves the colour of the mushrooms when compared with sun dried samples.

Naik *et al*. (2006) tried drying of oyster mushrooms under different drying methods including sun drying and hot air drying. The rehydration ratio and sensory evaluation scores were used as criteria for evaluating the product quality. The results revealed that, cabinet tray dried (at 600C and 1%KMS pretreatment) mushroom samples were found to be good. The KMS treated samples had highest rehydration ratio and sensory evaluation scores as compared to the control (untreated) and balanced samples.

Kotwaliwale *et al*. (2007) studied the textural (hardness, cohesiveness, springiness, and chewiness) and optical (spectral surface reflectance) properties of paddy straw mushroom (*Pleuratus* spp.) were monitored during hot air drying of mushrooms in a cabinet tray drier at different air temperatures 50, 55, 60, and 70 °C. Effect of pre-drying treatments, viz. blanching and sulphitation, was also monitored. Texture Analyser™ and Hunterlab Colorimeter were used to determine textural and optical properties, respectively. During drying, hardness and chewiness of mushrooms were increased, while cohesiveness and springiness increased initially and decreased at the final stage of drying. Hardness of mushroom dried at higher temperature was higher. Cohesiveness decreased with increased drying temperature. Blanched and dried mushrooms had more hardness compared to other dried samples. Whiteness index of mushrooms decreased while yellowness index increased during drying. Drying temperature had an inverse effect on whiteness of mushrooms.

Tiram (2013) investigated on drying mushrooms under sundrying, hot air drying and gas laboratory oven practices. All three samples were analyzed for beta-glucan content, water activity, colour, proximate analysis and dietary fibre concentration. The result showed that LHAB method confers the lowest water activity compared with the other two drying methods. It also has the lowest colour measurement for brightness. Mushroom samples dried by LHAB techniques contain the highest concentration of both fat and carbohydrate compared with the other two methods.

Tolera and Abera (2017) conducted studies to evaluate the effects of different levels of osmotic pretreatments prior to drying and different drying methods on nutritional quality of dried mushroom slices. The experiment consisted of sun, solar, and oven drying after dipping the slices in salt solutions of 5 and 10% concentrations for 50 minutes, the control being untreated mushroom sample. Significant differences in proximate composition were observed between the fresh and dried mushroom samples. The average mean value of crude protein, crude fat, crude fiber, ash, and carbohydrates of the fresh mushroom samples were 28.85, 2.47, 12.87, 9.76 and 48.16% as compared to 25.91, 2.18, 10.41, 10.91 and 42.14% for dried samples.

Kantrong *et al.* (2014) studied drying of shiitake mushrooms by two different drying methods, i.e., microwave-vacuum drying (MVD) and microwave-vacuum combined with infrared drying (MVD + IR). MVD was operated at microwave powers of 56, 143, 209 and 267 W under absolute pressures of 18.66, 29.32, 39.99 and 50.65 kPa, whereas infrared radiation was added in MVD + IR at 100 and 200 W. The effects of microwave power, absolute pressure and infrared power on drying characteristics, qualities and specific energy consumption were investigated. It was found that drying rate increased with lower absolute pressure, higher microwave power and higher infrared power. In particular, the results also indicated that drying undergoing MVD + IR could provide better qualities in terms of colour of dried shiitake mushroom, rehydration ratio and texture of rehydrated ones.

Rodrigues *et al.* (2007) studied drying kinetics of mushrooms under several operational conditions, to evaluate the effective diffusivity coefficient of moisture removing by a drying model and inverse calculus method in finite differences and to study the effect on the final quality of dehydrated mushrooms. Different ways of microwave vacuum drying were compared to freeze-drying. Results show that a decrement of the applied pressure produces a certain increase in the drying rate together with a lower moisture in the dehydrated product at the end. Temperature control inside the sample helps to ensure a better quality in the dehydrated product, than when controlled at the surface. Diffusivity coefficients show a correspondence with product temperature during drying.

Orsat *et al.* (2007) dried biological materials such as fruits and vegetables provide shelf-stable commodities ensuring food security and ease of distribution. There exist numerous drying processes available for the adequate drying of bio-materials. Applying microwave energy to a drying process provides an efficient means of transferring energy for moisture removal. A review of recent microwave assisted drying applications is presented here along with research results on drying of carrots under varying microwave power modes and the comparative drying of mushrooms by microwave/convection and microwave/vacuum.

Torringa *et al.* (2001) studied osmotic dehydration using NaCl solution as a pretreatment before combined MWhot-air drying of mushrooms. The MW hot-air drying greatly improved the structure and bulk volume of dried mushroom. However, the geometry of whole mushrooms caused center heating. Slicing mushrooms into halves before MWSD improved heating uniformity, shortened drying time, improved rehydration properties, reduced shrinkage and increased open-pore porosity.

Szadzińska and Mierzwa (2021) compared the qualities of mushrooms dried under convective and microwave treatments. The effects of microwave power (100 and 200 W) combined with convection, at two different air temperatures of 30 and 50 °C, on the total drying time, drying rate, effective diffusion coefficient, specific energy consumption and several quality indicators were studied. The drying data were approximated with few thin-layer drying models that originated from the Newton's law of cooling, Fick's second law of diffusion, and the empirical ones. Results showed that microwave-assisted convective drying was characterized by considerably shorter drying time, higher drying rate, increased moisture diffusivity, and is more energy efficient as compared to conventional drying. Based on the statistical analysis, it was found that the Page and Weibull models were the most valid in approximation of the experimental drying curves.

Wang *et al.* (2019) studied on drying kinetics, color, rehydration ratio, polysaccharide content and aromatic components composition of shitake mushrooms dried by using hot air drying, infrared drying and intermittent microwave assisted hot air drying. Intermittent microwave–assisted drying resulted in greatly reduced drying time and higher drying rate in comparison with the other methods. The highest polysaccharide content (240.28 mg/100 g) was achieved when microwave–assisted drying was used. Furthermore, microwave–assisted drying showed its predominance in the categories and amount of generated nitric aroma (1.17%) during drying, and it could be a method for improving fresh–like characteristics of dried vegetables due to the moderate level of aldehydes (0.26%) and ketones (4.22%) formed during drying.

2.5.1 Drying kinetics of mushrooms

Drying kinetics of microwave dried, microwave vacuum dried and hot air-dried silver carp slices were studied by Fu *et al.,* (2012). The drying kinetics was influenced significantly by the parameters such as power intensity, temperature and pressure. The drying constant, K value increased with power, but a reverse trend was noticed with decreasing pressure. Wang *et al.* (2018) compared various drying techniques of raw (hot air drying, vacuum hot air drying) and osmo-dehydrated (osmosis-microwave drying, osmosis vacuum microwave drying) tilapia fillets. The product qualities such as shrinkage ratio, rehydration rate, nutritional composition, textural attributes were comparable for O-VMD fillets and VMD fillets. Moreover, vacuum conditions aided in the development of a porous structure and helped to reduce drying time by 99% compared to hot air drying.

Tulek (2011) studied the drying kinetics of pleurotus ostreatus mushrooms dried using a cabinet-type convective dryer. Air temperatures of 50, 60 and 70 ^oC were used for the drying experiments. The experimental drying data were fitted to different theoretical models to predict the drying kinetics. Nonlinear regression analysis was performed to relate the parameters of the model with the drying conditions. The performance of these models was evaluated by comparing the correlation coefficient (R2), root mean square error (RMSE) and the chi-square (χ2) between the observed and the predicted moisture ratios. Among all the models, the model of Midilli *et al*. was found to have the best fit in this study. Effective moisture diffusivities (Deff), diffusivity constant (D0) and activation energy (Ea) were calculated. The Deff varied from 9. 619x10^{-10} to 1.556x10^{-9} m^2s^{-1} over the temperature range studied and E_a was 22.228 kJ mol $^{-1}$.

Bhattacharya *et al.* (2015) dried oyster mushroom samples under selected convective, microwave-convective drying conditions in a recirculatory hot-air dryer and microwave assisted hot-air dryer (2.45 GHz, 1.5 kW) respectively. Only falling rate period and no constant rate period, was exhibited in both the drying technique. Among all the models, Midilli *et al.* model was found to have the best fit as suggested by 0.99 of square correlation coefficient, 0.000043 of reduced-chi square and 0.0023 of residual sum of square. The highest effective moisture diffusivity varying from 10.16×10^{-8} to 16.18×10^{-8} m^2/s over the temperature range was observed in microwave-convective drying at an air velocity of 1.5 m/s and the activation energy was calculated to be 16.95 kJ/mol.

Walde *et al*. (2006) studied the dehydration of button mushrooms (*Agaricus bisporus*) and oyster mushrooms (*Pleurotus flavus*) dried in different dryers viz, hot air cabinet dryer, fluidized bed dryer, vacuum dryer and microwave oven. The drying times were less in the case of oyster mushrooms (7200–8100 s) compared to button mushroom (8700–10800 s) with cabinet drying. The time taken for drying from 7.5% (db) moisture to 2.0% (db) was in the order of vacuum dryer > cabinet moisture dryer > fluidized bed dryer > microwave oven. However, fluidized bed drying seems to be a promising method for drying mushrooms, when comparing the lower drying time and good quality products to the faster microwave drying. The diffusion coefficients evaluated were also found in the same order. In case of oyster mushroom, the diffusion coefficient was found maximum (469.7×10^{-6} m^2/s) for microwave dried mushroom and minimum (2.609×10^{-6} m^2/s) for the control cabinet tray dried sample.

Salehi *et al.* (2017) reported drying characteristics of button mushroom (*Agaricus bisporus*) were evaluated in a combined dryer system. The effects of drying parameters, including infrared radiation power (150–375 W), system pressure (5–15 kPa) and time (0–160 min) on the drying kinetics and characteristics of button mushroom slices were investigated. Both the infrared lamp power and vacuum pressure influenced the drying time of button mushroom slices. The rate constants of the nine different kinetics models for thin layer drying were established by nonlinear regression analysis of the experimental data which were found to be affected mainly by the infrared power level while system pressure had a little effect on the moisture ratios. The regression results showed that the Page model satisfactorily described the drying behavior of button mushroom slices with highest R value and lowest SE values. The effective moisture diffusivity increases as power increases and range between 0.83 and 2.33×10^{-9} m^2/s.

Dinani *et al.* (2014) evaluated hot air combined with electrohydrodynamic (EHD) drying behavior of thin layer mushroom slices in a laboratory scale dryer at voltages of 17, 19, and 21 kV and electrode gaps of 5, 6, and 7 cm. The drying curves were fitted to ten different mathematical models (Newton, Page, Modified Page, Henderson and Pabis, Logarithmic, Two-term exponential, Midilli and Kucuk, Wang and Singh, Weibull and Parabolic models) and a proposed new empirical model to select a suitable drying equation for drying mushroom slices in a hot air combined with EHD dryer. Coefficients of the models were determined by non-linear regression analysis and the models were compared based on their coefficient of determination (R^2), sum of square errors (SSE) and root mean square error (RMSE) between experimental and predicted moisture ratios.

2.5.2 Quality evaluation of dried mushroom

Tian *et al.* (2016) evaluated the effects of hot air, vacuum, microwave, and microwave vacuum drying techniques on important qualities and volatile compounds of whole shiitake (*Lentinus edodes*) mushrooms. These four drying methods resulted in a significantly ($p < 0.05$) increase in the content of total free amino acids and the relative content of sulfur compounds of dried products. Microwave vacuum drying helped to maintain larger amounts of taste-active amino acids, and improved nutrient retention and color attributes. Furthermore, the uniform honeycomb network created by microwave vacuum drying along with a less collapsed structure of dried samples can be used to explain the observed high rehydration ratio.

Hassan and Medany (2014) carried out to studies evaluate the effect of pretreatments prior drying as well as drying temperature on quality of the dried mushroom. Rehydration ratio and colour of the dried product are the most effective parameter for judging and evaluating the drying process. Pretreated and control mushroom samples were dried by hot air at 50, 60 and 70 ^{o}C until reached to constant weight. The dried product was evaluated immediately after drying. P. ostreatus required from 7-12 hr, while P. eryngi required 6.5- 11 h to reach moisture content around 7% depending on pretreatment and drying temperature. Control sample dried by using any tested drying temperature recorded the highest rehydration ratio compared to other pretreated samples dried at the same drying temperature. Drying process caused a considerable decrement in protein content and a severe reduction in total microbial counts of mushroom samples.

Argyropoulos *et al.* (2011) combined drying of hot air and microwave-vacuum has been proposed as an alternative method to improve the quality of dried mushrooms, especially the structural and textural properties. In the present study, the effect of different drying methods namely, convective hot-air drying, hot air combined with microwave-vacuum drying and freeze-drying on qualitative attributes of pretreated mushrooms was investigated. The quality assessment was based on colour, texture, density, porosity and rehydration characteristics of the dried mushrooms. Combined drying of hot air and microwave-vacuum resulted in a dried product of superior quality when compared to the slices dried completely by conventional hot air, exhibiting lower overall colour variation, higher porosity, greater rehydration ratio and softer texture.

Tolera and Abera (2017) investigated on sun, solar, and oven drying of mushrooms after dipping the slices in salt solutions of 5 and 10% concentrations for 50 minutes, the control being untreated mushroom sample. Significant differences in proximate composition were observed between the fresh and dried mushroom samples. The average mean value of crude protein, crude fat, crude fiber, ash, and carbohydrates of the fresh mushroom samples were 28.85, 2.47, 12.87, 9.76 and 48.16% as compared to 25.91, 2.18, 10.41, 10.91 and 42.14% for dried samples. Oven drying resulted in higher content of ash (11.06%) and carbohydrates (43.64%) and lower contents of crude protein (24.99%), crude fat (2.12%), and crude fiber (10.21%).

Nour *et al*. (2011) studied on drying of mushrooms in a tray dryer at drying air temperatures of 50^o and 70^o C and the drying characteristic curves were drawn. The total drying time required for drying of white button mushrooms slices pretreated with various chemicals and dehydrated at different temperature of drying air was determined. The qualities of dehydrated slices were evaluated on the basis of rehydration characteristics and colour. Evolution 600 UV/VIS Spectrophotometer equipped with DRA-EV-600 diffuse Reflectance Accessory was used to determine optical properties. Drying air temperature of 50o C was better as it resulted in dried products having better rehydration characteristics and lighter color. Pre-drying treatments had a significant effect on the whiteness and colour change of dried mushroom slices.

Giri and Prasad (2007) carried out drying of button mushrooms (*Agaricus bisporus*) under microwave-vacuum drying (MVD) technique to a moisture content of about 6% (d.b.), and the dried mushrooms were compared with hot-air and freeze-dried (FD) products on the basis of different quality attributes such as color, texture, rehydration ratio and sensory score. Statistical analysis of data revealed significant difference among the drying methods for all the attributes at $P \leq 0.05$. Although FD produced the best quality dehydrated products having maximum rehydration ratio, highest instrumental color (L value) and lowest hardness, the MVD mushrooms were rated as equal to FD samples by a sensory panel in terms of appearance, color and overall acceptability. MVD mushrooms had significantly higher rehydration potential, lower density, better color and softer texture than those obtained by air drying (AD). The effect of drying methods on the water sorption properties of dehydrated products was also evaluated at 20, 30 and 40C. It was found that FD products absorbed maximum water vapor and MVD products had a higher sorption capacity than conventional AD products.

Argyropoulos (2008) observed that the air temperature and slice thickness were significant factors affecting the hot-air drying characteristics of mushrooms. The effect of the observed range of relative humidity was insignificant. Two-phase drying at lower initial temperature resulted in a lighter slice colour, softer in texture with good reconstitution. Freeze drying produced dried mushroom slices of superior quality exhibiting the highest lightness, lowest hardness and maximum rehydration ratio. Samples dried by combination of hot-air and microwave-vacuum indicated improved quality parameters as compared to samples dried exclusively by hot air. In particular, the combined technique developed a dried product of puffed texture which could be considered as an important characteristic for manufacturing a snack type product.

Arumuganathan *et al.* (2010) studied effect of the drying methods on textural characteristics, protein content, and residual enzyme activities was studied. The mushrooms dried by the freeze-drying method showed the least firmness, with mean firmness force of 1.42 N and firmness strength of 4.27 N-mm. The highest firmness was observed in the osmo-air dried oyster mushrooms. High cutting force of 12.94 N and cutting energy of 14.73 N-mm were observed for those dried by osmo-air drying. Lower force of 1.07 N and energy of 1.58 N-mm were sufficient to fracture the freeze-dried mushrooms, and the highest fracture force and energy were observed for the fluidized-bed dried mushrooms. High protein content and residual activities of catalase and peroxidase were observed in mushrooms dried by the sun-drying method, which was closely followed by the osmo-air drying method. In terms of retention/improvement of texture in oyster mushrooms, osmo-air drying yielded hard and tough dried mushroom and freeze-drying method yielded very soft texture of mushrooms.

2.6 Storage studies on dried mushroom

Argyropoulos *et al.* (2011) conducted drying experiments in a laboratory hot-air dryer at temperatures of 50, 60, and 70^{0}C under thermal (water or steam blanching) and chemical (solution of potassium metabisulfite or citric acid) treatments. Changes in color were evaluated by the CIE LAB colour system and the experimental colour parameters (L* a* b*) were fitted to a first order kinetic model. Values of total colour difference (DE*), hue angle (h*), and chroma (C*) were also calculated.

Korley *et al*. (2015) reported that there were significant differences ($p< 0.05$) for L*, a*, b*, chroma, hue angle, browning index and overall colour change of fresh and dried mushrooms over the storage periods. There was an increase in a*values while L*, b*, C and H values decreased. The colour parameters were measured for fresh mushrooms (*Pleurotus ostreatus*) irradiated at 0, 1, 2 and 3 kGy at a dose rate of 1.7 kGy hr^{-1} after harvest (0 day) and then measured after storage (5 days).

Naik *et al.* (2005) carried out storage studies on dried oyster mushrooms packed in 75 microns (300) gauge polyethylene bags. Storage studies were carried out by adopting two methods of storage, namely ordinary heat seal storage (control) and vacuum storage. During the storage period of three months, the biochemical changes and organoleptic characters were determined at monthly intervals and the results showed that there was a reduction in protein and rehydration ratios with a progressive increase in moisture content in both the methods of storage.

Khan *et al.* (2016) studied the physico-chemical analysis (moisture, protein, sensory evaluation) of fresh and dried oyster mushroom. The maximum mean value of moisture was T0 (88.5) and minimum mean value was 5.16%. The maximum mean value of protein was 20.2% and minimum mean value was 3.43%. Maximum mean value of colour was 6.62 while the minimum mean value was 5.85. The maximum mean value of taste was 7.52, and the maximum mean value of taste was 7.14.

Giri and Prasad (2006) reported on the shrinkage characteristics of button mushrooms during microwave and convective drying methods. Microwave vacuum drying at two different power (150 and 250 W) and pressure (10 and 20 kPa) levels. The above properties during convective hot air drying at 60°C were also measured for comparison. In both microwave-vacuum and air-drying methods, the shrinkage (volumetric and diametric) of mushroom showed a linear behaviour with moisture content.

Isik and Izlin (2014) studied on the effects of microwave, convective and microwave-convective drying treatments on the drying parameters, colour and microstructure properties of mushroom samples. To select the best thin-layer drying models for the drying treatments, 9 mathematical models were fitted to the experimental data. Based on evaluation by statistical tests, the Midilli *et al*. (2005) model, the Diffusion Approach model, Logarithmic model, Wang and Singh model were found to be the best-fitting models to describe the drying behaviour of the mushroom samples. The shortest drying time was provided with microwave method at 500 W (35 min). However, the drying time was significantly reduced by combining microwave treatment with conventional drying.

Omari *et al.* (2018) carried out modeling of moisture content variation under variable microwave power in microwave-hot air dryer is challenging. In this study, one static and one dynamic of ANN were investigated for modeling of whole mushroom drying process. The experiments were done in three levels of hot air temperature (23, 50, and 70 C), three levels of microwave power density (MPD) (1.5, 2, and 2.5 W/g) and two statuses of microwave power during drying process (constant and variable).

Jafri *et al.* (2013) investigated on three preservation techniques, chemical treatment, modified atmosphere packaging (MAP) and low temperature storage to improve physico-chemical attributes of oyster mushrooms. Mushrooms were treated with a solution of sorbitol (0.05%, w/v), citric acid (3%, w/v) and CaCl2 (1%, w/v). Chemically treated mushrooms were packed under two different gas compositions.

Lyn *et al.* (2020) investigated the effect of combining modified atmosphere packaging with bilayer active packaging (MAP + BL) on the shelf life of oyster mushroom (Pleurotus ostreatus). The BL active packaging consisted of gelatin with pomegranate peel powder (PPP) coated on the polyethylene (PE) film (gelatin + PPP/PE). Pouches of single layer (SL) of PE was used for MAP without active function (MAP + SL). Three different conditions of MAP were used i.e. high oxygen packaging (HOP), medium oxygen packaging (MOP) and low oxygen packaging (LOP). Mushroom packaged with atmospheric air (ATM) was used as control. The mushroom packed in MOP with active layer successfully increased the shelf-life of mushroom up to 11 days as compared to the control (3 days).

Rosli and Solihah (2014) reported on the storage life of oyster mushroom (OM) incorporated chicken patties under degradable packaging material. The chicken patties were formulated with either 0, 25 or 50% of fresh OM. The results showed that chicken patty formulated with 25% PSC has protein content of 17.46% lower than the control patty which had 18.13% but it was not significant (p>0.05).

2.7 Economic analysis of dried food products

Srivasthava *et al.* (2021) studied on **f**unctional and economic studies on drying of grapes under solar drying conditions. The indirect solar dryer gives better quality raisins in contrast to the direct type solar dryer because direct exposure to sunlight harms the texture and color of raisins. Mixed-mode type dryers and hybrid type dryers required 15–25% more initial investment than an indirect solar dryer but drying time reduces 30–40% when using mixed-mode and hybrid technology. For the prediction of the drying behavior of grapes, mathematical models such as the Two-term & Midilli model were found best.

Qu *et al*. (2022) reported that traditional open sun drying is the most popular food-reservation technique to the local farmers due to near-zero capital cost and cheap labor cost. However, this method is highly energy intensive, unhygienic, and time demanding.

Kusuma *et al*. (2023) evaluated the drying kinetics of basil leaves using microwave-assisted drying (MAD) to determine moisture content, moisture ratio, drying rate, and economic analysis at various microwave power levels (136, 264, 440, and 616 W). This study discusses the economic analysis between microwave versus oven drying and this study has not been discussed in other studies. Authors evaluated each condition using five thin layer models: Henderson and Pabis, Midilli *et al.*, Hii *et al.*, Verma *et al.*, and Diffusion Approximation. Coefficient of correlation (R^2), Chi-square (X^2), Sum of Square Error (SSE), Root Mean Square Error (RMSE), and Mean Square Error (MSE) were used as the statistical parameters to determine the best drying kinetics model.

Sreekumar (2010) reported that the solar air heater was 46 m^2 and recorded a maximum temperature of 76.6 °C. The dryer was loaded with 200 kg of fresh pineapple slices 5 mm thick. The initial moisture content of 82% was reduced to the desired level (<10%) within 8 h. The performance of the dryer was analyzed in detail by three methods namely annualized cost, present worth of annual savings, and present worth of cumulative savings. The cost of drying 1 kg pineapple worked out to Rs. 11 which was roughly half of that of an electric dryer. The payback period worked out to 0.54 year, much less than the estimated life of the system (20 years).

Mohammed *et al.* (2020) compared the economy of operation of open sun drying (OSD) with an improved solar dryer (ISD) and solar photovoltaic and electric (SPE) dryer. Relative to the OSD method, the economic performance of the ISD and SPE dryers was analysed. The drying performance results show that the mean drying air temperatures achieved by the ISD and SPE dryers were 31.9 and 41.1 °C respectively; relative to the 27.6 °C for the OSD method. On average, the thermal energy attained by the ISD and SPE dryers were 3551 and 5757 Watts (W) respectively, as compared to 2952 (W) obtained for the OSD method.

Nwakuba *et al.* (2020) analysed the technical performance and economic analysis of a developed hybrid solar-electric dryer (HSED) Thermal characteristics and drying efficiency of the hybrid dryer, as well as the effect of different drying temperatures (50, 60, and 70°C), air velocities (0.5, 1.0, and 1.5 ms^{-1}), and sample thicknesses (10, 15, and 20 mm) on the overall and specific energy usage for 1,500 g batch size of fresh sliced tomato samples, were investigated. Results obtained indicate that the mean solar collector efficiencies during sunshine hours ranged between 24.6 and 70.3%. The economic analysis established that the HSED could save up to $1,490.33 per annum with a low payback period (0.72 years).

Yahya *et al*. (2018) investigated on the performance and economic analyses on solar-assisted heat pump fluidised bed dryer integrated with biomass furnace for rice drying. The dryer decreased the moisture content of rice from 32.85% (dry basis) to 16.29% (dry basis) in 22.95 min, with a mass flow rate of 0.1037 kg/s at an average temperature of 80.9 °C and average relative humidity of 8.14%. The specific moisture extraction rate varied from 0.13 kg/kWh to 0.40 kg/kWh, with an average value of 0.24 kg/kWh.

Materials and Methods

CHAPTER III

MATERIALS AND METHODS

The experimental set up and techniques used for the development and evaluation of semi-continuous microwave convective dryer are discussed in this chapter. Also, the methods for optimization of drying process parameters for shrimp and mushroom, performance evaluation of the prototype, empirical modelling of drying data and statistical analysis, comparative study of microwave and hot air drying for shrimp and mushroom, storage studies and cost analysis are mentioned.

3.1 Raw materials

Raw shrimps (*Metapenaeus dobsoni*) were purchased from Chaliyam Fish Harbor of Calicut, Kerala. The shrimps were counting around 350–380 nos./kg and were thoroughly cleaned with potable water. The length, width and thickness of shrimp were determined to be 45 ± 1.5, 24 ± 1.3, and 9 ± 0.6 mm, respectively.

Fresh Oyster mushrooms (*Pleurotus ostreatus*) were purchased from local market in Calicut and cleaned thoroughly with potable water to remove the adhering matter. The cap diameter, stalk length and stalk thickness of the selected oyster mushroom were 61.23±0.56 mm, 63.44±0.21 mm and 18.16±0.43 mm, respectively. Photographs of raw shrimp and oyster mushroom are shown in Plates 3.1 and 3.2, respectively.

Plate 3.1 Shrimp ((*Metapenaeus dobsoni*))

Plate 3.2 Oyster mushroom (*Pleurotus ostreatus*)

3.1.1 Determination of engineering properties

The engineering properties determined for shrimp and mushroom were bulk density, true density, porosity, angle of repose, coefficient of friction, thermal conductivity and specific heat.

3.1.1.1 Bulk density

Bulk density was calculated as the ratio between mass and bulk volume of the product including the presence of void volume (Sahin and Sumnu, 2006). Materials with large pore spaces among them have lower bulk densities compared with those having small pore spaces. The bulk density was determined by filling a cylindrical container of 500 ml volume with the shrimp/mushroom to a height of 150 mm at a constant rate and then weighing the contents (Gupta and Das, 1997; Garnayak et al., 2008). No additional compaction was done on the sample. The bulk density was calculated from the mass of the bulk material divided by the volume containing the mass (Davies *et al*., 2014).

$$\rho = \frac{Weight\ of\ sample\ (kg)}{Volume\ occupied\ by\ the\ sample(m^3)} \qquad \ldots (1)$$

Where, ρ is the bulk density in kg/m^3.

3..1.1.2 True density

The True density is defined as the ratio between the weight of the sample to the true volume of the sample that is devoid of void volume. True density of shrimp and mushroom were determined by toluene (C_7H_8) displacement method. Toluene is used for the determination of true density as it is absorbed to a lesser extent by the samples. The volume of toluene displaced was measured to determine the true density (Davies *et al*., 2014).

$$\rho_T = \frac{Weight\ of\ sample\ (kg)}{Volume\ of\ toluene\ displaced\ (m^3)} \quad \ldots (2)$$

Where ρ_T is the True density in kg/m^3.

3.1.1.3 Porosity

According to Mohsenin (1986) porosity (%) is the parameter indicating the amount of pore spaces in the bulk materials. It is calculated from the bulk and true density using the following equation.

$$Porosity = \frac{True\ density - Bulk\ density}{True\ density} \times 100 \ldots (3)$$

3.1.1.4 Coefficient of friction

Coefficient of friction (μ) of shrimp and mushroom on different surfaces such as stainless steel, mild steel and aluminium were determined using the standard procedure. Plate 3.3 depicts the determination of coefficient of friction. A known weight of sample was filled in a PVC cylinder (open bottom) which is placed on a plane surface made of stainless steel. This is the total normal force (N) acting on the surface (Davies *et al*., 2014). A loop and pulley arrangement are provided to add weight at the other end of the sliding surface. After keeping the cylinder with the samples at one end of the sliding surface add weight until the cylinder containing material tends to start sliding from its initial position. This is the weight required to overcome the frictional force (F). The procedure is repeated for other surfaces such as aluminium and mild steel. Coefficient of friction was calculated using the following equation.

$$\mu = \frac{F}{N} \qquad \ldots (4)$$

Where, μ is the coefficient of friction, F is the frictional force and N is the normal force acting on the surface.

Plate 3.3 Determination of coefficient of friction

3.1.1.5 Angle of repose

Angle of repose is the angle made by sample with the horizontal surface when piled from a known height. 500 g of shrimp was piled over a horizontal surface. Angle of repose is low for smooth and rounded samples; whereas very fine and sticky materials have high angle of repose due to the friction between them (Sirisomboon *et al*., 2007). The radius of pile was calculated from the circumference of the pile and the slant height of the pile was determined. The angle of repose was calculated using the formula:

$$\theta = Tan^{-1}(\frac{2h}{d}) \ldots (5)$$

Where, θ is the angle of repose, h is the altitude of the pile (cm) and d is the diameter of the pile (cm).

3.1.1.6 Specific heat

Specific heat was measured using differential scanning calorimeter, DSC (DSC-7, Perkin-Elmer Corporation, Norwalk, CT) (Ferrer *et al*., 2017). Specific heat is determined at temperatures of 32 – 57 °C so that the experiments could be carried out above room temperature. Due to presence of moisture in the samples, they must be sealed in volatile sample pans to prevent weight loss during heating. The equipment is calibrated for temperature and power and a sample pan containing 0.0265 g sapphire standard was placed in the sample holder and empty pan in the reference holder. The calorimeter was adjusted to the initial, baseline temperature and allowed to equilibrate isothermally at 300 K and then scanned dynamically at 5 K per min over the temperature range from 300 to 333 K. the sapphire run was followed by a blank run in which an empty sample holder was placed in both the sample and reference holders. The procedure was then repeated for each of the five replications of the test sample. After completing each run, the sample pan was removed and reweighed to assure no loss of sample during the run. The procedure was checked by running thermograms of distilled water in volatile sample pans. The abscissa of the chromatogram provides measure of temperature and time and ordinate represents the rate of heat evolution or absorption by the sample. The DSC method compares the rates of heat absorption of an unknown sample with rates of a standard material having known specific heats.

3.1.1.7 Thermal conductivity

Thermal conductivity was measured using line heat source probe with a diameter of 1.27mm. A set amount of current was allowed to flow through probe heater wire and voltage across the heater wire was measured using a digital voltmeter. Temperature signals from the probe were sampled at 1 Hz. Calibration of probe was done to get a calibration factor of 1.15. Temperature and time were recorded during the run periods (Hu *et al.*, 2007)

$$Q = \frac{kAdt}{dx} \ldots (6)$$

Where Q is the rate of heat transfer in W, k is the thermal conductivity in W/mK and dt/dx is the temperature gradient.

3.2 Development of microwave convective dryer

A semi continuous microwave convective dryer (hot air assisted microwave dryer (HAMW)) was developed for drying of foods with an initial moisture level of around 75 – 80 % w. b. Following assumptions were considered in dryer design (Table 3.1).

Table 3.1 Hot air assisted microwave dryer design assumptions

Factors	**Specifications**
Capacity	1 kg fresh product/h 0.6 kg/h moisture removal
Product type	Shrimp/mushrooms/perishable foods
Moisture percentage (initial)	75 - 80 % w. b.
Moisture percentage (final)	10-15 % w. b.
Drying air temperature	60-70 °C

Air flow rate	1 m/s
Air temperature (ambient)	30- 33 °C
Air relative humidity (ambient)	70 - 75%
Latent heat of vaporization of water at drying temperature	2260 kJ/kg
Specific heat capacity of air at constant pressure	1 kJ/ kg °C
Air density	1.225 kg/m^3
Specific heat of product	3.65 kJ/kg°C (shrimp) 3.27 kJ/kg°C (oyster mushroom)
Specific heat of water	4.2 kJ/kg°C
Drying time	3 - 5 h

3.2.1 Dryer design calculations

Assumptions:

Initial moisture content ≈ 75% (w.b.)

Final moisture content = 15% (w.b.)

Specific heat of fish above freezing point, $Cp_{>fp}$ = 0.9 kcal/kg °C

Dryer temperature = 45-55 °C (55 °C)

Ambient temperature = 30 °C

Specific heat of water = 1 kcal/kg °C

Latent heat of water = 540 kcal/kg

Initial weight of product = 50kg

- Initial mass of water in product = $\frac{75}{100} \times 50$
  = 37.5 kg
  Bone dry mass (BDM) = 12.5 kg

- Final mass of water in product: $\frac{15}{100} = \frac{Mw}{Mw+BDM}$

  $$\frac{15}{100} = \frac{Mw}{Mw+12.5}$$

  Mw = 2.2 kg

- Mass of water to be evaporated = 37.5-2.2
  = 35.3 kg

- Amount of heat required to evaporate 35.3 kg of water:

  Sensible heat to be removed = $m \times Cp \times \Delta T$

= 37.5 ×1×(55-30)
= 937.5 kCal

Latent heat of water to be removed = mL
= 35.3 ×540
= 19,062 kcal

Sensible heat of BDM = $m \times Cp \times \Delta T$
= 12.5×0.9×(55-30)
= 281.25 kcal

- Total heat required theoretically = (937.5+19,062+281.25) kcal
= 20,280.75 kcal
≈ 22,400 kcal

Assuming drying to be accomplished in 8 h, heat energy requirement =

22,400/8 kcal/h = 2800 kcal/h = 2800 × 4.18 $\frac{2800\times4.18J}{3600\ s}$ = 3.2 kW

Therefore, energy supplied by the heating source should be approximately 3.2 kW. Of this magnetron of capacity 1.45 kW and heater coil of capacity 1 kW can be used as heat source.

To supply this much heat, air requirement = m×C_{p}×ΔT
= m ×$C_{p\ air}$ × (heated air temperature - exhaust air temperature)

C_p of hot air = 0.24+0.45 H

Where, H is the humidity obtained from psychrometric chart corresponding to inlet conditions (30 °C temperature and 70% RH)

H = 0.01892 kg/kg of dry air

C_p of hot air = 0.24+045×0.01892
= 0.248 kCal/kg°C

m×0.248×(heated air temperature-exhaust air temperature) = X_m = 25,760 kCal (Taking 15% extra to met for heat losses in conveying)

m×0.248×(60-35) = X_m = 25,760 kCal

m = $\frac{25760}{0.248\times(60-35)}$

m = 4154.8 ≈ 4200 kg

4200 kg should be circulated during drying period ≈ 8 hours

i.e. $\frac{4200}{8}\ kg/h$ = $\frac{4200}{8\times60}\ kg/min$ = 7.5 kg/min

= 8.75 kg/min

= 0.146 kg/s

Specific volume of air under ambient condition = 0.882 m^3/kg (using Psychrometric chart)

Therefore, volume of air required = $0.882 \times 0.146 \frac{kg}{kg \times s} \times$ m^3

= 0.128772 m^3/s

= 7.7 m^3/min

3.2.1.1 Thermodynamic equilibrium calculation for energy balance

Energy balance in drying was calculated using the equation suggested by Exell, 1980:

$$M_w L = m_a C_p (T_i - T_f) \ldots (7)$$

M_w: mass of water to be removed, kg

L: LH of vaporization, kJ/kg

T_i: Initial temperature of air, ˚C

T_f: Final temperature of air, ˚C

m_a: Mass of air, kg

C_p: Specific heat capacity of air at constant pressure, kJ/kg ˚C

3.2.2 Amount of water to be removed from product

Amount of water evaporated was calculated as (Chakraverty, 1988):

$$M_w = \frac{W_i (M_i - M_f)}{100 - M_f} \ldots (8)$$

W_i: Product weight initially, kg

M_i, M_f: Initial and final content of moisture in of the sample, % w. b.

3.2.3 Hot air requirement for drying

Air requirement for drying was calculated as (Sahay and Singh, 1996):

$$M_a = \frac{M_w L}{C_p (T_i - T_f)} \ldots (9)$$

Flow rate of air is given as (Kiranoudis et al., 1997):

$$Mass\ flow\ rate\ of\ air\ \left(\frac{kg}{s}\right) = \rho \times V_a \quad \ldots (10)$$

$$Volumetric\ flow\ rate\ of\ air\ (V_a)\ \left(\frac{m^3}{s}\right) = A \times V \times n \quad \ldots (11)$$

V_a: Volumetric flow rate of air, m^3/s,

ρ: Air density, kg/m^3,

A: Area of air passage duct, m^2,

V: Air velocity, m/s and

n: Number of air passage ducts

3.2.4 Heat energy required for evaporation

Heat requirement for evaporation is the total of sensible heat required to raise the temperature of sample, sensible heat of water and latent heat of vaporization of water at specific temperature and it can be determined as (Sahay and Singh, 1996):

$Q_{Total} = Q_{sensible,product} + Q_{sensible,water} + Q_{Latent}$ …(12)

Sensible heat needed to raise the sample temperature:

$$Q_{sensible,product} = W_d\, C_{pp}\, (T_{fp} - T_{ip}) \quad \text{…(13)}$$

$Q_{sensible,product}$:Sensible heat of sample, kJ

W_d: Bone dry weight of product, kg

C_{pp}: Product specific heat, kJ/kg°C (shrimp - 3.65 kJ/kg°C, mushroom – 0.9 kJ/kg°C)

T_{ip}: Product temperature (initial), °C

T_{fp}: Temperature of product, (final), °C

Sensible heat for raising water temperature is estimated as:

$$Q_{sensible,water} = W_w\, C_{pw}\, (T_{fp} - T_{ip}) \quad \text{…(14)}$$

$Q_{sensible,water}$:Sensible heat of water (kJ)

W_w Mass of moisture in product, kg

C_{pw}: Specific heat of water, kJ/kg°C (4.12 kJ/kg°C)

Latent heat (LH) needed is represented as:

$$Q_{Latent} = M_w L \quad \text{…(15)}$$

Q_{Latent} LH of water evaporation, kJ

M_w: Mass of water evaporated from sample, kg

L: LH of vaporization of water, kJ/kg (2260 kJ/kg)

3.3 Components of hot air assisted microwave convective dryer

Microwave drying studies on shrimp and mushroom was carried out in the developed semi-continuous hot air-assisted microwave (HAMW) drying unit established at KCAET, Tavanur. A schematic diagram of the drying unit is shown in Figure 3.1. The drying unit consists of a drying chamber, microwave generator, hot-air provision, exhaust, fan, and control unit. The drying chamber is provided with a layer of heat-resistant Teflon conveyor belt with dimensions of 1.5 m × 0.5 m. The operation of Magnetron of 1.45 kW power at 2450 MHz generated microwave energy for heating the products spread as a thin layer on the conveyor. The hot air assistance was provided with a 1 kW heating element, an air inlet duct, and an axial fan with a recirculatory section. Fresh inlet air is taken into the top of the dryer with the help of an axial fan and the air deflection valve. The heated air is then uniformly passed over the products at a desired air flow rate. The exit moist air is recirculated into the chamber inlet using a fan and temperature control system for maximum energy savings. Technical specifications of the microwave dryer are given in Table 3.2.

Table 3.2 Technical specifications of hot air assisted microwave dryer

General system requirements		
1.	Mains supply	3-Phase, 50 Hz, 400 VAC
2.	Mains fluctuation permitted	±5% for both frequency and voltage
3.	Input power requirement	10 kVA
4.	Floor area	100 (W) × 1500 (H) × 1500 (L) in mm
5.	Approximate gross weight	180 kg
6.	Drying capacity	0.6 kg/h moisture removal
Processing chamber details		
7.	Internal dimensions	220 (W) × 300 (H) × 1000 (L) in mm
8.	Microwave inlet port	WR – 340 (1 no.)
9.	Door interlock switch	Limit switch (2 nos)
10.	Material of construction	SS – 304
11.	Maximum process temperature	100 °C
Insulation details		
12.	Make	Zircar or equivalent
13.	Thickness of insulation	50 mm on all sides
14.	Temperature grade of insulation	Minimum 600 °C
15.	Outside body temperature	Less than RT+ 50 °C
Microwave power supply and controls		
16.	Magnetron	1.45 kW×1no.
17.	Type of power supply	Average power continuously variable
18.	Power control range	0.2 – 1.45 kW
19.	Operating frequency	2450±50 MHz
20.	System operating mode	Manual (Set power mode)

Hot air system		
21.	Heaters	1 kW ×1no.
22.	Hot air temperature	RT – 75 °C
23.	Temperature measurement	Thermocouple with digital PID controller
24.	Outside body temperature	Less than RT + 50 °C
Conveyor system details		
25.	Conveyor belt width	200 mm
26.	Conveyor belt material type	Poly teterafluoroethylene (PTFE)
27.	Conveyor belt linear speed	200 – 200 mm/min
28.	Displays	Digital display speed
Hot air temperature measurement system		
29.	Sensor type	Thermocouple
30.	Measurement range	RT – 300 °C
31.	Sensor make	ENERZI or Equivalent
Safety measures		
32.	Magnetron surface/body temperature	80 °C body temperature cut off
33.	Process chamber door open	Suitable limit switch
34.	Other interlocks	Cooling fail, HV door open sense

3.3.1 Drying chamber

The developed microwave convective dryer works on 3-phase, 50 Hz, 400 VAC with an input power requirement of 10 kVA with an approximate weight of 180 kg. The floor volume and internal dimensions of the machine were 1000 (W) × 1500 (H) × 1500 (L) in mm and 220 (W) × 300 (H) × 1000 (L) in mm respectively. The drying capacity was expressed as 0.6 kg/h moisture removal. Drying chamber consisted of a single layer of conveyor belt of dimension 1.5 × 0.5 m, being derived from dryer design calculations with respect to the capacity and product bulk density. Samples being fed manually were conveyed along the belt made of heat resistant Teflon (PTFE) over SS rollers. A solid diagram of the microwave convective drying system (Enerzi Microwave Systems, India) is shown in Fig. 3.1 (SOLIDWORKS 3D CAD). The insulation of 50 mm on all sides was provided by Zincar material with a temperature resistance of 600 °C. it is a ceramic fibre based insulation with exceptional machinability and heat resistance.

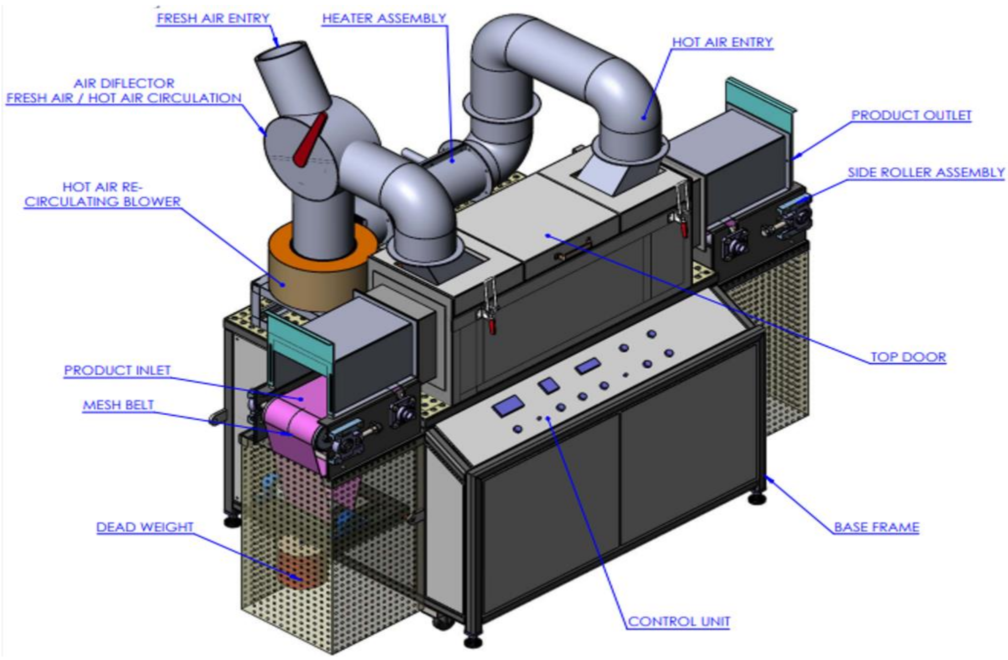


Fig. 3.1 Microwave convective dryer – Solid diagram (Courtesy: Enerzi Microwave Systems Pvt. Ltd., Belgaum, India)

3.3.1.1 Microwave generator system

The wave generator part of microwave heating system is the magnetron (Model: EMS-MAG-015-1, Make: Enerzi). Magnetron of 1.45 kW rated power, operating at 2450 MHz±50 MHz generated the microwaves for heating the products in the drying chamber. This air-cooled type continuous wave (CW) magnetron consisted of a vacuum tube with a central cathode surrounded by a structured anode. Cathode is at high negative potential and is made up of thorium for emitting electrons and tungsten to withstand the heat. The anode, made of copper is cut into a number of slots to form resonant cavities. A permanent magnet is placed along the length of tube. When the magnetron is switched on, electrons are boiled off from the cathode and these electrons are stretched between the cathode and anode due to the simultaneous electric and magnetic fields. As they move past the resonant cavity of anode, microwaves were generated and coupled to an antenna that transmits them to the waveguide. Air cooling fins were provided to carry away the heat produced in magnetron. The technical specifications of the magnetron are shown in Table 3.3. The photograph and design drawing of the magnetron used in the microwave dryer is depicted in Fig. 3.2.

Table 3.3 Technical specifications of the magnetron

Magnetron power	1.45 kW
Cooling type	Air cooled
Peak anode voltage	4.6 kV
Average anode current	450 mA
Filament voltage	4.3 V
Filament current	14 Amps
Net weight	1.4 kg

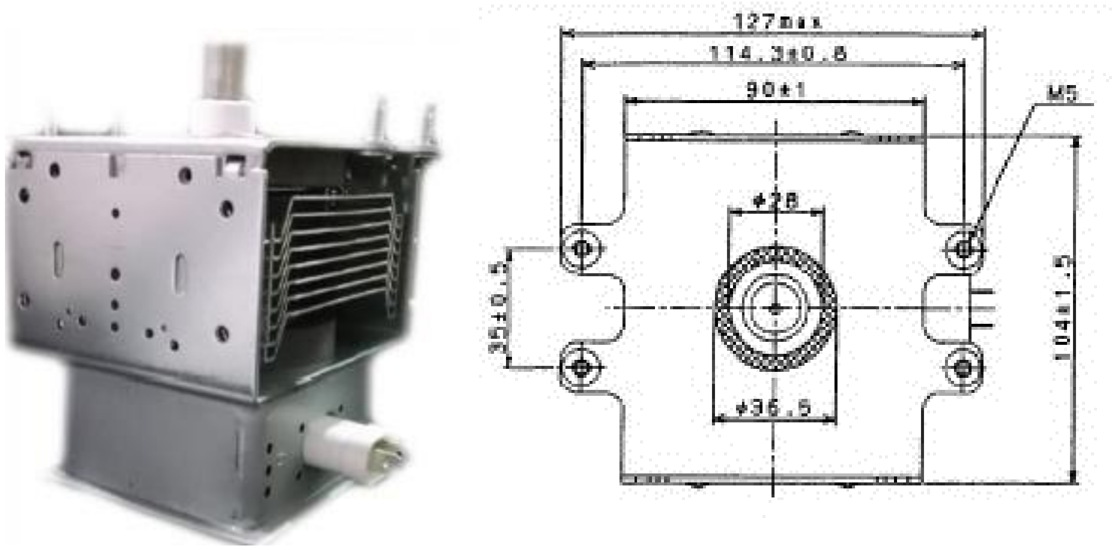


Fig 3.2 Photograph and design drawing of magnetron

3.3.1.2Wave guide

A wave guide (Model: WG-SET-340-SS1, Make: Enerzi) transmitted microwave radiation from the generator to the applicator. It is made up of aluminium which is highly conductive. Inner surfaces were made smooth to prevent any losses. Waveguide transmitted microwave energy from the magnetron to the samples. A waveguide size is primarily dependent on the wave frequency and mode of propagation. Waveguide led the microwaves to the drying chamber or applicator wherein the product (shrimp/oyster mushroom) were placed on the conveyor in thin layer of 1.0 – 1.5 cm. The wavelength of microwave radiation at frequencies of 2450 MHz was 11.0 – 12.2 cm. The technical specifications of the wave guide are shown in Table 3.4. The photograph and design drawing of the wave guide used in the microwave dryer is depicted in Fig. 3.3.

Table 3.4 Technical specifications of the wave guide

Wave guide type	WR340
Material of construction	Stainless steel and aluminium
Inside finish	Chromate conversion
Outside finish	Anti-corrosion grey paint
Dimension	200 (L)×95 (W)×370 (H) mm
Frequency	2450 MHz

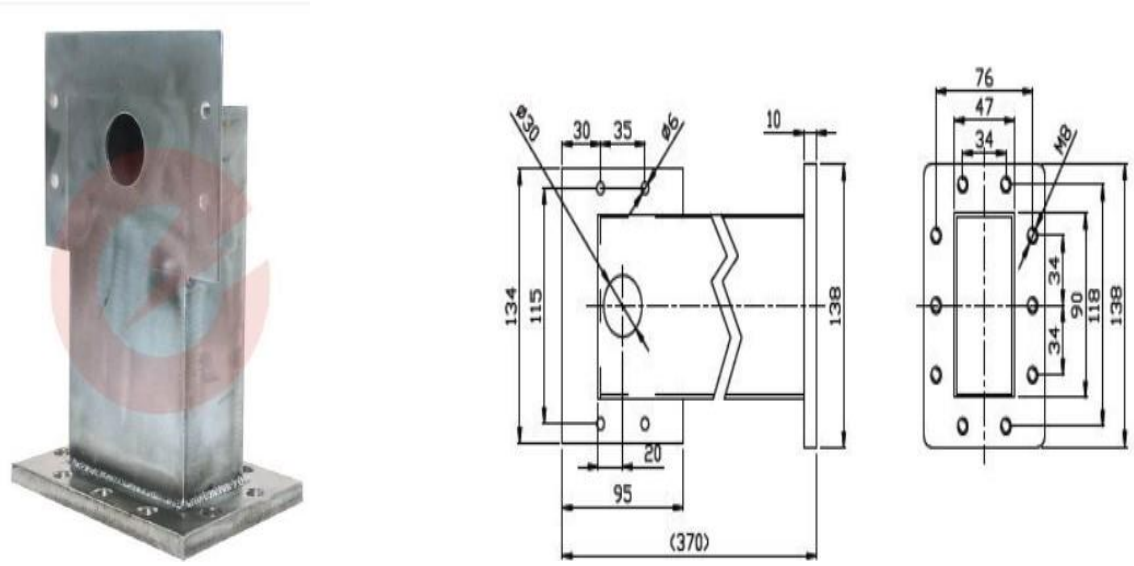
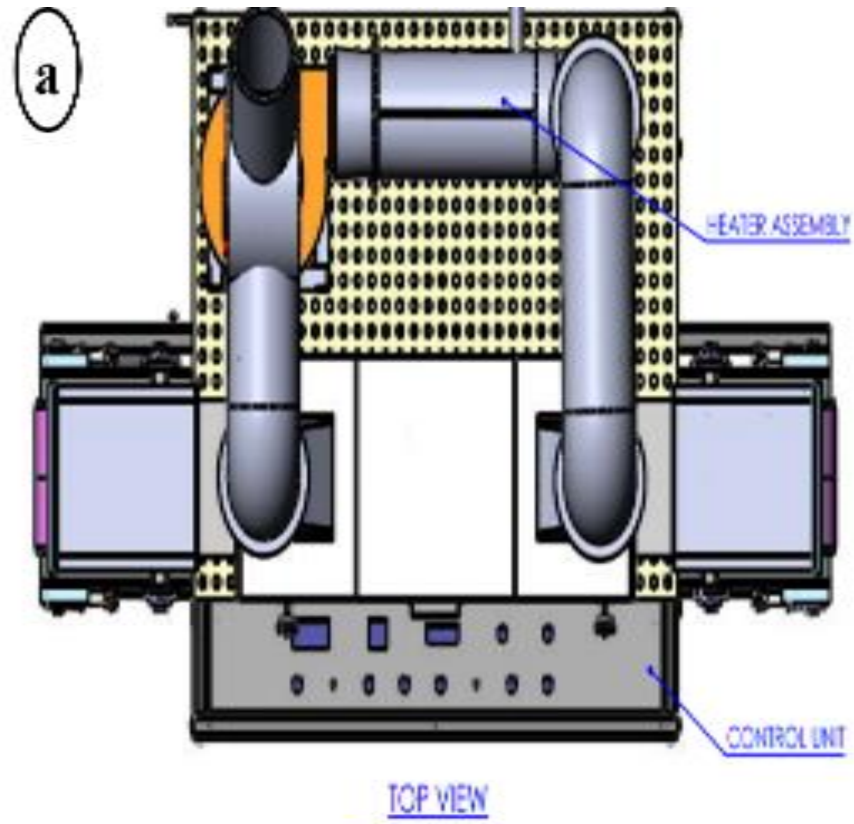
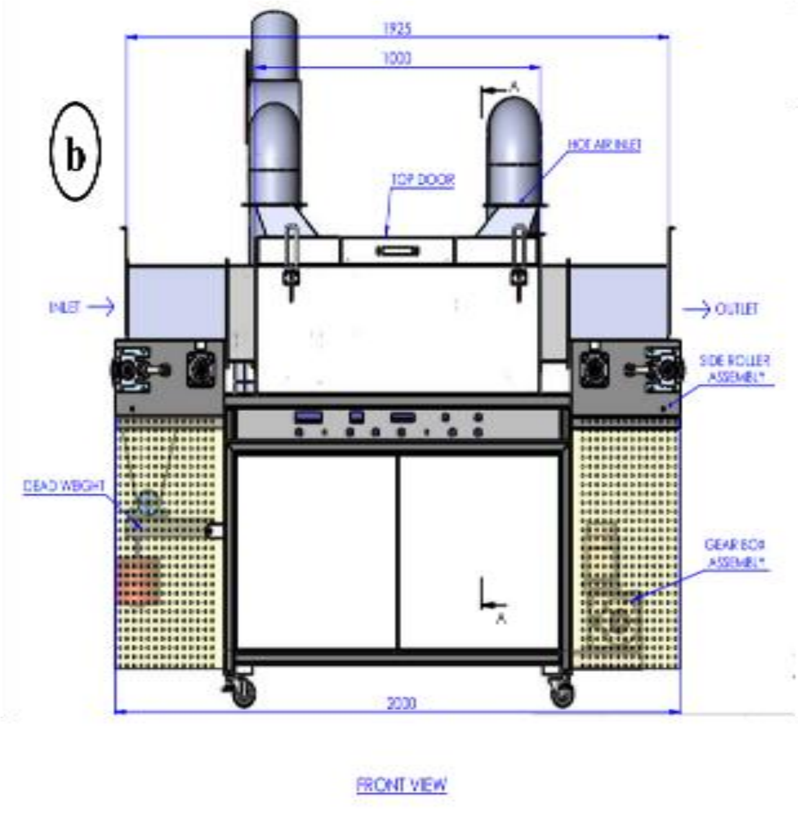


Fig 3.3 Photograph and design drawing of wave guide

3.3.2 Hot air generation system

The air heating zone consisted of air inlet duct (0.164 m diameter x 0.175 m length), axial fan (Make: Almonard, 50 W, 1350 rpm), with one air heater of one kilo watt and recirculation system. Ambient air entered into the top of dryer due to the pull of axial fan and is conveyed to the heater assembly by the air deflection valve. The heated air is then uniformly passed through the chamber at determined velocities. The moist air from the chamber is recirculated by means of blower and temperature control of heated air was achieved with an automatic thermal cut off arrangement. The top, front and side views of the hot air generation system is depicted in Fig. 3.4. The schematic of the hot air assisted microwave dryer is shown in Fig. 3.5. Temperature measurements were done using a thermocouple with digital PID controller. The detailed photograph of the microwave convective dryer and its control units are shown in Plate 3.4.


a
HEATER ASSEMBLY
CONTROL UNIT
TOP VIEW


b
1925
1000
HOT AIR INLET
TOP DOOR
INLET
OUTLET
SIDE ROLLER ASSEMBLY
DEAD WEIGHT
GEAR BOX ASSEMBLY
2000
FRONT VIEW

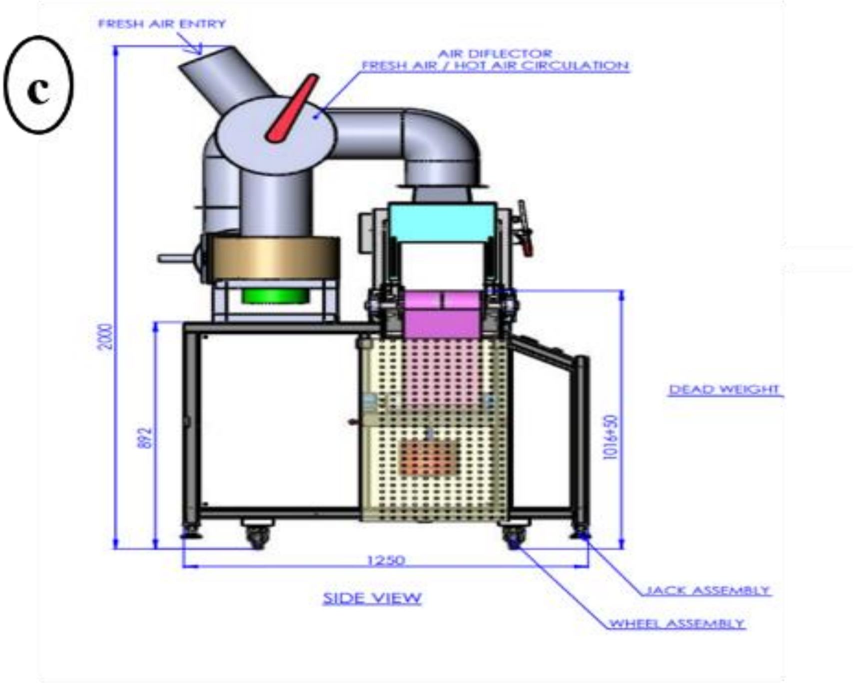
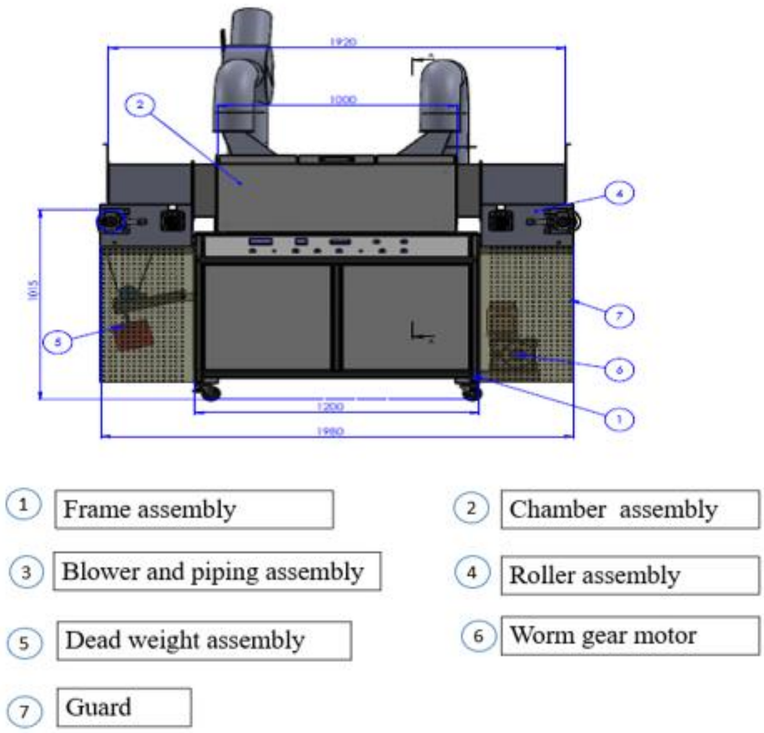


Fig. 3.4 Hot air generation system a. Top view, b. Front view and c. Side view (Courtesy: Enerzi Microwave Systems Pvt. Ltd., Bangalore, India)



Note: Dimensions given are in mm

Figure 3.5 Microwave convective dryer

Plate 3.4 Photograph of microwave convective dryer

3.4 Operating procedure of microwave dryer

The operating procedure for the microwave dryer is shown in Fig 3.6. Though microwaves are non-ionizing radiations, as part of safety it is advised to stay at a safe distance from the dryer during its operation.

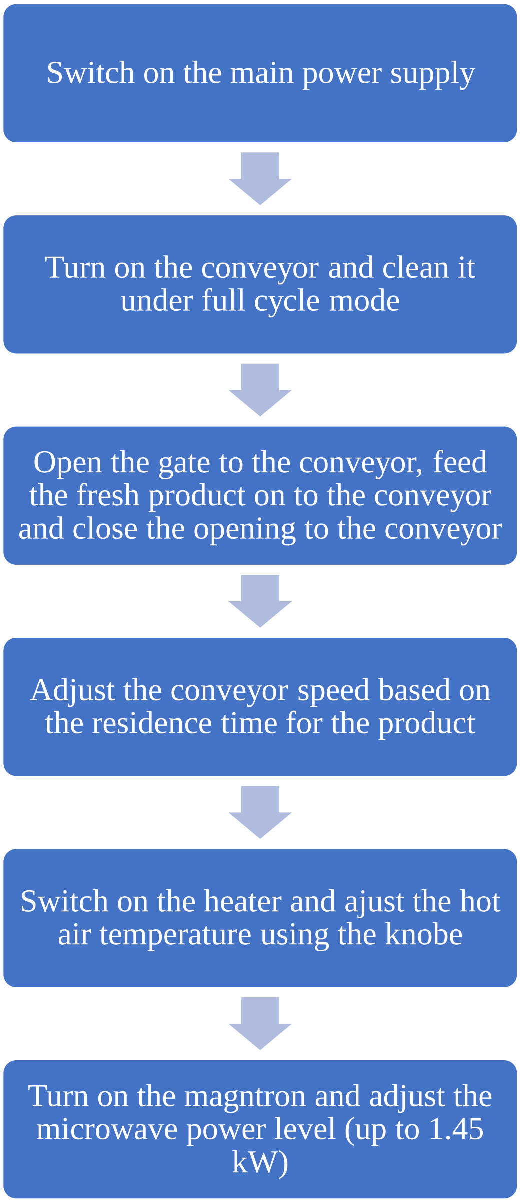


Fig. 3.6 Operating procedure of microwave dryer

However, the operating conditions of the dryer should be set depending on the products to be dried. Microwave power level of 600 – 1000 W and air temperature of 40 – 70 °C is the commonly applied ranges for agricultural and fishery products.

3.5 Studies under solar drying conditions

Comparative studies on microwave and solar drying were carried out to determine the quality and shelf stability of shrimp and mushrooms under both drying conditions. Solar drying studies were conducted in solar-LPG hybrid dryer developed by ICAR – Central Institute of Fisheries Technology, Cochin. Solar dryer consists of solar flat plate heat collectors, heating coils, drying chamber, exhaust and other controls. The schematic diagram and specifications of the dryer is given in Fig. 3.7 and Table 3.5, respectively.

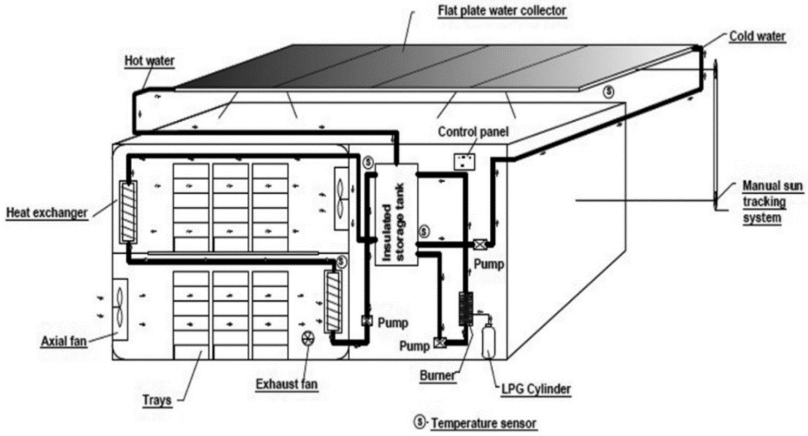


Fig. 3.7 Solar based LPG dryer – Schematic

Table 3.5 Specifications of solar-LPG dryer

Dryer capacity	50 - 60 kg
Material of construction	Multi-wood with MS angle frame for support & Heat resistant aluminum foil (0.5 mm) insulation; PUF insulated panel (6cm) with stainless steel inside and Powder coated GI outside
Overall dimension (m)	4.23 × 1.00 × 1.80 (L × W × H)
Drying chamber dimension (m)	2.46 × 1.00 × 1.80 (L × W ×H)
No. of solar radiation collector	4 Nos. Vacuum tube collectors (VTC) (2 X 1 m each)
Total heat absorbing area	12 m^2
Solar tracking system	Manual
Alternate energy back up	LPG
No. of trays	60
Tray dimension (L × W × H), m	0.80 × 0.45 × 0.25
Tray material	SS 304 Perforated tray, 18 Gauge Tray holder – 6 Nos
Blower	4 Nos. (0.5 HP) Dia – 12.5”, 2800rpm Standard: Crompton & greaves, EBM
Heat exchanger	2 Nos. 500 mm × 500 mm × 110 mm, Copper tubes with GI fins
Pre-heating element	2 Nos. (1000 W)
Exhaust fan	1 Nos. 0.15hp, Dia - 8”
Pump	3 Nos., 0.5 hp
Gas geyser	1 Nos., 15 L
Water tank	1 Nos., 100 ltrs (Insulated)
Other accessories	Temperature controller – 3Nos Temperature & RH Sensor – 4 Nos Toggle switch - 4 Nos Indicator, Cable, Control panel box

3.6 Experimental design

The independent and dependent variables considered for various experiments in the study are given below:

3.6.1 Optimization of drying process parameters for shrimp and mushroom using Response Surface Methodology

Shrimp	
Independent variables (Factors)	• Hot air temperature (50, 60 and 70 °C) • Microwave power (600, 800 and 1000 W) • Air velocity (0.5, 1.0 and 1.5 m/s)
Dependent variables (Responses)	• Moisture content (%) • Water activity • Rehydration ratio (%)

3.6.2 Optimization of drying process parameters for shrimp and mushroom using Response Surface Methodology

Oyster mushroom	
Independent variables (Factors)	• Hot air temperature (40, 50 and 60 °C) • Microwave power (600, 800 and 1000 W) • Air velocity (0.5, 1.0 and 1.5 m/s)
Dependent variables (Responses)	• Moisture content (%) • Water activity • Rehydration ratio (%)

3.6.3 Performance evaluation of microwave dryer

Shrimp and mushroom	
Independent variables (Factors)	• Drying temperature • Microwave power • Drying time
Dependent variables (Responses)	• Thermal efficiency (%) • Specific energy consumption (kJ/kg)

3.6.4 Storage studies on dried products

Shrimp	
Independent variables (Factors)	Packaging technology (2 levels) • Ambient • Vacuum packaging Packaging materials (3 levels) • LDPE 150 microns • Polyester polyethylene laminate (Outer layer: polyester, 12 microns and inner layer: LDPE, 60 microns) • Metallised polyester (Outer layer: polyester, 12 microns; Middle layer: metallised polyester, 12 microns and inner layer: polyethylene, 60 microns)
Dependent variables (Responses)	• Moisture content (%) • Water activity • Rehydration ratio • Shrinkage (%) • Hardness (N) • Total colour change • Browning index • Total plate count (cfu/ml) • Free fatty acids (mg/g) • Peroxide value (meq/mg lipid) • TMA (mg N/100 g) • TVBN (mg N/100 g) • TBARS (MDA/kg) • Carbohydrates (%) • Protein (%) • Fat (%) • Ash(%)

3.6.5 Storage studies on dried products

Oyster mushroom	
Independent variables (Factors)	Pac Packaging technology • Ambient • Vacuum packaging Packaging materials (3 levels) • LDPE 150 microns • Polyester polyethylene laminate (Outer layer: polyester, 12 microns and inner layer: LDPE, 60 microns) • Metallised polyester (Outer layer: polyester, 12 microns; Middle layer: metallised polyester, 12 microns and inner layer: polyethylene, 60 microns)
Dependent variables (Responses)	• Moisture content (%) • Water activity • Rehydration ratio • Shrinkage (%) • Hardness (N) • Total colour change • Whiteness index • Total plate count (cfu/ml) • Carbohydrates (%) • Protein (%) • Fat (%) • Ash(%)

3.7 Drying experiments using RSM

The drying experiments were performed according to a second-order Box-Behnken design (BBD) with three factors at three levels: microwave power (600, 800 and 1000 W), air temperature (50, 60 and 70 °C for shrimp and 40, 50 and 60 °C for oyster mushroom) , and air velocity (0.5, 1.0 and 1.5m/s). Drying time, water activity, and rehydration ratio were selected as the response variables. The levels were selected based on literature reviews (Darvishi et al., 2012; Farhang *et al*., 2011; Lee *et al*., 2021). A three-factor, three-level Box-Behnken design (BBD) experimental design was used in optimizing the drying conditions for shrimp and oyster mushroom in a hot air-assisted microwave (HAMW) drying system. The quadratic model for predicting the optimum solution was expressed using the following equation:

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_i \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \ldots (40)$$

Where, Y is the response, Xi and Xj are variables (I and j range from 1 to k), 0 is the model intercept coefficient; j, jj and ij are interaction coefficients of linear, quadratic and second-order terms, respectively, k is the number of independent parameters (k=3) and e_i is the error. A lack of fit test was used to evaluate the appropriateness of the selected model.

The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 centre points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 9.0.0 trial version (Stat Ease Inc., Minneapolis, MN, USA) was used to perform statistical analysis. Analysis of variance (ANOVA) was carried out to check the significance of the model and process variables. The experimental runs were carried out as per the design details provided in Tables 3.6 and 3.7 for shrimp and oyster mushroom, respectively.. Microwave power levels were adjusted from the control panel of the microwave generator. The air temperature inside the drying chamber was measured using a digital temperature indicator. The air velocity was measured using a vane anemometer. Drying experiments were conducted till the moisture content of 12-18 % (w.b.) is reached. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28±2°C). The weight loss of the shrimp and oyster mushroom were measured every 30 minutes of the drying operation.

Table 3.6 RSM design for hot air assisted microwave drying of shrimp

3	Air temperature (^{0}C) Factor: 1	Microwave power (W) Factor: 2	Air velocity (m/s) Factor: 3
1	50 (-1)	600(-1)	1.00(0)
2	60 (0)	800(0)	1.00(0)
3	50(-1)	800(0)	0.50(-1)
4	60(0)	800(0)	1.00(0)
5	60(0)	600(-1)	0.5(-1)
6	50(-1)	800(0)	1.50(+1)
7	70(+1)	800(0)	0.50(-1)
8	60(0)	1000(+1)	1.50(+1)
9	50(-1)	1000(+1)	1.00(0)
10	60(0)	1000(+1)	0.50(-1)
11	70(+1)	600(-1)	1.00(0)

12	60(0)	600(-1)	1.50(+1)
13	60(0)	800(0)	1.00(0)
14	70(+1)	800(0)	1.50(+1)
15	70(+1)	1000(+1)	1.00(0)
16	60(+1)	800(0)	1.00(0)
17	60(+1)	800(0)	1.00(0)

Note: Figures in the parenthesis signify the coded values.

Table 3.7 RSM design for hot air assisted microwave drying of oyster mushroom

Run	Factor 1	Factor 2	Factor 3
	A: Air temperature ^{0}C	B: Microwave power W	C: Air velocity m/s
1	60(+1)	800(0)	1.5(+1)
2	50(0)	1000(+1)	0.5(-1)
3	40(-1)	600(-1)	1(0)
4	40(-1)	800(0)	0.5(-1)
5	50(0)	800(0)	1(0)
6	50(0)	600(-1)	0.5(-1)
7	50(0)	800(0)	1(0)
8	60(+1)	600(-1)	1(0)
9	40(0)	1000(+1)	1(0)
10	50(0)	1000(+1)	1.5(+1)
11	40(-1)	800(0)	1.5(+1)
12	60(+1)	800(0)	0.5(-1)
13	50(0)	600(-1)	1.5(+1)
14	60(+1)	1000(+1)	1(0)
15	50(0)	800(0)	1(0)
16	50(0)	800(0)	1(0)
17	50(0)	800(0)	1(0)

Note: Figures in the parenthesis signify the coded values.

3.8 Drying studies

Shrimp and oyster mushroom were dried under two drying conditions namely microwave convective drying (Microwave convective dryer, KCAET, Tavanur) and solar drying (Solar LPG hybrid dryer, ICAR-CIFT, Cochin).

Performance evaluation of microwave convective drying system was carried out using shrimp and mushroom under microwave power of 600 – 1000 W and hot air temperature of 40 – 60°C. Drying was continued up to moisture contents of 12-18 % and 6 – 8% w.b for shrimp and oyster mushroom, respectively. Drying studies were conducted as per the runs generated in response surface methodology. For each drying experiment, 1000 g of cleaned samples were taken and fed to the conveyor. A handheld infrared thermometer (METRAVI, Kolkata, India) was used to measure chamber and shrimp temperature during drying. Relative humidity of air ranged from 67 ± 1% to 36 ± 1% during drying. Based on the preliminary experiments, microwave power levels were optimized for the desired temperature range for drying of shrimps and mushrooms. Dried products were packed in suitable packaging material and stored at ambient temperature (28±2°C). Weight loss of the shrimp and mushroom were measured in every 30 minutes of drying operation.

Shrimp and oyster mushroom were dried under two drying conditions namely solar drying (Solar LPG hybrid dryer, ICAR-CIFT, Cochin) and microwave drying (Microwave dryer, KCAET, Tavanur). Solar drying experiments were conducted during January – February 2022 at ICAR-CIFT, Cochin, India (9.9822° N, 76.2424 °E). Solar drying studies on shrimp and oyster mushroom were done under optimum drying temperature of 50-55 °C inside the drying chamber which was maintained by sunshine and LPG backup heating system whereas MW drying was carried out under microwave power of 600 – 1000 W. Drying was continued up to 12-18 % and 6 – 8% w.b. moisture content for shrimp and oyster mushroom respectively. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28±2°C). Weight loss of the shrimp and oyster mushroom was measured every 30 minutes of the drying operation. Schematic representation of solar-LPG dryer is shown in Fig. 3.2. Technical specifications of the solar-LPG dryer are given in Table 3.2. Weight loss of the shrimp was measured every 30 minutes of the drying operation.

3.8.1 Drying characteristics

Drying studies comprised of determination of moisture content, drying rate, moisture ratio and effective moisture diffusivities during hot air assisted microwave drying and solar drying of shrimp and mushrooms.

3.8.1.1 Moisture content

Weight of water in the product is represented by moisture content and can be expressed as dry and wet basis values, as given below:

$$M_w(\%) = \frac{W_I - W_F}{W_I} \times 100 \ldots (16)$$

$$M_d(\%) = \frac{W_I - W_F}{W_F} \times 100 \ldots (17)$$

where M_d, M_w are moisture content (%) dry and wet basis respectively; W_I is the sample weight before drying (kg), W_F is the sample weight after drying (kg). Moisture analyser used to determine the moisture content (% w.b.)is shown in Plate 3.5.

Plate 3.5 Infrared moisture analyzer

3.8.1.2 Drying rate

Amount of moisture removed in terms of time is described by drying rate and is determined as follows (Sodha et al., 1987):

$$DR = \frac{M_t - M_{t+dt}}{dt} \ldots(18)$$

where DR, the drying rate is obtained as kg of water per kg dry mass per h, M_t is moisture content at time t (kg water/kg dry mass), M_{t+dt} is moisture content at time, t + dt (kg water/kg dry mass and dt is the difference in drying time, in hour.

3.8.1.3 Moisture ratio

Moisture ratio was determined as below:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \ldots(19)$$

where MR stands for moisture ratio, M_0, M_e and M_t are the percent moisture contents initial, equilibrium and at time, t (in % db), respectively. Above equation takes the form as equation (19) by omitting the term M_e, as it is very small comparable with M_0 and M_t values (Sacilik *et al*. 2006).

$$MR = \frac{M_t}{M_0} \ldots (20)$$

3.8.1.4 Effective moisture diffusivity

Diffusion, which is the major driving force for moisture removal in drying is expressed by effective moisture diffusivity that determine the overall mass transfer process. It is the rate of movement of moisture and give insight to the migration of water during drying and hence needed for optimization process. Movement of water inside hygroscopic material during falling rate drying is given by Fick's law as:

$$\frac{\delta M}{\delta t} = \nabla.\left(D_{eff}\, \nabla M\right) \ldots(21)$$

where M denotes moisture content of the sample in kg water/kg dry matter, t stands for drying time in s, and D_{eff} represents the effective moisture diffusivity in m^2/s.

It was assumed that shrimp for drying were cylindrical in shape for the diffusivity calculation. For an infinite cylinder (where the moisture diffusion takes place in radially outward direction only), the assumptions considered for calculating diffusivity were (Crank, 1975):

- Uniform distribution of moisture initially in the sample
- Symmetric mass transfer with reference to cylindrical centre

- Surface mass transfer resistance is very less compared with internal resistance to mass transfer
- Shrinkage of product is negligible with constant diffusion coefficient

For cylindrical material, Crank's solution for equation (20) is given by:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{4}{b_n^2} \, exp\left(-\frac{D_{eff} b_n^2 t}{r^2}\right) \ldots (22)$$

Taking the initial term, diffusivity is calculated as (Zogzas et al., 1996):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{4}{b_n^2} \, exp\left(-\frac{D_{eff} b_n^2 t}{r^2}\right) \ldots (23)$$

In the above equation, r represents mean radius of sample in metres, n denotes positive integer and b_n are the root of Bessel's function (2.405, 5.52, 8.654……). For n>1, solution is obtained as (Lopez et al. 2000):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{4}{b_1^2} \, exp\left(-\frac{D_{eff} b_1^2 t}{r^2}\right) \ldots (24)$$

Where b_1 is 2.405

The simplified form of equation (24) in logarithmic form is written as:

$$\ln(MR) = A - B \times t \ldots (25)$$

Here, B represents the slope of line and is related to moisture diffusivity as:

$$B = \frac{b_1^2 D_{eff}}{r^2} \ldots (26)$$

Thus, moisture diffusivity is determined from the slope obtained from plot of linear regression of ln (MR) with time (equation 26)

$$D_{eff} = -\frac{B\, r^2}{b_1^2} \ldots (27)$$

3.8.2 Mathematical modelling of drying behaviour

Drying data were substituted in thin layer drying equations (Table 3.8) to predict behavior, control parameters and improve efficiency. The solutions to the values of model constants and non-linear regression analysis were executed by MATLAB (R2021b) software (Alfiya *et al*., 2018). The prediction on the model of best fit was done with respect to higher coefficient of determination (R^2) and lower percentage root mean square (RMSE) and reduced chi-square ($\chi 2$).

Table 3.8 Modeling of drying data

S. No.	Model name	Equation	Reference
1	Logarithmic	$MR = \frac{M-Me}{Mo-Me} = ae^{-kt} + c\ldots(28)$	Moradi et al., 2020
2	Henderson and Pabis	$MR = \frac{M-Me}{M0-Me} = ae^{-kt}\ldots(29)$	Arslan et al., 2010
3	Modified page	$MR = \frac{M-Me}{Mo-Me} = e^{(-kt)^n}\ldots(30)$	Karacabey and Buzurul, 2017
4	Two-term exponential	$MR = \frac{M-Me}{Mo-Me} = \mathrm{a} * \exp(-\mathrm{k1} * \mathrm{t}) + \mathrm{b} * \exp(-\mathrm{k2} * \mathrm{t})\ldots(31)$	Togrul and Pehlivan, 2004
5	Wang and Singh	$MR = \frac{M-Me}{Mo-Me} = 1 + at + bt^2\ldots(32)$	Wang et al., 2005
6	Verma *et al*	$MR = \frac{M-Me}{Mo-Me} = ae^{-kt} + (1-a)e^{-gt}\ldots(33)$	(Yaldys and Ertekýn, 2001)
7	Page	$\boldsymbol{MR = \frac{M-Me}{Mo-Me} = e^{-kt^n}}\ldots(34)$	Roy et al., 2022
8	Newton	$MR = \frac{M-Me}{Mo-Me} = e^{-kt}\ldots(35)$	Benseddik et al., 2018

3.8.3 Drying efficiency and specific energy consumption

3.8.3.1 Microwave drying efficiency

The efficiency of MW drying was calculated as the ratio of heat utilized for vaporisation of water to the heat provided by the dryer (Soysal et.al., 2007).

$$\eta = \frac{Mw \times L}{P \times t} \quad \ldots(36)$$

where where η is the HAMW drying efficiency (%); P is the MW power (W); M_w is the mass of water evaporated (kg), and L is the LH of vaporization of water expressed in J/kg (2257 kJ/kg), t is the drying time (s).

3.8.3.2 Solar collector efficiency

The efficiency of the collector is determined as the ratio of energy absorbed by water in the collector tubes to the incident solar energy (Sukhatme and Naik 2008). The equation for collector efficiency is given as:

$$Collector\ eficiency = \frac{m_w \times c_{pw} \times (T_{co-}T_{ci})}{A_c \times I\ \times 3600} \times 100\ldots(37)$$

Where, m_w is the mass flow rate of water (kg/h), C_{pw} is the specific heat water (kJ/kgK), T_{ci} and T_{co} are the temperatures of water collector at inlet and outlet respectively (K), A_c is the solar water collector area and I is the average incident solar irradiation (W/m^2)

3.8.3.3 Solar drying efficiency

The efficiency of drying in a solar-LPG hybrid drying system was calculated by taking the sum of energy observed by the solar collector, consumed by a blower/pump/fan and supplemented by an LPG water heater (Nabnean *et al*., 2016). The LPG utilized was determined as the change in weight of the LPG cylinder before and after the study (Lopez *et al*., 2013). The amount of LPG consumed was expressed in terms of calorific value in MJ. Drying efficiency is the ratio of energy required to the energy supplied for removing water from the product (Murali et al., 2020).

$$Drying\ efficiency\ (\%) = \frac{Energy\ required\ (M_W \times L_H)}{Energy\ supplied\ (E_{lpg} + E_{sc} + E_{pb}\ )} \times 100 \ldots(38)$$

Here, M_w denotes the water to be removed (kg), L_H, the latent heat of vaporization of water (kJ/kg) and E_{lpg}, E_{sc} and E_{pb} and are the energy supplied by LPG burner, solar collector, pump and blower (in W).

3.8.3.4 Specific energy consumption (SEC)

SEC is determined using the following equation and is expressed as kWh/kg of water evaporated (Wang and Sheng, 2006).

$$SEC = \frac{E_T}{M_W} \ldots(39)$$

Where E_T is the total energy (kWh) and M_W is mass of water evaporated (kg).

3.9 Determination of quality parameters of dried products

3.9.1 Rehydration ratio

To determine the rehydration ratio of dried sample, 5g of sample was soaked in 200 ml distilled water at room temperature. Weight of the samples were taken at every 30-minute interval, until constant value was obtained (Doymaz and Ismail, 2011).

$$Rehydration\ ratio = \frac{Weight\ of\ rehydrated\ sample\ (g)}{Weight\ of\ dried\ sample\ (g)} \ldots(41)$$

3.9.2 Shrinkage

The volume changes in foods during drying is expressed in terms of shrinkage. Difference in volume of samples before and after drying were estimated by comparing the dimensions of sample in three directions using Vernier caliper (accuracy of ±0 .05 mm) before and after drying. Equation to calculate shrinkage is given as (Tirawanichakul *et al.*, 2008):

$$Shrinkage\ (\%) = \frac{D_{Initial} - D_{Final}}{D_{Initial}} \times 100 \ldots (42)$$

where $D_{Initial}$ and D_{Final} are geometric mean diameter of sample before and after drying, respectively (Paksoy *et al.*, 2014).

3.9.3 Water activity

Water activity is defined as the partial pressure of water in the product to that of pure water. Water activity of dried shrimp and mushroom were determined using Aqualab Series 3L water activity meter, Decagon Devices, Inc. Pullman, Washington, DC) at 28±^{0}C. the equipment used to determine water activity pf dried shrimp and oyster mushroom is shown in Plate 3.6.

Plate 3.6 Water activity meter

3.9.4 Biochemical analysis

Biochemical analysis of raw and dried shrimp samples was determined for TMA (trimethyl amine), TVB-N (total volatile basic nitrogen) and TBARS (thiobarbituric acid). TMA and TVB-N were estimated in terms of mg N/100 g (Conway, 1962) and TVBN in mg malonaldehyde/kg of lipid (Tarladgis et al., 1960).

3.9.5 Estimation of trimethyl amine

Two ml of N/70 sulphuric acid were added to the centre compartment of a standard Conway unit. A measured volume of extract prepared according to procedure 3 above (0.5-1.0 ml) made up to 2 ml with water and 0.5 ml formalin (5006) were added to the outer chamber.

1 ml of K_2CO_3, solution was added to the outer chamber and the unit quickly and carefully closed with a waxed cover plate. The unit was incubated at room temperature for 24 hr, after which the cover plate was removed, 5 drops of Tashiro's indicator added to the centre well, the contents of which were then titrated with N/70 sodium hydroxide. One ml of N/70 H_2SO_4 is equivalent to 0.2 mg TMA. Assays were run in triplicate.

3.9.6 Estimation of total volatile basic nitrogen

Twenty-five grams of the sample was homogenated with 75 ml of distilled water and 2 M HCL was used to bring the pH up to 5.2. This was then heated slowly to 70 ^{0}C and cooled down to room temperature. The mixture was then filtered. Two milli litre of 0.01 M HCL was added into the centre compartment of the Conway dish and 2 ml of the filtrate was added into the outer compartment with 1 ml of saturated potassium carbonate. The dish was covered with a glass plate and left at 37 C$^{\circ}$ for 2 hours. The HCL was titrated with 0.01 N NaOH using 2 – 3 drops of methyl red indicator.

$$\frac{Milligram\ TVBN}{100\ g\ sample} = \frac{0.01 \times (2-t) \times 96 \times 14 \times 100}{25 \times 2} = 26.88\ (2-t) \ldots (43)$$

Where, t is the volume of NaOH used in titration, assuming that 96 ml of water is taken in which the sample weight is dispersed and that 25 g chopped shrimp is contained in 4 g dry matter.

3.9.7 Estimation of thiobarbituric acid

Thiobarbituric acid reactive substances (TBARS) are formed as a by-product of lipid oxidation and can be detected by the TBARS assay using thiobarbituric acid (TBA) as a reagent. This is an indirect measure of reactive oxygen species (ROS). The TBA reacts with malondialdehyde (MDA), which is one of the several low-molecular weight end products formed from the decomposition of some primary and secondary lipid peroxidation products. Also, MDA is neither the sole end product of fatty peroxide formation and decomposition, nor a substance generated exclusively through lipid peroxidation. Thiobarbituric acid reactive substances (TBARS) are formed as a by-product of lipid oxidative damage (i.e., as degradation products of fats) and can be detected by the TBARS assay using thiobarbituric acid (TBA) as a reagent. This is an indirect measure of ROS. The TBA reacts with malondialdehyde (MDA), which is one of the several low-molecular weight end products formed from the decomposition of some primary and secondary lipid peroxidation products. Not all peroxidation reaction generates MDA and also MDA is not the only substance generated exclusively through lipid peroxidation. TBARS was determined by distillation method. A steam distillate of an acidified food sample was taken and an aliquot is then reacted with excess TBA. Based on a standard curve, results were expressed as mg malonaldehyde eq/kg sample.

Accurately weighed 10 g homogenized food sample on weighing paper was transferred to a 500-ml round-bottomed flask. Each sample was assayed in triplicates. 95 ml distilled water, 2.5 ml antioxidant solution, 2.5 ml of 4 N HCl (final 0.1 N, to adjust pH to ∼1), a few drops of antifoam A emulsion, 3 to 5 glass beads (to prevent bumping) were added to the falsk. The contents were swirled well.

A standard distillation column with a condenser was attached and distilled rapidly using a heating mantle until 50 ml distillate was collected. The distillation step was completed in 15-20 min. TBA reaction on 5 ml distillate was performed and absorbance was measured. A standard curve was prepared and malonaldehyde recovery was measured. TBA was calculated as follows:

$$TBA\ value\ (\frac{mg\ MDA\ eq}{kg\ sample})\ = K \times A_{532} \ldots(44)$$

$$K = \frac{[\left(\frac{mol\ MA}{5\ ml}\right)A_{532} \times MA\ mol.wt. \times DF \times 10^6 \times (100\%\ recovery)]}{m} \ldots(45)$$

Where, K is the constant derived from assay and A_{532} is the absorbance of test sample at 532 nm, (mol MA/5 ml)/A532 represented 1/slope of the standard curve, mol wt of melonaldehyde is 72.03 g/mol, DF is the dilution factor, 106 converts the unit so that the results can be expressed as mg melonaldehydeeq/kg of sample, % recovery is the average recovery value and m is the mass of the sample.

3.9.8 Estimation of peroxide value

Estimation was conducted as per the standard AOCS, 2009. About 5 ± 0.05 g sample in 250 ml close Erlenmeyer and add 30 ml acetate acid. Shake the mixture so it blends thoroughly. Add 0.5 ml KI. Rest for 1 minute and shake once a while and then add 30 ml distilled water. Titrate with 0.1 N Na2S2O3 until the yellow color disappears. Add 0.5 ml starch liquid; continue titration until the blue colors begin to disappear. Peroxide value is recorded in ml-equivalent from peroxide in every 1000 g.

$$Peroxide\ value\ = \frac{ml\ Na_2S_2O_3\ \times Normality\ Na_2S_2O_3}{Weight\ of\ sample} \times 100\ \ \ldots(46)$$

3.9.9 Estimation of free fatty acids

The standard method of AOAC (2001) was used to determine for free fatty acids in crude oil. Ten grams of ground sample was taken in a conical flask. To the sample 50 ml of neutral alcohol was added and allowed to boil in a water bath. The well-boiled sample was filtered and the filtrate was taken. Phenolphthalein was used as the indicator and titrated against

0.02NKOH till the appearance of pale pink colour. the FFA analysis was performed in triplicate.

$$\text{FFA (\%)} = \frac{282 \times 0.02\text{NKOH} \times \text{ml of alkali used} \times 100}{1000 \times \text{Weight of sample taken} \times 100} \ldots(47)$$

3.9.10 Proximate analysis

Fresh shrimp and shrimp dried under were examined for its proximate composition like moisture, crude protein, crude fat and ash (AOAC, 1990).

3.9.10.1 Estimation of carbohydrates

The total carbohydrate content is estimated by the Anthrone method as described by (Sadasivam, 1996). All the sugars present in the food substance were made hydrolysed by concentrated sulphuric acid into monosaccharide which is hydrated by the acid to hydroxy methyl furfural. The furfural designated is then condensed with anthrone to give the green colour. the intensity depends on the concentration of sugar in the substance. Prepare the standard glucose: 100mg of stock (glucose) was dissolved in 100 ml water. The working standard was prepared by diluting 10ml of stock in 100ml of distilled water. Prepare the standards by taking 0, 0.2, 0.4, 0.6, 0.8, and 1ml of working standard. 0 serves as the blank. Make up the volume to 1ml in all the test tubes including sample tubes by adding distilled water. Then add 4ml of anthrone reagent. Heat it for 8 minutes in a boiling water bath and cool rapidly and read the green to dark green colour at 630nm. Shimadzu UV -1800 optical spectrophotometer and analysis are carried out. 100mg of the crushed sample was taken into the boiling tube and the sample was hydrolysed by keeping it in the boiling water bath for three hours with 5 ml 2.5N HCl and cooling to room temperature. After 3h, the solution was neutralized with solid sodium carbonate until the effervescence ceases. Later it was made up to 100ml and centrifuged. The supernatant was taken for analysis (0.2ml). The volume was made up to 1 ml in all the tubes with distilled water. Then, 4 ml of Anthrone reagent was added to all test tubes. The tubes were heated for 8 minutes in a boiling water bath. It was cooled rapidly and read the green to dark colour at 630nm in a Shimadzu 1800 optical spectrophotometer and total carbohydrate was expressed in percentage (w /w). The standard was prepared by taking 0.2, 0.4, 0.6, 0.8, and 1ml of the working standard, and the graph was obtained with the concentration of the standard on the X-axis versus absorbance on the Y-axis.

$$Carbohydrates, \% = \frac{\text{mg of glucose} \times 100}{\text{Volume of the test sample}} \ldots(48)$$

3.9.10.2 Estimation of protein

Protein was estimated according to Kjeldahl method (Anonymous, 1970). The nitrogen in protein or any other organic material is converted to ammonium sulphate by $H2SO_4$ during digestion. On steam-distillation, it liberates ammonia which is collected in boric acid solution and titrated against standard acid. Since 1ml of 0.1 N acid is equivalent to 1.401mg N, calculation is made to arrive at the nitrogen content of the sample.

Accurately weighed l00 mg of the sample (containing 1-3mg nitrogen) was transferred to a 30 ml digestion flask and digested. To this sample, 1.9 ± 0.l g potassium sulphate and 80 ± l0 mg mercuric oxide was added along with 2 ml con. H2SO4 and digested. As sample size was larger than 20 mg dry weight, 0.l ml H2SO4 was added for each l0 mg dry material. Boiling chips were also added and digested till sample solution becomes colourless. The solution was cooled and diluted with a small quantity of distilled ammonia-free water and transferred to the distillation apparatus When the nitrogen content of the sample is high, the digest was made up to a known volume and an aliquot transferred to the distillation flask. The Kjeldahl flask was rinsed with successive small quantities of water. An l00 ml conical flask containing 5 ml of boric acid solution with a few drops of mixed indicator was placed at the tip of the condenser. Sodium hydroxide solution (10 ml) was added to the test solution in the apparatus. After distillation, ammonia was collected (at least 15-20 ml of distillate should be collected). Tip of the condenser was rinsed and the solution was titrated against the standard acid until the first appearance of violet colour as the end point. A blank was prepared with an equal volume of distilled water and subtracted the titration volume from that of sample titre volume.

$$Nitrogen\ (\%) = \frac{(ml\ HCl - ml\ blank) \times Normality\ \times 14.01}{Weight\ of\ sample\ (g)} \times 100 \ldots (49)$$

3.9.10.3 Estimation of total fats

Total fat was estimated based on the method described by Ranganna (1986). A piece of filter paper was folded in such a way to hold the banana flour. Second filter paper was wrapped around the top like a thimble. A piece of cotton wool was placed at the top to evenly distribute the solvent as it drops on the sample during extraction. A sample packet was placed in the butt tube of the soxhlet extraction apparatus. Oil was extracted with petroleum ether (150 drops per minute) for 6 h without interruption by gentle heating and allowed to cool and dismantled the extraction flask. Ether was evaporated on a steam or water bath until no odour of ether remains and cooled at room temperature. The dirt or moisture was removed carefully outside the flask and the flask was weighted. Drying was repeated until constant weight was recorded.

$$Oil\ (\%) = \frac{Weught\ of\ oil\ collected\ (g)}{Weight\ of\ sample\ (g)} \times 100 \ldots (50)$$

3.9.10.4 Estimation of crude fibre

The crude fibre content was determined by the method described by Maynard (1970). Crude fibre consists largely of cellulose and lignin (97%) plus some mineral matter. It represents only 60 to 80 per cent of the cellulose and 4 to 6 per cent of the lignin. The crude fibre content is commonly used as a measure of the nutritive value of poultry and livestock feeds and also in the analysis of various foods and food products to detect adulteration, quality and quantity (Landry, 1997; Pellet and Young, 1980). During the acid and subsequent alkali treatment, oxidative hydrolytic degradation of the native cellulose and considerable degradation of lignin occur. The residue obtained after final filtration is weighed, incinerated, cooled and weighed again. The loss in weight gives the crude fibre content.

About 2 g of powdered sample was extracted with ether or petroleum ether to remove fat (initial boiling temperature 35-38°C and final temperature 52°C). If fat content is below one per cent, extraction may be omitted. After extraction with ether boil 2 g of dried material was boiled with 200 ml of sulphuric acid for 30 min with bumping chips. Filter through muslin and wash with boiling water until washings are no longer acidic. Boil with 200 ml of sodium hydroxide solution for 30 min. Filtered through muslin cloth again and washed with 25 ml of boiling 1.25 per cent H_2SO_4, three 50 ml portions of water and 25 ml alcohol. The residue removed and transfered to ashing dish (preweighed dish W_1). The residue was dried for 2 h at 130 ± 2°C. Cooled in a desiccator and weigh (W_2). Ignited for 30 min at 600 ± 15°C. Cool in a desiccator and reweigh (W_3).

$$Crude\ fibre\ (\%) = \frac{Loss\ in\ weight\ on\ ignition\ (W_2 - W_1) - (W_3 - W_1)}{Weight\ of\ sample\ (g)} \times 100 \ldots (51)$$

3.9.11 Colour analysis

Hunter Lab colour flex meter was used for the measurement of colour changes in dried products. It works on the principle of collecting the light and measures energy from the sample reflected across the entire visible spectrum. The meter uses filters and mathematical models which rely on "standard observer curves" that defines the amount of green, red and blue primary lights required to match a series of colour across the visible spectrum. It provides a reading in terms of 'L', 'a' and 'b', The 'L' coordinate measures the value or luminance of a colour and ranges from black at 0 to white at 100. The 'a' coordinate measures red when positive and green when negative and 'b' measures yellow when positive and blue when negative. All the three standard colour parameters 'L', 'a' and 'b' were observed for day light colour. The colour meter was standardized using black and white ceramic calibration tiles.

Readings were observed from three replicates of each sample and the mean values of 'L', 'a' and 'b' were reported. Colorimetric values (L*, a*, b*) were measured to find out the color changes of samples and was performed using a colorimeter (Hunterlab, Colorflex: EZ). Conventionally, the Hunter color scale is represented by L* for lightness or darkness (L* = 0 for darkness and L* = 100 for whiteness), a* for redness or greenness (a* > 0 for redness and a* < 0 for greenness) and b* for yellowness or blueness (b* > 0 for yellowness and b* < 0 for blueness). The total variation ΔE, is given as (Pathare *et al*., 2013):

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \ldots (52)$$

where L^*, a^*, b^* and L_0, a_0, b_0 indicated the colour parameters for dried and raw samples, respectively. More variation from control is represented by higher ΔE values. Hunterlab colorflex meter used in the study is shown in Plate 3.7. Browning index (BI) and whiteness index (WI) were calculated as follows (Brochert *et. al.*, 2014, Li *et al*., 2020).

$$BI = 100 \times \frac{X - 0.31}{0.17} \ldots (53)$$

$$X = \frac{a^* + 1.75\,L^*}{5.645\,L + a^* - 3.012 b^*} \ldots (54)$$

$$WI = 100 - [\,(100 - L*)^2 + a^{*2} + b^{*2}] \ldots (55)$$

Plate 3.7 Hunterlab Colourimeter

3.9.12 Textural analysis

Hardness of the dried samples during storage were measured using Texture analyzer (Model: TA-XT2 Stable Micro Systems, Texture Technologies Crop). Stored samples were placed on the plate of the equipment with a hole of 20 mm diameter. A probe (P_4) was moved perpendicularly to the food surface at a constant speed of 0.5 mm/s until the probe passed through the sample. Force and deformation were noted at rupture point. For each test three samples were analysed and the average value was taken. Texture profile analyser is depicted in Plate 3.8.

Plate 3.8 Texture profile analyser

3.9.13 Microbial analysis

Microbiological quality of the dried samples was tested for Total Plate Count (TPC) as per the standard procedures of Food and Drug Administration (FDA), Bacteriological Analytical Manual (Andrews *et al*., 2018). Ten grams of the shrimp sample was aseptically cut into a sterile petridish and blended with 90 ml of sterile normal saline (NS) in a stomacher and made two-fold serial dilution up to 10^{-6}. For total plate count on Total Plate Count Agar

(TPA), one ml of the appropriate dilutions was pipetted and pour plated with the corresponding medium in duplicate plates. These plates were allowed to set, inverted and incubated at 37°C for 18-24 h. The diluted plates contained colonies ranging from 25-250 numbers. The experiments were done in triplicates and the average value was recorded.

Microbiological quality of the dried samples was tested for the Total Viable Bacterial Count (TVBC), Total Enterobacteriaceae count (TE), Staphylococcal count and *E. coli* count as per the standard procedures of Food and Drug Administration (FDA), Bacteriological Analytical Manual (BAM, 2020). In brief, 10 g of the fish sample are aseptically cut into a sterile petridish and blended with 90 ml of sterile normal saline (NS) in a stomacher and made two- fold serial dilution up to 10^{-6}. For total plate count on Total Plate Count Agar (TPA), and total enterobacteriaceae count on Violet Red Bile Glucose Agar (VRBGA) plates, 1 ml each of the appropriate dilutions are pipetted and pour plated with the corresponding medium in duplicate plates. For *E. coli*, 0.5 ml each of the appropriate dilutions are spread plated on to Tergitol-7 (T-7) plates using sterile bent glass rod. For *S. aurues*, 0.3, 03 and 0.4 ml each of the dilutions are spread plated on to Baird Parker Agar (BPA) Plates in triplicate from each dilution. These Plates are allowed to set, inverted and incubated at 37°C for 18-24 hrs for *E. coli* and Enterobacteriaceae and 48hrs for total viable bacterial count, and Staphyloccal count.

For total plate count on Total Plate Count Agar (TPA), 1ml each of the appropriate dilutions are pipetted and pour plated with the corresponding medium in duplicate plates. These Plates are allowed to set, inverted and incubated at 37°C for 18-24 h.

Bacterial count (TPC): Selected the diluted plates containing colonies ranging from 25-250 numbers and counted all the colonies on the TPC duplicate plates. Taken average of the duplicate plate with respect to the dilution.

Enterobacteriaceae: Typical colony of Red, small (2-4 mm dia) are counted as Enterobacteriaceae colonies. Take average count of duplicate plates on VRBGA.

Total Enterobacteriaceae count / g = Average count x dilution factor.

E. coli: A typical colony of lime yellow colour, occasionally with rust brown centre and a yellow zone around on T-7 plates. Take average of duplicate plates.

E. coli/g = Average count x 2 x dilution factor.

Confirmation of *E. coli* was carried out by streak on to Eosine Methyle Blue Agar (EMB). Well isolated colonies, 2-3mm. dia with a greenish metallic sheen by reflected light and dark purple centre by transmitted light is picked and subcultured on TGA slants and incubated at 37°C for 18-24 hrs and tested for Indole, Methy Red, Voges-Proskauer and Citrate utilization tests (IMViC).

IMVIC tests: From the TGA slants above, inoculate to the following media.

Inoculated a little of the culture to Tryptone broth and incubate at 37°C for 48 hrs and tested for indole production using Kovac's indole reagent. A red or pink colour at top indicates +ve test. Inoculated each culture into 2 tubes of MRVP medium and incubate at 37°C for 48 hrs. Into one tube, add Methyl Red indicator and red colour indicates +ve MR test. The remaining 1 ml of the culture from the second tube and an eosine pink colour indicates +ve VP test. Streak a little of the culture to Simmmon's citrate agar slants and incubate at 37°C for 48 hrs. Growth indicated by a change in the colour of the medium in the innoculated tubes from green to blue indicates a +ve test for citrate utilisation by the bacterial culture

A culture was confirmed as *E. coli* by + + - and – with IMViC tests. *E.* coli cultures will grow and produce gas in EC broth at 44.5± 0.5°C in 24-48h.

Staphylococcus aureus: Observe after 36-48 hours. Staphylococcus aureus colonies are black with thin white margin and a zone of clearance around.

Total *S. aureus* count / g = Average count x dilution factor…(53)

Confirmation of *Staphylococcus aureus*: *S. aureus* is confirmed by Coagulase test. Difco Bacto-coagulase -EDTA is used for the test. To 0.5 ml. of coagulase reagent in a small sterile test tube, add 2 drops of 24 hr. old bacterial culture (grown in Brain heart infusion broth); incubate in a serological water bath at 37°C. Observe every 30 minutes upto 4 hrs. Coagulation (jell formation) of the contents of the tube indicates a +ve reaction for coagulase.

3.9.14 Microstructural analysis: Scanning Electron Microscopy

The Scanning Electron Microscope creates 3D black and white magnified images by using electrons instead of light waves. SEM works under vacuum in a column, where an electron gun emits a beam of high-energy electrons. This beam travels downward through a series of magnetic lenses designed to focus the electrons to a very fine spot. Near the bottom, a set of scanning coils moves the focused beam back and forth across the specimen, row by row. As the electron beam hits each spot on the sample, secondary electrons are knocked loose from its surface. A detector counts these electrons and sends the signals to an amplifier. The final image is built up from the number of electrons emitted from each spot on the sample. Micrographs of the samples were obtained using a FEI QUANTA 250 scanning electron microscope with a tungsten electron source, secondary electron detector and back scatter. Photograph of the scanning electron microscope is shown in Plate 3.9.

Plate 3.9 Standard electron microscope and computer system for SEM analysis

3.9.15 Sensory evaluation

Dried shrimp and oyster mushroom samples were evaluated for sensory parameters like appearance, texture, color, odour and overall acceptability (Chavan et al. 2008). Sensory analysis was carried out using 9-point hedonic scale with 9 – like extremely, 8 – like very much, 7 – like moderately, 6 – like slightly, 5- neither like nor dislike, 4 – dislike slightly, 3 – dislike moderately, 2 – dislike very much and 1 – dislike extremely. The evaluation was done by 25 semi-trained panel members. The members were the staff and researchers of ICAR-CIFT who were general fish consumers and were able communicate and report variations in the sample.

3.10 Storage studies on dried products

Storage studies on dried shrimp and mushroom were done under three levels of packaging materials and two levels of packaging conditions. By dried samples (under optimum conditions) were packed in LDPE (250 µ), polyester-polyethylene laminated pouches (60 µ) and metallized polyethylene packages (80 µ) under MAP and vacuum-packed conditions. The selection of packaging materials was done based on preliminary studies. During the storage parameters such as moisture content, water activity, rehydration ratio, shrinkage, total colour change, hardness, total plate count (cfu/ml), TMA (mg N/100 g), TBARS (MDA/kg), FFA (mg/g), peroxide value (meq/kg lipid), sensory and proximate analysis were done for shrimp samples. For the optimized microwave dried and solar dried mushroom samples, parameters such as moisture content, water activity, rehydration ratio, shrinkage, total colour change, hardness, total plate count (cfu/ml), sensory and proximate analysis were carried out during storage. For both dried shrimp and dried mushroom, analysis were carried out at an interval of 30 days. Physical properties of the films used in the study is given in Table 3.9. Packaging materials used in the present study os shown in Plate 3.10.

Table 3.9 Physical properties of packaging materials

Packaging film properties	**LDPE**	**Polyester LDPE laminate**	**Metallized polyester laminate**
WVTR (g/cm^2/24 h at 38 ^{0}C & 90% RH)	6.7	6.0	6.2
OTR (cc/cm^2/24 h/atmos)	5700	102	212
Tensile strength (kg/cm^2) Machine direction Cross direction	130 120	500 400	450 400
Elongation at breakage (%)	300	75	90
Heat seal strength (kg/cm^2) Machine direction Cross direction	115 85	200 200	200 200
Thickness	150 microns	72 microns	72 microns
Dimensions (l × b mm)	210 × 120	210 × 120	210 × 120

Plate 3.10 Packaging materials used in the study

3.11 Economic analysis

Economic attributes such as life-cycle cost, annual benefit, benefit cost ratio and payback period were determined to find out the economic feasibility of the drying shrimp under solar and microwave conditions. Life cycle cost is the sum of all costs associated with the dryer in its lifetime and considers the money value at present instant of time (Singh et al. 2021) and is calculated as follows:

$$\text{Life cycle cost (LCC)} = \text{Initial investment} + \text{Operation and maintenance cost} - \text{Salvage value} \ldots (56)$$

Life cycle benefit is determined as the total annual benefit from the dried product. Benefit cost ratio is the ratio of discounted benefits to the discounted values of all costs and is expressed as

$$Benefit - ciost\ ratio = \frac{Life\ cycle\ benefit}{Life\ cycle\ cost} \ldots (57)$$

Payback period is the length of time from the beginning of the project before the net benefits return the cost of capital investments.

$$Pay\ back\ period = -Life\ cycle\ cost + Life\ cycle\ benefits = 0 \ldots (58)$$

3.12 Statistical analysis

The data obtained were statistically analysed by two factor completely randomized block design (CRBD) using the statistical package R software (4.3.0). The Analysis of variance (ANOVA) and mean table for different process parameters were tabulated and the level of significance was reported.

Result and Discussion

CHAPTER IV

RESULTS AND DISCUSSION

This chapter presents the details of the development of semi-continuous microwave convective dryer as well as the results of the observations and analysis carried out in this research work. It also discusses and interprets the obtained results systematically. The experiments conducted in optimizing the process conditions for shrimp and oyster mushroom under hot air assisted microwave drying (HAMW) technology and studies on quality characteristics of the dried products under optimized conditions are elaborated in this chapter.

4.1 Engineering properties of shrimp and oyster mushrooms

Engineering properties of fresh shrimp and oyster mushrooms were determined prior to the development of microwave convective dryer. The engineering properties viz. moisture content, colour, hardness, bulk density, coefficient of friction, thermal conductivity, angle of repose and specific heat for fresh shrimp and mushroom were obtained as per the standard procedures and is tabulated in Table 4.1a and 4.1b. The moisture content of fresh shrimp and oyster mushroom were 80.55±1.54 and 92.35±1.30%, respectively. The colour values of fresh shrimp were 41.21±1.63, 3.56±1.54 and 12.42±0.65, respectively for Hunter colour lab values of L, a and b. The L, a and b colour values for fresh oyster mushroom were 69.23±1.24, 3.64±0.93 and 16.13±1.31 respectively. Kortei *et al*. (2015) made similar reports on the colour analysis of fresh and dried mushrooms. It was observed by the authors that fresh mushroom exhibited L, a and b values in range of 60.46 – 61.30, 3.47 – 3.91 and 18.13 – 19.39, respectively. Drying of the mushrooms decreased the L and b values to the range of 59.86 – 61.18 and 18.09 – 19.27, respectively, whereas the value increased to the range of 3.47 – 3.91. The hardness of fresh shrimp and oyster mushroom were 12.3 N and 3.4 N, respectively. Mittal *et al.* (2012) published that hardness values of fresh, hot air and microwave dried mushrooms were 1.9 N, 3.15 N and 5.9 N, respectively. Bulk density of fresh shrimp and oyster mushroom were 1020±1.50 and 1130±0.64 kg/m^3, respectively. The coefficient of friction of shrimp and oyster mushroom were 0.49±0.10 and 0.57±0.41, respectively. The thermal conductivity of shrimp and mushroom were 0.52±0.23 and 0.64±0.15 W/mK respectively. Specific heat of fresh shrimp and oyster mushroom were determined to be 0.9 and 2.21 kcal/kg°C. The slight increase in values of oyster mushroom for bulk density, thermal conductivity and angle of repose is attributed to the higher moisture content. Jadhav and Patil (2008) reported specific heat, thermal conductivity and thermal diffusivity of fresh mushrooms in range of 2.284 – 4.008 kJ/kg°C, 0.212 – 0.668 W/mK and 1.064×10^{-7} – 1.962×10^{-7} m^2/s respectively which is in line with the findings of this study. Patinho *et al.* (2021) investigated on the effect of various process parameters on quality of oyster mushroom and observed bulk densities in range of 1008 – 1213 kg/m^3. The authors also inferred that increase in moisture content had a positive effect on the bulk density of mushrooms.

Table 4.1a Physical properties of raw shrimp

Parameter	**Value**
Dimensions (l × b × h)	45 ± 1.5, 24 ± 1.3, and 9 ± 0.6 mm
Nos./ kg	350 – 380 nos.
Moisture content	80.55 ± 1.54 (% w. b.)
Colour	L = 41.31±1.63 a = 3.56 ±1.54 b = 12.42 ±0.65 Whiteness index =39.90 Browning index = 60.01
Hardness	8.3 N
Bulk density	1020 ± 1.50 kg/m^3
True density	1154 ± 1.2 kg/m^3
Porosity	0.116
Coefficient of friction	0.0.49±0.10
Thermal conductivity	0.52 ± 0.23 W/mK
Angle of repose	27.45±0.22 °
Specific heat above freezing point	0.9 kCal/kg °C

Table 4.1b Physical properties of raw Oyster mushroom

Parameter	**Value**
Diameter (cap)	36±0.43 mm
Thickness (cap)	3.5±1.0 mm
Moisture content	92.35 ± 1.54 (% w. b.)
Colour	L = 69.23±1.24 a = 3.64 ±0.93

	b = 16.13 ±1.31 Whiteness index = 65.06
Hardness	3.4 N
Bulk density	1130 ± 0.64 kg/m^3
True density	1250 ± 050 kg/m^3
Porosity	0.096
Coefficient of friction	0.57±0.41
Thermal conductivity	0.64 ± 0.15 W/mK
Angle of repose	24.01± 0.53°
Specific heat above freezing point	2.21 kCal/kg °C

4.2 Development of microwave convective dryer

Microwave drying studies on shrimp and mushroom was carried out in the developed semi-continuous hot air-assisted microwave drying unit established at KCAET, Tavanur. A schematic diagram of the drying unit is shown in Fig. 3.1. The drying unit consists of a drying chamber, microwave generator, hot-air provision, exhaust, fan, and control unit. The drying chamber is provided with a layer of heat-resistant Teflon conveyor belt with dimensions of 1.5 m × 0.5 m. The operation of Magnetron of 1.45 kW power at 2450 MHz generated microwave energy for heating the products spread as a thin layer on the conveyor. The hot air assistance was provided with a 1 kW heating element, an air inlet duct, and an axial fan with a recirculatory section. Fresh inlet air is taken into the top of the dryer with the help of an axial fan and the air deflection valve. The heated air is then uniformly passed over the products at a desired air flow rate. The exit moist air is recirculated into the chamber inlet using a fan and temperature control system for maximum energy savings. Photographs of microwave dryer is shown in Plates 4.1 and 4.2.

Plate 4.1 Photograph of microwave convective dryer installed at KCAET, Tavanur

Plate 4.2 Working photograh on microwave convective dryer

4.3 Drying experiments using RSM

The drying experiments were performed according to a second-order Box-Behnken design (BBD) with three factors at three levels: microwave power (600, 800 and 1000 W), air temperature (50, 60 and 70 °C), and air velocity (0.5, 1.0 and 1.5m/s). Drying time, water activity, and rehydration ratio were selected as the response variables. The levels were selected based on literature reviews (Darvishi *et al*., 2012; Farhang *et al*., 2011; Lee *et al*., 2021). A three-factor, three-level Box-Behnken design (BBD) experimental design was used in optimizing the drying conditions for shrimp in a hot air-assisted microwave (HAMW) drying system. The quadratic model for predicting the optimum solution was expressed using the following equation:

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_i \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \quad \ldots (4.1)$$

Where, Y is the response, Xi and Xj are variables (I and j range from 1 to k), 0 is the model intercept coefficient; j, jj and ij are interaction coefficients of linear, quadratic and second-order terms, respectively, k is the number of independent parameters (k=3) and e_i is the error. A lack of fit test was used to evaluate the appropriateness of the selected model.

The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 center points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 9.0.0 trial version (Stat Ease Inc., Minneapolis, MN, USA) was used to perform statistical analysis. Analysis of variance (ANOVA) was carried out to check the significance of the model and process variables. The experimental runs were carried out as per the design details provided in Table 4.2. Microwave power levels were adjusted from the control panel of the microwave generator. The air temperature inside the drying chamber was measured using a digital temperature indicator. The air velocity was measured using a vane anemometer. Drying experiments were conducted till the moisture content of 12-18 % (w.b.) is reached. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28±2°C). The weight loss of the shrimp was measured every 30 minutes of the drying operation.

Table 4.2 Drying time, water activity and rehydration ratio under various drying conditions for shrimp

Run	Air temperature (^{0}C) Factor: 1	Microwave power (W) Factor: 2	Air velocity (m/s) Factor: 3	Drying time (h) Response: 1	Water activity Response: 2	Rehydration ratio Response:3
1	50 (-1)	600(-1)	1.00(0)	6	0.579	2.23
2	60 (0)	800(0)	1.00(0)	3.5	0.531	2.51
3	50(-1)	800(0)	0.50(-1)	4	0.56	2.32
4	60(0)	800(0)	1.00(0)	3.5	0.54	2.52
5	60(0)	600(-1)	0.5(-1)	5.5	0.574	2.2
6	50(-1)	800(0)	1.50(+1)	5	0.521	2.49
7	70(+1)	800(0)	0.50(-1)	5	0.521	2.29
8	60(0)	1000(+1)	1.50(+1)	3	0.572	2.43
9	50(-1)	1000(+1)	1.00(0)	4	0.524	2.41
10	60(0)	1000(+1)	0.50(-1)	3	0.543	2.41
11	70(+1)	600(-1)	1.00(0)	5	0.589	2.24
12	60(0)	600(-1)	1.50(+1)	6	0.567	2.35
13	60(0)	800(0)	1.00(0)	3.5	0.541	2.52
14	70(+1)	800(0)	1.50(+1)	4.5	0.576	2.39
15	70(+1)	1000(+1)	1.00(0)	2.5	0.524	2.41
16	60(+1)	800(0)	1.00(0)	3.5	0.539	2.54
17	60(+1)	800(0)	1.00(0)	3.5	0.541	2.52

Note: Figures in the parenthesis signify the coded values.

4.3.1 Model fitting

Response surface methodology was used to optimize the process conditions of shrimp in a hot air-assisted continuous microwave dryer. Drying time varied for shrimp under hot air-assisted microwave conditions varied from 2.5 to 6 h, water activity from 0.521 to 0.589 and rehydration ratio from 2.2 to 2.54. The actual measured values were fitted into various regression models to select the appropriate model. ANOVA was done to test the lack of fit and to determine the significance of the selected model and its coefficients (Table: 4.3 – 4.5). Results showed that the model selected for responses was significant. This means that the selected model is appropriate to represent the relationship between responses and factors. To evaluate the model adequacy, R^2, Adj $R^{2,}$ and coefficient of variation (CV) values were calculated. The coefficient of variation (%) for drying time, water activity and rehydration ratio were 0.93, 0.97 and 0.94, respectively. A very low p-value (<0.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequate precision values of all responses are above 4.0 which indicates the existence of adequate model difference. Also, a low prediction error sum of squares (PRESS) value for responses indicates model suitability. The desirability function was applied to obtain the optimized values for each dependent variable.

The values of R^2, Adj R^2 and coefficient of variation (CV) values were determined to evaluate the adequacy of the selected model. The R^2 is the measure of the degree of fit and was obtained as 0.93, 0.92 and 0.98 for drying time, water activity and rehydration ratio, respectively and the corresponding adjusted R^2 values were 0.84, 0.83 and 0.96, respectively. A very low value of the coefficient of variation (3.7, 2.17 and 0.8) indicated greater reliability of the experimental data. Therefore, a very low p-value (<0.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequacy precision values of all responses are above 4.0 which indicates the existence of adequate model difference. The model suitability is also indicated by a low PRESS value for response.

4.3.2 Optimization of process variables for drying of shrimp

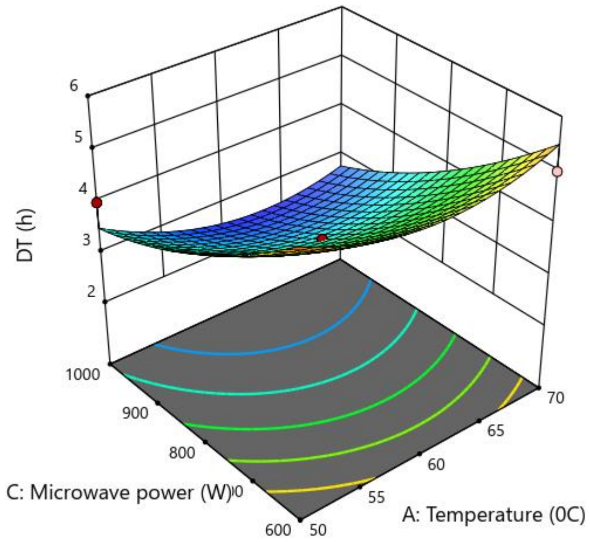
The response surface methodology plots showing the interactions between air temperature, microwave power, and air velocity on drying time are shown in Fig. 4.1 (a, b, c). Analysis of variance (Appendix A-1) showed that the process parameters viz., air temperature ($p \leq 0.05$), microwave power ($p \leq 0.05$) and air velocity ($p \leq 0.05$) had a significant effect on drying from R squared values of 0.93. It is evident from the figure that drying time decreased with an increase in air temperature (50 to 70°C) and microwave power (600 to 1000W). Synergistic effects of air temperature and microwave power led to a reduction in drying times due to the volumetric heating effects of microwaves supplemented by increased temperature gradient created by hot air. However, the increase in air velocity and temperature reduced the drying times to a certain limit, beyond which air velocity increased the drying times at all temperatures (50-70°C) due to the lesser temperature gradient on the product. Moreover, at the highest microwave power (1000W) with the intermediate air velocity (1 m/s) lowest drying time of shrimp can be obtained. Similar trends were seen in the interaction reported by Han *et al*. (2010) for microwave drying of apple slices.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

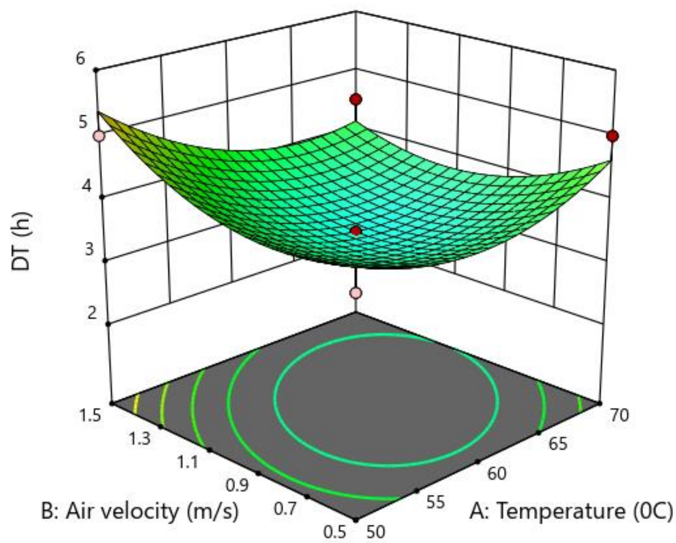
$$Drying\ time = +3.50 - 0.25 * A - 0.12 * B - 1.25 * C + 0.56 * A^2 + 0.31 * B^2 + 0.56 * C^2 - 0.12 * A * B - 0.38 * A * C - 0.13 * B * C \quad \ldots (4.2)$$

Where, A, B and C denotes air temperature, air velociity and microwave power, respectively.

a)



b)



c)

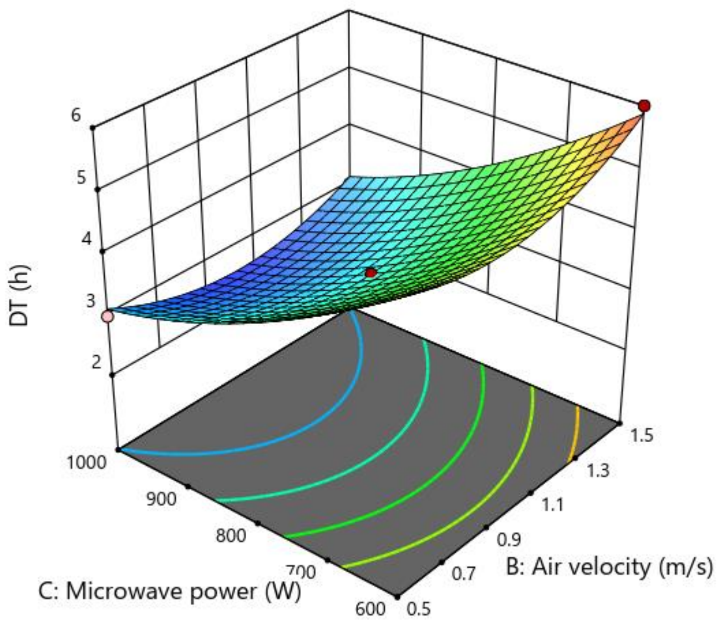


Fig. 4.1 Effect of process parameters on drying time (DT)

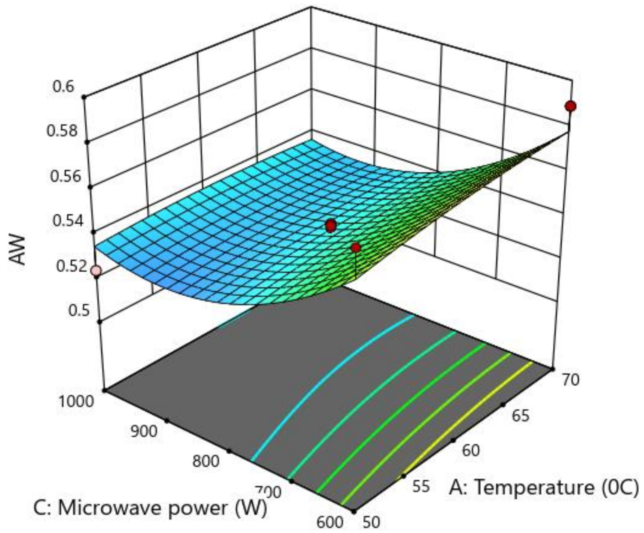
4.3.4 Effect of process parameters on water activity

The effect of air temperature, microwave power, and air velocity on the water activity of the dried product is shown in Fig. 4.2 (a, b, and c) as air velocity increased (0.5 – 1.5 m/s), water activity decreased to a certain limit, further which it increased. Analysis of variance (Appendix A-2) showed that the process parameters viz., air temperature ($p \leq 0.05$), microwave power ($p \leq 0.05$) and air velocity ($p \leq 0.05$) had a significant effect on drying from R squared values of 0.9122. As the water activity of the product is directly related to its moisture content, an increase in moisture content has enhanced the water activity of the products. An increase in microwave power and air temperature reduced the water activity due to increased drying rates. The water activity of the samples decreased significantly with increased temperature, probably due to the lower moisture content of samples at higher temperatures. At higher temperatures, food structure becomes more porous which accelerates the loss of water. Also, proteins become denatured due to higher temperature thereby losing their water binding capacity leading to more removal of water and reducing the water activity (Azizpour *et al*., 2016). Most enzymes and bacteria will be inactive when the food system has water activity below 0.80. To some extent increase in air velocity, enhances the drying rate, and further reduces the drying rate due to evaporative cooling on the surface of the product (Kilic, 2009). The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

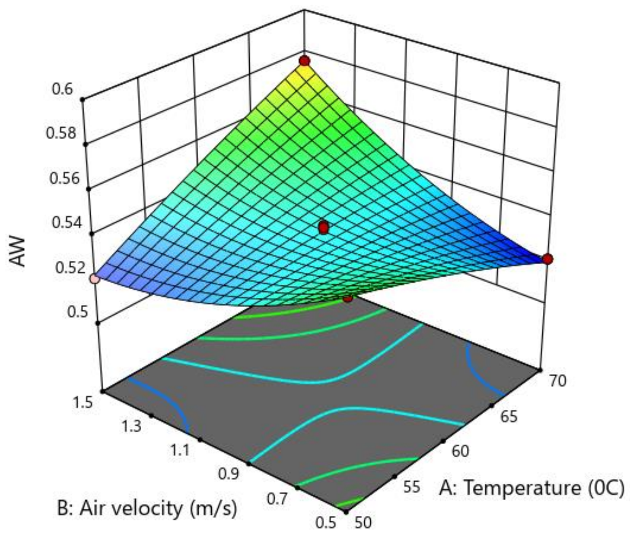
$$Water\ activity = +0.54 - 0.14 * A - 0.018 * B - 1.31 * C - 0.054 * A^2 + 0.015 * B^2 + 0.59 * C^2 + 0.03 * A * B - 0.24 * A * C - 0.67 * B * C$$
...(4.3)

Where, A, B and C denotes air temperature, air velociity and microwave power respectively.

a)



b)



c)

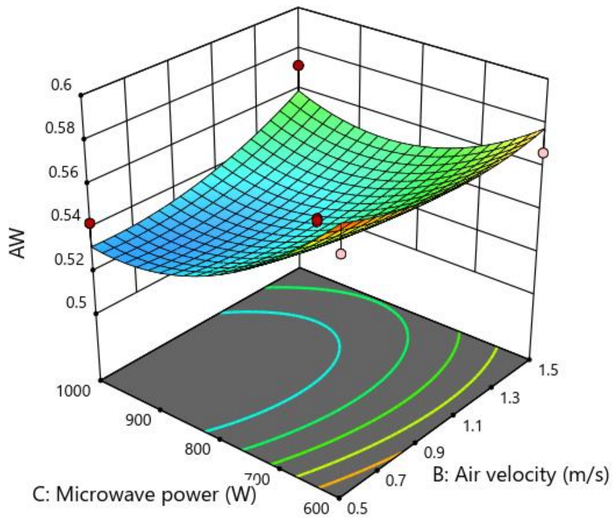


Fig. 4.2 Effect of process parameters on water activity (AW)

4.3.5 Effect of process parameters on rehydration ratio

The rehydration ratio is an important factor indicating the efficiency of the drying process as the rate of rehydration is will be less when the cells and tissues are collapsed or irreversibly damaged (Bozkir et al., 2019). Air temperature, microwave power, and air velocity had a significant effect on the rehydration ratio ($p \leq 0.01$) (Fig. 4.3: a,b,c) (Appendix A-3). . The regression coefficient is positive and maximum for microwave power levels, which indicates better rehydration properties of dried shrimp dried at high microwave power levels. This can be attributed to the high internal pressure development at higher microwave power levels. Higher microwave power causes more internal heating that creates a flux of rapidly escaping water vapor, which opens up the pores. This in turn prevents shrinkage and gives better rehydration properties (Giri and Prasad, 2007). Duan *et al*. (2011) reported that the rehydration ratio increased with increasing the duration of microwave drying at constant microwave power and also that the rehydration ratio increased with an increase in microwave power at constant time. Qin *et al*. (2020) observed that microwave combined with hot-air drying could reduce the irreversible structural damage in drying grass carp fillets and further, the rehydration rate increased along with microwave drying time.

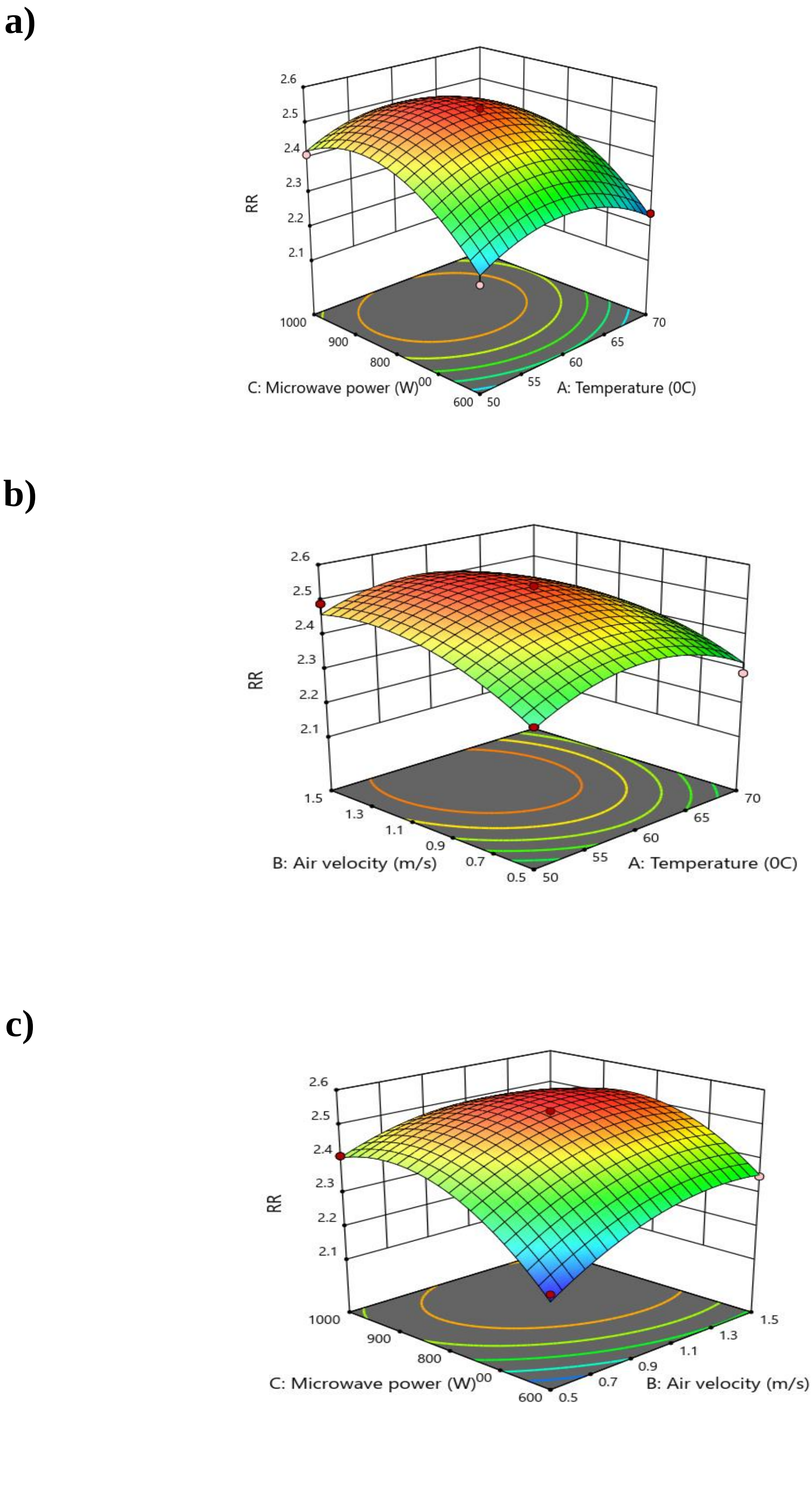


Fig. 4.3 Effect of process parameters on rehydration ratio (RR)

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results,

$$Rehydration\,ratio = +2.52 - 0.01 * A + 0.080 * B + 0.55 * C - 0.087 * A^2 - 0.1 * B^2 - 0.062 * C^2 + 0.27 * A * C + 0.13 * B * C - 0.06\,A * B$$
...(4.4)

Where, A, B and C denotes air temperature, microwave power and air velocity respectively.

4.3.6 Determination of optimized conditions

The optimization of drying process parameters was done based on Derringer's desirability function. Microwave power (600 – 900 W), air temperature (50–70 °C) and air velocity (0.5–1.5m/s) were set within the range with minimization of drying time and water activity and maximization of rehydration ratio. Based on the value of maximum desirability (0 to 1), optimum conditions were selected. Predicted versus observed values of various responses are depicted in Fig. 4.4 – 4.6. The methodology of desired function was applied to indicate 61.74 °C air temperature, 922.61 W microwave power and 1.0 m/s air velocity which indicated the drying time, water activity and rehydration ratio of 2.8 h and 0.424 and 2.51, respectively with a desirability value of 0.949 (Fig 4.7).

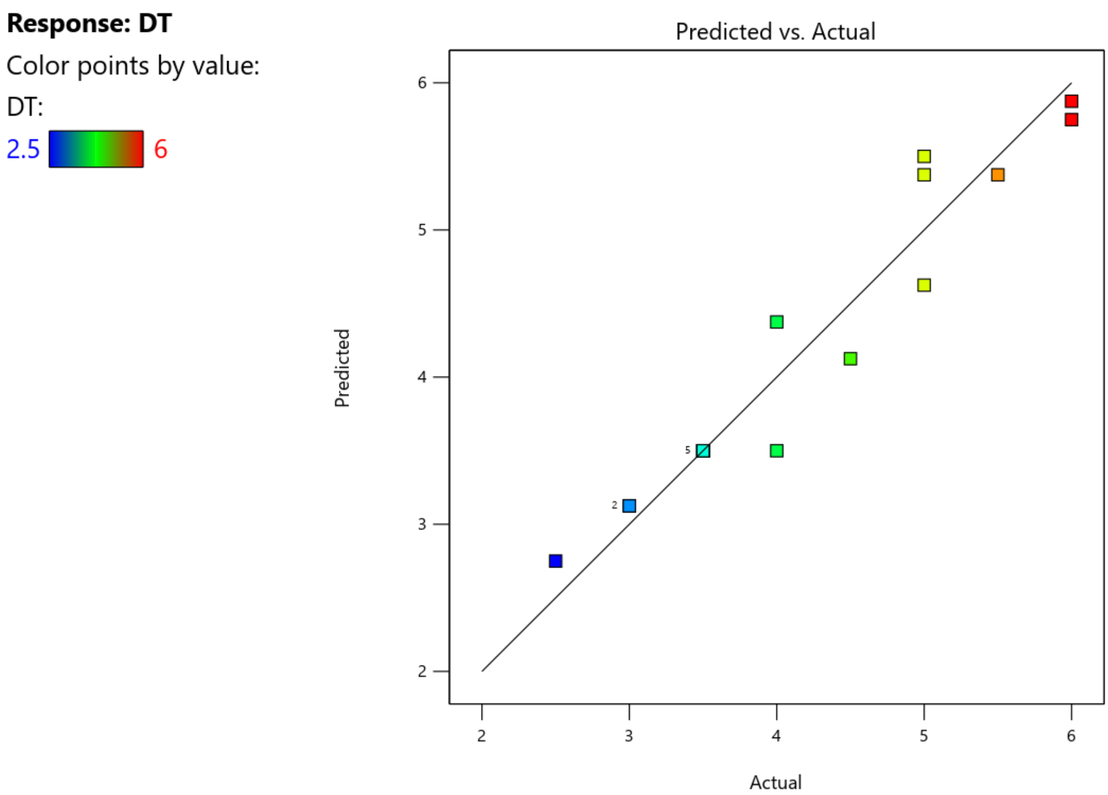


Figure 4.4 Predicted versus actual values of response: Drying time (for shrimp)

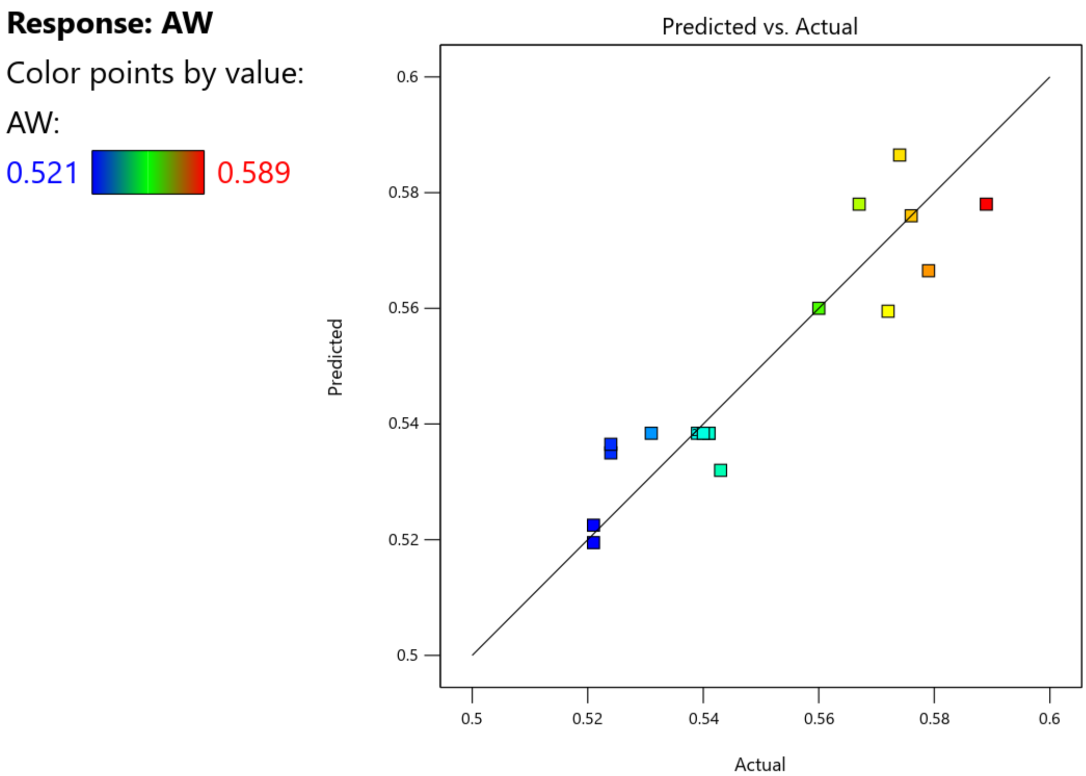


Figure 4.5 Predicted versus actual values of response: Water activity (for shrimp)

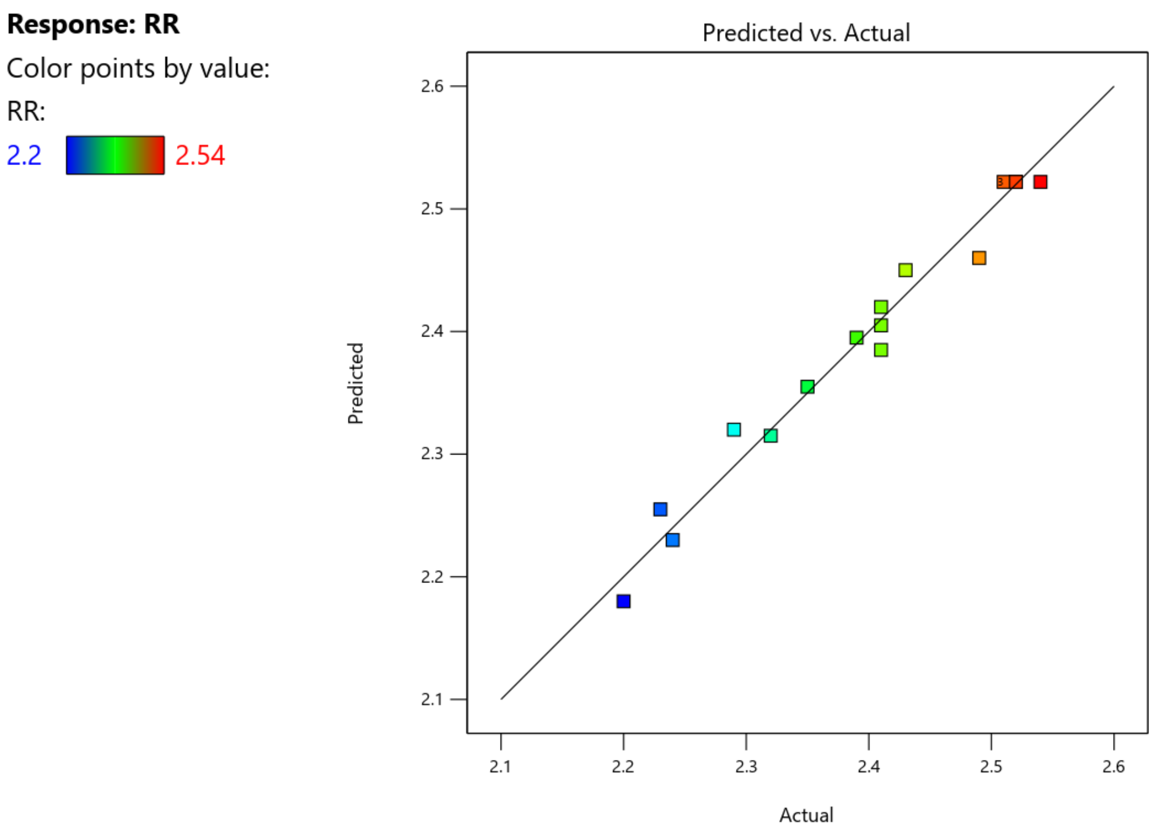


Figure 4.6 Predicted versus actual values of response: Rehydration ratio (for shrimp)

4.3.7 Confirmation of results

4.3.7.1 Error percentage

The predicted values of response variables under optimized conditions were confirmed by performing experiments under optimized conditions under three replications. The average of the values of response variables were used to determine the error percentage. The error percentage obtained for drying time, water activity and rehydration ratio were 3.44%, 3.85% and 0.79%, respectively, which further confirmed the acceptability of the selected model under RSM.

Table 4.3 Confirmation of RSM results of shrimp

Responses	Predicted value	Experimental value	Error percentage
Drying time	2.8	2.9	3.44%
Water activity	0.424	0.441	3.85 %
Rehydration ratio	2.51	2.53	0.79 %

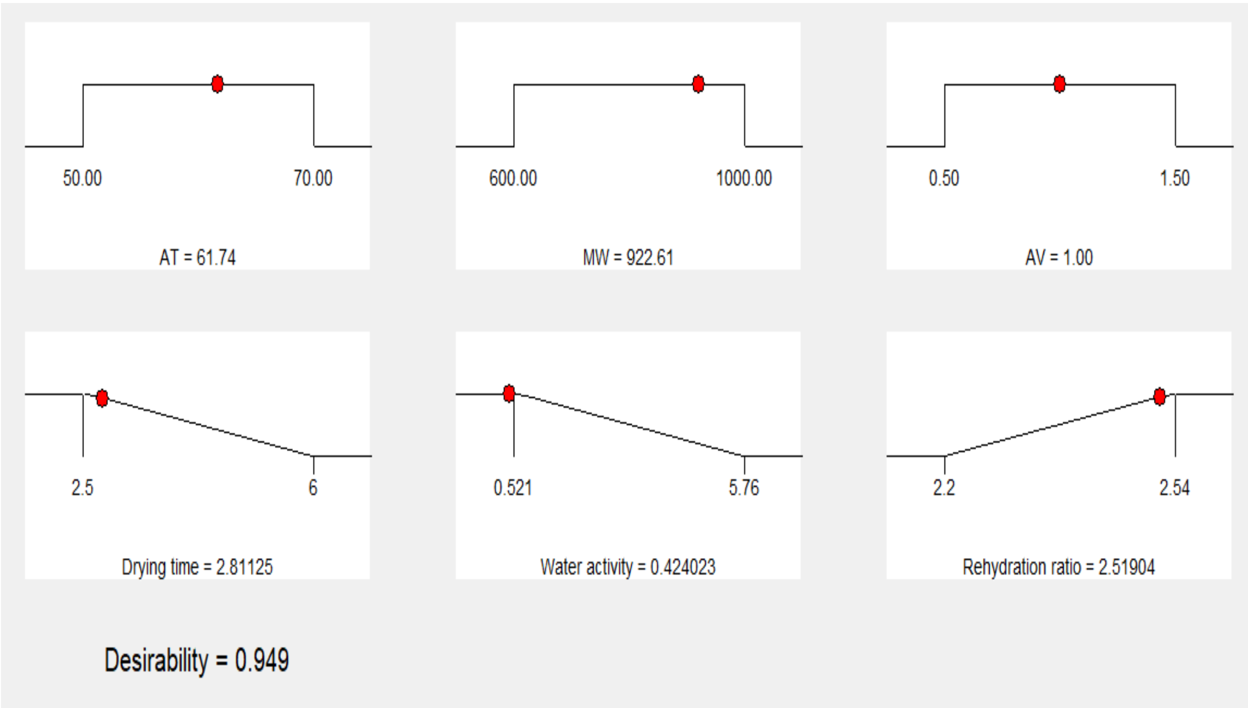


Fig. 4.7 Desirability ramps for the optimized conditions of shrimp drying under a hot air-assisted microwave drying system

Plate 4.3 Photograph of shrimp before (a) and after drying (b) under a hot air-assisted microwave drying system

4.4 Determination of quality parameters of dried shrimp under optimized drying conditions

The dried shrimp under optimized conditions were evaluated for moisture content, effective moisture diffusivity, colour, texture, shrinkage, total plate count, biochemical, proximate and scanning electron microscopy analysis. Thin layer model fitting was done to find out the best fit drying model to predict the drying times.

4.4.1 Drying rate and moisture content during drying

Moisture percentage of shrimp was found to be 80.55 ± 1.54 (% w. b.) by gravimetric method (AOAC 1990). Variation in moisture content and drying rate with respect to drying time for shrimp under HAMW drying conditions is shown in Fig. 4.9 and 4.10. It is evident from the graph that moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% within 2.9 h of drying. Volumetric heating effect of microwaves can be attributed for the reduction in drying time. Microwave heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Mohd and Ng (2010) made laboratory studies on microwave heating and published that moisture content of sardine fish was reduced from 2.76 to 0.01 (dry basis) within 4.25 min under microwave power of 500 W. LIn *et al*. (1999) reported that drying of shrimps from a moisture level of 83% to 20% was achieved within 60 min in microwave assisted vacuum dryer, which is only 25% of the time required for hot air drying of the same. Darvishi *et al.* (2012) also reported that at microwave powers of 200, 300, 400 and 500 W, time taken to dry shrimp from moisture levels of 3.103% (d.b.) to 0.01% (d.b.) were 11.75, 7, 4.75 and 4 min respectively. Lower drying times is also related to higher drying rates of shrimp under HAMW treatment. Drying rate exhibited maximum value of 2.74 during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation. Dipole rotation arises owing to the presence of water molecules in the sample that tends to change the polarity depending on the rapidly changing electromagnetic field induced by the magnetron. As the moisture content reduces, the magnitude of dipole rotation also reduces and thereby lowering the drying rate. As moisture removal rate is less towards the end, drying occurred under falling rate period. Olatunde *et al*. (2017) concluded that higher core temperature of materials together with the consistent direction of heat transfer and moisture diffusion enhanced the drying rate in microwave drying.

4.4.2 Effective moisture diffusivity

Sum of liquid and vapor diffusion during drying is represented by effective moisture diffusivity of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gives the slope value to determine the diffusivity (Fig. 4.11). Effective moisture diffusivity during drying of HAMW of shrimp was determined to be 6.7 $\times 10^{-7} m^2/s$. Effective moisture diffusivity was estimated from the experimental data based on Fick's law of diffusion. This parameter represented the intrinsic mechanism by which moisture transport was facilitated by means of liquid diffusion, vapor diffusion, hydrodynamic flow and other means. The volumetric heating effect of microwaves resulted in higher drying rates and decreased drying times due to higher moisture diffusivity. Thus, moisture diffusivity served as the quantitative parameter at molecular level for explaining drying kinetics. Kaveh *et al*. (2021) opined that microwave drying exhibited higher values of diffusivity compared to convective drying based on his study on drying of pomegranate arils. Darvishi *et al.* (2014) studied microwave drying effects on mulberry and reported diffusivities in range of 1.06×10^{-8} to 3.45×10^{-8} m^2/s as the microwave power was varied from 100 to 500 W. Microwave drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s at 120 W and 4.63×10^{-6} m^2/s at 600 W under varying operating conditions (Celen, 2019).

4.4.3 Evaluation of drying models

HAMW of shrimp was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying were fitted into thin layer drying models by non-linear regression analysis (Table 4.4). Page model was identified as the best fit model with higher R^2 value of 0.9984, lower $\chi 2$ value of 0.000134 and RMSE value of 0.01552. To verify the acceptability of the selected page model, observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9984 which implies that the selected model satisfactorily described the drying behaviour of shrimp under the HAMW dryer (Fig. 4.8). Similar study was published by Murali *et al.* (2021) for drying of shrimp in solar-LPG hybrid dryer.

Table 4.4 Modelling of drying data for HAMW drying of shrimp

S. No.	Model name	Equation	R^2	RMSE	Reduced χ2	Constants
1	Logarithmic (Moradi *et al.*, 2020)	$MR = \frac{M-Me}{Mo-Me} = ae^{-kt} + c$ …(4.5)	0.9954	0.02853	0.000466	a=1.086 b=0.7624 c=0.0688
2	Henderson and Pabis (Arslan *et al.*, 2010)	$MR = \frac{M-Me}{M0-Me} = ae^{-kt}$ …(4.6)	0.9979	0.01698	0.000405	a=1.01 b=0.9793
3	Modified page (Karacabey and Buzurul, 2017)	$MR = \frac{M-Me}{Mo-Me} = e^{(-kt)^n}$ …(4.7)	0.9979	0.01698	0.000367	a=1.01 b=0.9698
4	Two-term exponential (Togrul and Pehlivan, 2004)	$MR = \frac{M-Me}{Mo-Me} = a*\exp(-k1*t) + b*\exp(-k2*t)$ …(4.8)	0.9972	0.02973	0.001144 0.000362	a=14.32 b=13.32 k1=0.7225 k2=0.7075
5	Wang and Singh (Wang *et al.*, 2005)	$MR = \frac{M-Me}{Mo-Me} = 1 + at + bt^2$ …(4.9)	0.9887	0.04396	0.000324	a=0.6979 b=0.1253
6	Verma *et al* (Yaldys and Ertekýn, 2001)	$MR = \frac{M-Me}{Mo-Me} = ae^{-kt} + (1-a)e^{-gt}$ …(4.10)	0.9977	0.01919	0.000378	a=0.1973 b=0.9468 g=0.9664
7	**Page (Roy *et al.*, 2022)**	$MR = \frac{M-Me}{Mo-Me} = e^{-kt^n}$ …(4.11)	**0.9984**	**0.01552**	**0.000134**	**a=0.9592 b= 1.052**
8	Newton (Benseddik *et al.*, 2018)	$MR = \frac{M-Me}{Mo-Me} = e^{-kt}$ …(4.12)	0.9977	0.01622	0.000412	a=0.9704

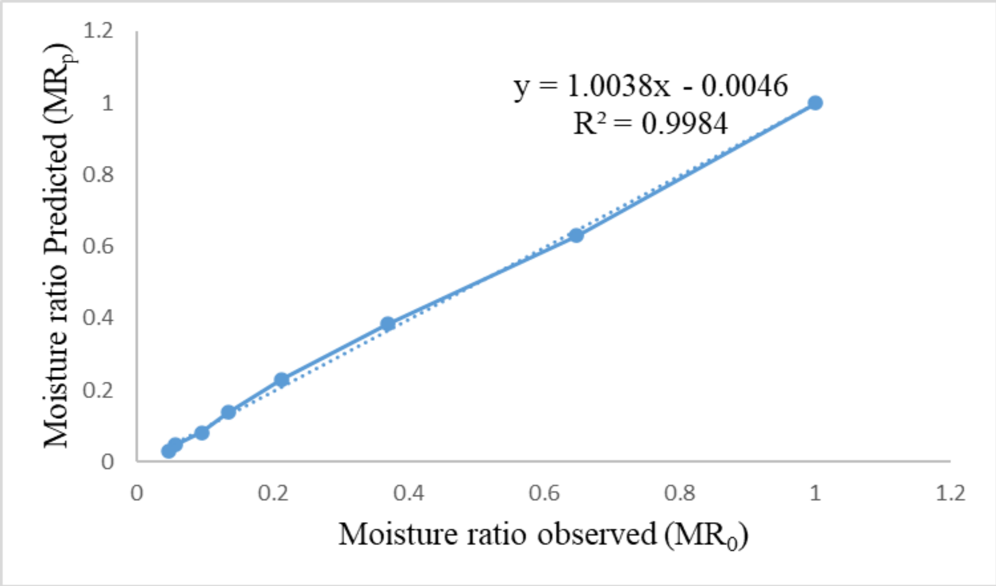


Fig. 4.8 Best fit page model

4.4.4 Drying efficiency

Drying efficiency of the dryer under HAMW mode was calculated as per the equation mentioned in 3.36 and observed to be 35.71%. This was a result of volumetric heating effect of microwave radiation combined with convective effect of hot air. Hassan (2016) published that since microwaves acts only on polar molecules, microwave drying efficiency decreased with time and increased with moisture content of sample during studies on microwave drying of date. Maximum drying efficiency of 32% was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein *et al.* (2013) observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W, respectively during drying of apple slices in laboratory scale MW dryer.

4.4.5 Specific energy consumption (SEC)

The SEC value for HAMW of shrimp was found to be 1.75 kWh/kg. Sharma and Prasad (2006) reported SEC of 26.32 MJ/kg for drying of garlic under MW power of 40 W and HA temperature of 70 ^{0}C. MW and convective drying of pomegranate arils were calculated to have SEC of 35.42 kWh/kg and 145.12 kWh/kg (Kaveh *et al.* 2021). It is understood that as moisture content decreases the energy requirement and specific energy consumption increases due to difficulties in removing water other than free and unbound moisture in the product. But the volumetric heating effect of microwaves in the study tended to fasten the drying process leading to higher drying rates and subsequently lower SEC as compared with convective drying. As moisture content of product decreased the microwave energy absorbed by the shrimp also reduced leading to higher SEC during later stages of drying. SEC in MW drying was observed to have 70% more energy savings as compared to convective drying (Sadi and Meziane., 2015).

4.4.6 Colour change

The total value of colour change (ΔE) determined for dried shrimp was 16.95 ± 2.14. The 'L' value of the dried shrimp (41.31 ± 1.63) decreased during drying whereas the 'a' and 'b' values increased from 3.56 ± 1.54 to 14.23± 2.36 and 12.42 ± 0.65 to 19.42 ± 1.61 during the drying process. Darker colour of shrimps can be attributed to the process of Maillard browning reaction that might have occurred during drying. The development of redness was due to the release of astaxanthin during the breakdown of carotenoproteins. Yellowness of shrimp increased as a consequence of the formation of yellow pigments due to browning reactions during drying. Celen (2019) evaluated the colour of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE respectively at microwave power of 600 W. It was also observed that higher microwave powers may cause unstable microwave field that may affect the colour quality of products. Taib and Ng (2011) also showed that in microwave drying of catfish slices, hot air treatment imparted brighter colour to dried products shifting towards red and yellow.

4.4.7 Shrinkage

Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extend of shrinkage depends on the method of drying. Shrinkage percentage of dried shrimp was observed to be 14.14%. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin *et al.*, 2005). Reduction in shrinkage percentage was due to the rapid evaporation of moisture by microwave radiation that created a vapor flux thereby preventing case hardening. Giri and Prasad (2007) reported that MW vacuum drying of mushrooms resulted in dried products with very less shrinkage compared to hot air-dried samples. MW dried herbs exhibited lesser shrinkage and better retention of biochemical constituents as reported by Kathirvel *et al.* (2006). The reason for a lower percentage of shrinkage was due to controlled drying of shrimp which has resulted in the rapid removal of moisture, thus created an internal porous structure in the dried shrimp. Tirawanichukal *et al.* (2007) reported shrinkage values of 11.45% – 32.36% during drying of shrimp under hot air temperatures in range of 50 - 70°C. Niamuy *et al*. (2007) investigated on the shrinkage, rehydration ratio and hardness of shrimp at hot air temperatures of 80 – 120 °C and published values of 68.79% and 74.50%, respectively for small and large shrimps.

4.4.8 Rehydration ratio

The structural and cellular degradation occurred within the sample during drying is explained by rehydration ratio. The values of rehydration ratio of dried shrimp with respect to time is shown in Fig. 4.12. Within the first hour of soaking shrimp in water, a rapid rise was seen in rehydration ratio. Average rehydration ratio was observed to be 2.53. Rehydration ratio of Tilapia fillets increased with MW power and air temperature during HAMW drying of the fish (Duan *et al*, 2011). Akonor *et al*. (2016) also reported similar range of rehydration ratio for shrimp. Initially a high rate of rehydration was observed which may be due to the porosity of the samples. However, after the first hour, rehydration is slowed down for the next four hours and thereafter the process reached equilibrium at the end of 7 h. Hence, the rehydration ratio of 2.53 for the dried shrimp shows that less structural damage could have occurred in the product during drying.

4.4.9 Water activity

In this study, water activity value of dried shrimp was determined to be 0.441 that indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf life extension of products (Jayaraman and Gupta, 2020).

4.4.10 Microbiological quality

Microbial load in food samples is quantified in terms of total bacterial count, halophilic bacteria and yeast and mould counts (cfu/g). However halophilic and yeast and mould counts are usually assessed for samples treated with higher concentration salt and sugar, respectively. Hence in this work, total bacterial count was assessed. The total plate count of raw shrimp was 3.6×10^6 CFU/g of a sample. Drying reduced the TPC value of shrimp to 2×10^4 CFU/g, which is lower than raw samples. The lower values of TPC are also an indication of good handling practices involved in drying and storage of shrimp. Sun dried shrimp samples showed larger values of bacterial counts than the samples dried under controlled drying conditions. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample (IS 14950 2001). This confirms that dried shrimps prepared with hot air assisted microwave dryer was microbiologically safe for consumption. A similar result of microbial reduction was reported by Murali *et al*. (2021) for shrimp drying.

4.4.11 Proximate and biochemical analysis

Results of proximate analysis of fresh and dried shrimp is shown in Fig. 4.13. The moisture content of the fresh shrimp was decreased from 80.55% (w.b) to 16.5% (w.b) in the developed dryer. Moisture removal was due to the microwave power applied with the assistance of hot air generated in the dryer. Similar result was reported by Lin *et al*. (1999) for drying shrimp from 83% to 20% moisture levels under vacuum assisted microwave drying system. Protein content of shrimp increased from 15.12% to 60.24% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried shrimp. Rasul *et al*. (2018) reported similar increase in protein content of dried silver carp during drying. This ensures the maximum retention of fat during drying. The higher ash content in dried shrimp was due to the moisture reduction as the ash content is directly related with moisture content and temperature. As moisture content decreases, ash content increases (Adeyeye, 2000). Akonor *et al*. (2016) reported ash content increase in shrimp during drying due to moisture reduction and concentration of chemical components.

4.4.12 Microstructure analysis

The optimized sample was analyzed for microstructure to study the pore size distribution in the dried product. Scanning electron microscopy analysis of dried shrimp showed the formation of pores of diameters ranging from 3.17 – 10.6 µm (Fig 4.14). The reason for higher rehydration ratio of hot air assisted microwave dried shrimp can be the presence of these pores. The volumetric heating effects of microwave causes abrupt removal of water molecules which left the internal lattice vacant there by creating pores of varying diameters. Mounir *et al*. (2020) studied the porosity and microstructure of shrimp snacks and concluded that higher porosity improved the functional behaviour and drying process and quality attributes of the products.

4.4.13 Sensory evaluation

Sensory attributes of cooked dried shrimps were evaluated for colour, appearance, flavour, taste and overall acceptability by a 9-point Hedonic scale (Appendix B - 1). The nine-point Hedonic scale is the most commonly used measure of assessing liking and preference of foods. The scores of sensory evaluations of dried shrimp are depicted in Fig. 4.15. Twenty-five semi-trained panel members comprising of research scholars and staff assigned maximum score to 'overall acceptability' of the samples. This can be due to the degree of uniformity in the samples, final moisture content and better colour retention of the samples. Mounir *et al*. (2020) also reported highest overall acceptability to the intermittent microwave dried shrimp snacks coupled with instant controlled pressure drop treatment.

4.5 Comparative studies on solar and microwave drying of shrimp

4.5.1 Moisture content and drying rate

Solar radiation, ambient temperature and RH were measured using sensors at each hour of the study. The solar radiation intensity during the experimental conditions was observed to be in range of 320 to 840 W/m^2, ambient temperature varied from 27.5 to 36.5 ^{0}C and RH from 62.45% to 77.24% on a typical day of the experiment. The moisture content of shrimp was reduced from 80.2% to 15.7% (w.b.) within 6 h of drying in the solar dryer. The drying conditions were maintained at temperature, air velocity and RH of 55±1.5 ^{0}C, 1.5 ± 0.25 m/s and 60±0.5 % respectively (Fig. 4.9). Initially, moisture evaporated from the shrimp as if from a free water surface due to the temperature difference between the drying medium (hot air) and the product. As drying progressed, moisture removal took place due to the vapor pressure gradient. Similar results were reported by Alfiya *et al*. (2018) for drying glassy perchlet in the solar-electrical hybrid dryer. Sankat and Mujaffar (2004) also reported that as drying proceeded, the implication of air flow was less as compared to the temperature of the drying medium during drying of shark fillets in a solar cabinet dryer. It is evident from Fig. 4.12 that during MW drying moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% within 2.9 h of drying. The volumetric heating effect of microwaves can be attributed to the reduction in drying time. Microwave heating falls under the dielectric heating method wherein the moisture content of the product directly influenced the heating rate. Lin *et al.* (1999) reported that drying of shrimps from a moisture level of 83% to 20% was achieved within 60 min in microwave assisted vacuum dryer, which is only 25% of the time required for hot air drying of the same. Lower drying times are also related to higher drying rates of shrimp under MW treatment. Photographs of solar and microwave dried shrimps are shown in Plate 4.3.

The drying rate of solar and microwave dried shrimp was found to be 1.63 kg/kgh and 2.74 kg/kgh at the beginning of drying (Fig. 4.10). Drying rate exhibited a maximum value of 2.74 during the initial stages of drying that can be due to the higher moisture content of a sample that created more friction and heat generation due to dipole rotation. In both the studies, the rate of moisture removal decreased with time, and hence drying was under a falling rate period. Bellagaha *et al*., 2002 reported that the drying rate increases with air flow rate but is affected by the formation of crust on the surface of fish during the studies on the drying of sardine.

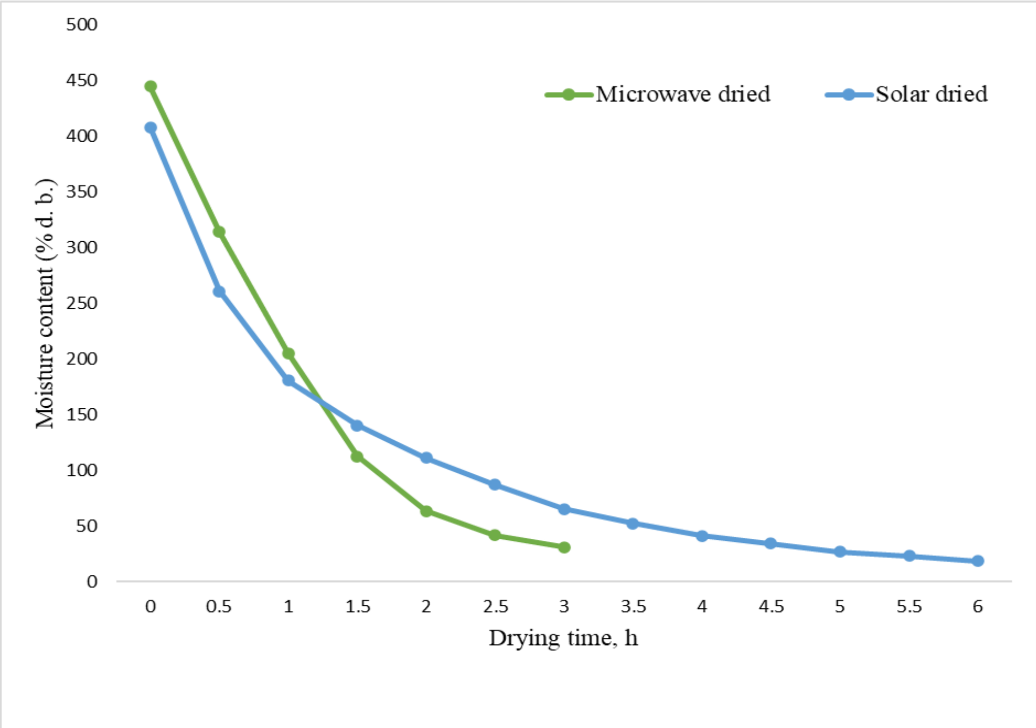


Fig. 4.9 Moisture content versus drying time for solar and microwave drying of shrimp

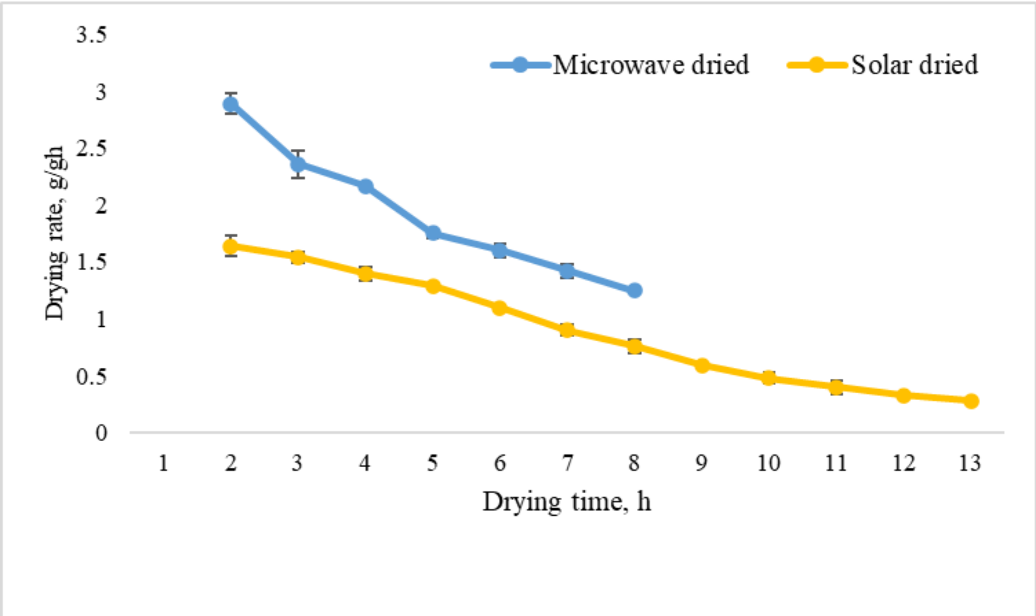


Fig. 4.10 Drying rate versus drying time for solar and microwave drying of shrimp

4.5.2 Effective moisture diffusivity

The sum of liquid and vapor diffusion during drying is represented by effective moisture diffusivity of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gave the slope value to determine the diffusivity (Fig. 4.11). Effective moisture diffusivity during SD and MWD of shrimp were determined to be 2.3×10^{-10} m^2/s and 6.7×10^{-7} m^2/s, respectively. Kaveh *et al.* (2021) opined that microwave drying exhibited higher values of diffusivity compared to convective drying based on his study on drying of pomegranate arils. Darvishi *et al*. (2014) studied microwave drying effects on mulberry and reported diffusivities in the range of 1.06×10^{-8} to 3.45×10^{-8} m^2/s as the microwave power was varied from 100 to 500 W. Microwave drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s and 4.63×10^{-6} m^2/s under varying operating conditions (Celen, 2019). Moisture diffusivity during sun drying of shrimp was found to be 11.11×10^{-10} m^2/s (Jain and Pathare, 2007). Murali *et al* (2021) reported effective moisture diffusivity value of 1.04×10^{-9} m^2/s for drying of shrimp in solar LPG dryer.

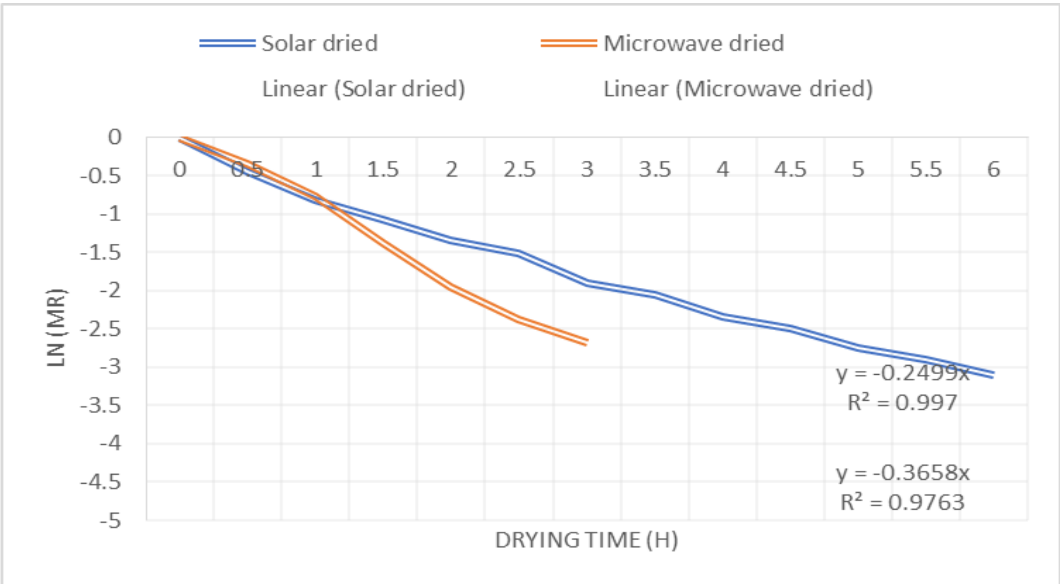


Fig. 4.11 Plot of LN MR versus drying time for solar and microwave drying of shrimp

4.5.3 Drying efficiency

The efficiency of the collector was calculated using the whole collector area and solar irradiation received instantaneously during drying. The instantaneous collector efficiency values varied in the range of 32.5 to 41.2%. However, maximum efficiency was related directly to the hours of maximum solar irradiation received which is from 12:30 AM to 2:30 PM (Fig. 4.12). Efficiency of solar collectors was found to vary to the tune of 21-69% in the drying of osmotically dehydrated cherry tomatoes (Nabnean *et al.*, 2016). The efficiency of shrimp drying was determined by considering the energy supplied by the collector, pump, blower, exhaust and water heater for LPG. The efficiency of drying varied from 26.3 to 33.4% (Fig. 4.12), achieving a maximum at 1:30 PM. Maximum available irradiation that enhanced the outlet temperature of water in the collector reduced the LPG consumption for drying at this stage. The values of drying efficiency were in concurrence with the reports of Fudholi *et al*., (2013) for salted drying of silver jaw fish using solar hybrid dryer. Murali *et al*. (2022) published a drying efficiency of 20.22% for solar drying of shrimps under controlled conditions.

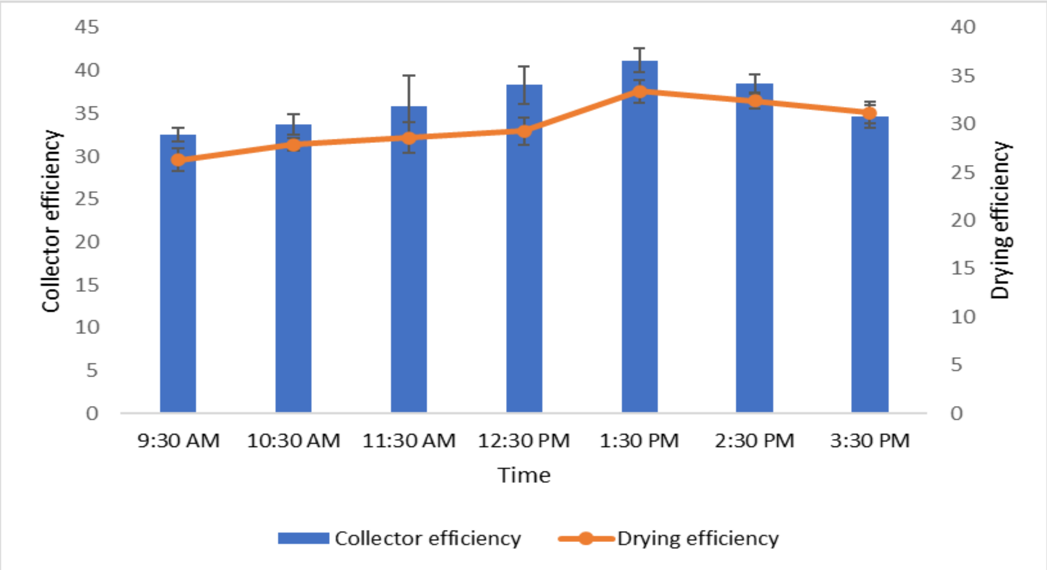


Fig. 4.12 Instantaneous collector and drying efficiencies during SD of shrimp

The drying efficiency of the shrimp under MWD mode was observed to be 35.71%. This was a result of the volumetric hearing effect of microwave radiation combined with the convective effect of hot air. Hassan (2016) published that since microwaves act only on polar molecules, microwave drying efficiency decreased with time and increased with moisture content of sample during studies on microwave drying of dates. Maximum drying efficiency of 32% was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein *et al*. (2013) observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W respectively during the drying of apple slices in a laboratory scale MW dryer.

4.5.4 Hardness

The textural analysis of dried products is important in determining their palatability. Textural attributes of dried products are generally expressed in terms of hardness indicated by the maximum compressive force needed to crush the product by the molars. Average hardness values of raw, solar dried and microwave dried shrimp obtained from the plots of compressive force (N) versus time (s) were 8.4, 12.3 and 11.93 N respectively (Fig. 4.13). Hardness of the products should increase as the moisture content decreases. Since the final moisture levels of solar dried and microwave dried shrimp were in the same range, solar dried were found to be less hard than microwave dried shrimp. Niamuy *et al*. (2007) reported that higher drying temperature resulted in lesser hardness value of shrimp. As drying time was more in solar dried samples, the exposure to higher temperatures might have resulted in less hard products. Tapaneyasin *et al*. (2005) also opined that the texture of shrimp dried at lower temperatures was superior during their studies on jet spouted drying of shrimp at 100 and 120 ^{0}C, wherein the former was found to be easy to crush and palatable. He reported a maximum shear force of 1038 kN/m^2 and 1139 kN/m^2 for shrimps dried at 100 and 120 ^{0}C respectively. There were also investigations made by Lin *et al*. (1999) on shrimp drying showing that microwave-dried shrimp had lower texture scores, though they retained color and appearance very well.

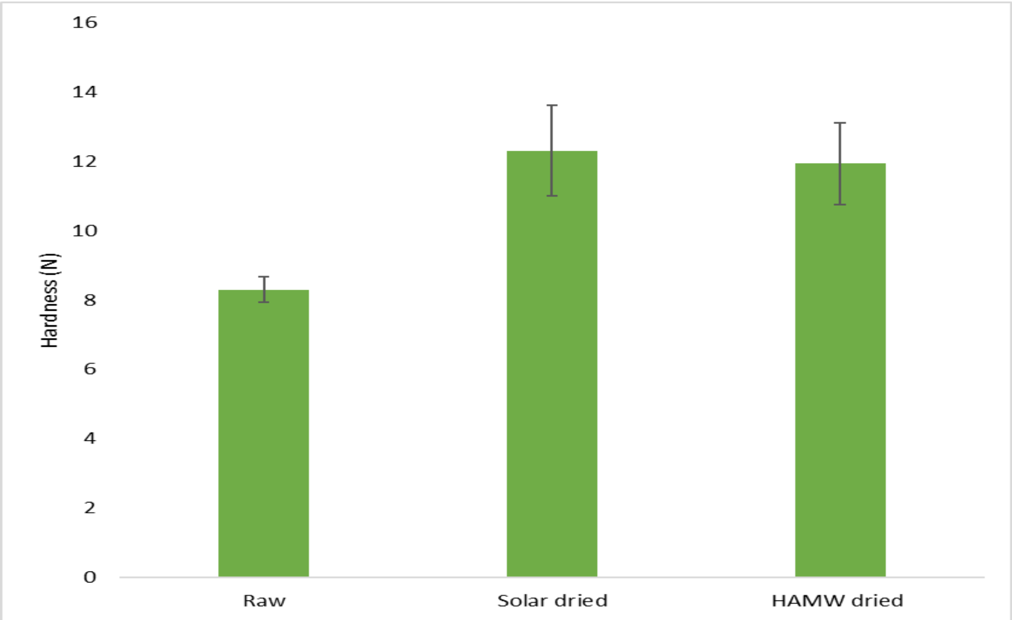


Fig. 4.13 Hardness values of raw, solar dried and microwave dried shrimp

4.5.5 Rehydration ratio

The values of rehydration ratio of SD and MWD shrimp with respect to time is shown in Fig. 4.14. Under both drying methods, within the first hour of soaking shrimp in the water, a rapid rise was seen in the rehydration ratio. The average rehydration ratio was observed to be 2.39 and 2.53 for SD and MWD respectively. Akonor (2016) reported that solar-dried shrimp exhibited higher values of rehydration ratio more rapidly than hot air-dried samples. Due to the volumetric heating of MW radiation, the moisture movement is fast leaving a porous matrix in the cells which can be accounted for their higher moisture absorption properties. The rehydration ratio of Tilapia fillets increased with MW power and air temperature during hot air aided microwave drying of the fish (Duan *et al.*, 2011).

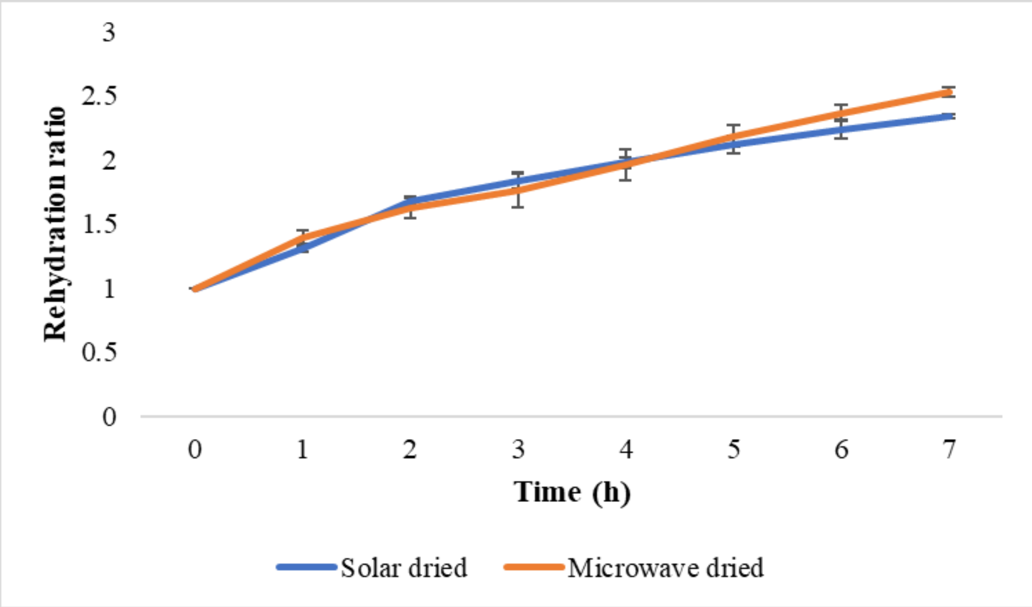


Fig. 4.14 Rehydration ratio of solar and microwave dried shrimp

4.5.6 Shrinkage

Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extent of shrinkage depends on the method of drying. The shrinkage percentage of SD and MWD shrimp was observed to be 24.67 and 14.14% respectively. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin *et al.*, 2005). The reduction in shrinkage percentage was due to the rapid evaporation of moisture by microwave radiation that created a vapor flux thereby preventing case hardening.

4.5.7 Biochemical analysis

The values of TVB-N, TMA and TBARS determined the quality of sea food products. TMA values for fresh, solar dried and microwave dried shrimp were 3.04, 7.7 and 8.23 mg N/100g respectively. TMA was responsible for the unpleasant odour in shrimp. There is no significant difference in TMA values of solar and microwave dried samples. Zhang *et al.* (2011) observed TMA for dried *A. chinensis* varied from 7.93 ± 1.21 to 16.06 ± 2.01 during its storage. TVB-N for fresh shrimp increased from 13.42 mgN/100g to 24.06 and 21.49 mg/100 g respectively when it was dried under solar and microwave radiation. However, the dried samples were adhering to the permissible values of TVB-N (<50 mgN/100 g) (Connell, 1980). TBARS values showed the extent of lipid oxidation and were determined to be 0.64, 0.72 and 0.75 MDA/kg of lipid for fresh, solar dried and microwave dried samples. Sampaio *et al*. (2006) also opined that owing to lipid oxidation, TBARS values of shrimps increased with time after harvest. The increase in values of all biochemical constituents represented the degree of spoilage due to higher microbial activity. Similar results were published by Murali et al., 2021 for drying of shrimp in solar-LPG dryer. The attainment of final moisture content is in same range for both solar and microwave dried products, which might be the reason that there is no significant difference in the biochemical analysis of these samples (Fig. 4.15).

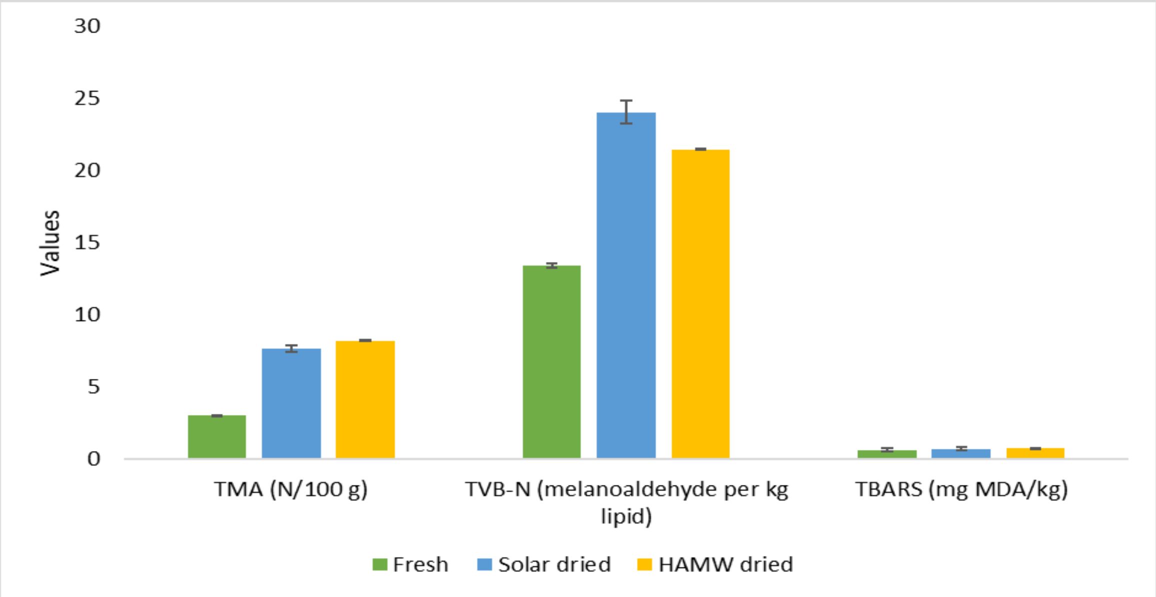


Fig. 4.15 Biochemical analysis of fresh, solar dried and HAMW dried shrimp

4.5.8 Microbiological quality

The total plate count of raw shrimp was 4.3 $\times 10^6$ CFU/g of a sample. Drying reduced the TPC value of shrimp to 1.65 $\times$ 10^4 and 2.6$\times$ 10^4 CFU/g and to for SD and MWD respectively which is significantly ($p< 0.05$) lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample (IS 14950 2001). A similar result of microbial reduction was reported by Murali *et al*. (2021) for shrimp drying.

4.5.9 Colour change

Solar dried shrimp were found to be darker (L= 41.31 ± 1.63) compared to microwave dried samples (49.5±1.28). This may be due to the exposure to higher temperatures for longer times. Total colour change (ΔE) determined for SD and MWD samples were 14.25±1.94 and 16.95 ± 2.14 respectively. Redness of samples increased during both drying methods due to the release of astaxanthin from carotenoids during drying (Muriana *et al*., 1993). Similar results of colour change were also reported by Akonor *et al*., 2016 for solar drying of shrimp. Celen (2019) evaluated the color of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE respectively at a microwave power of 600 W. Browning index of SD and HAMW dried shrimp was found to be 63.93 and 56.74, respectively. It was also observed that higher microwave powers may cause an unstable microwave field that may affect the colour quality of products. Taib and Ng (2011) also showed that in microwave drying of catfish slices, hot air treatment imparted brighter colour to dried products shifting towards red and yellow.

4.5.10 Water activity

In this study, the water activity value of dried shrimp was determined to be 0.552 and 0.441 under SD and MWD, respectively which indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf-life extension of products (Jayaraman and Gupta, 2020).

4.5.11 Microstructure analysis

The optimized sample was analysed for microstructure to study the pore size distribution in the dried product. The pore size for solar dried shrimp samples ranged from 4.96 – 22.10 µm (Fig. 4.16). Scanning electron microscopy analysis of microwave dried shrimp showed the formation of pores of diameters ranging from 1.26 – 10.30 µm (Fig 4.17). The reason for higher rehydration ratio of hot air assisted microwave dried shrimp can be the presence of these pores. The volumetric heating effects of microwave causes abrupt removal of water molecules which left the internal lattice vacant there by creating pores of varying diameters. Due to longer drying times in solar drying, there was greater diffusion and evaporation happening across the interior to exterior surface of the samples that resulted in more shrinkage and pores of relatively larger sizes as compared to microwave drying. Niamuy *et a.l* (2007) evaluated microstructure of dried shrimp using electron microscope of 10 kV and concluded that shrimp dried at 80 °C exhibited a denser structure and lesser pores as compared to those dried at higher temperatures of 100 and 120°C under hot air drying. Nmasanguan *et al*. (2004) reported that dried products with more porous structure resulted in lower density and lower shrinkage and larger pores resulted in larger shrinkage. Also, it was observed by the authors that microstructure determined the overall texture; more the pore space, softer the samples. These observations were made during the investigations on hot air and heat pump based drying of shrimps.

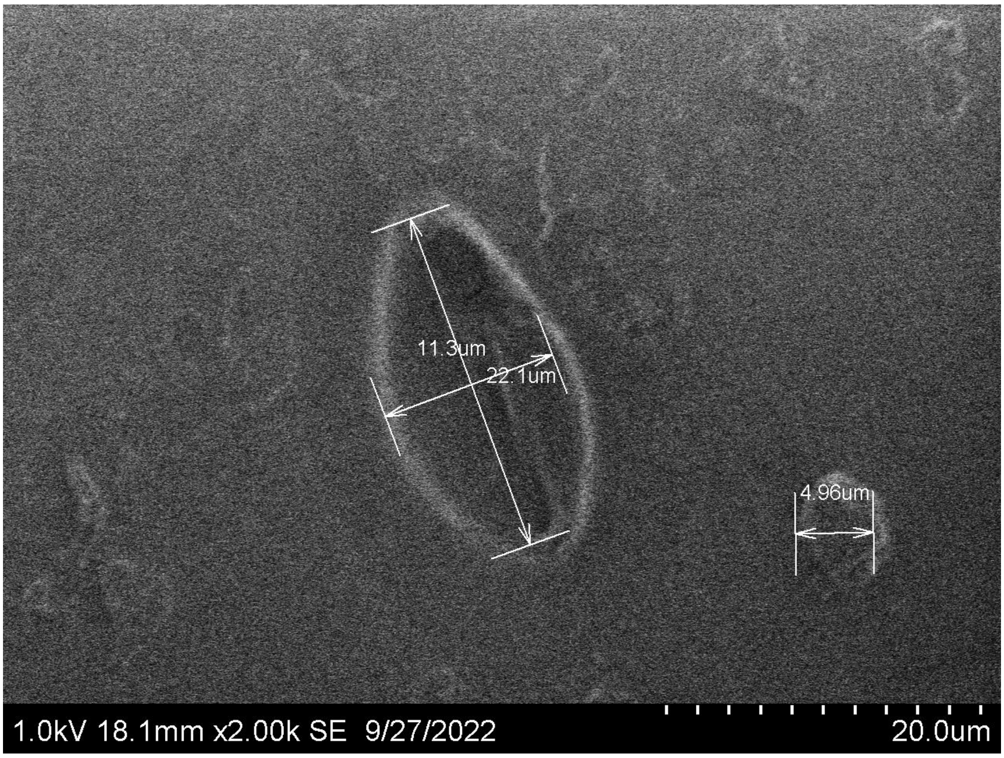
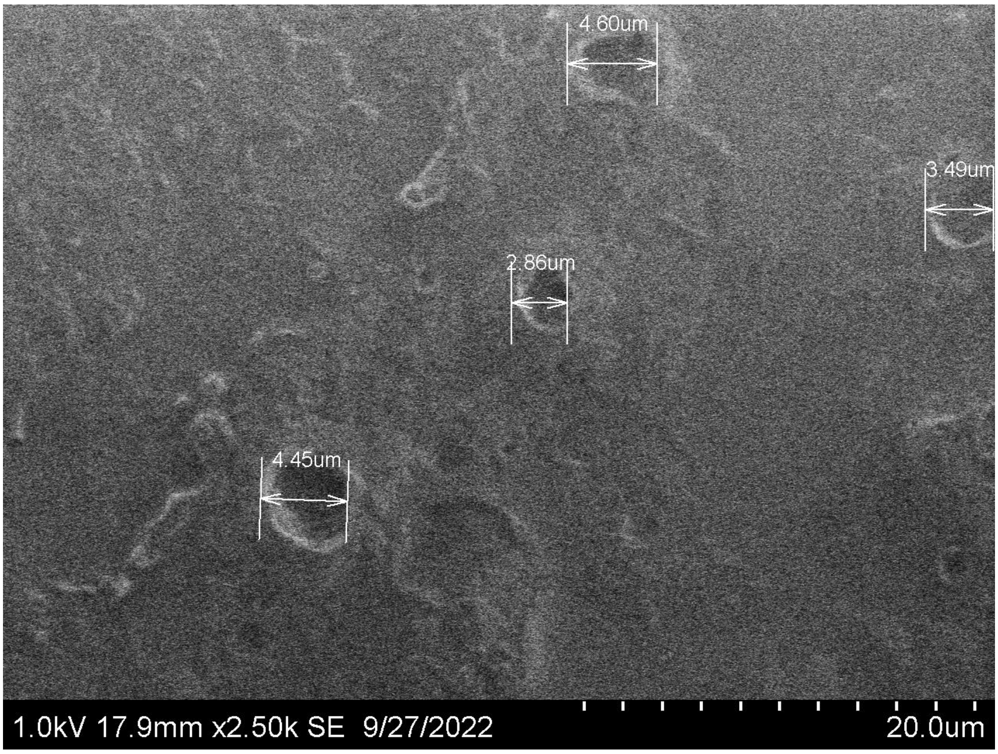


Fig. 4.16 SEM images of solar dried shrimp



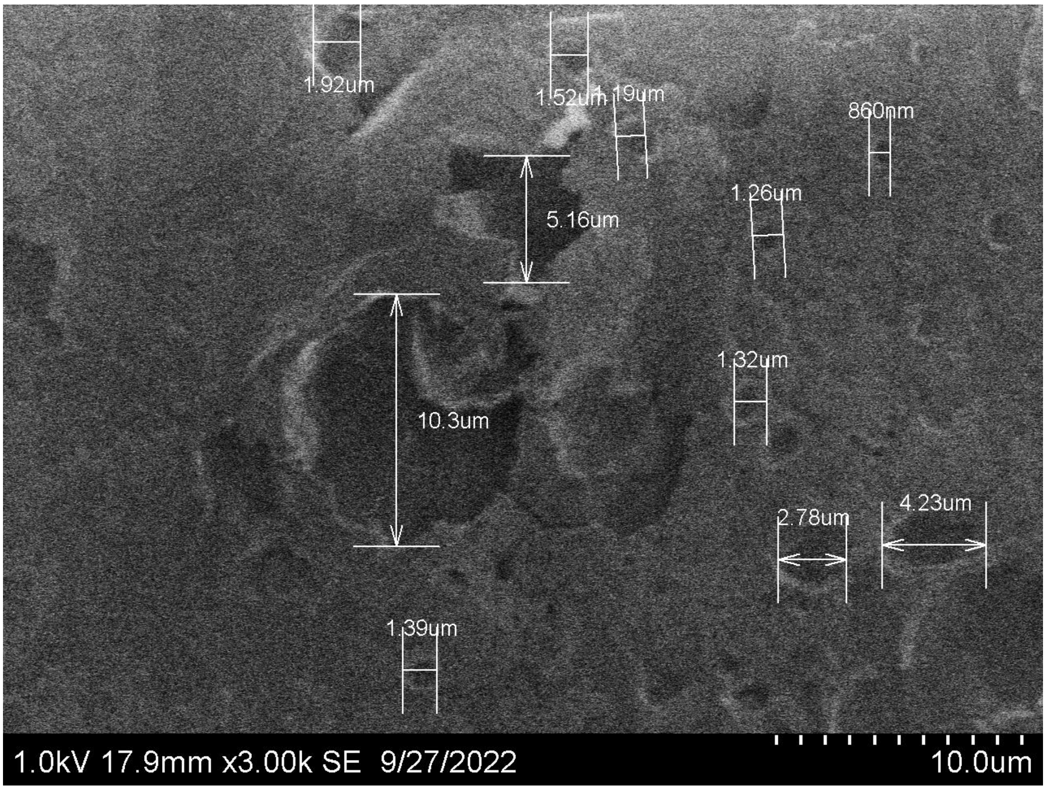


Fig. 4.17 SEM images of microwave dried shrimp

4.5.12 Sensory analysis

The scores of sensory evaluations of dried shrimp are depicted in Fig. 4.18. Twenty-five semi-trained panel members comprising research scholars and staff assigned maximum scores to the 'texture' 'overall acceptability' of the SD samples. Whereas for the MWD samples, 'color' and 'appearance' scored more. Higher drying rates of MWD must have resulted in better color and appearance due to shorter drying times. Uniformity of the samples led to better overall acceptability for SD shrimp. Mounir *et al*. (2020) also reported the highest overall acceptability to the intermittent microwave dried shrimp snacks coupled with instant controlled pressure drop treatment. However, market value of dried shrimps is more for solar and microwave dried samples due to the unhygienic practices adopted in traditional sun drying. The photographs of solar and microwave dried shrimps are depicted in Plate 4.4.

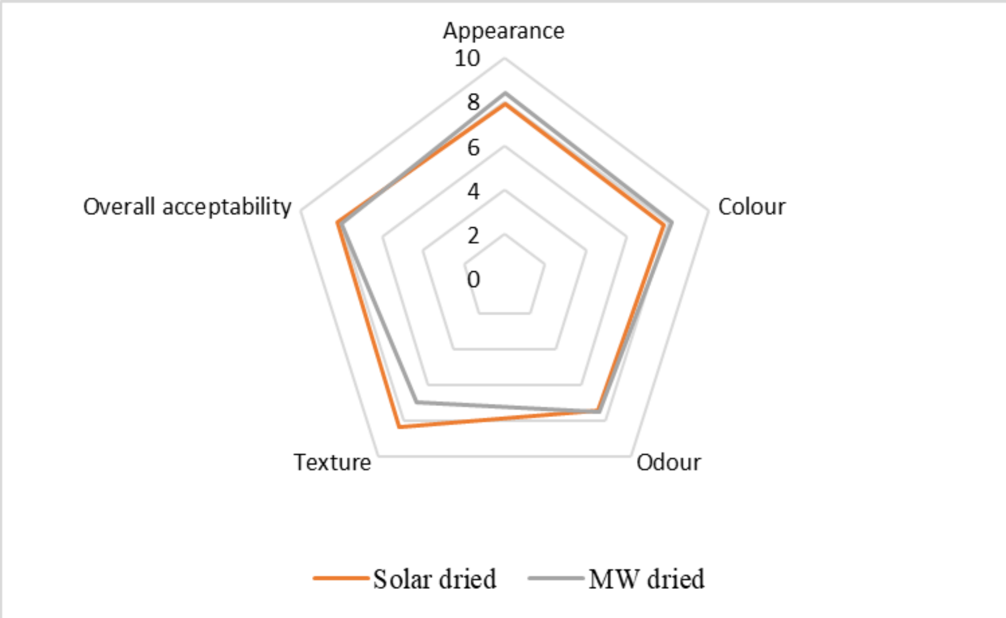


Fig. 4.18 Radar diagram of sensory scores of SD and MWD shrimp

Solar dried shrimp **Microwave dried shrimp**

Plate 4.4 Photographs of solar and microwave dried shrimp under optimized conditions

4.6 Economic analysis

Economic analysis was carried out for drying of shrimp in solar-LPG dryer and hot air assisted microwave dryer and is summarized in Table 4.5. The values of economic attributes indicated the economic feasibility of the production of dried shrimp under both drying technologies. However, solar drying is found to be economically more viable than microwave drying technology for the quality production of dried shrimp. Solar drying was found to have less carbon emissions in terms of electricity usage as 70% of the energy consumption is met with solar radiation. Supplementary heating by LPG is aided only at times of lacunae in availability of solar radiation. Whereas the working of microwave system requires a 1.4 kW magnetron to be run throughout the drying process. But microwave system highly reduced the drying times and thereby the related electricity consumption. Though microwave dryers may not be economical for the first few years, with respect to ergonomic and quality aspects, it can be recommended. Philip *et al.* (2022) published that the cost of drying in solar dryers is always lesser than in any other electrical based drying systems. The authors reported payback period of 1.5 – 2.1 years depending on the agricultural products to be dried. Sreekumar (2010) studied on the techno-economic feasibility of operating solar dryers for pineapple and reported payback period of 0.54 years.

Table 4.5 Economic analysis of solar and microwave drying of shrimp

Sl. No	Parameters	Values	
		Solar -LPG dryer	**Hot air assisted microwave dryer**
1.	Operation and maintenance cost (₹) including raw material cost	4,20,000	4,99,000
2.	Salvage value (10% of initial investment) (₹)	1,50,000	2,10,000
3.	Life cycle cost (₹)	42,000	49,000
4.	Annual benefit (₹)*	5,28,000	6,60,000
5.	Benefit-cost ratio	7,11,000	6,66,150
6.	Payback period	1.4	1.31
7.		1.03 years	1.48 years

* Dried shrmp output - 10kg/day; price of dried shrimp - ₹ 500/kg; expenditure - ₹ 1450/day(solar dried) and ₹ 1700/day (microwave dried) ; profit- ₹ 3555/day (solar dried) and ₹3330/day (microwave dried); working days - 200 days/year.

4.7 Storage studies on dried shrimp

Storage studies were carried out for the shrimp dried under microwave and solar drying conditions to evaluate the shelf stability of the products, which can add to its commercial value. Experiments were done under two levels of packaging technologies (ambient and vacuum) and three levels of packaging materials (LDPE, polyester polyethylene laminate and metallised polyester). The specifications of the packaging materials are given below:

- LDPE 150 microns
- Polyester polyethylene laminate (Outer layer: polyester, 12 microns and inner layer: LDPE, 60 microns)
- Metallised polyester (Outer layer: polyester, 12 microns; Middle layer: metallised polyester, 12 microns and inner layer: polyethylene, 60 microns)

4.7.1 Effect of low density polyethylene (150 μ) on quality of microwave dried shrimp under ambient storage conditions

Variation in quality parameters of dried shrimp under LDPE packaging at ambient conditions (Temperature: 27 – 30 ^{0}C, Relative humidity: 60-70 %) is explicated in Table 4.6. Moisture content of dried shrimp varied from 16.35±1.21 to 17.9±0.21% during 30 days of storage. Water activity, shrinkage and total colour change increased from 0.449±0.10 to 0.510±0.19, 14.14±0.21 to 14.84±0.41 and 16.5±2.10 to 17.15±1.65% respectively during 30 days of storage. Rehydration ratio exhibited a slight decrease from 2.53±0.34 to 2.48±0.14. Texture of the dried shrimp varied from 8.33±1.40 – .18±1.21 N within one month of storage. Total plate count increased from 1.95 × 10^4 to 2.1 × 10^5. TMA (mgN/100 g), TVBN (mg N/100 g) and TBARS (MDA/kg) 9showed an increase from 8.12±0.24 – 8.64±0.42, 19.46±0.27 – 21.94±0.21 and 0.72±0.23 – 0.80±0.13 respectively during one month storage. Free fatty acids (mg/g) and peroxide value (meq/kg lipid) varied from 2.89±0.15 to 3.10±0.20 and 15.28±0.21 to 15.56±0.22 respectively. Sensory score of dried shrimps decreased from 8.78±0.11 to 7.9±0.12. Proximate analysis of dried shrimp showed slight variation with respect to protein (58.24±0.12 – 58.29±0.14%), carbohydrates (17.21±0.10 – 16.9±0.16%), fat (1.79±0.21 – 1.61±0.25%) and ash (7.24±0.30 – 6.8±0.24%) contents. Owing to the total plate count exceeding the desirable limit (2.1 × 10^5 cfu/ml), shelf life of dried shrimp was limited to 30 days under LDPE packaging at ambient conditions.

Table 4.6 Storage studies of microwave dried shrimp in LDPE (150 µ) under MAP conditions

Storage period (months)	**Moisture content (%)**	**Water activity**	**Rehydration ratio**	**Shrinkage (%)**	**Total colour change**	**Texture/Hardness (N)**	**Total plate count (cfu/ml)**	**TMA (mg N/100 g)**	**TVBN (mg N/100 g)**	**TBARS (MDA/kg)**	**FFA (mg/g)**	**PV(meq/kg lipid)**	**Sensory score**	**Protein (%)**	**CHO ()**	**Fat (%)**	**Ash (%)**
0	16.35 ± 1.21^{a}	0.441 ± 0.10^{a}	2.53 ± 0.34^{a}	14.14 ± 0.21^{a}	16.95 ± 2.10^{a}	8.3 ± 1.40^{a}	$1.95 \times 10^{4\,a}$	8.12 ± 0.24^{a}	19.46 ± 0.27^{a}	0.72 ± 0.23^{a}	2.89 ± 0.15^{a}	15.28 ± 0.21^{a}	8.78 ± 0.11^{a}	58.24 ± 0.12^{a}	17.21 ± 0.10^{a}	1.79 ± 0.21^{a}	7.24 ± 0.30^{a}
1	17.9 ± 0.21^{b}	0.51 ± 0.19^{b}	2.48 ± 0.14^{b}	14.84 ± 0.41^{b}	17.15 ± 1.65^{b}	9.18 ± 1.21^{b}	$\mathbf{2.1 \times 10^{5}}$ **b**	8.64 ± 0.42^{b}	21.94 ± 0.21^{b}	0.80 ± 0.13^{b}	3.10 ± 0.20^{b}	15.56 ± 0.22^{a}	7.9 ± 0.12^{b}	58.29 ± 0.14^{a}	16.9 ± 0.16^{a}	1.61 ± 0.25^{a}	6.8 ± 0.24^{b}

Note: Means that do not share a letter are significantly different

4.7.2 Effect of packaging material (polyester-polyethylene laminate) on quality of microwave dried shrimp under ambient storage conditions

Variation in quality parameters of dried shrimp under polyester-polyethylene laminate (72 µ) packaging at ambient conditions (Temperature: 27 – 30 ^{0}C, Relative humidity: 60-70 %) is explicated in Table 4.7. In PE PS laminated packages under ambient conditions, moisture content of dried shrimp varied from 16.35±1.21 to 16.96±1.2, 17.21±2.12, 17.43±1.53 and 18.24±1.50% during 30, 60, 90 and 120 days of storage. Water activity of dried shrimp varied from 0.441±0.10 to 0.515±0.40, 0.565±0.20, 0.578±0.11 and 0.589±0.11 respectively during 30, 60, 90 and 120 days of storage. Rehydration ratio of dried shrimp varied from 2.53±0.34 to 2.5±0.20, 2.41±0.15, 2.12±0.31 and 1.7±0.24 respectively during 30, 60, 90 and 120 days of storage. Shrinkage of dried shrimp varied from 14.14±0.21 to 14.72±0.21, 15.24±0.17, 16.25±0.30 and 17.49±0.32% respectively during 30, 60, 90 and 120 days of storage. Total colour change of dried shrimp varied from 16.5±2.10 to 17.19±1.81, 17.95±1.50, 23.21±2.14 and 27.54±2.12 respectively during 30, 60, 90 and 120 days of storage. Texture of the dried shrimp varied from 8.33±1.40 to 11.89±1.31, 12.42±1.51, 13.01±1.11 and 13.94±1.21 N respectively during 30, 60, 90 and 120 days of storage. Total plate count increased from 1.95 × 10^4 to 2.76 × 10^4, 7.41 × 10^4, 8.94 × 10^4 and 1.24 × 10^5 cfu/ml respectively during 30, 60, 90 and 120 days of storage. TMA (mgN/100 g) showed an increase from 8.12±0.24 to 8.45±0.23, 8.52±0.14, 9.02±0.31 and 9.59±0.40 respectively during 30, 60, 90 and 120 days of storage. TVBN (mg N/100 g) showed an increase from 19.46±0.27 to 21.49±0.20, 24.51±0.40, 26.12±0.32 and 27.57±0.21 respectively during during 30, 60, 90 and 120 days of storage. TBARS (MDA/kg) showed an increase from 0.72±0.23 to 0.81±0.15, 0.82±0.20, 0.97±0.24 and 1.0±0.41 respectively during 30, 60, 90 and 120 days of storage. Free fatty acids (mg/g) increased from 2.89±0.15 to 2.96±0.40, 3.05±0.13, 3.23±0.15 and 3.69±0.20 respectively during 30, 60, 90 and 120 days of storage. Peroxide value (meq/kg lipid) varied from 15.28±0.21 to 15.84±0.30, 15.87±0.10, 17.21±0.23 and 19.61±0.21 respectively during 30, 60, 90 and 120 days of storage. Sensory score of dried shrimps decreased from 8.78±0.11 to 8.55±0.35, 8.0±0.15, 7.7±0.10 and 7.3±0.10 respectively during 30, 60, 90 and 120 days of storage. Protein content of dried shrimp varied from 58.24±0.12 to 57.2±0.10, 56.10±0.50, 56.02±0.13 and 55.10±0.21% respectively during 30, 60, 90 and 120 days of storage. Carbohydrate content of dried shrimp varied from 17.21±0.10 to 15.59±0.16, 14.21±0.22, 13.92±0.10 and 13.62±0.11% respectively during 30, 60, 90 and 120 days of storage. Fat content of dried shrimp varied from 1.79±0.21 to 1.58±0.14, 1.41±0.44, 1.39±0.21 and 1.34±0.15% during 30, 60, 90 and 120 days of storage. Ash content of dried shrimp varied from 7.24±0.3 to 6.93±0.20, 6.51±0.20, 6.49±0.20 and 6.433±0.12% respectively during 30, 60, 90 and 120 days of storage. As the total plate count exceeded the desirable limit (1.2 × 10^5 cfu/ml), shelf life of dried shrimp was limited to 120 days month under polyester-polyethylene laminated packaging at ambient conditions. Dried shrimp under vacuum and ambient packaging is shown in Plates 4.5 and Plate 4.6.

Plate 4.5 Dried shrimp under vacuum packaging

Plate 4.6 Dried shrimp under ambient packaging

Table 4.7 Storage studies of microwave dried shrimp in polyester polyethylene laminate (72 µ) under MAP conditions

Months	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.35±1.21^{a}	0.441±0.10^{a}	2.56±0.34^{a}	14.14±0.21^{a}	16.5±2.10^{a}	8.33±1.40^{a}	1.95×10^{4} ^{a}	8.12±0.24^{a}	19.46±0.27^{a}	0.72±0.23^{a}	2.89±0.15^{a}	15.28±0.21^{a}	8.78±0.11^{a}	58.24±0.12^{a}	17.21±0.10^{a}	1.79±0.21^{a}	7.24±0.30^{a}
1	16.96±1.20^{b}	0.515±0.40^{b}	2.50±0.20^{b}	14.72±0.21^{b}	17.79±1.81^{ab}	11.89±1.31^{b}	2.76×10^{4} ^{b}	8.45±0.23^{b}	21.49±0.20^{b}	0.81±0.15^{b}	2.96±0.40^{ab}	15.84±0.30^{b}	8.55±0.35^{b}	57.2±0.10^{b}	15.59±0.16^{a}	1.58±0.14^{ab}	6.93±0.20^{a}
2	17.21±2.12^{b,c}	0.565±0.20^{b,c}	2.41±0.15^{c}	15.21±0.17^{b}	19.95±1.50^{bc}	12.42±1.51^{b}	7.41×10^{4} ^{c}	8.52±0.14^{b}	24.51±0.40^{c}	0.82±0.20^{b}	3.05±0.13^{b}	15.87±0.10^{b}	8.0±0.15^{c}	56.10±0.50^{b}	14.21±0.22^{b}	1.41±0.44^{b}	6.51±0.20^{a}
3	17.43±1.53^{c}	0.578±0.11^{c}	2.12±0.31^{d}	15.41±0.30^{c}	20.21±2.14^{c}	13.01±1.11^{c}	8.94×10^{4} ^{d}	9.02±0.31^{c}	26.12±0.32^{d}	0.97±0.24^{c}	3.23±0.15^{c}	17.21±0.23^{c}	7.7±0.24^{d}	56.02±0.13^{c}	13.92±0.10^{c}	1.39±0.21^{c}	6.49±0.20^{a}
4	18.24±1.50^{d}	0.589±0.11^{d}	1.75±0.24^{e}	15.71±0.32^{c}	21.54±2.12^{c}	13.94±1.21^{c}	**1.24×10^{5} ^{e}**	9.59±0.40^{d}	27.57±0.21^{e}	1.05±0.4^{d}	3.69±0.20^{d}	19.61±0.21^{d}	7.3±0.10^{e}	55.10±0.21^{d}	13.62±0.11^{d}	1.34±0.15^{d}	6.43±0.12^{a}

Note: Means that do not share a letter are significantly different

4.7.3 Effect of packaging material (metallized polyester) on quality of microwave dried shrimp under ambient storage conditions

Variation in quality parameters of dried shrimp under metallized polyester packaging at ambient conditions (Temperature: 27 – 30 ^{0}C, Relative humidity: 60-70 %) shows moisture content variation from 16.35±1.21 to 17.12±1.30, 18.49±1.40 and 19.12±1.23% during 30, 60 and 90 days of storage (Table 4.8). Water activity of dried shrimp varied from 0.441±0.10 to 0.56±0.12, 0.58±0.10 and 0.59±0.12 respectively during 30, 60 and 90 days of storage. Rehydration ratio of dried shrimp varied from 2.53±0.34 to 2.46±0.34, 2.21±0.13 and

1.9±0.32 respectively during 30, 60 and 90 days of storage. Shrinkage of dried shrimp varied from 14.14±0.21 to 14.75±0.21, 15.36±0.30 and 16.12±0.20% respectively during 30, 60 and 90 days of storage. Total colour change of dried shrimp varied from 16.5±2.10 to 18.54±1.32, 22.12±2.24 and 26.28±2.25 respectively during 30, 60 and 90 days of storage. Texture of the dried shrimp varied from 8.33±1.40 to 11.97±1.30, 12.24±1.21 and 13.6±1.34 N respectively at 30, 60 and 90 days of storage. Total plate count increased from 1.95×10^4 to 3.43×10^4, 5.41×10^4 and 2.74×10^5 cfu/ml respectively at 30, 60 and 90 days of storage. TMA (mgN/100 g) showed an increase from 8.12±0.24 to 8.44±0.15, 8.91±0.43 and 10.01±0.42 respectively during 30, 60 and 90 days of storage. TVBN (mg N/100 g) showed an increase from 19.46±0.27 to 22.14±0.16, 25.62±0.29 and 29.42±0.13 respectively during 30, 60 and 90 days of storage. TBARS (MDA/kg) showed an increase from 0.72±0.23 to 0.81±0.29, 1.16±0.25 and 1.03±0.16 respectively during 30, 60 and 90 days of storage. Free fatty acids (mg/g) increased from 2.89±0.15 to 3.02±0.21, 3.13±0.15 and 3.36±0.27 respectively during 30, 60 and 90 days of storage. Peroxide value (meq/kg lipid) varied from 15.28±0.21 to 15.69±0.23, 16.9±0.21 and 17.45±0.32 respectively during 30, 60 and 90 days of storage. Sensory score of dried shrimps decreased from 8.78±0.11 to 8.1±0.12, 7.4±0.24 and 7.2±0.42 respectively during 30, 60 and 90 days of storage. Protein content of dried shrimp varied from 58.24±0.12 to 57.23±0.15, 56.12±0.3 and 56.04±0.40% respectively during 30, 60 and 90 days of storage. Carbohydrate content of dried shrimp varied from 17.21±0.10 to 16.59±0.23, 15.36±0.10 and 14.24±0.29% respectively during 30, 60 and 90 days of storage. Fat content of dried shrimp varied from 1.79±0.21 to 1.64±0.16, 1.59±0.16 and 1.53±0.23% respectively during 30, 60 and 90 days of storage. Ash content of dried shrimp varied from 7.24±0.3 to 6.65±0.21, 6.54±0.12 and 6.12±0.27% respectively during 30, 60 and 90 days of storage. As the total plate count exceeded the desirable limit (2.74×10^5 cfu/ml), shelf life of dried shrimp was limited to 90 days month under laminated aluminium packaging at ambient conditions.

Table 4.8 Storage studies of microwave dried shrimp in metallized polyester (84 µ) under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.35±1.21^{a}	0.441±0.10^{a}	2.53±0.34^{a}	14.14±0.21^{a}	16.5±2.10^{a}	8.33±1.40^{a}	1.95×10^{4} ^{a}	8.12±0.24^{a}	19.46±0.27^{a}	0.72±0.23^{a}	2.89±0.15^{a}	15.28±0.21^{a}	8.78±0.11^{a}	58.24±0.12^{a}	17.21±0.10^{a}	1.79±0.21^{a}	7.24±0.30^{a}
1	17.12±1.30^{b}	0.56±0.12^{b}	2.46±0.15^{b}	14.75±0.21^{ab}	18.54±1.32^{a}	11.97±1.30^{b}	3.43×10^{4} ^{b}	8.44±0.15^{b}	22.14±0.16^{b}	0.81±0.29^{b}	3.02±0.21^{b}	15.69±0.23^{a}	8.1±0.12^{b}	57.23±0.15^{b}	16.59±0.23^{b}	1.64±0.16^{b}	6.65±0.21^{b}
2	18.49±1.40^{c}	0.58±0.10^{b}	2.21±0.13^{c}	15.36±0.30^{bc}	22..12±2.24^{b}	12.24±1.21^{c}	5.41×10^{4} ^{c}	8.91±0.43^{c}	25.62±0.29^{c}	1.16±0.25^{c}	3.13±0.15^{c}	16.9±0.21^{b}	7.4±0.24^{c}	56.12±0.3^{c}	15.36±0.10^{c}	1.59±0.16^{c}	6.54±0.12^{b}
3	19.12±1.23^{d}	0.59±0.12^{b}	1.9±0.32^{c}	16.12±0.20^{c}	26.28±2.25^{b}	13.6±1.34^{d}	**2**.74×10^{5} ^{d}	10.01±0.42^{d}	29.42±0.13^{d}	1.03±0.16^{d}	3.36±0.27^{d}	17.45±0.32^{c}	7.2±0 42^{d}	56.01±0.40^{c}	14.24±0.29^{d}	1.53±0.23^{c}	6.12±0.27^{c}

Note: Means that do not share a letter are significantly different

4.7.4 Effect of low density polyethylene (150 µ) on quality of microwave dried shrimp under vacuum storage conditions

Variation in quality parameters of dried shrimp under vacuum packaging in LDPE packaging showed moisture variation 16.35±1.21 to 17.83±0.15% during 30 days of storage (Table 4.9). Water activity, shrinkage and total colour change increased from 0.441±0.10 to 0.571±0.14, 14.14±0.21 to 15.13±0.0.15% and 16.5±2.10 to 17.42±2.14 respectively during 30 days of storage. Rehydration ratio exhibited a slight decrease from 2.53±0.34 to 2.31±0.12. Texture of the dried shrimp varied from 8.33±1.40 to 13.52±1.56 N within one month of storage. Total plate count increased from 1.95 × 10^{4} to 1.5 × 10^{5}. TMA (mgN/100 g), TVBN (mg N/100 g) and TBARS (MDA/kg) showed an increase from 8.12±0.24 to

8.95±0.41, 19.46±0.27 to 22.12±0.22 and 0.72±0.23 to 0.81±0.24 respectively during one month storage. Free fatty acids (mg/g) and peroxide value (meq/kg lipid) varied from 2.89±0.15 to 3.01±0.15 and 15.28±0.21 to 15.48±0.24 respectively. Sensory score of dried shrimps decreased from 8.78±0.11 to 8.75±0.21. Proximate analysis of dried shrimp showed slight variation with respect to protein (58.24±0.12 – 58.3±0.21%), carbohydrates (17.21±0.10 – 15.1±0.12%), fat (1.79±0.21 – 1.63±0.21%) and ash (7.24±0.30 – 6.90±0.12%) contents. Owing to the total plate count exceeding the desirable limit (1.5×10^5 cfu/ml), shelf life of dried shrimp was limited to 30 days under vacuum in LDPE packaging.

Table 4.9 Storage studies of microwave dried shrimp in LDPE (150 μ) under vacuum packed conditions

Storage period	**Moisture content (%)**	**Water activity**	**Rehydration ratio**	**Shrinkage (%)**	**Total colour change**	**Texture/Hardness (N)**	**Total plate count**	**TMA (mg N/100 g)**	**TVBN (mg N/100 g)**	**TBARS (MDA/kg)**	**FFA (mg/g)**	**PV (meq/kg lipid)**	**Sensory score**	**Protein (%)**	**Carbohydrates (%)**	**Fat (%)**	**Ash (%)**
0	16.35±1.21^{a}	0.441±0.10^{a}	2.53±0.34^{a}	14.14±0.21^{a}	16.5±2.10^{a}	8.33±1.40^{a}	1.95×10^{4} ^{a}	8.12±0.24^{a}	19.46±0.27^{a}	0.72±0.23^{a}	2.89±0.15^{a}	15.28±0.21^{a}	8.78±0.11^{a}	58.24±0.12^{a}	17.21±0.10^{a}	1.79±0.21^{a}	7.24±0.30^{a}
1	17.83±0.1.5^{b}	0.571±0.14^{b}	2.31±0.12^{b}	15.13±0.15^{b}	17.42±2.14^{b}	13.52±1.56^{b}	**1.5×10^{5} ^{b}**	8.95±0.41^{b}	22.12±0.22^{b}	0.81±0.24^{b}	3.01±0.15^{b}	15.48±0.24^{b}	8.75±0.21^{a}	58.3±0.21^{a}	15.1±0.12^{b}	1.63±0.21^{b}	6.90±0.12^{b}

Note: Means that do not share a letter are significantly different

4.7.5 Effect of packaging material (polyester-polyethylene laminate) on quality of microwave dried shrimp under vacuum packed conditions

Variation in quality parameters of dried shrimp under vacuum packaging in polyester-polyethylene laminate packages showed moisture variation from 16.35±1.21 to 16.92±1.51, 17.13±1.16, 17.49±2.14, 18.12±2.10, 19.46±1.38 and 19.97±1.15% during 30, 60, 90, 120, 150 and 180 days of storage (Table 4.10). Water activity of dried shrimp varied from 0.441±0.10 to 0.531±0.12, 0.534±0.45, 0.542±0.10, 0.55±0.21, 0.58±0.14 and 0.59±0.12 respectively during 30, 60, 90, 120, 15 and 180 days of storage. Rehydration ratio of dried shrimp varied from 2.53±0.34 to 2.51±0.25, 2.49±0.13, 2.39±0.14, 2.32±0.16, 2.19±0.22 and 1.9±0.22 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Shrinkage of dried shrimp varied from 14.14±0.21 to 14.15±0.23, 14.21±0.11, 14.48±0.15, 14.57±0.17, 15.89±0.11 and 16.23±0.27% respectively during 30, 60, 90, 120, 150 and 180 days of storage. Total colour change of dried shrimp varied from 16.5±2.10 to 17.12±1.21, 17.89±1.95, 18.10±1.23, 18.29±2.10, 19.56±2.16 and 24.12±2.12 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Texture of the dried shrimp varied from 8.33±1.40 to 11.03±1.86, 12.01±1.72, 12.42±1.52, 12.57±1.24, 12.89±2.14 and 13.47±1.61 N respectively during 30, 60, 90, 120, 150 and 180 days of storage. Total plate count increased from 1.95×10^4 to 2.89×10^4, 4.45×10^4, 7.91×10^4, 8.5×10^4, 9.92×10^4 and 2.6×10^5 cfu/ml respectively during 30, 60, 90, 120, 150 and 180 days of storage. TMA (mgN/100 g) showed an increase from 8.12±0.24 to 8.31±0.26, 8.35±0.16, 8.39±0.15, 8.42±0.13, 9.4±0.25, 9.57±0.42 respectively during 30, 60, 90, 120, 150 and 180 days of storage. TVBN (mg N/100 g) showed an increase from 19.46±0.27 to 21.54±0.15, 21.59±0.19, 21.58±0.31, 23.57±0.45, 25.69±0.31 and 27.36±0.17 respectively during 30, 60, 90, 120, 150 and 180 days of storage. TBARS (MDA/kg) showed an increase from 0.72±0.23 to 0.77±0.30, 0.79±0.12, 0.79±0.40, 0.81±0.21, 0.91±0.19 and 0.94±0.14 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Free fatty acids (mg/g) increased from 2.89±0.15 to 2.96±0.21, 2.98±0.12, 2.97±0.13, 3.02±0.19, 3.29±0.34 and 3.46±0.23 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Peroxide value (meq/kg lipid) varied from 15.28±0.21 to 15.61±0.13, 15.74±0.21, 15.79±0.24, 15.86±0.12, 16.13±0.15 and 17.12±0.16 respectively during 30, 60, 90,120, 150 and 180 days of storage. Sensory score of dried shrimps decreased from 8.78±0.11 to 8.7±0.36, 8.68±0.24, 8.65±0.16, 8.41±0.16, 8.0±0.11 and 7.9±0.10 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Protein content of dried shrimp varied from 58.24±0.12 to 59.2±0.21, 58.7±0.16, 58.23±0.14, 57.32±0.49, 56.5±0.24 and 57.14±0.20% respectively during 30, 60, 90, 120, 150 and 180 days of storage. Carbohydrate content of dried shrimp varied from 17.21±0.10 to 16.12±0.23, 16.10±0.23, 16.05±0.22, 15.98±0.22, 14.23±0.27 and 15.79±0.13% respectively during 30, 60, 90, 120, 150 and 180 days of storage. Fat content of dried shrimp varied from 1.79±0.21 to 1.52±0.45, 1.54±0.21, 1.54±0.23, 1.43±0.41, 16.5±0.13 and 1.61±0.14% during 30, 60, 90, 120, 150 and 180 days of storage. Ash content of dried shrimp varied from 7.24±0.3 to 6.9±0.12, 6.88±0.10, 6.87±0.21, 6.81±0.27, 6.1±0.12 and 6.6±0.14% respectively during 30, 60, 90, 120, 150 and 180 days of storage. As the total plate count exceeded the desirable limit (2.6×10^5 cfu/ml), shelf life of dried shrimp was limited to 180 days month under vacuum conditions in polyester-polyethylene laminated packaging.

Table 4.10 Storage studies of microwave dried shrimp in polyethylene polyester (72 µ) under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.35 ± 1.21^{a}	0.441 ± 0.10^{a}	2.53 ± 0.34^{a}	14.14 ± 0.21^{a}	16.5 ± 2.10^{a}	8.33 ± 1.40^{a}	1.95×10^{4} a	8.12 ± 0.24^{a}	19.46 ± 0.27^{a}	0.72 ± 0.23^{a}	2.89 ± 0.15^{a}	15.28 ± 0.21^{a}	8.78 ± 0.11^{a}	58.24 ± 0.12^{a}	17.21 ± 0.10^{a}	1.79 ± 0.21^{a}	7.24 ± 0.30^{a}
1	16.92 ± 1.51^{b}	0.531 ± 0.12^{a}	2.51 ± 0.25^{b}	14.15 ± 0.23^{a}	17.12 ± 1.21^{ab}	11.03 ± 1.86^{b}	2.89×10^{4} b	8.31 ± 0.26^{b}	21.54 ± 0.15^{bc}	0.77 ± 0.30^{b}	2.96 ± 0.21^{bc}	15.61 ± 0.13^{b}	8.70 ± 0.36^{b}	59.2 ± 0.21^{ab}	16.12 ± 0.23^{b}	1.523 ± 0.45^{bc}	6.90 ± 0.12^{bc}
2	17.13 ± 1.16^{b}	0.534 ± 0.45^{a}	2.49 ± 0.13^{c}	14.21 ± 0.11^{ab}	17.89 ± 1.95^{bc}	12.01 ± 1.72^{c}	4.45×10^{4} c	8.35 ± 0.16^{bc}	21.59 ± 0.19^{cd}	0.79 ± 0.12^{b}	2.98 ± 0.12^{bc}	15.74 ± 0.21^{b}	8.68 ± 0.24^{c}	58.7 ± 0.16^{ab}	16.10 ± 0.23^{b}	1.54 ± 0.21^{bc}	6.88 ± 0.10^{cd}
3	17.49 ± 2.14^{c}	0.542 ± 0.10^{a}	2.39 ± 0.14^{cd}	14.48 ± 0.15^{ab}	18.10 ± 1.23^{c}	12.42 ± 1.52^{cd}	7.91×10^{4} d	8.39 ± 0.15^{cd}	21.58 ± 0.31^{d}	0.79 ± 0.40^{b}	2.97 ± 0.13^{bc}	15.79 ± 0.24^{bc}	8.65 ± 0.16^{cd}	58.23 ± 0.14^{b}	16.05 ± 0.22^{b}	1.54 ± 0.23^{cd}	6.87 ± 0.21^{d}
4	18.12 ± 2.10^{d}	0.55 ± 0.2^{a}	2.32 ± 0.16^{de}	14.57 ± 0.17^{b}	18.29 ± 2.10^{c}	12.57 ± 1.24^{d}	8.5×10^{4} e	8.42 ± 0.13^{d}	23.57 ± 0.45^{e}	0.81 ± 0.21^{b}	3.02 ± 0.19^{c}	15.86 ± 0.12^{c}	8.41 ± 0.18^{cd}	57.32 ± 0.49^{b}	15.98 ± 0.22^{bc}	1.432 ± 0.41^{cd}	6.81 ± 0.27^{d}
5	$19.46.\pm1.38^{e}$	0.58 ± 0.14^{a}	2.19 ± 0.22^{f}	15.89 ± 0.11^{c}	19.56 ± 2.16^{d}	12.89 ± 2.14^{d}	9.92×10^{4} f	9.4 ± 0.25^{e}	25.69 ± 0.31^{f}	0.91 ± 0.19^{c}	3.29 ± 0.34^{d}	16.13 ± 0.15^{d}	8.0 ± 0.11^{d}	56.5 ± 0.24^{b}	14.23 ± 0.27^{c}	1.65 ± 0.13^{d}	6.1 ± 0.12^{d}
6	19.97 ± 1.15^{f}	0.59 ± 0.12^{a}	1.9 ± 0.22^{f}	16.23 ± 0.27^{c}	20.12 ± 2.12^{e}	13.47 ± 1.61^{e}	**2.6×10^{5} g**	9.57 ± 0.42^{f}	27.36 ± 0.17^{g}	0.94 ± 0.14^{c}	3.46 ± 0.23^{e}	17.12 ± 0.16^{e}	7.9 ± 0.10^{d}	57.14 ± 0.2^{b}	15.79 ± 0.13^{d}	1.61 ± 0.14^{e}	6.6 ± 0.14^{e}

Note: Means that do not share a letter are significantly different

4.7.6 Effect of packaging material (metallized poyester) on quality of microwave dried shrimp under vacuum storage conditions

Variation in quality parameters of microwave dried shrimp under vacuum packaging in metallized polyester packages showed moisture variation from 16.35±1.21 to 17.45±1.15, 18.93±1.12, 19.12±1.24 and 21.5±1.21% during 30, 60, 90 and 120 days of storage (Table 4.11). Water activity of dried shrimp varied from 0.441±0.10 to 0.54±0.21, 0.57±0.10, 0.578±0.10 and 0.6±0.10 respectively during 30, 60, 90 and 120 days of storage. Rehydration ratio of dried shrimp varied from 2.53±0.34 to 2.48±0.12, 2.30±0.21, 2.09±0.21 and 1.87±0.12 respectively during 30, 60, 90 and 120 days of storage. Shrinkage of dried shrimp varied from 14.14±0.21 to 14.21±0.33, 14.66±0.10, 16.13±0.12 and 17.12±0.21% respectively during 30, 60, 90 and 120 days of storage. Total colour change of dried shrimp varied from 16.5±2.10 to 17.88±1.84, 18.19±2.20, 19.56±2.10 and 26.12±2.23 respectively during 30, 60, 90 and 120 days of storage. Texture of the dried shrimp varied from 8.33±1.40 to 12.23±1.23, 12.68±1.26, 12.89±2.14 and 14.1±1.21 N respectively during 30, 60, 90 and 120 days of storage. Total plate count increased from 1.95×10^4 to 3.12×10^4, 5.2×10^4, 7.9×10^4 and 2.41×10^5 cfu/ml respectively during 30, 60, 90 and 120 days of storage. TMA (mgN/100 g) showed an increase from 8.12±0.24 to 8.41±0.15, 8.53±0.18, 9.4±0.25 and 10.01±0.42 respectively during 30, 60, 90 and 120 days of storage. TVBN (mg N/100 g) showed an increase from 19.46±0.27 to 23.26±0.11, 23.65±0.27, 25.69±0.31 and 29.42±0.13 respectively during 30, 60, 90 and 120 days of storage. TBARS (MDA/kg) showed an increase from 0.72±0.23 to 0.77±0.12, 0.83±0.31, 0.91±0.31 and 1.03±0.16 respectively during 30, 60, 90 and 120 days of storage. Free fatty acids (mg/g) increased from 2.89±0.15 to 2.99±0.31, 3.13±0.14, 3.29±0.34 and 3.52±0.13 respectively during 30, 60, 90 and 120 days of storage. Peroxide value (meq/kg lipid) varied from 15.28±0.21 to 15.78±0.22, 15.88±0.23, 16.13±0.15 and 18.1±0.15 respectively during 30, 60, 90 and 120 days of storage. Sensory score of dried shrimps decreased from 8.78±0.11 to 8.65±0.24, 8.3±0.15, 8.0±0.11 and 7.4±0.12 respectively during 30, 60, 90 and 120 days of storage. Protein content of dried shrimp varied from 58.24±0.12 to 58.59±0.16, 56.12±0.24, 56.5±0.24 and 56.1±0.30% respectively during 30, 60, 90 and 120 days of storage. Carbohydrate content of dried shrimp varied from 17.21±0.10 to 15.14±0.21, 15.12±0.12, 14.23±0.27 and 14.24±0.10% respectively during 30, 60, 90 and 120 days of storage. Fat content of dried shrimp varied from 1.79±0.21 to 1.56±0.31, 1.39±0.10, 1.65±0.13 and 1.59±0.16% during 30, 60, 90 and 120 days of storage. Ash content of dried shrimp varied from 7.24±0.3 to 6.86±0.15, 6.79±0.20, 6.26±0.14 and 6.54±0.12% respectively during 30, 60, 90 and 120 days of storage. As the total plate count exceeded the desirable limit (2.41 × 10^5 cfu/ml), shelf life of dried shrimp was limited to 120 days under vacuum conditions in metallized polyester packaging.

Table 4.11 Storage studies of microwave dried shrimp in metallized polyester (84 µ) under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.35±1.21^{a}	0.551±0.10^{a}	2.53±0.34^{a}	14.32±0.21^{a}	16.5±2.10^{a}	10.59±1.40^{a}	1.95×10^{4} ^{a}	8.12±0.24^{a}	19.46±0.27^{a}	0.72±0.23^{a}	2.89±0.15^{a}	15.28±0.21^{a}	8.78±0.11^{a}	58.24±0.12^{a}	17.21±0.10^{a}	1.79±0.21^{a}	7.24±0.30^{a}
1	17.45±1.15^{b}	0.54±0.21^{a}	2.48±0.12^{b}	14.21±0.33^{a}	17.88±1.84^{b}	12.23±1.23^{b}	3.12×10^{4} ^{b}	8.41±0.15^{b}	23.269±0.11^{b}	0.77±0.12^{b}	2.99±0.31^{b}	15.78±0.22^{b}	8.65±0.24^{b}	58.59±0.16^{a}	15.14±0.21^{a}	1.56±0.31^{b}	6.86±0.15^{b}
2	18.93±1.12^{c}	0.57±0.10^{a}	2.30±21^{c}	14.66±0.10^{b}	18.19±2.20^{b}	12.68±1.26^{bc}	5.20×10^{4} ^{c}	8.53±0.18^{c}	23.65±0.27^{b}	0.83±0.31^{c}	3.13±0.14^{c}	15.88±0.23^{bc}	8.3±0.15^{c}	56.12±0.24^{b}	15.12±0.12^{b}	1.39±0.10^{c}	6.79±0.20^{c}
3	19.12±1.24^{d}	0.578±0.10^{b}	2.09±0.2^{d}	16.13±0.12^{c}	19.56±2.10^{c}	12.89±2.14^{c}	7.9×10^{4} ^{d}	9.4±0.25^{d}	25.69±0.31^{c}	0.91±0.19^{d}	3.29±0.34^{d}	16.13±0.15^{c}	8.0±0.11^{d}	56.5±0.24^{b}	14.23±0.27^{b}	1.65±0.13^{d}	6.26±0.14^{d}
4	20.57±1.21^{e}	**0.6±0.10^{c}**	1.87±0.12^{e}	17.12±0.21^{d}	19.9712±2.23^{c}	14.1±1.21^{d}	**2.41×10^{5} ^{e}**	10.01±0.42^{e}	29.42±0.13^{d}	1.03±0.16^{e}	3.52±0.13^{e}	18.1±0.15^{d}	7.4±0.12^{e}	56.12±0.3^{b}	14.24±0.10^{c}	1.59±0.16^{e}	6.54±0.12^{e}

Note: Means that do not share a letter are significantly different

4.7.7 Effect of low-density polyethylene (150 µ) on quality of solar dried shrimp under ambient storage conditions

Variation in quality parameters of solar dried shrimp under LDPE packaging at ambient conditions (Temperature: 27 – 30 ^{0}C, Relative humidity: 60-70 %) showed moisture variation from 16.5±1.24 to 17.3±0.21% during 30 days of storage (Table 4.12). Water activity, shrinkage and total colour change increased from 0.551±0.12 – 0.58±0.24, 24.67±0.16 –

26.13±0.10% and 16.95±2.14 – 18.12±1.56 respectively during 30 days of storage. Rehydration ratio exhibited a slight decrease from 2.39±0.24 to 2.32±0.56. Texture of the dried shrimp varied from 11.93±1.69 to 13.41±1.23 N within one month of storage. Total plate count increased from 2.6 × 10^4 to 1.4 × 10^5cfu/ml. TMA (mgN/100 g), TVBN (mg N/100 g) and TBARS (MDA/kg) showed an increase from 8.23±0.25 – 8.73±0.22, 21.49±0.31 – 22.41±0.10 and 0.75±0.40 – 0.83±0.20 respectively during one month storage. Free fatty acids (mg/g) and peroxide value (meq/kg lipid) varied from 2.93±0.13 – 3.21±0.30 and 15.48±0.24 – 15.96±0.20 respectively. Sensory score of dried shrimps decreased from 8.75±0.21 to 8.10±0.20. Proximate analysis of dried shrimp showed slight variation with respect to protein (59.5±0.1 – 58.3±0.30%), carbohydrates (16.14±0.14 – 16.1±0.50%), fat (1.72±0.23 – 1.69±0.31%) and ash (6.92±0.03 – 6.53±0.10%) contents. Owing to the total plate count exceeding the desirable limit (1.4 × 10^5), shelf life of solar dried shrimp was limited to 30 days under LDPE packaging at ambient conditions.

Table 4.12 Storage studies of solar dried shrimp in LDPE (150 µ) under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.5±1.24	0.551±0.12^{a}	2.39±0.24^{a}	24.67±0.16^{a}	16.95±2.14^{a}	11.93±1.69^{a}	2.6×10^{4} ^{a}	8.23±0.25$^{a\ a}$	21.49±0.31	0.75±0.40^{a}	2.93±0.13^{a}	15.48±0.24^{a}	8.75±0.21^{a}	59.5±0.1^{a}	16.14±0.14^{a}	1.72±0.23^{a}	6.92±0.03^{a}
1	17.3±0.21^{b}	0.58±0.24^{b}	2.32±0.56^{b}	26.13±0.10^{b}	18.12±1.56^{b}	13.41±1.23^{b}	**1.4×10^{5} ^{b}**	8.73±0.22^{b}	22.41±0.10^{b}	0.83±0.20^{b}	3.21±0.30^{b}	15.96±0.24^{b}	8.10±0.20^{b}	58.3±0.30^{b}	16.10±0.50^{b}	1.69±0.31^{b}	6.53±0.10^{b}

Note: Means that do not share a letter are significantly different

4.7.8 Effect of packaging material (polyester-polyethylene laminate) on quality of solar dried shrimp under ambient storage conditions

Variation in quality parameters of solar dried shrimp under polyester-polyethylene laminate (72 µ) packaging at ambient conditions (Temperature: 27 – 30 °C, Relative humidity: 60-70 %) is explicated showed moisture variation from 16.5±1.24 to 17.22±2.10, 17.79±1.20, 18.10±1.10 and 18.92±1.20% during 30, 60, 90 and 120 days of storage (Table 13). Water activity of dried shrimp varied from 0.551±0.12 to 0.554±0.20, 0.56±0.23, 0.57±0.20 and 0.59±0.30 respectively during 30, 60, 90 and 120 days of storage. Rehydration ratio of dried shrimp varied from 2.39±0.24 to 2.35±0.15, 2.2±0.10, 1.9±0.20 and 1.8±0.42 respectively during 30, 60, 90 and 120 days of storage. Shrinkage of dried shrimp varied from 24.67±0.16 to 27.57±0.17, 29±0.11, 31.94±0.10 and 32.54±0.20% respectively during 30, 60, 90 and 120 days of storage. Total colour change of dried shrimp varied from 16.95±2.14 to 18.29±2.10, 19.56±2.10, 22.50±2.10 and 23.42±1.25 respectively during 30, 60, 90 and 120 days of storage. Texture of the dried shrimp varied from 11.93±1.69 to 12.57±1.24, 12.89±2.14, 13.40±1.40 and 13.56±1.70 N respectively during 30, 60, 90 and 120 days of storage. Total plate count increased from 2.6×10^4 to 4.4×10^4, 7.9×10^4, 8.2×10^4 and 1.5×10^5 cfu/ml respectively during 30, 60, 90 and 120 days of storage. TMA (mgN/100 g) showed an increase from 8.23±0.25 to 8.42±0.13, 9.4±0.25, 9.49±0.20 and 9.53±0.40 respectively during 30, 60, 90 and 120 days of storage. TVBN (mg N/100 g) showed an increase from 21.49±0.31 to 23.57±0.45, 25.69±0.31, 26.41±0.12 and 26.93±0.15 respectively during during 30, 60, 90 and 120 days of storage. TBARS (MDA/kg) showed an increase from 0.75±0.40 to 0.81±0.21, 0.9±0.19, 0.93±0.22 and 0.95±0.21 respectively during 30, 60, 90 and 120 days of storage. Free fatty acids (mg/g) increased from 2.93±0.13 to 3.02±.19, 3.29±.34, 3.3±0.61 and 3.5±0.32 respectively during 30, 60, 90 and 120 days of storage. Peroxide value (meq/kg lipid) varied from 15.48±0.24 to 15.86±0.12, 16.13±0.15, 16.89±0.26 and 17.24±0.21 respectively during 30, 60, 90 and 120 days of storage. Sensory score of dried shrimps decreased from 8.75±0.21 to 8.41±0.18, 8.2±0.11, 8.0±0.30 and 7.8±0.12 respectively during 30, 60, 90 and 120 days of storage. Protein content of dried shrimp varied from 59.5±0.1 to 57.32±0.49, 56.5±0.24, 56.4±0.20 and 56.13±0.30% respectively during 30, 60, 90 and 120 days of storage. Carbohydrate content of dried shrimp varied from 16.14±0.14 to 15.89±0.20, 14.23±0.27, 14.21±0.11 and 14.20±0.10% respectively during 30, 60, 90 and 120 days of storage. Fat content of dried shrimp varied from 1.72±0.23 to 1.6±0.41, 1.65±0.13, 1.59±0.10 and 1.56±0.15% during 30, 60, 90 and 120 days of storage. Ash content of dried shrimp varied from 6.92±0.03 to 6.79±0.25, 6.1±0.12, 6.3±0.20 and 6.6±0.10% respectively during 30, 60, 90 and 120 days of storage. As the total plate count exceeded the desirable limit (1.5 × 10^5 cfu/ml), shelf life of solar dried shrimp was limited to 120 days month under polyester-polyethylene laminated packaging at ambient conditions.

Table 4.13 Storage studies of solar dried shrimp in polyester polyethylene laminated package (72 µ) under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.5±1.24^{a}	0.551±0.12^{a}	2.39±0.24^{a}	14.14±0.16^{a}	16.95±2.14^{a}	11.93±1.69^{a}	2.6×10^{4} ^{a}	8.23±0.25^{a}	21.49±0.31^{a}	0.75±0.40^{a}	2.93±0.13^{a}	15.48±0.24^{a}	8.75±0.21^{a}	59.5±0.1^{a}	16.14±0.14^{a}	1.72±0.23^{a}	6.92±0.03^{a}
1	17.22±2.10^{a}	0.54±0.20^{b}	2.35±0.15^{a}	27.57±0.17^{a}	18.29±2.10^{b}	12.57±1.24^{bc}	4.45×10^{4} ^{b}	8.42±0.13^{a}	23.57±0.45^{b}	0.81±0.21^{b}	3.02±0.19^{a}	15.86±0.12^{a}	8.41±0.18^{b}	57.32±0.49^{a}	15.89±0.20^{a}	1.66±0.41^{a}	6.79±0.25^{a}
2	17.79.±1.20^{b}	0.56±0.23^{c}	2.2±0.10^{b}	29.89±0.11^{b}	19.56±2.10^{c}	12.89±2.14^{c}	7.9×10^{4} ^{c}	9.4±0.25^{b}	25.69±0.31^{c}	0.91±0.19^{c}	3.29±0.34^{b}	16.13±0.15^{b}	8.2±0.11^{c}	56.5±0.24^{a}	14.23±0.27^{a}	1.65±0.13^{ab}	6.1±0.12^{a}
3	18.10±1.10^{bc}	0.57±0.20^{cd}	1.9±0.20^{c}	31.94±0.10^{bc}	21.50±1.20^{d}	13.40±1.40^{d}	8.2×10^{4} ^{d}	9.49±0.20^{b}	26.41±0.12^{d}	0.93±0.22^{cd}	3.3±0.61^{bc}	16.89±0.26^{bc}	8.0±0.30^{d}	56.40±0.20^{b}	14.21±0.11^{b}	1.59±0.10ab	6.3±0.20^{a}
4	18.92.12±1.20^{c}	0.59±0.30^{d}	1.8±0.42^{d}	32.54±0.20^{d}	22.42±1.25^{e}	13.56±1.70^{d}	**1.5×10^{5} ^{e}**	9.53±0.40^{b}	26.93±0.15^{d}	0.95±0.21^{d}	3.5±0.32^{c}	17.24±0.21^{a}	7.8±0.12^{e}	56.13±0.30^{c}	14.20±0.10^{c}	1.56±0.15^{b}	6.6±0.10^{a}

Note: Means that do not share a letter are significantly different

4.7.9 Effect of packaging material (metallized polyester) on quality of solar dried shrimp under ambient storage conditions

Variation in quality parameters of solar dried shrimp under metallized polyester packaging at ambient conditions (Temperature: 27 – 30 °C, Relative humidity: 60-70 %) showed moisture variation from 16.5±1.24 to 17.96±1.52, 19.21±1.20, 19.53±1.21% during 30, 60 and 90 days of storage (table 4.14). Water activity of dried shrimp varied from 0.551±0.12 to 0.54±0.20, 0.56±0.12 and 0.61±0.20 respectively during 30, 60 and 90 days of storage. Rehydration ratio of dried shrimp varied from 2.39±0.24 to 2.33±0.14, 2.12±0.10 and 1.96±0.20 respectively during 30, 60 and 90 days of storage. Shrinkage of dried shrimp varied from 24.67±0.16 to 26.23±0.20, 29.42±0.10 and 31.59±0.20% respectively during 30, 60 and 90 days of storage. Total colour change of dried shrimp varied from 16.95±2.14 to 18.12±1.25, 20.23±1.50 and 25.20±1.30 respectively during 30, 60 and 90 days of storage. Texture of the dried shrimp varied from 11.93±1.69 to 12.96±1.50, 13.82±2.20 and 14.56±1.10 N respectively at 30, 60 and 90 days of storage. Total plate count increased from 2.6×10^4 to 4.5×10^4, 8.9×10^4 and 2.1×10^5 cfu/ml respectively at 30, 60 and 90 days of storage. TMA (mgN/100 g) showed an increase from 8.23±0.25 to 8.82±0.20, 9.45±1.1 and 10.56±0.30 respectively during 30, 60 and 90 days of storage. TVBN (mg N/100 g) showed an increase from 21.49±0.31 to 22.3±0.10, 26.72±0.20 and 30.56±0.40 respectively during 30, 60 and 90 days of storage. TBARS (MDA/kg) showed an increase from 0.75±0.40 to 0.89±0.30, 0.95±0.15 and 1.6±0.10 respectively during 30, 60 and 90 days of storage. Free fatty acids (mg/g) increased from 2.93±0.13 to 3.4±0.24, 3.9±0.20 and 4.4±0.12 respectively during 30, 60 and 90 days of storage. Peroxide value (meq/kg lipid) varied from 15.48±0.24 to 16.12±0.20, 17.41±0.12 and 19.62±0.24 respectively during 30, 60 and 90 days of storage. Sensory score of dried shrimps decreased from 8.75±0.21 to 8.10±0.10, 7.8±0.15 and 7.4±0.20 respectively during 30, 60 and 90 days of storage. Protein content of dried shrimp varied from 59.5±0.1 to 57.12±0.56, 56.5±0.25 and 56.10±0.20% respectively during 30, 60 and 90 days of storage. Carbohydrate content of dried shrimp varied from 16.14±0.14 to 15.2±0.10, 14.9±0.24 and 14.1±0.2% respectively during 30, 60 and 90 days of storage. Fat content of dried shrimp varied from 1.72±0.23 to 1.62±0.12, 1.6±0.10 and 1.58±0.20% respectively during 30, 60 and 90 days of storage. Ash content of dried shrimp varied from 6.92±0.03 to 6.81±0.10, 6.5±0.23 and 6.41±0.23% respectively during 30, 60 and 90 days of storage. As the total plate count exceeded the desirable limit (2.1×10^5 cfu/ml), shelf life of solar dried shrimp was limited to 90 days under laminated aluminium packaging at ambient conditions.

Table 4.14 Storage studies of solar dried shrimp in metallized polyester (84 µ) under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.5±1.24^{a}	0.551±0.12^{b}	2.39±0.24^{a}	24.674±0.16^{a}	16.95±2.14^{a}	11.93±1.69^{a}	2.6×10^{4} a	8.23±0.25^{a}	21.49±0.31^{a}	0.75±0.40^{a}	2.93±0.13^{a}	15.48±0.24^{a}	8.75±0.21^{a}	59.5±0.1^{a}	16.14±0.14^{a}	1.72±0.23^{a}	6.92±0.03^{a}
1	17.96±1.52^{b}	0.54±0.20^{b}	2.33±0.14^{b}	26.23±0.20^{b}	18.12±1.25^{b}	12.96±1.50^{b}	4.5×10^{4} b	8.82±0.20^{b}	22.30±0.10^{b}	0.89±0.30^{b}	3.40±0.24^{bc}	16.12±0.20^{ab}	8.10±0.10^{b}	57.12±0.56^{ab}	15.20±0.10^{b}	1.62±0.12^{a}	6.81±0.10^{a}
2	19.21±1.20^{c}	0.56±0.12^{b}	2.12±0.10^{cd}	29.42±0.10^{c}	19.23±1.50^{c}	13.82±2.20^{c}	8.9×10^{4} c	9.45±1.1^{c}	26.72±0.20^{c}	0.95±0.15^{c}	3.9±0.20^{c}	17.41±0.12^{b}	7.8±0.15^{c}	56.5±0.25^{b}	14.90±0.24^{b}	1.60±0.10^{a}	6.50±0.23^{c}
3	19.53±1.21^{c}	0.61±0.20^{a}	1.96±0.20^{d}	31.59±0.20^{d}	20.20±1.30^{d}	14.56±1.10^{d}	**2.1×10^{5} d**	10.56±0.30^{d}	30.56±0.40^{d}	1.6±0.10^{d}	4.40±0.12^{d}	19.62±0.24^{c}	7.4±0.20^{d}	56.10±0.2^{c}	14.10±0.20^{c}	1.58±0.20^{b}	6.41±0.23^{c}

Note: Means that do not share a letter are significantly different

4.7.10 Effect of low density polyethylene (150 µ) on quality of solar dried shrimp under vacuum packed conditions

Variation in quality parameters of solar dried shrimp under vacuum packaging in LDPE packaging showed moisture variation varied from 16.5±1.24 to17.2±1.30% during 30 days of storage (Table 4.15). Water activity, shrinkage and total colour change increased from 0.551±0.12 to 0.571±0.10, 24.67±0.15 to 25.40±0.10% and 16.95±2.14 to18.1±1.40 respectively during 30 days of storage. Rehydration ratio exhibited a slight decrease from 2.51±0.24 to 2.26±0.10. Texture of the dried shrimp varied from 11.93±1.69 to 14.23±1.20 N within one month of storage. Total plate count increased from 2.6 × 10^{4} to 1.7 × 10^{5}. TMA (mgN/100 g), TVBN (mg N/100 g) and TBARS (MDA/kg) showed an increase from 8.23±0.25 to 9.3±0.40, 21.49±0.31 to 24.20±0.20 and 0.75±0.40 to 0.91±0.20 respectively during one month storage. Free fatty acids (mg/g) and peroxide value (meq/kg lipid) varied from 2.93±0.13 to 3.3±0.10 and 15.48±0.24 to 15.59±0.54 respectively. Sensory score of dried shrimps decreased from 8.75±0.21 to 8.1±0.30. Proximate analysis of dried shrimp showed slight variation with respect to protein (59.5±0.10 – 59.1±0.31%), carbohydrates (16.14±0.14 – 15.52±0.10%), fat (1.72±0.23 – 1.64±0.3%) and ash (6.92±0.33 – 6.87±0.10%) contents. Owing to the total plate count exceeding the desirable limit (1.7 × 10^5 cfu/ml), shelf life of dried shrimp was limited to 30 days under vacuum in LDPE packaging.

Table 4.15 Storage studies of solar dried shrimp in LDPE (150 µ) under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory sc	Protein ore (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.5±1.24^{a}	0.551±0.12^{a}	2.39±0.24^{a}	24.67±0.15^{a}	16.95±2.14^{a}	11.93±1.69^{a}	2.6×10^{4} ^{a}	8.23±0.25^{a}	21.49±0.31^{a}	0.75±0.40^{a}	2.93±0.13^{a}	15.48±0.24^{a}	8.75±0.21^{a}	59.5±0.1^{a}	16.14±0.14^{a}	1.72±0.23^{a}	6.92±0.33^{a}
1	17.20±1.30^{b}	0.571±0.10^{b}	2.26±0.10^{b}	25.41±0.10^{b}	18.10±1.40^{b}	14.23±1.20^{b}	**1.7×10^{5} ^{b}**	9.3±0.40^{b}	24.20±0.20^{b}	0.91±0.20^{b}	3.3±0.10^{b}	15.59±0.54^{b}	8.1±0.30^{b}	59.10±0.31^{b}	15.52±0.10^{b}	1.64±0.30^{b}	6.87±0.10^{b}

Note: Means that do not share a letter are significantly different

4.7.11 Effect of packaging material (polyester-polyethylene laminate 72 µ) on quality of solar dried shrimp under vacuum packed conditions

Variation in quality parameters of solar dried shrimp under vacuum packaging in polyester-polyethylene laminate packages showed moisture variation from 16.5±1.24 to 16.87±1.50, 17.25±1.30, 18.12±1.10, 18.59±1.12, 19.26±1.30 and 20.24±1.20% during 30, 60, 90, 120, 150 and 180 days of storage. Water activity of dried shrimp varied from 0.551±0.12 to 0.552±0.12, 0.556±0.12, 0.57±0.10, 0.579±0.10, 0.586±0.21 and 0.615±0.10 respectively during 30, 60, 90, 120, 15 and 180 days of storage. Rehydration ratio of dried shrimp varied from 2.39±0.24 to 2.52±0.20, 2.46±0.12, 2.35±0.10, 2.28±0.12, 2.10±0.24 and 1.80±0.12

respectively during 30, 60, 90, 120, 150 and 180 days of storage. Shrinkage of dried shrimp varied from 24.67±0.16 to 25.46±0.32, 27.51±0.10, 28±0.50, 29.79±0.10, 31.54±0.31 and 32.48±0.20%, respectively during 30, 60, 90, 120, 150 and 180 days of storage. Total colour change of dried shrimp varied from 16.95±2.14 to 18.24±1.10, 18.95±1.90, 19.12±1.30, 19.39±2.20, 19.84±1.50 and 22.53±1.23 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Texture of the dried shrimp varied from 11.93±1.69 to 12.3±1.6, 12.94±2.10, 13.40±2.50, 14.62±1.22, 15.10±1.50 and 15.62±1.20 N respectively during 30, 60, 90, 120, 150 and 180 days of storage. Total plate count increased from 2.6×10^4 to 3.6×10^4, 4.5×10^4, 6.9×10^4, 7.5×10^4, 9.2×10^4 and 1.4×10^5 cfu/ml respectively during 30, 60, 90, 120, 150 and 180 days of storage. TMA (mgN/100 g) showed an increase from 8.23±0.25 to 8.29±0.10, 8.36±0.15, 8.4±0.12, 8.89±0.10, 9.6±0.20, 10.24±0.40 respectively during 30, 60, 90, 120, 150 and 180 days of storage. TVBN (mg N/100 g) showed an increase from 24.49±0.31 to 21.60±0.10, 22.50±0.22, 23.46±0.20, 24.61±0.20, 26.32±0.13 and 29.30±0.10 respectively during 30, 60, 90, 120, 150 and 180 days of storage. TBARS (MDA/kg) showed an increase from 00.75±0.4 to 0.78±0.20, 0.84±0.63, 0.91±0.74, 0.96±0.10 and 1.3±0.10 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Free fatty acids (mg/g) increased from 2.93±0.13 to 2.98±0.12, 3.0±0.20, 3.2±0.10, 3.52±0.61, 3.71±0.30 and 4.2±0.20 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Peroxide value (meq/kg lipid) varied from 15.48±0.24 to 15.51±0.20, 15.53±0.12, 15.57±0.44, 15.81±0.36, 16.19±0.10 and 16.72±0.26 respectively during 30, 60, 90,120, 150 and 180 days of storage. Sensory score of dried shrimps decreased from 8.75±0.21 to 8.72±0.30, 8.5±0.20, 8.2±0.28, 7.9±0.10, 7.8±0.21 and 7.7±0.20 respectively during 30, 60, 90, 120, 150 and 180 days of storage. Protein content of dried shrimp varied from 59.5±0.1 to 59.1±0.30, 58.9±0.24, 58.5±0.12, 57.8±0.29, 56.3±0.63 and 56.14±0.10% respectively during 30, 60, 90, 120, 150 and 180 days of storage. Carbohydrate content of dried shrimp varied from 16.14±0.14 to 16.10±0.30, 15.56±0.20, 16.01±0.20, 15.78±0.12, 15.5±0.20 and 15.21±0.30% respectively during 30, 60, 90, 120, 150 and 180 days of storage. Fat content of dried shrimp varied from 1.72±0.23 to 1.63±0.40, 1.61±0.20, 1.59±0.43, 1.55±0.10, 1.52±0.13 and 1.51±0.10% during 30, 60, 90, 120, 150 and 180 days of storage. Ash content of dried shrimp varied from 6.2±0.33 to 6.86±0.10, 6.88±0.42, 6.89±0.29, 6.71±0.42 and 6.63±0.15% respectively during 30, 60, 90, 120, 150 and 180 days of storage. As the total plate count exceeded the desirable limit (2.6×10^5 cfu/ml), shelf life of dried shrimp was limited to 180 days month under vacuum conditions in polyester-polyethylene laminated packaging.

Table 4.16 Storage studies of solar dried shrimp in polyester polyethylene laminated package (72 µ) under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.5±1.24^{a}	0.551±0.12^{a}	2.39±0.24^{a}	24.67±0.16^{a}	16.95±2.14^{a}	11.93±1.69^{a}	2.6×10^{4a}	8.23±0.25^{a}	21.49±0.31^{a}	0.75±0.40^{a}	2.93±0.13^{a}	15.48±0.24^{a}	8.75±0.21^{a}	59.5±0.1^{a}	16.14±0.14^{a}	1.72±0.23^{a}	6.92±0.33^{a}
1	16.87±1.50^{b}	0.555±0.12^{a}	2.52±0.20^{b}	25.46±0.32^{ab}	18.24±1.10^{b}	12.3±1.60^{ab}	3.6×10^{4b}	8.29±0.10^{a}	21.60±0.10^{a}	0.78±0.20^{a}	2.98±0.12^{a}	15.51±0.20^{ab}	8.72±0.30^{a}	59.1±0.30^{a}	16.10±0.30^{a}	1.63±0.40^{b}	6.86±0.10^{b}
2	17.25±1.30^{c}	0.556±0.12^{ab}	2.46±0.12b^{c}	27.51±0.10^{ab}	18.95±1.90^{c}	12.94±2.10^{b}	4.5×10^{4c}	8.36±0.15^{a}	22.50±0.22^{ab}	0.81±0.21^{ab}	3.0±0.20^{a}	15.53±0.12^{ab}	8.5±0.20^{b}	58.9±0.24^{b}	15.56±0.20^{b}	1.61±0.20^{bc}	6.88±0.42^{b}
3	18.12±1.10^{d}	0.570±0.10^{bc}	2.35±0.10c^{d}	28.65±0.50^{ab}	19.12±1.30^{d}	13.40±1.50^{c}	6.9×10^{4d}	8.40±0.12^{a}	23.46±0.20^{ab}	0.84±0.63^{ab}	3.2±0.10^{b}	15.57±0.44^{bc}	8.2±0.28^{c}	58.5±0.12^{bc}	16.01±0.20^{c}	1.59±0.43^{c}	6.89±0.29^{bc}
4	18.59±1.12^{e}	0.579±0.20^{cd}	2.28±0.12d^{e}	29.79±0.10^{ab}	19.39±2.20^{de}	14.62±1.22^{d}	7.5×10^{4e}	8.89±0.10^{b}	24.61±0.40^{b}	0.91±0.74^{ab}	3.52±0.61^{c}	15.81±0.36^{c}	7.9±0.10^{d}	57.8±0.29^{c}	15.78±0.12^{d}	1.55±0.10^{d}	6.85±0.62^{cd}
5	19.26.±1.30^{f}	0.586±0.21^{cd}	2.10±0.24^{e}	31.54±0.31^{ab}	19.84±1.50^{e}	15.10±1.50^{de}	9.2×10^{4f}	9.6±0.20^{c}	26.32±0.13^{b}	0.96±0.10^{b}	3.71±0.30^{c}	16.19±0.10^{d}	7.8±0.21^{de}	56.3±0.63^{d}	15.50±0.20^{e}	1.52±0.13^{de}	6.71±0.42^{d}
6	20.24±120^{g}	**0.615±0.10^{e}**	1.80±0.12^{e}	32.48±0.20^{b}	22.53±1.23^{f}	15.62±1.20^{e}	**1.4×10^{5g}**	10.24±0.40^{d}	29.30±0.10^{c}	1.3±0.10^{c}	4.2±0.20^{d}	16.72±0.26^{d}	7.7±0.20^{e}	56.14±0.10^{de}	15.21±0.30^{f}	1.51±0.10^{e}	6.63±0.15^{e}

Note: Means that do not share a letter are significantly different

4.7.12 Effect of packaging material (metallized polyester) on quality of solar dried shrimp under vacuum packed conditions

Variation in quality parameters of solar dried shrimp under vacuum packaging in metallized polyester packages showed moisture variation from 16.5±1.24 to 17.25±1.2, 18.56±1.5, 19.24±1.22 and 20.12±0.30% during 30, 60, 90 and 120 days of storage (Table 4.17). Water activity of dried shrimp varied from 0.551±0.12 to 0.57±0.20, 0.585±0.20, 0.592±0.12 and 0.62±0.30 respectively during 30, 60, 90 and 120 days of storage. Rehydration ratio of dried shrimp varied from 2.39±0.24 to 2.33±0.13, 2.31±0.22, 2.1±0.20 and 1.82±0.12 respectively during 30, 60, 90 and 120 days of storage. Shrinkage of dried shrimp varied from 24.67±0.16 to 26.12±0.20, 27.12±0.34, 29.59±0.10 and 31.41±0.20% respectively during 30, 60, 90 and 120 days of storage. Total colour change of dried shrimp varied from 16.95±2.14 to 18.10±1.52, 19.21±1.20, 21.12±2.12 and 24.6±1.30 respectively during 30, 60, 90 and 120 days of storage. Texture of the dried shrimp varied from 11.93±1.69 to 13.12±1.10, 13.69±1.23, 13.98±1.20 and 14.26±1.20 N respectively during 30, 60, 90 and 120 days of storage. Total plate count increased from 2.6×10^4 to 4.2×10^4, 7.42×10^4, 9.2×10^4 and 2.30×10^5 cfu/ml respectively during 30, 60, 90 and 120 days of storage. TMA (mgN/100 g) showed an increase from 8.23±0.25 to 8.52±0.21, 8.94±0.10, 9.7±0.20 and 11.12±0.40 respectively during 30, 60, 90 and 120 days of storage. TVBN (mg N/100 g) showed an increase from 21.49±0.31 to 22.96±0.10, 24.56±0.72, 26.62±0.31 and 29.42±0.13 respectively during 30, 60, 90 and 120 days of storage. TBARS (MDA/kg) showed an increase from 0.75±0.40 to 0.77±0.12, 0.83±0.31, 0.9±0.10 and 1.12±0.15 respectively during 30, 60, 90 and 120 days of storage. Free fatty acids (mg/g) increased from 2.93±0.13 to 3.10±0.21, 3.24±0.12, 3.36±0.30 and 3.61±0.10 respectively during 30, 60, 90 and 120 days of storage. Peroxide value (meq/kg lipid) varied from 15.48±0.24, 15.69±0.20, 15.81±0.10 and 17.94±0.13 respectively during 30, 60, 90 and 120 days of storage. Sensory score of dried shrimps decreased from 8.75±0.21 to 8.42±0.20, 8.10±0.12, 7.9±0.10 and 7.3±0.21 respectively during 30, 60, 90 and 120 days of storage. Protein content of dried shrimp varied from 59.5±0.1 to 59.12±0.10, 58.23±0.14, 57.56±0.20 and 57.13±0.20% respectively during 30, 60, 90 and 120 days of storage. Carbohydrate content of dried shrimp varied from 16.14±0.14 to 15.92±0.30, 15.64±0.10, 15.23±0.20 and 15.2±0.10% respectively during 30, 60, 90 and 120 days of storage. Fat content of dried shrimp varied from 1.72±0.23, to 1.63±0.21, 1.45±0.20, 1.32±0.12 and 1.2±0.15% during 30, 60, 90 and 120 days of storage. Ash content of dried shrimp varied from 6.92±0.33 to 6.72±0.10, 6.23±0.12, 6.215±0.10 and 6.10±0.20% respectively during 30, 60, 90 and 120 days of storage. As the total plate count exceeded the desirable limit (2.3 × 10^5 cfu/ml), shelf life of solar dried shrimp was limited to 120 days month under vacuum conditions in aluminium laminated packaging.

Table 4.17 Storage studies of solar dried shrimp in metallized polyester package (84 µ) under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	TMA (mg N/100 g)	TVBN (mg N/100 g)	TBARS (MDA/kg)	FFA (mg/g)	PV (meq/kg lipid)	Sensory score	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	16.5±1.24	0.551±0.12	2.39±0.24	24.67±0.16	16.95±2.14	11.93±1.69	2.6 × 10^4	8.23±0.25	21.49±0.31	0.75±0.40	2.93±0.13	15.48±0.24	8.75±0.21	59.5±0.1	16.14±0.14	1.72±0.23	6.92±0.33
1	17.25±1.2	0.57±0.10	2.33±0.13	26.12±0.20	18.10±1.52	13.12±1.10	4.20× 10^4	8.52±0.21	22.96±0.10	0.77±0.12	3.10±0.21	15.69±0.20	8.42±0.20	59.12±0.10	15.92±0.30	1.63±0.21	6.72±0.10
2	18.56±1.5	0.585±0.20	2.31±0.22	27.12±0.34	19.21±1.20	13.69±1.23	7.420 × 10^4	8.94±0.10	24.56±0.72	0.83±0.31	3.24±0.12	15.81±0.10	8.10±0.12	58.23.±0.14	15.64±0.10	1.45±0.20	6.23±0.12
3	19.24±1.22	0.592±0.12	2.1±0.20	29.59±0.10	21.12±2.12	13.98±1.20	9.2 × 10^4	9.7±0.20	26.62±0.31	0.90±0.10	3.36±0.30	16.20±0.12	7.9±0.10	57.56±0.20	15.23±0.20	1.32±0.12	6.15±0.10
4	20.12±1.30	**0.62±0.30**	1.82±0.12	31.41±0.20	24.62±1.30	14.26±1.20	**2.30× 10^5**	11.12±0.40	29.42±0.13	1.12±0.15	3.61±0.10	17.94±0.13	7.3±0.21	57.13±0.20	15.20±0.10	1.20±0.15	6.10±0.20

Note: Means that do not share a letter are significantly different

The limiting factors in the storage were the bitter taste during storage which was probably due to rancidity and the critical factor taken was the increase in total plate count. Omodara (2015) also reported that protein and moisture contents varied between 62.8% and 71.90% and 8.80 and 10.50% during the storage of catfish in polyethylene-paper-polyethylene packages. Plahar *et al*., (1991) also proved that storage under polyethylene was unsatisfactory leading to storage life of one month due to high humidity retention favouring microbial reactions leading to high degree of lipolytic and proteolytic reactions. Taib and Ng (2011) reported a shift towards red and yellow for microwave dried fish.

The shelf life of dried anchovies packed in LDPE stored at 27–30 ˚C and RH of 80–90% is limited to 12 weeks. However, the shelf life is extended up to 32 weeks in the plain polyester polythene laminate at the same storage conditions (Gopal *et al*., 1998). Water activity provided the extend of microbial growth, oxidation of lipids, enzymatic and non-enzymatic activities that is directly correlated to the deterioration of quality (Rahman and Labuza, 2007; Belessiotis and Delyannis, 2011). Pathogenic bacteria cannot grow when the water activity is below 0.85–0.86 (Rahman and Labuza, 2007); however, yeasts and molds cannot tolerate water activity less than 0.62. the intensity of Maillard reaction occurring in the fish muscle during drying is maximum when water activity is in range of 0.65 – 0.70 (Labuza and Saltmarch, 1981).

The external reflection of the micro and macro structure of foods are expressed in terms of its texture (Aguilera and Stanley, 1999). Textural changes are attributed to the moisture loss and changes in biochemical and proximate constituents. Textural changes in shrimp muscles are a reflection of the changes in drying temperature, air velocity and relative humidity during drying. The firmness of air-dried squid increased with drying temperatures due to changes in the protein matrix (Vega-Galvez *et al*., 2011). When drying rates are higher the dried fish products tends to have a crust on surface that increases the firmness whereas lower drying rates resulted in uniform products (Brennan, 1994). Tapaneyasin *et al*. (2005) reported that shear force for shrimp dried at 120 ^{0}C was more than that for shrimp dried at 70 ^{0}C.

Gopal and Shankar (2011) reported that shelf life of dried anchovies packed in LDPE and plain polyester polyethylene laminate at 27 – 30 ^{0}C, RH = 80 – 90% exhibited a shelf life of 32 weeks. Sarkardei and Howell (2007) reported that the peroxide value of horse mackerel increased gradually up to 3 weeks of storage which further showed sharp increase until 8 weeks of storage after which the value decreased sharply.

Sensory scores of ambient and vacuum-packed dried shrimps under both storage conditions were significant ($p<0.05$) during the storage. The acceptability of the dried shrimp decreased ($p<0.05$) during storage. There was no significant difference ($p>0.05$) for proximate values of the dried shrimp between the various treatments.

TVB-N values of vacuum and ambient stored dried shrimp stored non-significant ($p>0.05$) differences between the packaging materials. Maximum acceptability value of TVB-N was 20 mg/100 g of flesh. TMA values increased during storage, though there was no significant difference ($p>0.05$) within the packaging materials. The limiting values for TMA was 5 mg/100 g (Sikorski *et al*., 1990). However, the limit was not exceeded during the storage studies.

Free radicals that can attack the lipid molecules resulting in peroxides and a new free radical which further undergoes oxidation to form low molecular compounds responsible for off flavour and off odour in dried shrimp (Hamilton *et al*., 1997). The FFA and peroxide values increased during storage though there was no significant (p>0.05) rise within the packaging material. Similar results for dried fish products were reported by Selmi *et al* (2010).

Melondialdehyde (MDA) is an important product of secondary oxidation in shrimp and fish products and is used as a measure to determine oxidative damage in dried shrimp (Andersen *et al*., 2007). TBA values directly gives the amount of MDA synthesis and is used to quantify oxidative damage. TBA values increased during storage and were maximum at the end of storage in ambient as well as in vacuum packaging conditions. Similar results were reported by Hamre *et al.* (2003).

Gopal *et al.* (1998) conducted studies on storage of dried anchovy and reported that polyester laminated films were capable of enhancing the storage file of the dried fish to 32 weeks compared to LDPE packaging films. Free fatty acids concentration was determined to be more in LDPE pouches due to their relatively higher OTR than the laminated packaging films.

There was no significant difference (p<0.05) on the storage characteristics of microwave and solar dried shrimp as the moisture content in both cases were in the required levels (14 – 16 %). Storage life of dried shrimp under ambient conditions were 0, 3 and 2 months in LDPE, polyester polyethylene laminated films and metallized polyester packages respectively. Storage life of dried shrimp under vacuum packed conditions were 0, 5 and 3 months in LDPE, polyester polyethylene laminated films and metallized polyester packages respectively. Though the shelf life of dried shrimp and fish products is about 9 months – 12 months, it varies depending on drying process, moisture contents, packaging and salting process (Mexis *et al*, 2009). LDPE had lower tensile strength, bursting strength and tearing resistance compared to laminated films which was the reason for its poor barrier properties. A slight rancid flavour was in the samples towards the end of the storage studies. Moisture uptake was more predominant in the LDPE packaging films compared to the laminated films due to the higher WVTR of the monolayer films. Graphical abstract of drying shrimp in solar-LPG dryer is shown in Fig. 4.19 a.

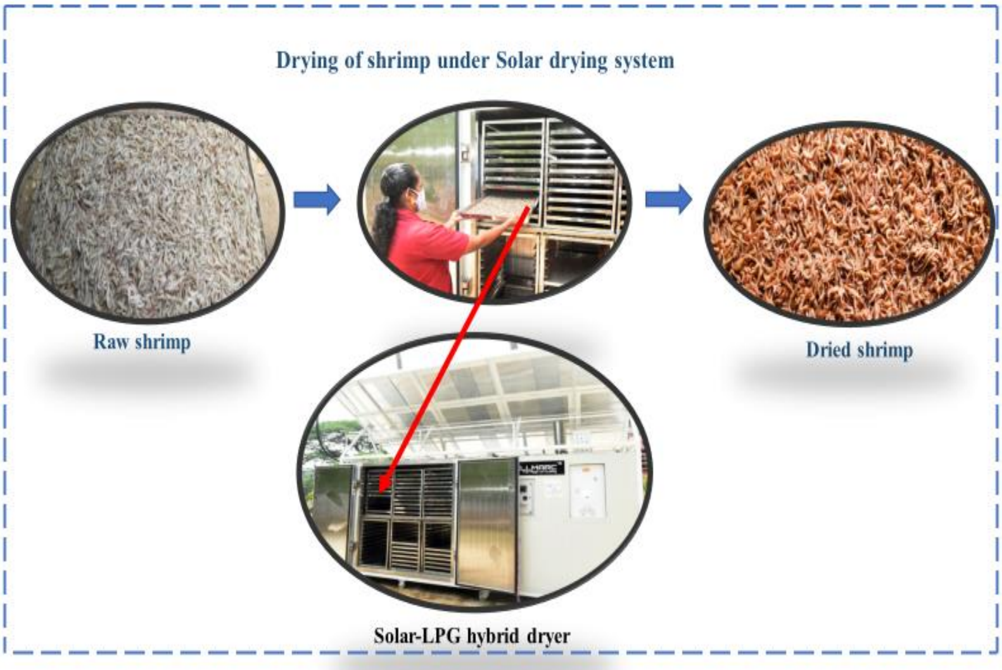


Fig. 4.19 Drying of shrimp under solar drying system

4.8 Drying studies on Oyster mushroom

Oyster mushrooms were dried under three levels of microwave power (600, 800 and 1000 W), three levels of hot air temperature (40, 50 and 60 °C) and three levels of air velocities (0.5, 1.0 and 1.5 m/s) to optimize the drying conditions based on drying time, water activity and rehydration ratio. Graphical representation of hot-air assisted microwave drying of Oyster mushroom is depicted in Fig. 4.20. The physical properties of Oyster mushroom are represented in Table 4.18.

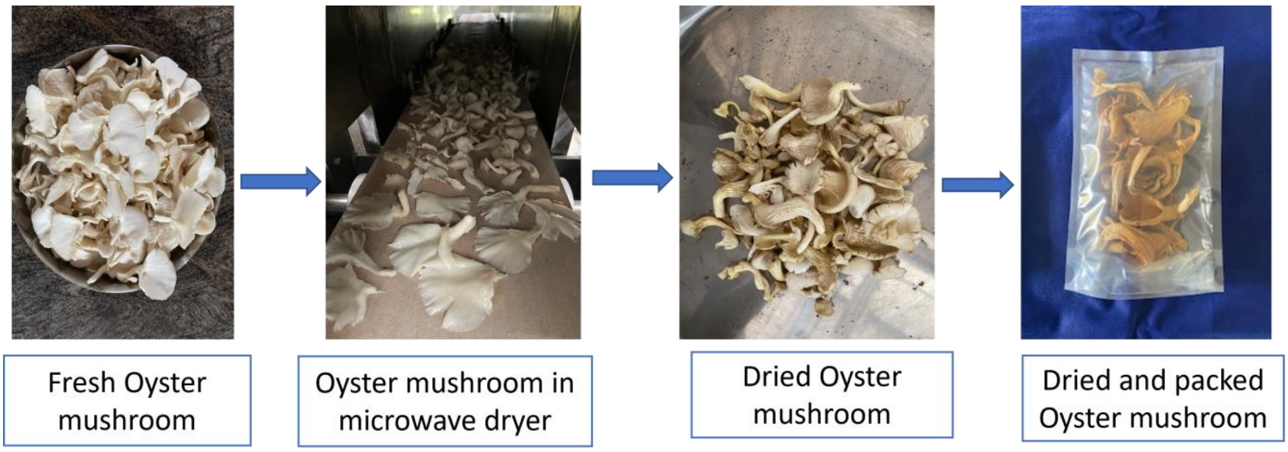


Fig. 4.20 Drying of oyster mushroom under HAMW drying system

Table 4.18 Physical properties of raw Oyster mushroom

Parameter	**Value**
Dimensions (l × b × h)	45 ± 1.5, 24 ± 1.3, and 9 ± 0.6 mm
Moisture content	92.35 ± 1.54 (% w. b.)
Colour	L = 69.23±1.24 a = 3.64 ±0.93 b = 16.13 ±1.31
Hardness	3.4 N
Bulk density	1130 ± 0.64 kg/m^3
Coefficient of friction	0.57±0.41
Thermal conductivity	0.64 ± 0.15 W/mK
Angle of repose	24.01± 0.53°
Specific heat above freezing point	2.21 kCal/kg °C

4.9 Drying experiments using RSM

The drying experiments were performed according to a second-order Box-Behnken design (BBD) with three factors at three levels: microwave power (600, 800 and 1000 W), air temperature (40, 50 and 60 °C), and air velocity (0.5, 1.0 and 1.5m/s). Drying time, water activity, and rehydration ratio was selected as the response variables. The levels were selected based on literature reviews (Li *et al*., 2021; Lombraña *et al*., 2010). A three-factor, three-level Box-Behnken design (BBD) experimental design was used in optimizing the drying conditions for shrimp in a hot air-assisted microwave (HAMW) drying system. The quadratic model for predicting the optimum solution was expressed using the following equation:

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_i \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \ldots(4.13)$$

Where, Y is the response, Xi and Xj are variables (I and j range from 1 to k), 0 is the model intercept coefficient; j, jj and ij are interaction coefficients of linear, quadratic and second-order terms, respectively, k is the number of independent parameters (k=3) and e_i is the error. A lack of fit test was used to evaluate the appropriateness of the selected model.

The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 centre points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 9.0.0 trial version (Stat Ease Inc., Minneapolis, MN, USA) was used to perform statistical analysis. Analysis of variance (ANOVA) was carried out to check the significance of the model and process variables. The experimental runs were carried out as per the design details provided in Table 4.21. Microwave power levels were adjusted from the control panel of the microwave generator. The air temperature inside the drying chamber was measured using a digital temperature indicator. The air velocity was measured using a vane anemometer. Drying experiments were conducted till the moisture content of 8 – 10 % (w.b.) (Arumuganathan *et al*., 2010) is reached. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28±2°C). The weight loss of the mushroom was measured every 30 minutes of the drying operation.

4.9.1 Model fitting

Response surface methodology was used to optimize the process conditions of oyster mushroom in a hot air-assisted continuous microwave dryer. Drying time varied for oyster mushroom under hot air-assisted microwave conditions varied from 5 to 7.5 h, water activity from 0.504 to 0.572 and rehydration ratio from 2.21 to 2.51 The actual measured values were fitted into various regression models to select the appropriate model. ANOVA was done to test the lack of fit and to determine the significance of the selected model and its coefficients (Table: 4.21 – 4.23). Results showed that the model selected for responses was significant. This means that the selected model is appropriate to represent the relationship between responses and factors. To evaluate the model adequacy, R^2, Adj $R^{2,}$ and coefficient of variation (CV) values were calculated. The coefficient of variation (%) for drying time, water activity and rehydration ratio were 0.9342, 0.8961 and 0.9236 respectively. A very low p-value (<0.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequate precision values of all responses are above 4.0 which indicates the existence of adequate model difference. Also, a low PRESS value for responses indicates model suitability. The desirability function was applied to obtain the optimized values for each dependent variable.

The values of R^2, Adj R^2 and coefficient of variation (CV) values were determined to evaluate the adequacy of the selected model. The R^2 is the measure of the degree of fit and was obtained as 0.9342, 0.8961 and 0.9236 for drying time, water activity and rehydration ratio respectively and the corresponding adjusted R^2 values were 0.8453, 0.8321 and 0.9690 respectively. A very low value of the coefficient of variation (3.14, 2.62 and 1.24) indicated greater reliability of the experimental data. Therefore, a very low p-value (<0.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequacy precision values of all responses are above 4.0 which indicates the existence of adequate model difference. The model suitability is also indicated by a low PRESS value for response.

4.9.2 Effect of process parameters on drying time

The response surface methodology plots showing the interactions between air temperature, microwave power, and air velocity on drying time are shown in Fig. 4.21 (a, b, c). It is evident from the figure that drying time decreased with an increase in air temperature (40 to 60°C) and microwave power (600 to 1000W). Synergistic effects of air temperature and microwave power led to a reduction in drying times due to the volumetric heating effects of microwaves supplemented by increased temperature gradient created by hot air. However, the increase in air velocity and temperature reduced the drying times to a certain limit, beyond which air velocity increased the drying times at all temperatures (40-60°C) due to the lesser temperature gradient on the product. Moreover, at the highest microwave power (1000 W) with the intermediate air velocity (1 m/s) lowest drying time of shrimp can be obtained. Similar trends were seen in the interaction reported by Han *et al*. (2010) for microwave drying of apple slices.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

$$Drying\ time = +3.50 - 0.25 * A - 1.25 * B + 0.12 * C + 0.56 * A^2 + 0.31 * B^2 + 0.56 * C^2 - 0.38 * A * B - 0.12 * A * C - 0.13 * B * C \quad \ldots(4.14)$$

Where, A, B and C denotes air temperature, microwave power and air velocity respectively.

4.9.3 Effect of process parameters on water activity

Water activity of HAMW dried mushrooms ranged from 0.504 to 0.572 under various drying conditions of inlet air temperature, microwave power and air velocity. The effect of air temperature, microwave power, and air velocity on the water activity of the dried product is shown in Fig. 4.22 (a, b, and c) as air velocity increased (0.5 – 1.5 m/s), water activity decreased to a certain limit, further which it increased. As the water activity of the product is directly related to its moisture content, an increase in moisture content has enha nced the water activity of the products. An increase in microwave power and air temperature reduced the water activity due to increased drying rates. The water activity of the samples decreased significantly with increased temperature, probably due to the lower moisture content of samples at higher temperatures. At higher temperatures, food structure becomes more porous which accelerates the loss of water. Also, proteins become denatured due to higher temperature thereby losing their water binding capacity leading to more removal of water and reducing the water activity (Azizpour *et al*., 2016). However, with both thicknesses, aw dramatically decreased with an increase in temperature. Most enzymes and bacteria will be inactive when the food system has water activity below 0.80. To some extent increase in air velocity, enhances the drying rate, and further reduces the drying rate due to evaporative cooling on the surface of the product (Kilic, 2009). The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

$$Water\ activity = +0.54 + 3.250E - 0.30 * A - 0.48 * B + 4.750\,E - 0.13 * C - 1.950E - 003 * A^2 + 0.015 * B^2 + 8.050E - 003 * C^2 - 2.500E - 0.15 * A * B + 0.024 * A * C + 9.000E - 0.103 * B * C$$

…4(15)

Where, A, B and C denote air temperature, microwave power and air velocity respectively.

4.9.4 Effect of process parameters on rehydration ratio

Rehydration ratio of HAMW dried mushrooms were in range of 2.21 – 2.51 under various drying conditions of inlet air temperature, microwave power and air velocity. Giri and Prasad (2007) also reported rehydration ratios in range of 2.3 – 3.4 for microwave dried mushrooms. Further the results were in line with the studies of Durance and Wang (2002). However, rehydration ratio is an important factor indicating the efficiency of the drying process as the rate of rehydration is will be less when the cells and tissues are collapsed or irreversibly damaged (Bozkir *et al*., 2019). Air temperature, microwave power, and air velocity had a significant effect on the rehydration ratio ($p \leq 0.01$) (Fig. 4.23: a,b,c). The regression coefficient is positive and maximum for microwave power levels, which indicates better rehydration properties of dried mushroom dried at high microwave power levels. This can be attributed to the high internal pressure development at higher microwave power levels. Higher microwave power causes more internal heating that creates a flux of rapidly escaping water vapor, which opens up the pores. This in turn prevents shrinkage and gives better rehydration properties (Giri and Prasad, 2007). Duan *et al*. (2011) reported that the rehydration ratio increased with increasing the duration of microwave drying at constant microwave power and also that the rehydration ratio increased with an increase in microwave power at constant time. Qin *et al*. (2020) observed that microwave combined with hot-air drying could reduce the irreversible structural damage in drying grass carp fillets and further, the rehydration rate increased along with microwave drying time.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results,

$$\text{Rehydration ratio} = +2.52 - 0.01 * A + 0.080 * B + 0.055 * C - 0.087 * A^2 - 0.1 * B^2 - 0.062 * C^2 - 2.500E - 0.012 * A * B - 0.018 * A * C - 0.033 * B * C$$

…(4.16)

Where, A, B and C denotes air temperature, microwave power and air velocity, respectively.

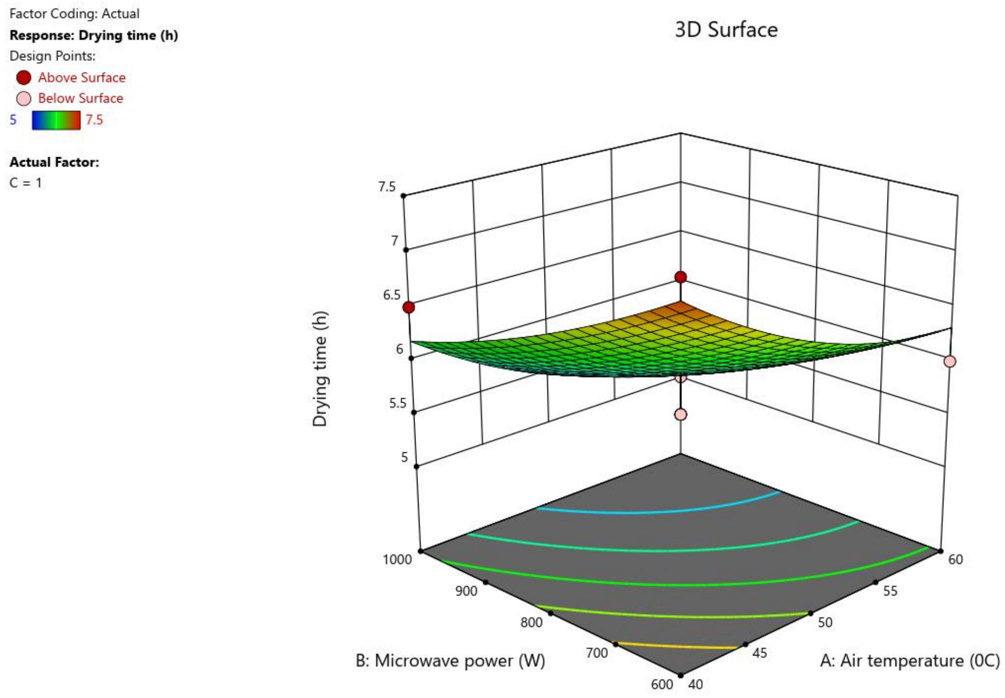
4.9.5 Determination of optimized conditions

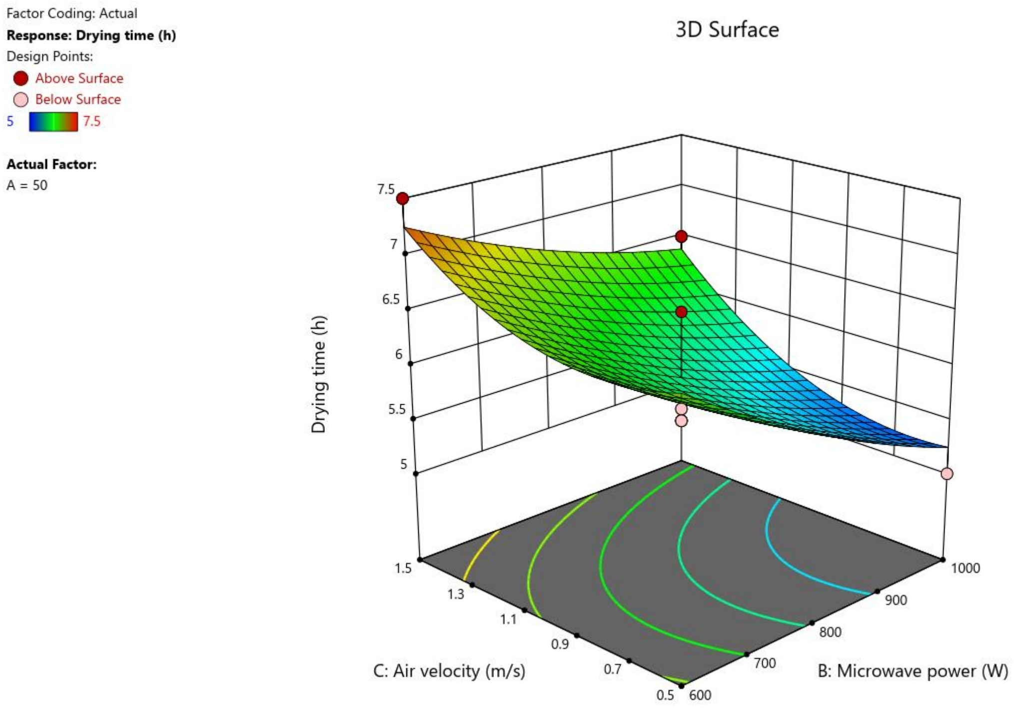
The optimization of drying process parameters was done based on Derringer's desirability function. Microwave power (600 – 1000 W), air temperature (40–60 °C) and air velocity (0.5–1.5m/s) were set within the range with minimization of drying time and water activity and maximization of rehydration ratio. Based on the value of maximum desirability (0 to 1), optimum conditions were selected. The plots of predicted versus obtained values of responses drying time, water activity and rehydration ratio is shown in Fig. 4.24, 4.25 and 4.26, respectively. The ANOVA for the process variables on drying time are shown in Appendix A-4 to A-6. The methodology of desired function was applied to indicate 55.05 ℃ air temperature, 1000 W microwave power and 0.81 m/s air velocity which indicated the drying time, water activity and rehydration ratio of 5.05 h and 0.532 and 2.49, respectively with a desirability value of 0.830 (Fig. 4.28).

Table 4.19 Drying time, water activity and rehydration ratio under various conditions of oyster mushroom drying

Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3
A: Air temperature ^0C	B: Microwave power W	C: Air velocity m/s	Drying time h	Water activity	Rehydration ratio
60	800	1.5	6.5	0.564	2.28
50	1000	0.5	5	0.557	2.47
40	600	1	7.5	0.549	2.45
40	800	0.5	6.5	0.551	2.39
50	800	1	6.5	0.544	2.31
50	600	0.5	6.5	0.542	2.34
50	800	1	6.5	0.51	2.46
60	600	1	6	0.572	2.21
40	1000	1	6.5	0.534	2.45
50	1000	1.5	6.5	0.562	2.32
40	800	1.5	7	0.541	2.41
60	800	0.5	6	0.571	2.3
50	600	1.5	7.5	0.535	2.23
60	1000	1	5	0.545	2.43
50	800	1	5.5	0.504	2.51
50	800	1	5.5	0.534	2.49
50	800	1	5.5	0.521	2.51

Note: Figures in the parenthesis signify the coded values





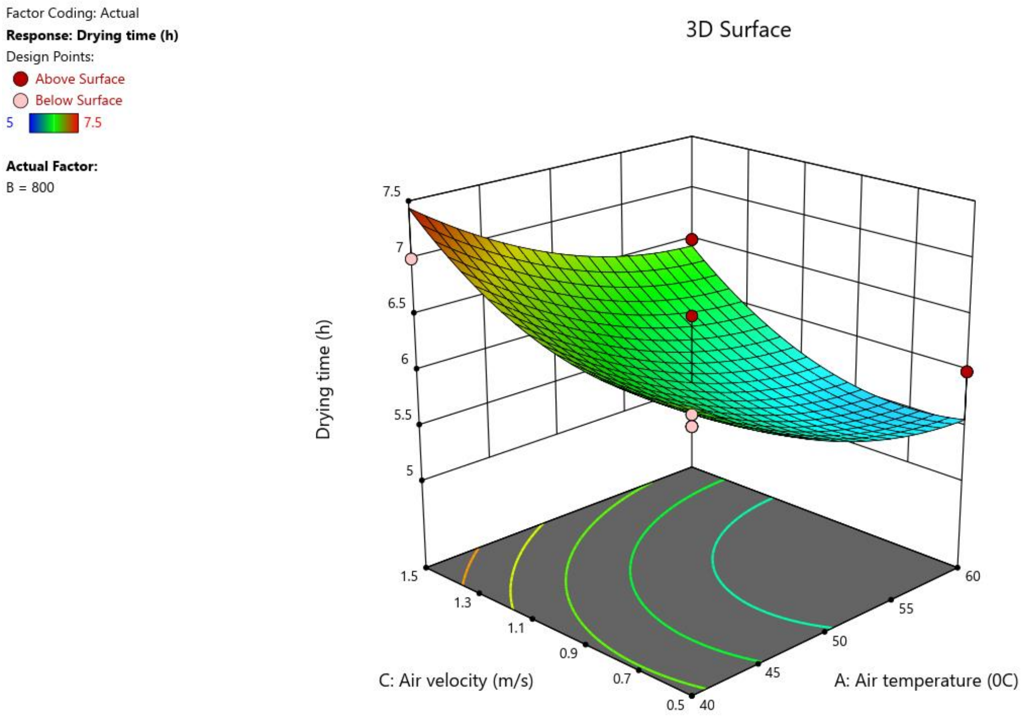
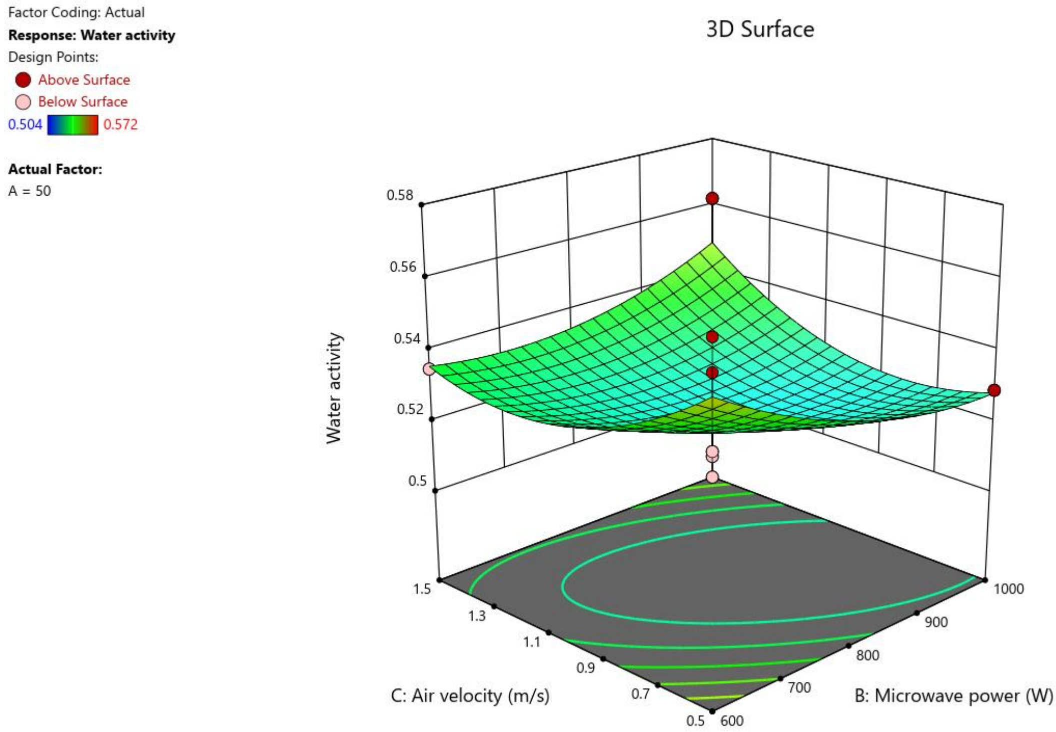
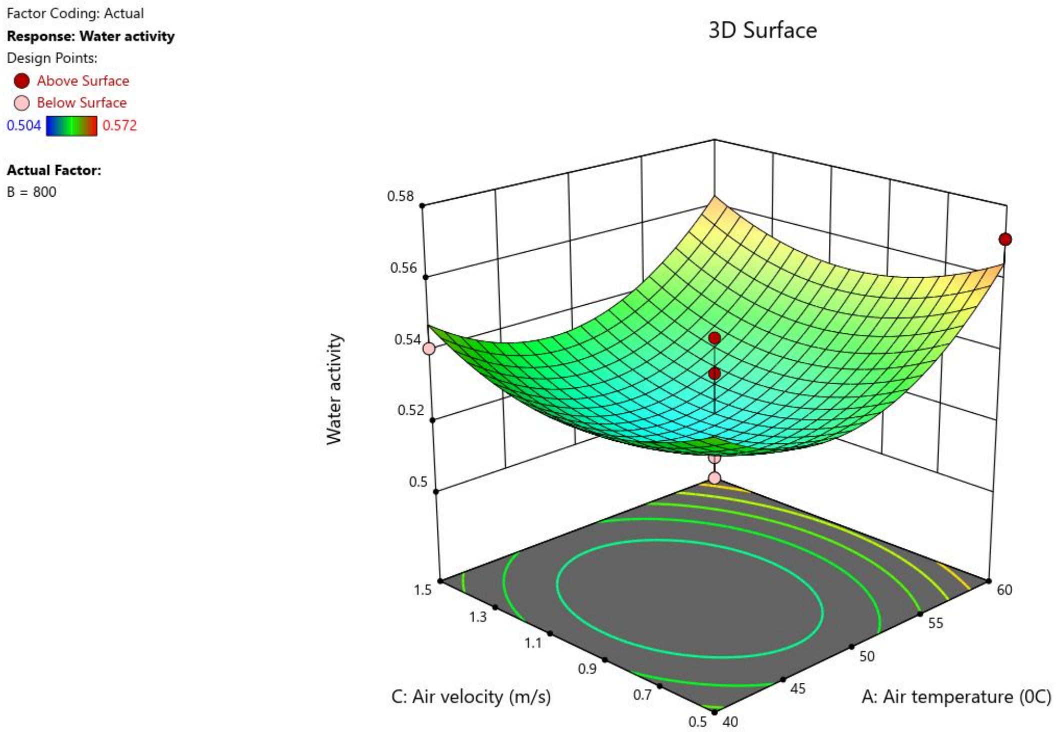


Fig. 4.21 Effect of process parameters on drying time of Oyster mushroom


Factor Coding: Actual
Response: Water activity
Design Points:
Above Surface
Below Surface
0.504
0.572
Actual Factor:
A = 50
3D Surface
Water activity
0.58
0.56
0.54
0.52
0.5
C: Air velocity (m/s)
1.5
1.3
1.1
0.9
0.7
0.5
B: Microwave power (W)
600
700
800
900
1000


Factor Coding: Actual
Response: Water activity
Design Points:
Above Surface
Below Surface
0.504
0.572
Actual Factor:
B = 800
3D Surface
Water activity
0.58
0.56
0.54
0.52
0.5
C: Air velocity (m/s)
1.5
1.3
1.1
0.9
0.7
0.5
A: Air temperature (0C)
40
45
50
55
60

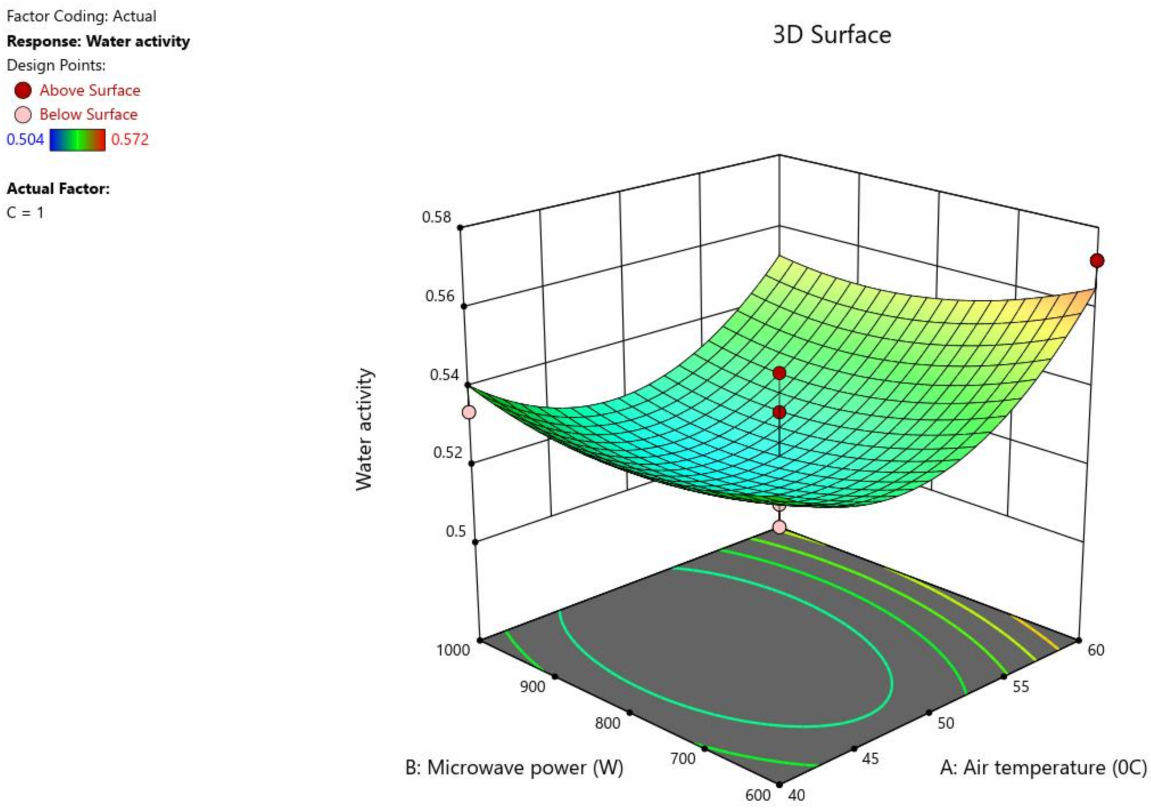
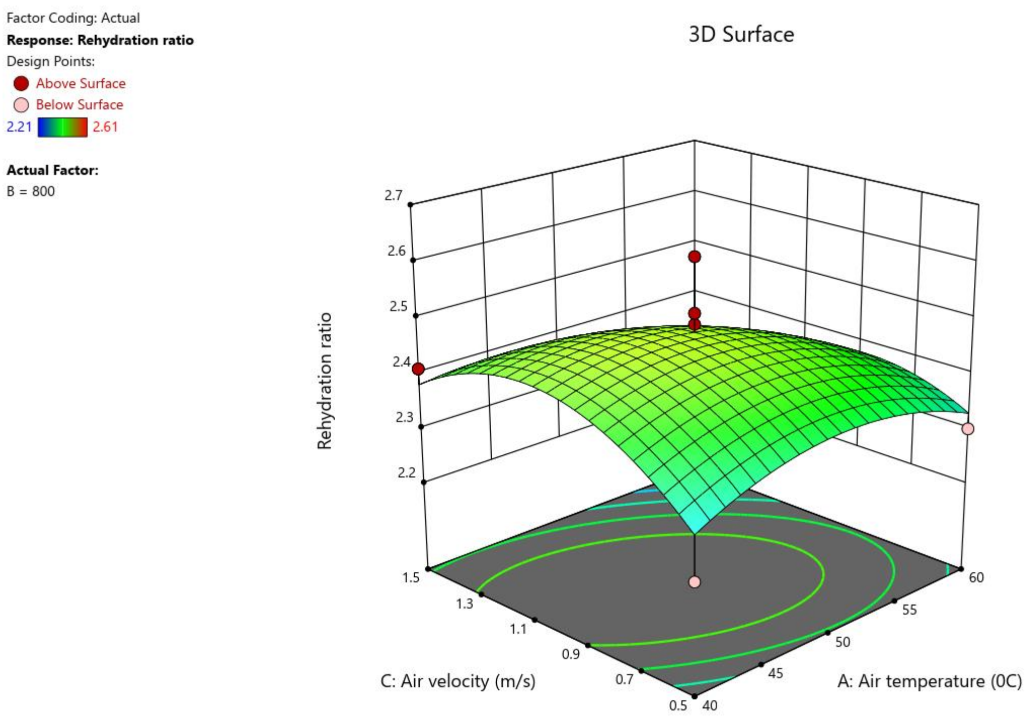
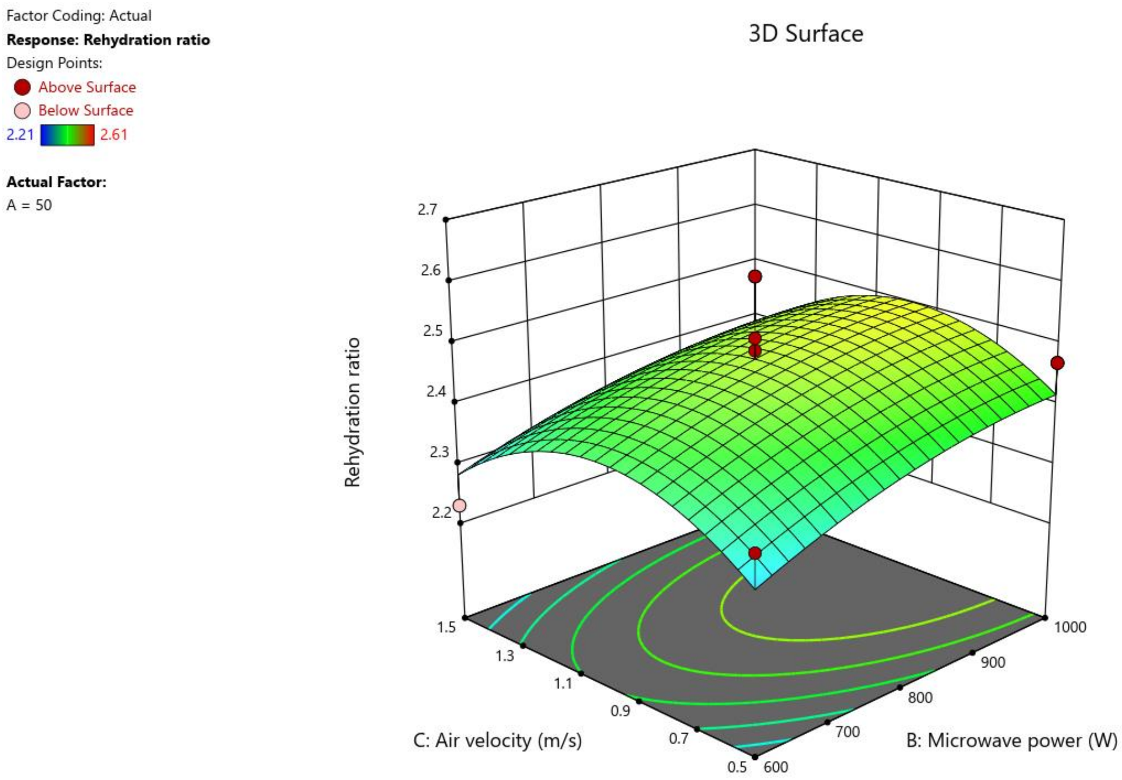


Fig. 4.22 Effect of process parameters on water activity of Oyster mushroom





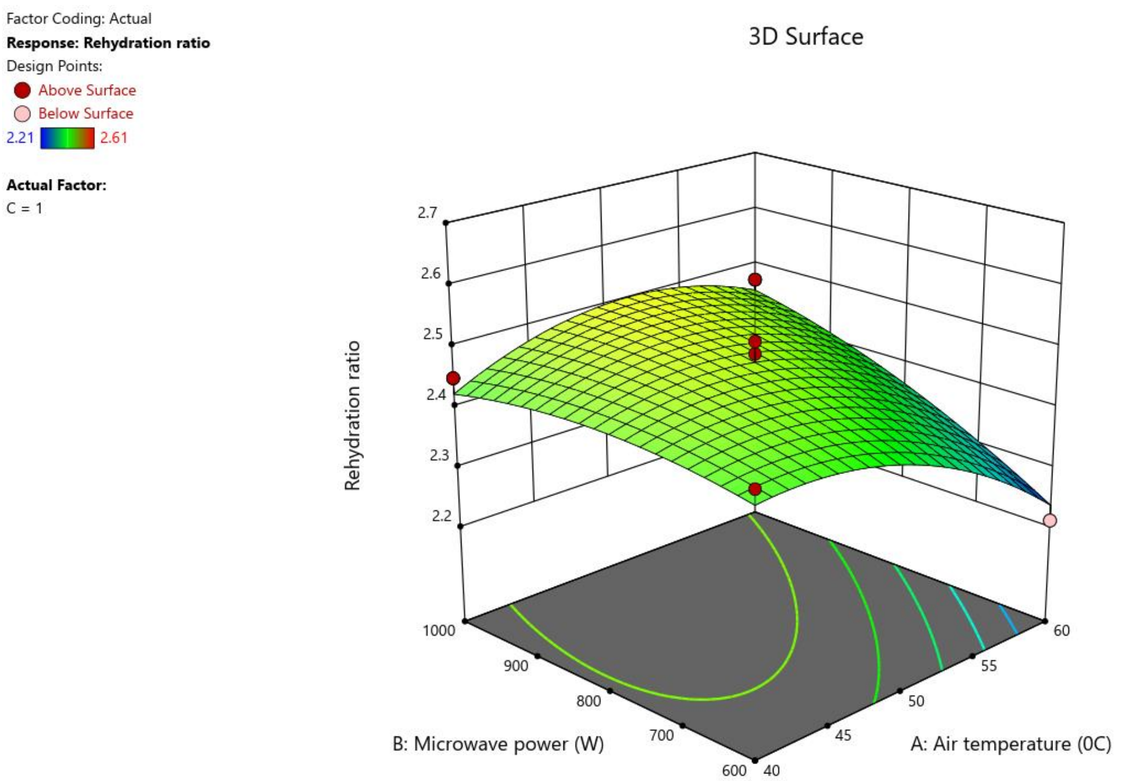


Fig. 4.23 Effect of process parameters on rehydration ratio of Oyster mushroom mushroom

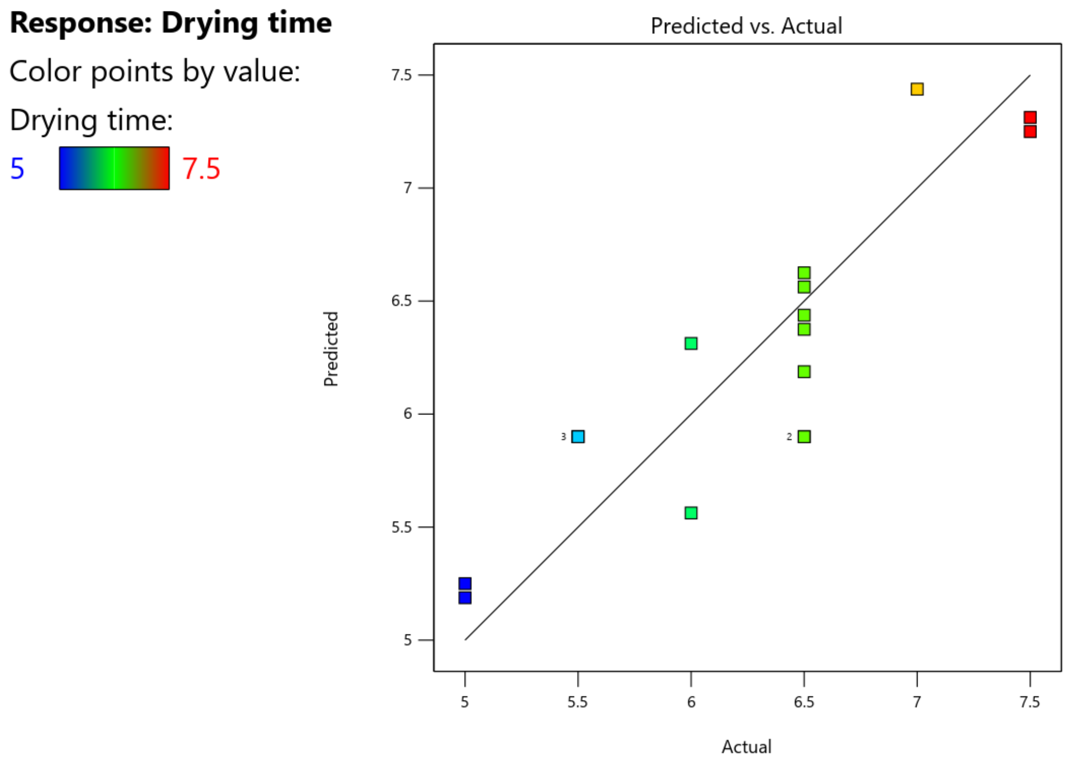


Fig. 4.24 Predicted Vs actual values of response: Drying time (Oyster mushroom)

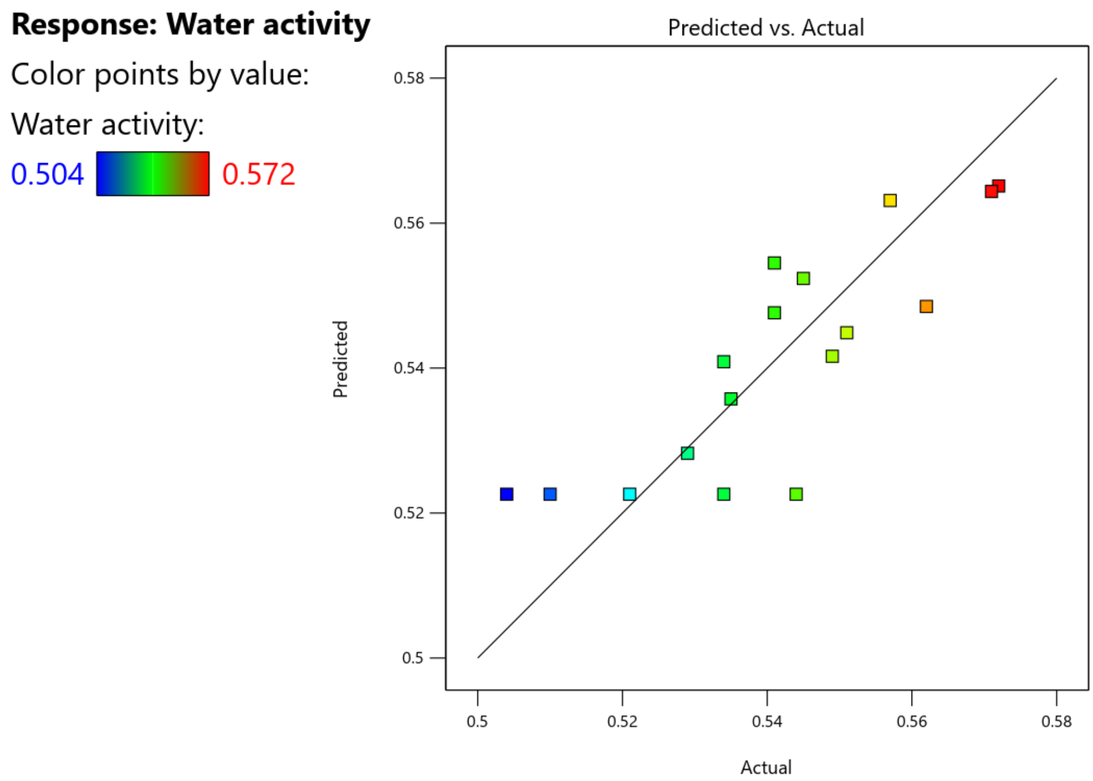


Fig. 4.25 Predicted Vs Actual values pf response: Water activity (Oyster mushroom)

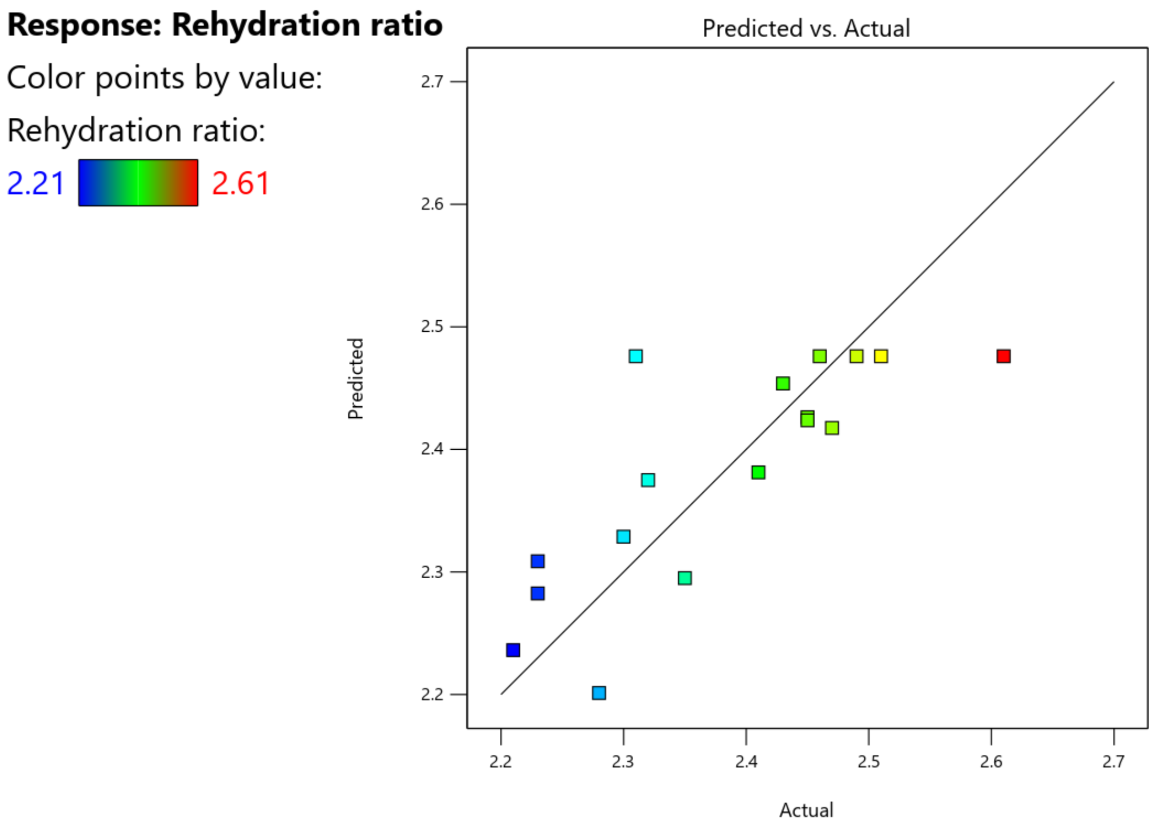


Fig. 4.26 Predicted Vs Actual values of response: Rehydration ratio (Oyster mushroom)

4.9.6 Confirmation of results

4.9.6.1 Error percentage

The predicted values of response variables under optimized conditions were confirmed by performing experiments under optimized conditions under three replications. Desirability ramps for hot air assisted microwave drying of oyster mushroom is depicted in Fig. 4.27. The average of the values of response variables were used to determine the error percentage. The error percentage obtained for drying time, water activity and rehydration ratio were 1.17%, 0.564% and 0.0.80% respectively, which further confirmed the acceptability of the selected model under RSM (Table 4.20).

Table 4.20 Confirmation of RSM results for oyster mushroom

Responses	Predicted value	Experimental value	Error percentage
Drying time	5.09	5.00	1.76%
Water activity	0.532	0.529	0.564 %
Rehydration ratio	2.49	2.47	0.80 %

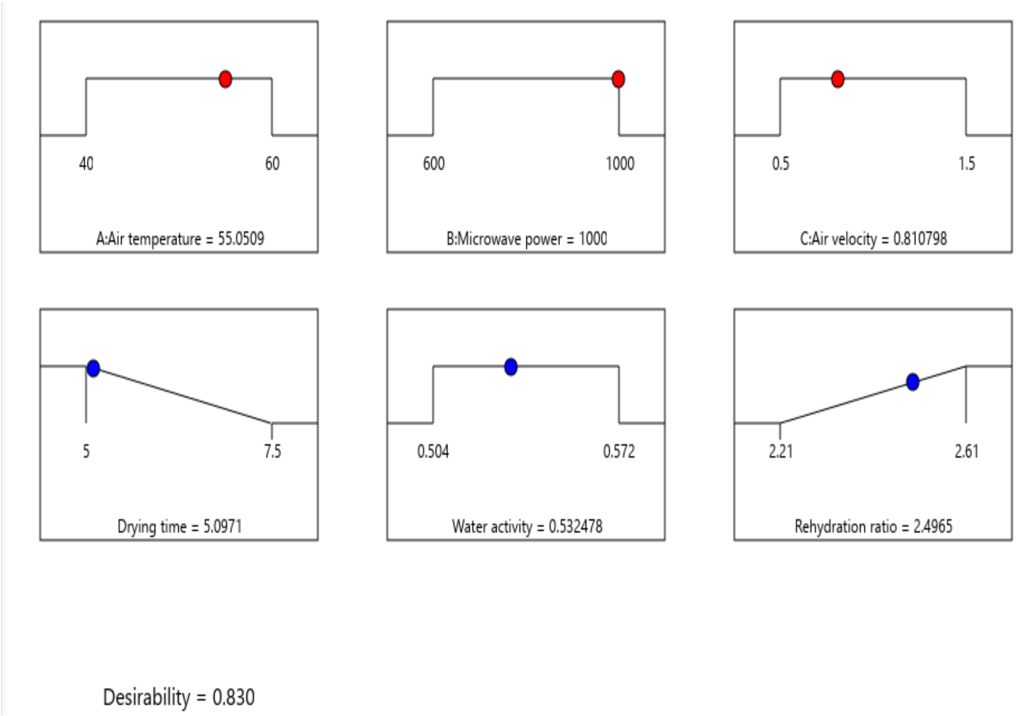


Fig. 4.27 Desirability ramp for process optimization of oyster mushroom drying

4.10 Quality evaluation of dried oyster mushrooms

The dried oyster mushroom under optimized conditions were evaluated for moisture content, effective moisture diffusivity, colour, texture, shrinkage, total plate count, biochemical, proximate and scanning electron microscopy analysis. Thin layer model fitting was done to find out the best fit drying model to predict the drying times.

4.10.1 Drying rate and moisture content during drying of oyster mushroom

Initial moisture content of the oyster mushroom was 92.35±1.24 (% w. b.) by gravimetric method (AOAC 1990). The variation in moisture content and drying rate of oyster mushroom with respect to drying time is shown in Fig. 4.28. It is evident that moisture content decreased from 92.35 to 8.42% within 5 h of drying. Volumetric heating effect of microwaves can be attributed for the reduction in drying time. Microwave heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Das and Arora (2018) studied the drying characteristics of mushroom using microwaves and hot air and stopped the drying when moisture content attained 10-12 % dry basis. Omari *et al*., 2018 reported that increased air temperature reduces surface mass transfer resistance and moisture content is released more quickly. Moisture content of 9.2% (db) was achieved in the studies carried out by Walde *et al.* (2006) in evaluating the effects of various pretreatments on quality of dried mushroom. Lower drying times is also related to higher drying rates of oyster mushrooms under HAMW treatment. Drying rate exhibited maximum value of 3.47 during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation. Dipole rotation arises owing to the presence of water molecules in the sample that tends to change the polarity depending on the rapidly changing electromagnetic field induced by the magnetron. As the moisture content reduces, the magnitude of dipole rotation also reduces and thereby lowering the drying rate. As moisture removal rate is less towards the end, drying occurred under falling rate period. Olatunde *et al.* (2017) concluded that higher core temperature of materials together with the consistent direction of heat transfer and moisture diffusion enhanced the drying rate in microwave drying. Nour *et. al.* (2011) declared that, the moisture content of the fresh button mushrooms (both untreated and treated samples) was found in range of 90-91% which reduced to 9-12 % after tray drying for various temperatures of air drying. Also, Tulek (2011) found that, the final moisture content of dried *P.ostreatus* was 10%.

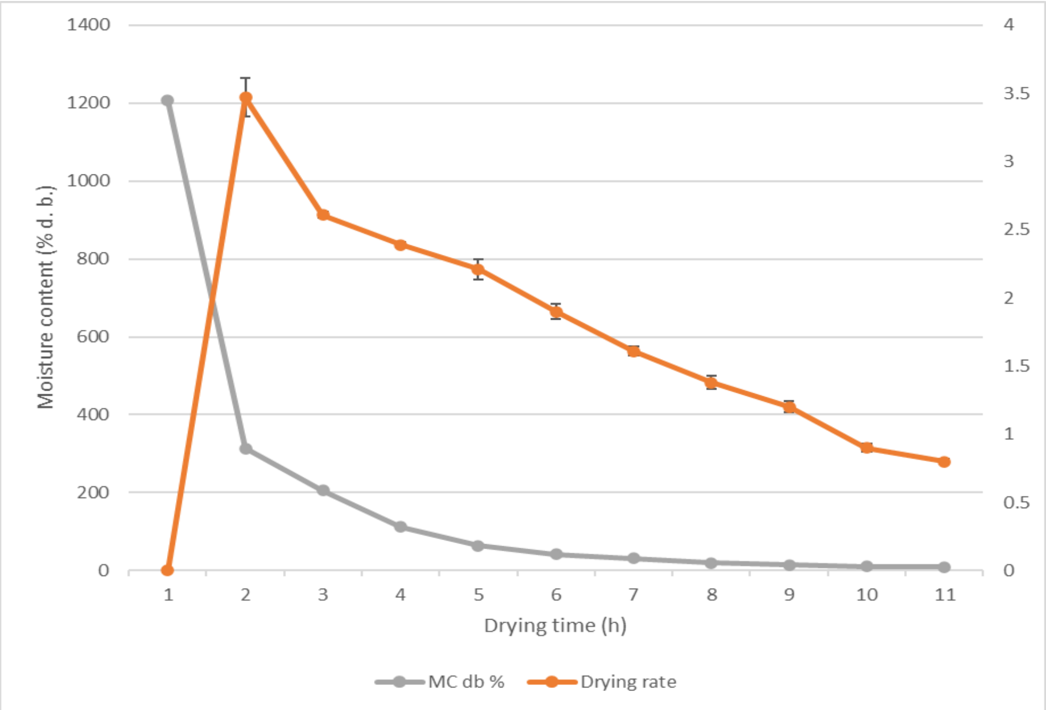


Fig. 4.28 Variation in drying rate and moisture content during HAMW drying of Oyster mushroom

4.10.2 Effective moisture diffusivity

The plot of ln (MR) against time gave the slope value to determine the diffusivity (Fig. 4.29). Effective moisture diffusivity during drying of HAMW of oyster mushroom was determined to be 2.9 x 10 $^{-7}$ m^2/s. Effective moisture diffusivity was estimated from the experimental data based on Fick's law of diffusion. This parameter represented the intrinsic mechanism by which moisture transport was facilitated by means of liquid diffusion, vapor diffusion, hydrodynamic flow and other means. The volumetric heating effect of microwaves resulted in higher drying rates and decreased drying times due to higher moisture diffusivity. Thus, moisture diffusivity served as the quantitative parameter at molecular level for explaining drying kinetics. Walde *et al*. (2006) reported that the effective moisture diffusivity of oyster mushrooms was maximum (2.9 x 10^{-6} m^2/s) for microwave dried samples when compared to cabinet dried mushrooms (0.3225 x 10^{-6} m^2/s). Microwave drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s and 4.63×10^{-6} m^2/s under varying operating conditions (Celen, 2019). Arumuganathan *et al*. (2008) studied on drying of milky mushrooms in fluidised bed dryer and found that the effective moisture diffusivity increased as the drying air temperature increased. The moisture diffusivity in milky mushroom increased from1.55 - 4.02 x 10^{-9} m^2s^{-1} during the initial stage of drying, and from 8.76 -16.5 x 10^{-9} m^2s^{-1} during the later stage of drying.

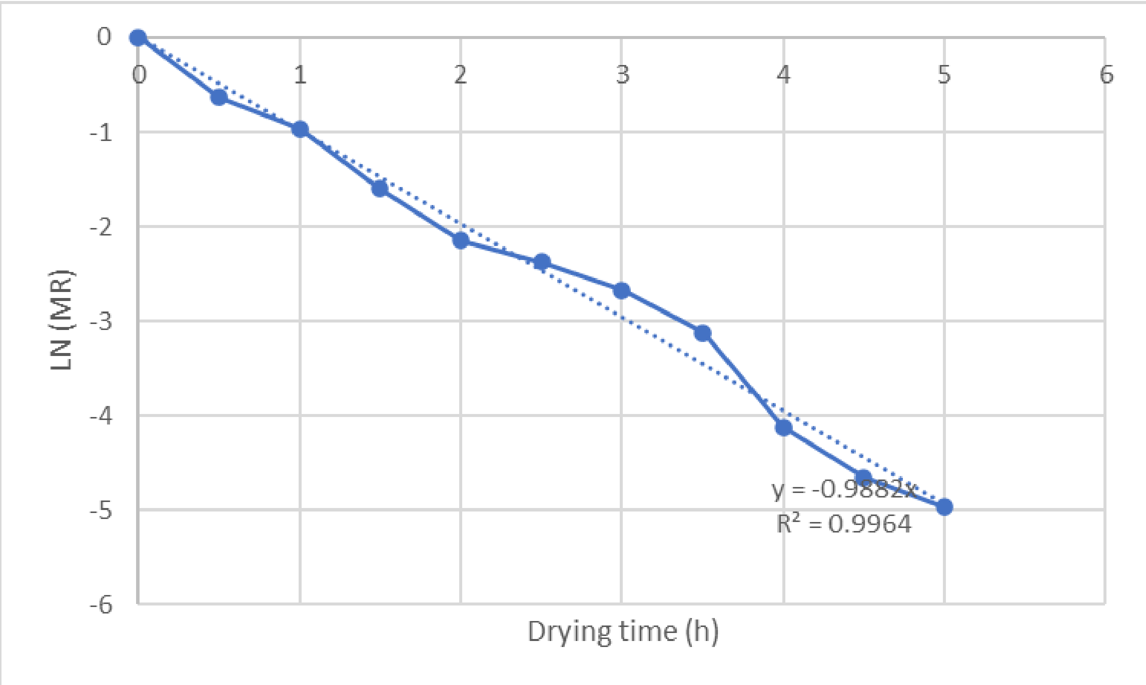


Fig. 4.29 Dying time versus LN (MR) for microwave drying of oyster mushroom

4.10.3 Evaluation of drying models

HAMW of oyster mushrooms was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying were fitted into thin layer drying models by non-linear regression analysis (Table 4.21). Logarithmic model was identified as the best fit model with higher R^2 value of 0.9967, lower $\chi 2$ value of 0.000405 and RMSE value of 0.01938. To verify the acceptability of the selected Logarithmic model, observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9958 which implies that the selected model satisfactorily described the drying behaviour of oyster mushrooms under the HAMW dryer (Fig. 4.30). Wang and Sing model explained the drying process of milky mushrooms in fluidised bed dryer. Bingol *et al*. (2008) studied on microwave drying of grapes and found that Midilli model best explained the drying of grapes under microwave convective drying. Based on evaluation by statistical tests, Isik and Izlin (2014) concluded that the Midilli *et al*. model, the diffusion approach model, Logarithmic model, and Wang and Singh model were found to be the best-fitting models to describe the drying behaviour of the mushroom samples. Wang *et al*. (2007) studied on microwave drying of apple pomace and the results indicated that the Page model was most adequate in predicting moisture transfer for fresh and pre-dried apple pomace where a falling rate period was observed in the microwave drying processes.

Table 4.21 Modelling of drying data for HAMW drying of oyster mushroom

S. No.	Model name and reference	R^2	RMSE	Reduced $\chi 2$	Constants
1	Modified page (Karacabey and Buzurul, 2017)	0.9051	0.09507	0.0005537	k = 0.6393 n = 0.6869
2	Henderson and Pabis (Arslan et al., 2010)	0.9715	0.05211	0.000466	a = 1.295 k = 0.5876
3	**Logarithmic (Moradi et al., 2020)**	**0.9967**	**0.01938**	**0.000405**	**a =1.362** **c = -0.1624** **k= 0.9494**
4	Two-term exponential (Togrul and Pehlivan, 2004)	0.9616	0.0471	0.000567	a = 43.49 b= -42.21 k1 = 0.4058 K2 = 0.4017
5	Wang and Singh (Wang et al., 2005)	0.9248	0.02244	0.001144	a = -0.3906 b = 0.04663
6	Verma et al (Yaldys and Ertekýn, 2001)	0.9051	0.1041	0.000478	a = -0.007179 b = 0.3826 g = 0.4387

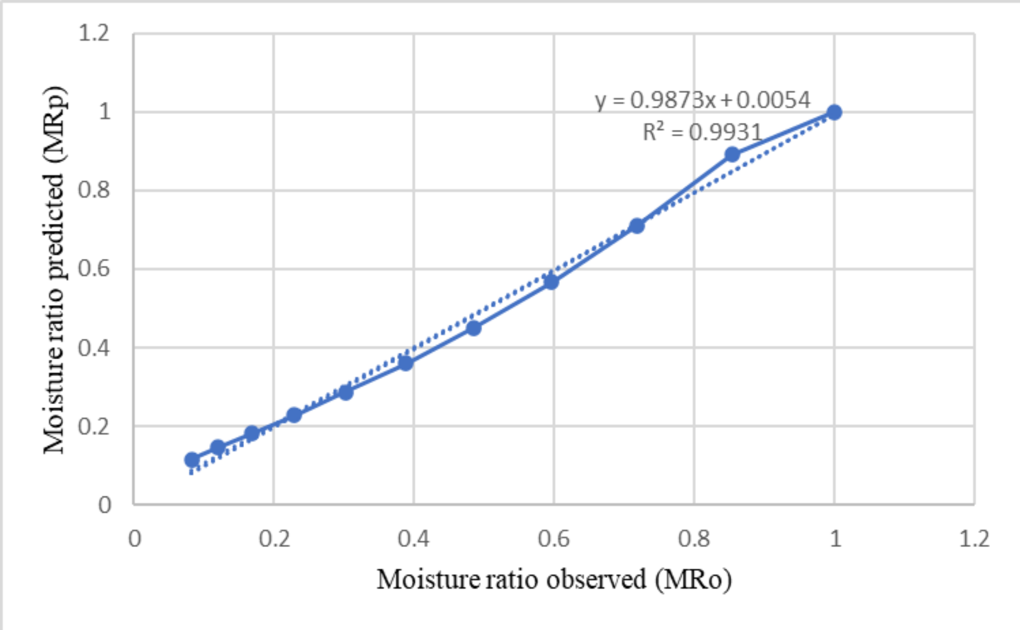


Fig. 4.30 Best fit Logarithmic model for HAMW of Oyster mushroom

4.10.4 Drying efficiency

Drying efficiency of the dryer under HAMW mode was observed to be 23.12%. This was a result of volumetric hearing effect of microwave radiation combined with convective effect of hot air. Hassan (2016) published that since microwaves acts only on polar molecules, microwave drying efficiency decreased with time and increased with moisture content of sample during studies on microwave drying of date. Maximum drying efficiency of 32% was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein *et al.* (2013) observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W respectively during drying of apple slices in laboratory scale MW dryer. An *et al.* (2022) published that energy consumption of MWD depends on a variety of factors such as equipment structure, drying conditions (microwave power, frequency, temperature, and air velocity), material properties, and combined/hybrid drying technologies. The drying system can be effectively improved if these parameters are adjusted appropriately and taking the processing cost into consideration. Soysal *et al.* (2007) reported microwave drying efficiency of 32% for drying of parsley at power levels of 900 W.

4.10.5 Specific energy consumption

The SEC value for HAMW of oyster mushroom was found to be 2.71 kWh/kg. Sharma and Prasad (2006) reported SEC of 26.32 MJ/kg for drying of garlic under MW power of 40 W and HA temperature of 70 ^{0}C. MW and convective drying of pomegranate arils were calculated to have SEC of 35.42 kWh/kg and 145.12 kWh/kg (Kaveh *et al*., 2021). It is understood that as moisture content decreases the energy requirement and specific energy consumption increases due to difficulties in removing water other than free and unbound moisture in the product. But the volumetric heating effect of microwaves in the study tended to fasten the drying process leading to higher drying rates and subsequently lower SEC as compared with convective drying. As moisture content of product decreased the microwave energy absorbed by the oyster mushroom also reduced leading to higher SEC during later stages of drying. SEC in MW drying was observed to have 70% more energy savings as compared to convective drying (Sadi and Meziane., 2015).

3.6 Colour change

The L*, a* and b* colour values of fresh mushrooms were determined to be 84.12±0.46, 3.3±0.24 and 15.57±0.62 respectively. The colour values of the microwave dried mushrooms under optimized conditions were recorded as 56.15±0.25 (L*), 4.95±0.24 (a*) and 20.85±0.51 (b*) respectively. The 'L' value of the dried oyster mushroom decreased whereas the 'a' and 'b' values increased during microwave convective drying. Darker colour of oyster mushroom can be attributed to the process of Maillard browning reaction that might have occurred during drying. Soto *et al*. (2001) published that colour was a critical parameter in evaluating the quality of dried mushrooms that determines the acceptance of final product. Products with higher L* values were better preferred by consumers. Furthermore, a decrease in L* value as the microwave power or temperature increased was reported by Funebo and Ohlsson (1998) for drying of apples. Yellowness of oyster mushrooms increased as a consequence of the formation of yellow pigments due to browning reactions during drying. Celen (2019) evaluated the colour of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE respectively at microwave power of 600 W. It was also observed that higher microwave powers may cause unstable microwave field that may affect the colour quality of products.

4.10.6 Shrinkage

Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extend of shrinkage depends on the method of drying. Shrinkage percentage of dried oyster mushroom was observed to be 29.63%. The initial diameter of oyster mushroom samples was in range of 4.9 – 6.4 cm which was reduced to 2.4 – 4.1 cm upon drying. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin *et al*., 2005). Reduction in shrinkage percentage was due to the rapid evaporation of moisture by microwave radiation that created a vapor flux thereby preventing case hardening. Giri and Prasad (2007) reported that MW vacuum drying of mushrooms resulted in dried products with very less shrinkage compared to hot air-dried samples. MW dried herbs exhibited lesser shrinkage and better retention of biochemical constituents as reported by Kathirvel *et al.* (2006). The reason for a lower percentage of shrinkage was due to controlled drying which has resulted in the rapid removal of moisture, thus created an internal porous structure in the dried shrimp.

4.10.7 Rehydration ratio

The structural and cellular degradation occurred within the sample during drying is explained by rehydration ratio. The values of rehydration ratio of dried oyster mushrooms with respect to time is shown in Fig. 4.31. Within the first hour of soaking mushroom in water, a rapid rise was seen in rehydration ratio. Average rehydration ratio was observed to be 2.47. Giri and Prasad (2006) studied on drying of button mushrooms of 6 – 14 mm thickness and determined rehydration ratio in range of 2.3 – 3.4.

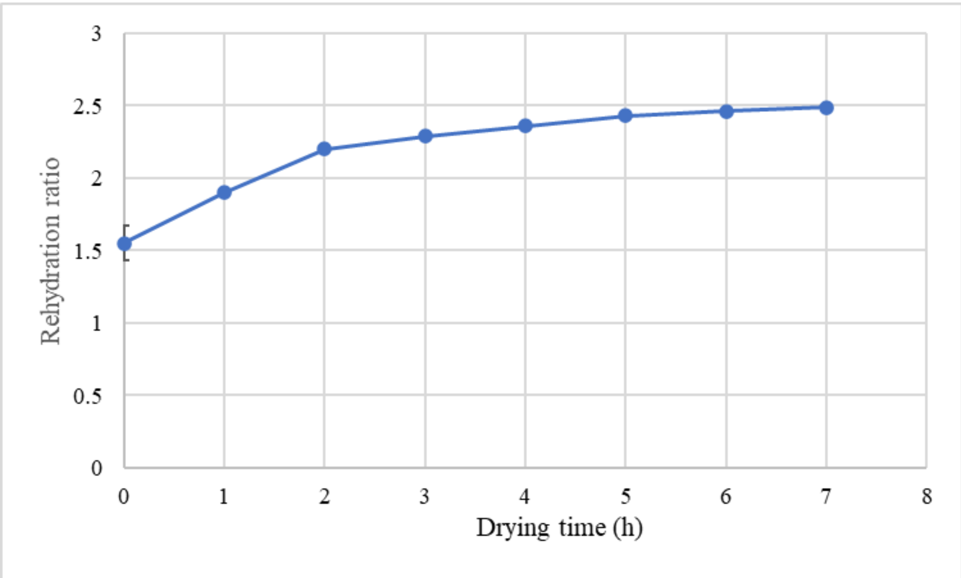


Fig. 4.31 Rehydration ratio of HAMW dried oyster mushroom

4.10.8 Water activity

In this study, water activity value of dried oyster mushroom was determined to be 0.529 that indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf-life extension of products (Jayaraman and Gupta, 2020).

4.10.9 Microbiological quality

The total plate count of raw oyster mushroom was 3.9 $\times 10^5$ CFU/g of a sample. Drying reduced the TPC value of oyster mushroom to 1.2 $\times$ 10^4 CFU/g, which is lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried vegetables is less than 10^5 CFU/g of a sample (IS 14950 2001). This confirms that dried oyster mushrooms prepared with hot air assisted microwave dryer was microbiologically safe for consumption. The destruction of microorganisms with MW radiations at sublethal temperatures has been explained by selective heating, electroporation, cell membrane rupture, and disruption of internal components (Chandrasekaran, 2013). Yaghmaee and Durance (2007) dried carrots and parsley with MW vacuum drying and a combination of MW vacuum drying and MW drying at atmospheric pressure.

4.10.10 Proximate and biochemical analysis

Results of proximate analysis of fresh and dried oyster mushroom is shown in Figure 4.32. The moisture content of the fresh oyster mushroom was decreased from 92.35% (w.b) to 8.14% (w.b) in the dryer. Moisture removal was due to the microwave power applied with the assistance of hot air generated in the dryer. Carbohydrate content of dried oyster mushrooms was found to be 47.34%. Tolera and Abera (2017) reported that the average value of crude protein, crude fat, crude fibre, ash, and carbohydrates of the fresh mushroom samples were 28.85, 2.47, 12.87, 9.76 and 48.16% as compared to 25.91, 2.18, 10.41, 10.91 and 42.14% for dried samples. This is in line to the results of present study. Protein content of oyster mushroom increased from 4.57% to 33.21% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried sample. Naknaen *et al*. (2015) reported that all dried mushrooms were found to be good sources of proteins, with contents varying in the ranges of 21.23–28.23 g/100 g dry weight while the fat content was very low (1.47–2.57 g/100 g dry weight). Fat content showed a slight increase from 0.57 to 1.26%. The higher ash content in oyster mushroom was due to the moisture reduction as the ash content is directly related with moisture content and temperature. As moisture content decreases, ash content increases (Adeyeye, 2000).

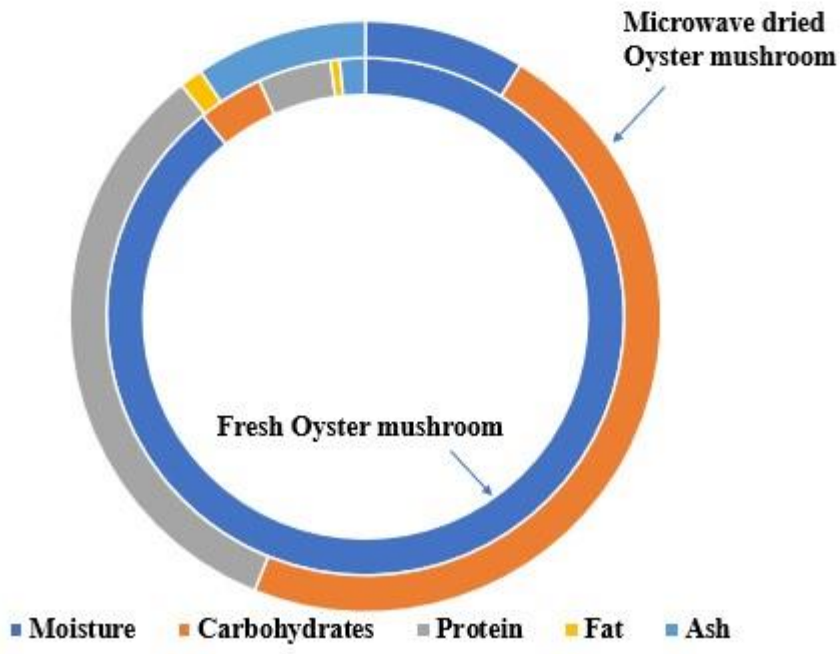


Fig. 4.32 Proximate composition of fresh and HAMW dried oyster mushrooms

4.10.11 Sensory evaluation

The scores of sensory evaluation of dried oyster mushroom are depicted in Fig. 4.33. Twenty-five semi-trained panel members comprising of research scholars and staff assigned maximum score to 'overall acceptability' of the samples. This can be due to the degree of uniformity in the samples, final moisture content and better colour retention of the samples. Muyanja *et al.* (2012) studied on the effect of pretreatments and drying process on sensory aspects oyster mushroom and published that there was no significant effect of pretreatments on sensory evaluation and solar dried samples gained sensory scores to the maximum. However, in the present study average of appearance, colour, odour, texture and overall acceptability values for microwave dried oyster mushroom were 8.2, 8.1, 8.1, 8.0, and 8.1 respectively.

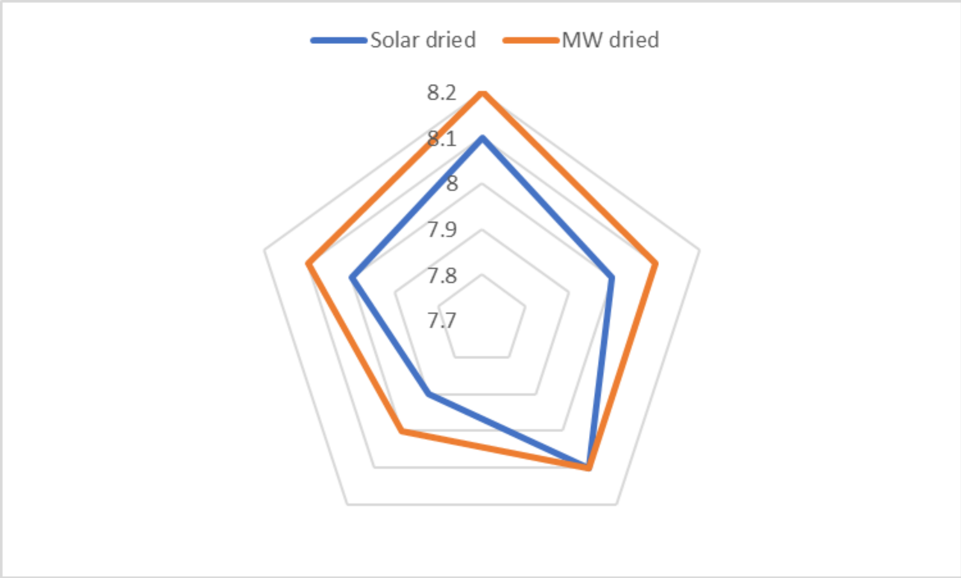


Fig. 4.33 Sensory scores of microwave and solar dried oyster mushroom

4.11 Comparative studies on solar and microwave drying of oyster mushroom

4.11.1 Moisture content and drying rate

Solar radiation, ambient temperature and RH were measured using sensors at each hour of the study. The solar radiation intensity during the experimental conditions was observed to be in range of 320 to 840 W/m^2, ambient temperature varied from 27.5 to 36.5 ^{0}C and RH from 62.45% to 77.24% on a typical day of the experiment. The moisture content of oyster mushroom was reduced from 91.24% to 8.21% (w.b.) within 8.5 h of drying in the solar dryer. The drying conditions were maintained at temperature, air velocity and RH of 55±1.5 ^{0}C, 1.5 ± 0.25 m/s and 60±0.5 % respectively. Initially, moisture evaporated from the product as if from a free water surface due to the temperature difference between the drying medium (hot air) and the product. As drying progressed, moisture removal took place due to the vapor pressure gradient.

It is evident from Fig. 4.34 that during MW drying moisture content of oyster mushroom decreased from an initial value of 92.35% to a final value of 8.42% within 5 h h of drying. The volumetric heating effect of microwaves can be attributed to the reduction in drying time. Microwave heating falls under the dielectric heating method wherein the moisture content of the product directly influenced the heating rate. Bashir *et al.* (2020) reported moisture content of solar and microwave dried oyster mushrooms to be in range of 5.16 to 8.15%. The initial moisture content of the white oyster mushroom was 92.67% and reached 7.97% after solar drying taking 12 -13 h for drying under 50-60 ^{0}C. It was also found that at 55 ^{0}C, despite the presence of pores, a structure similar to the fresh sample was obtained. Bala *et al*. (2009) also studied on drying of mushrooms in solar tunnel dryer and determined a moisture reduction from mushrooms were dried from 89.41% to 6.14% in 8 h.

The drying rate of solar and microwave dried oyster mushrooms were found to be 3.47 kg/kgh and 2.14 kg/kgh at the beginning of drying (Fig. 4.35). Drying rate exhibited a maximum value of 3.47 during the initial stages of drying that can be due to the higher moisture content of a sample that created more friction and heat generation due to dipole rotation. In both the studies, the rate of moisture removal decreased with time, and hence drying was under a falling rate period. The drying rate of oyster mushroom was decreased when the moisture content was decreased and the drying rate appeared almost the double, when the temperature was increased from 48 $^{\circ}$C to 60 $^{\circ}$C (Mustayen *et al*., 2015). Photographs of HAMW and solar dried oyster mushrooms are shown in Plates 4.7 and 4.8, respectively.

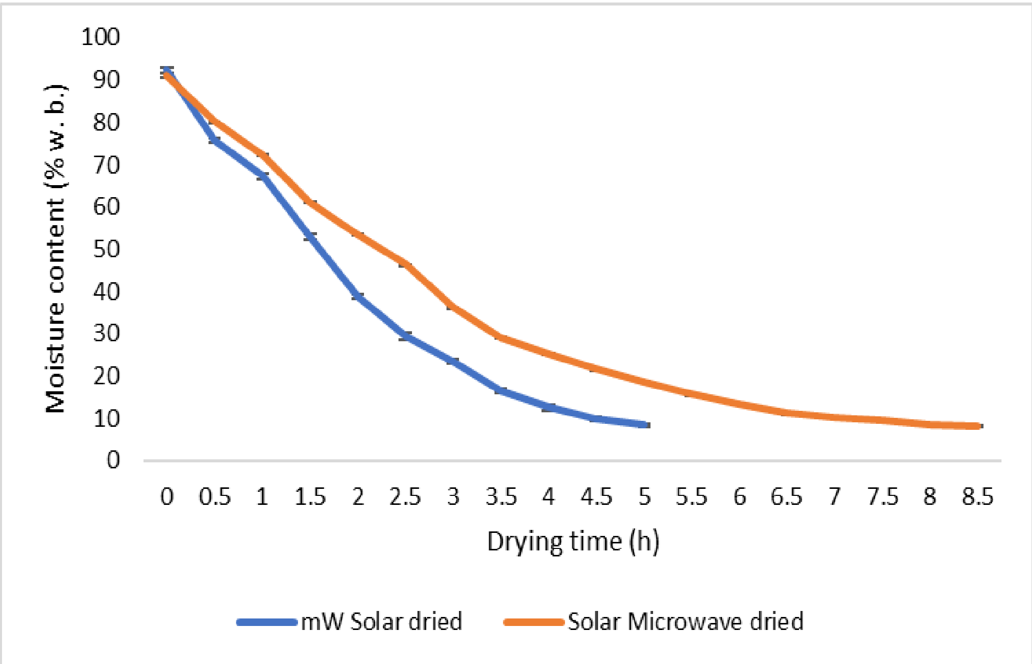


Fig. 4.34 Moisture content versus drying time for solar and microwave drying of oyster mushroom

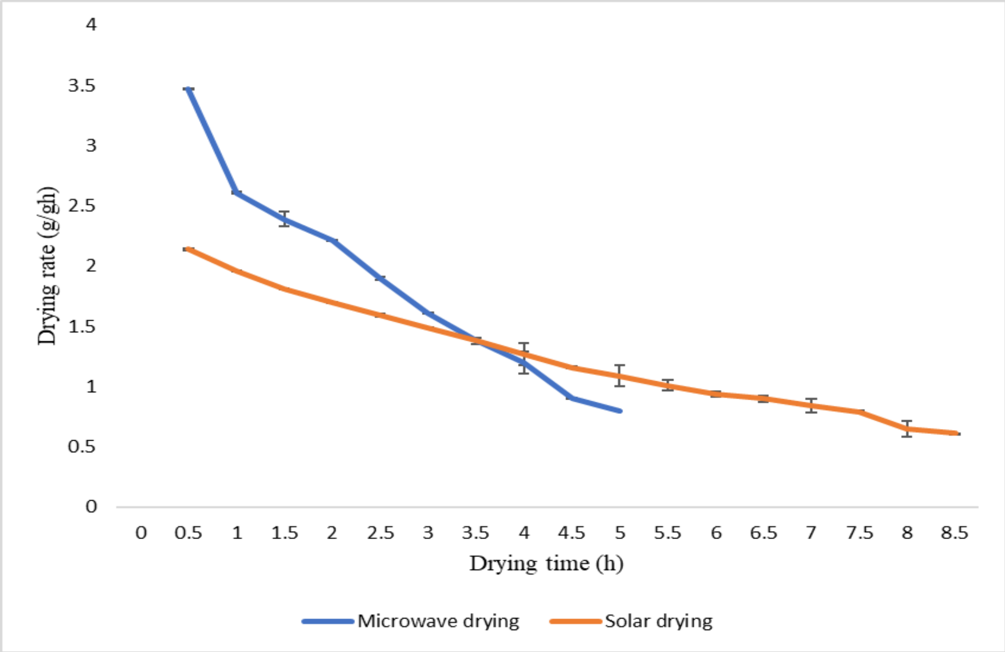


Fig. 4.35 Drying rate versus drying time for solar and microwave drying of oyster mushroom

Plate 4.7 HAMW dried oyster mushrom

Plate 4.8 Solar dried oyster mushroom

4.11.2 Effective moisture diffusivity

The sum of liquid and vapor diffusion during drying is represented by effective moisture diffusivity of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gave the slope value to determine the diffusivity (Fig. 4.36). Effective moisture diffusivity during SD and MWD of oyster mushroom were determined to be 2.49×10^{-7} m^2/s and 5.63×10^{-9} m^2/s respectively. Kaur *et al*. 2018 reported the highest effective moisture diffusivity for solar and microwave was 1.46×10^{-7} m^2/s and 6.33×10^{-6} m^2/s at microwave power level of 1350 W. In a combination of solar and microwave drying the highest EMD value of 1.16×10^{-7} and 2.29×10^{-5} was recorded for initial and later stage of drying. The effective moisture diffusivity during infrared vacuum drying of button mushrooms ranged between 0.83 and 2.33×10^{-9} m^2 /s. Kaveh *et al*. (2021) opined that microwave drying exhibited higher values of diffusivity compared to convective drying based on his study on drying of pomegranate arils. Darvishi *et al*. (2014) studied microwave drying effects on mulberry and reported diffusivities in the range of 1.06×10^{-8} to 3.45×10^{-8} m^2/s as the microwave power was varied from 100 to 500 W. Microwave drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s and 4.63×10^{-6} m^2/s under varying operating conditions (Celen, 2019).

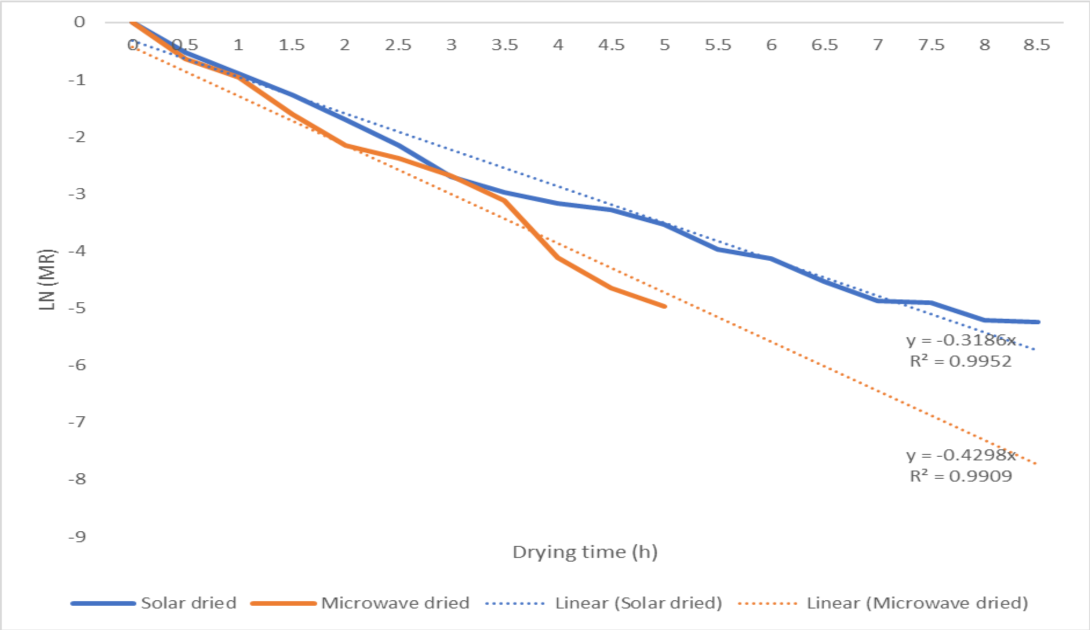


Fig. 4.36 Plot of LN MR Vs drying time for solar and microwave drying of oyster mushroom

4.11.3 Evaluation of drying models

HAMW of oyster mushroom was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying were fitted into thin layer drying models by non-linear regression analysis (Table 4.22). Two term exponential was identified as the best fit model with higher R^2 value of 0.9616, lower $\chi 2$ value of 0.000437 and RMSE value of 0.0176 (Table 4.22). To verify the acceptability of the selected Two term exponential model observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9994 which implies that the selected model satisfactorily described the drying behaviour of oyster mushroom under the solar drying Fig. 4.37). Based on statistical results, logarithmic model gave best goodness of fit on the experimental data during drying of oyster mushrooms under microwave drying (Kaur *et al*., 2018). Wang and Singh model gave comparatively the higher R^2 values with lower chi-square and RMSE values in all the drying temperatures during drying of milky mushrooms in fluidized bed dryer. Thus, the Wang and Singh model may be assumed to represent the thin layer drying of milky mushroom slices in a fluidized bed dryer (Arumuganathan *et al*., 2008).

Table 4.22 Modelling of drying data for solar drying of oyster mushroom

S. No.	Model name and reference	R^2	RMSE	Reduced χ2	Constants
1	Modified page (Karacabey and Buzurul, 2017)	0.9051	0.09507	0.0005537	k = 0.6393 n = 0.6869
2	Henderson and Pabis (Arslan et al., 2010)	0.9715	0.05211	0.000466	a = 1.295 k = 0.5876
3	Logarithmic (Moradi et al., 2020)	0.9567	0.02130	0.000465	a =1.362 c = -0.1624 k= 0.9494
4	**Two-term exponential (Togrul and Pehlivan, 2004)**	**0.9616**	**0.0171**	**0.000437**	**a = 43.49** **b= -42.21** **k1 = 0.4058** **K2 = 0.4017**
5	Wang and Singh (Wang et al., 2005)	0.9248	0.02244	0.001144	a = -0.3906 b = 0.04663
6	Verma et al (Yaldys and Ertekýn, 2001)	0.9051	0.1041	0.000478	a = -0.007179 b = 0.3826 g = 0.4387

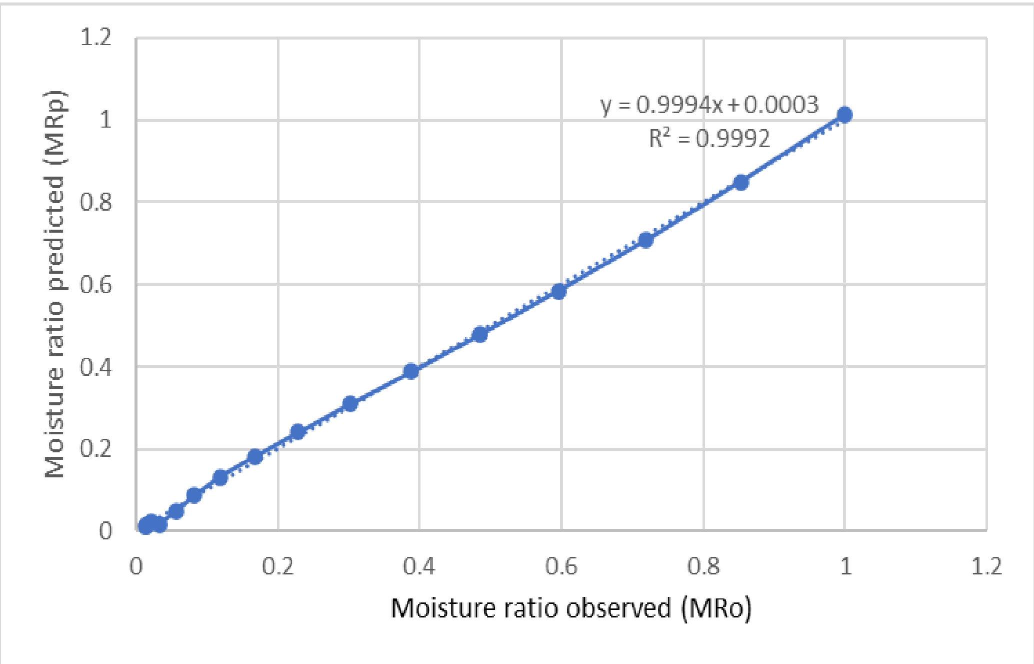


Fig. 4.37 Best fit Two-term exponential model

4.11.4 Drying efficiency

The atmospheric and drying chamber conditions during solar drying of Oyster mushrooms are shown in Fig. 4.38 and 4.39 respectively. The efficiency of the collector was calculated using the whole collector area and solar irradiation received instantaneously during drying. The instantaneous collector efficiency values varied in the range of 30.9 to 42.4%. However, maximum efficiency was related directly to the hours of maximum solar irradiation received which is from 12:30 PM to 2:30 PM (Fig. 4.38). Efficiency of solar collectors was found to vary to the tune of 21-69% in the drying of osmotically dehydrated cherry tomatoes (Nabnean *et al*., 2016). The efficiency of oyster mushroom drying was determined by considering the energy supplied by the collector, pump, blower, exhaust and water heater for LPG. The efficiency of drying varied from 25.3 to 34.1% (Fig. 4.40), achieving a maximum at 1:30 PM. Maximum available irradiation that enhanced the outlet temperature of water in the collector reduced the LPG consumption for drying at this stage. Bala *et al.* (2009) investigated on the performance evaluation of solar tunnel drying of mushrooms under solar radiation intensities varying from 273 – 885 W/m^2. Drying chamber temperatures varied from 37 to 66.5 °C in drying mushrooms from a moisture content of 89.41 to 6.14 % w. b. in about 8 hours. In the study, the authors reported collector and drying efficiencies of 33.73 and 51.64 respectively, with an overall efficiency of 34.6%. The findings of the present study are in line with these reports. Asnaz and Dolcek (2021) conducted studies to determine collector efficiencies for thin layer drying of mushrooms in various solar dryers between 9 am and 6 pm. The average solar radiation intensity during the study was 790 W/m^2 and the average thermal efficiencies obtained were 59.74 and 67.66% respectively for natural and forced convection drying systems.

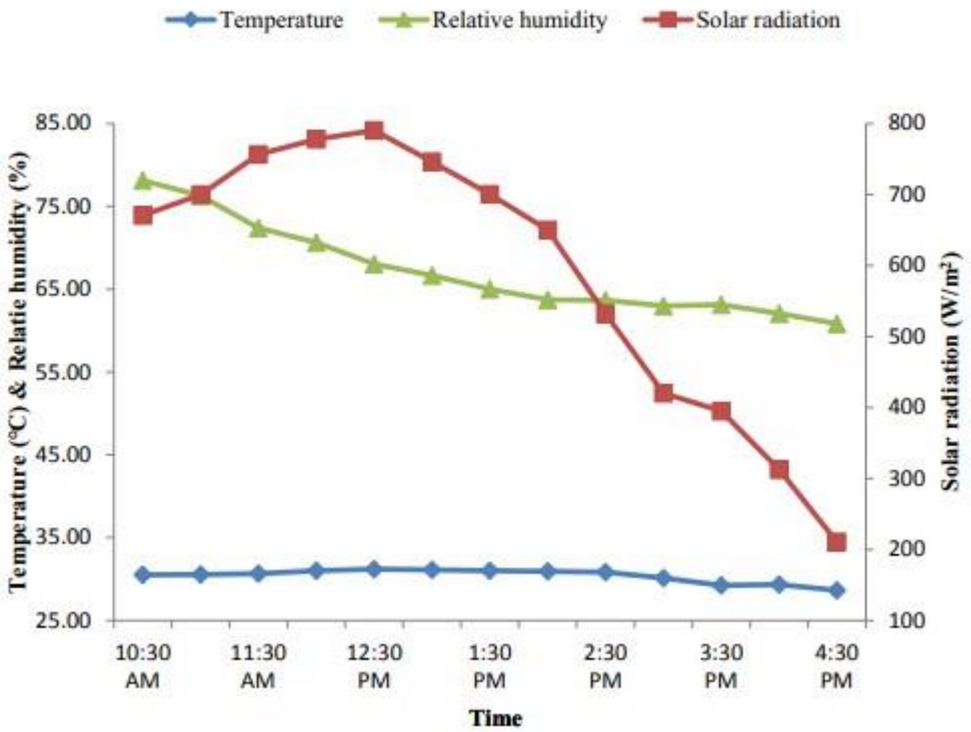


Fig. 4.38 Average atmopspheric conditions during drying experiments

The temperature of drying chamber was lower and relative humidity was higher, however as the day progressed temperature of drying air increased and relative humidity decreased. This could be due to the gradual increase in solar radiation during drying, correspondingly higher collector outlet water temperature and maximum heat transfer to drying air. Even at 4:30 p.m. when the solar radiation is very low (235 W/m^2), drying air temperature is still high (52.5 ^{0}C). This is because thermal energy stored as sensible heat in the water was used in this period. It was also observed that there was no significant difference in temperature of drying air between upper and lower drying chambers at any point of time during drying implying that the homogeneous drying conditions were obtained in the dryer. The average range of values of drying air temperature, relative humidity and air velocity were recorded as 29.4 to 52.5 ^{0}C, 50.23 to 80.42% and 0.75 to 1 m/s respectively (Fig. 4.39).

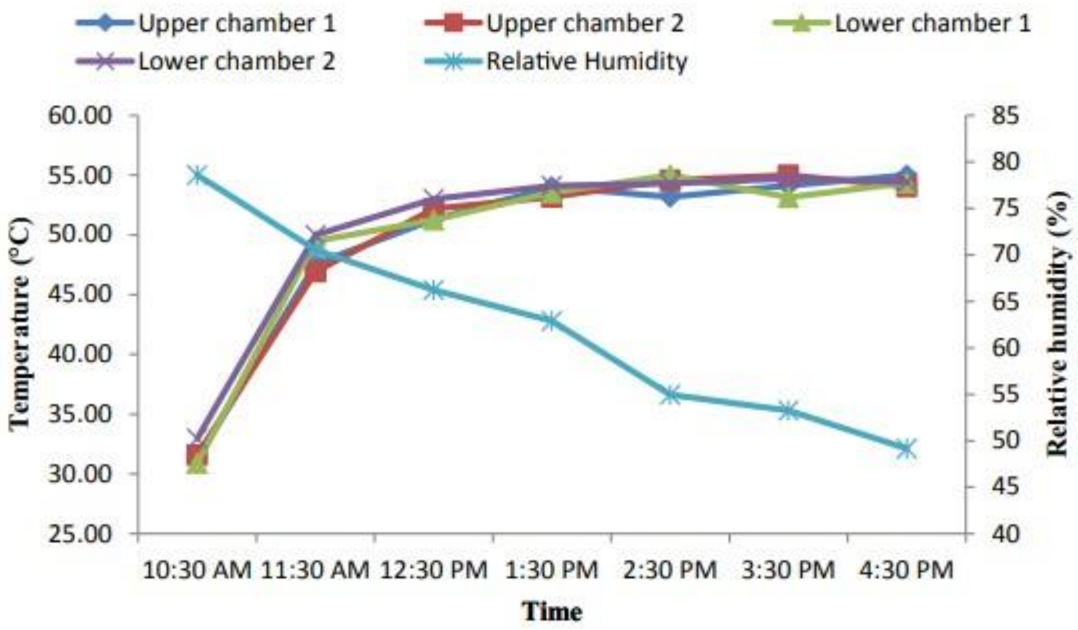


Fig. 4.39 Average drying chamber conditions during solar drying

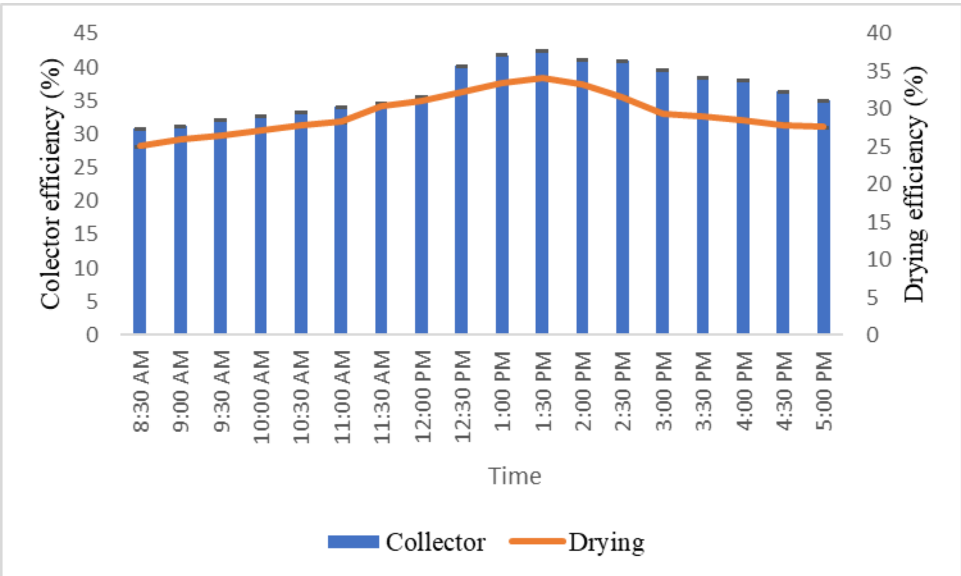


Fig. 4.40 Instantaneous collector and drying efficiencies during SD of oyster mushroom

Drying efficiency of the dryer under HAMW mode was observed to be 23.12%. This was a result of volumetric hearing effect of microwave radiation combined with convective effect of hot air. Hassan (2016) published that since microwaves acts only on polar molecules, microwave drying efficiency decreased with time and increased with moisture content of sample during studies on microwave drying of date. Maximum drying efficiency of 32% was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein *et al.* (2013)

observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W respectively during drying of apple slices in laboratory scale MW dryer. An *et al*. (2022) published that energy consumption of MWD depends on a variety of factors such as equipment structure, drying conditions (microwave power, frequency, temperature, and air velocity), material properties, and combined/hybrid drying technologies. The drying system can be effectively improved if these parameters are adjusted appropriately and taking the processing cost into consideration. *Soysal et al*. (2007) reported microwave drying efficiency of 32% for drying pf parsley at power levels of 900 W.

4.11.5 Hardness

The textural analysis of dried products is important in determining their palatability. Textural attributes of dried products are generally expressed in terms of hardness indicated by the maximum compressive force needed to crush the product by the molars. A 5 mm diameter needle probe was used to measure hardness as the force required to puncture an individual mushroom slice placed over a plate with an 8 mm diameter hole. The crosshead speed was maintained at 100 mm/min. The mean value of ten measurements was recorded for each trial. The puncture force required to penetrate mushroom at low moisture content was higher than that of fresh samples. The average hardness of fresh, solar dried and microwave dried mushroom samples were 3.4, 7.4 and 9.3 N respectively (Fig. 4.41). The puncture force required to penetrate mushroom at low moisture content was higher than that of fresh samples. This can be attributed to the case hardening of samples at higher temperatures. Argyropoulos *et al.* (2011) studied on the effects of colour and texture in convective drying of mushroom (*Boletus edulis*) and recommended that physical treatment, in the form of either steam or water blanching, is not recommended for the pre-processing of mushrooms when color and texture are desirable quality criteria of the dried product. The results showed that during convective drying, lightness decreased slightly while yellowness and redness increased. Chemical pre-treatments did not influence the color of mushrooms positively while blanching caused intensive color deterioration. During solar drying, which is relatively for a longer duration as compared to microwave drying, a rigid product was obtained. During drying, moisture migrated by diffusion from the inside of the sample carrying the water-soluble components with it to the surface. At the surface, moisture is laden way by the hot air leaving behind the water-soluble components. These components concentrated on surface preventing further transfer of moisture from the cells. This in turn caused case hardening and substantially higher force was required to puncture the samples (Lewicki and Pawalak, 2005).

Physical treatment, in the form of either steam or water blanching, is not recommended for the pre-processing of B. edulis mushrooms when colour and texture are desirable quality criteria of the dried product. Argyropoulos *et al.* (2008) opined that hot-air drying probably caused heat damage and collapse of the internal mushroom structure throughout the drying process affecting adverse quality characteristics like texture. Combined microwave-vacuum and hot-air drying creates a more porous structure of the samples due to quick microwave heating that causes rapid evaporation of water and diffusion out of the tissue, while the vacuum facilitates water evaporation at a lower temperature.

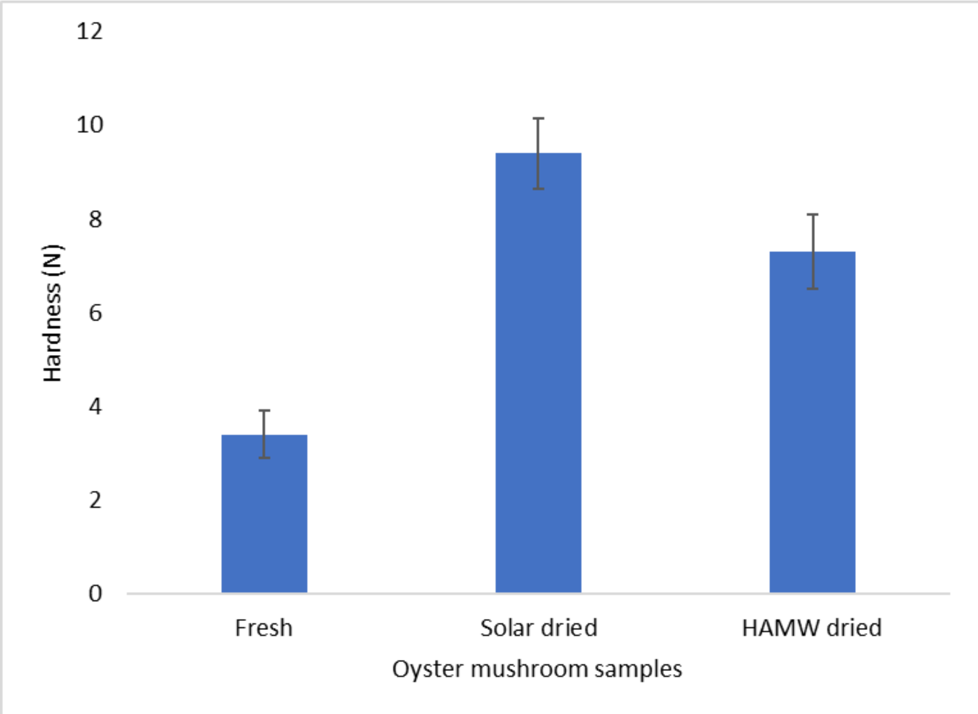


Fig. 4.41 Hardness values of raw, solar dried and microwave dried Oyster mushroom

4.11.6 Rehydration ratio

The values of rehydration ratio of SD and MWD oyster mushroom with respect to time is shown in Fig. 4.42. Under both drying methods, within the first hour of soaking the sample in the water, a rapid rise was seen in the rehydration ratio. The average rehydration ratio was observed to be 2.21 and 2.47 for SD and MWD respectively. The reduction in in longer drying times resulted in overheating of surface, darkening on surface and loss of flavour and rehydration characteristics. Giri and Prasad (2007) investigated on the effects of microwave vacuum drying on the drying kinetics and quality of button mushrooms and obtained similar results as that of the present study. It was reported that the rehydration ratio of microwave and hot air-dried mushrooms were 3.4 and 2.3 respectively. The rate of rehydration was faster for the microwave dried samples compared to the hot air-dried samples. Microwave drying created more porous structure with lesser shrinkage in the lattice that paved the way for better and faster rehydration. Nour *et al.* (2011) investigated on colour and rehydration ratio of hot air-dried mushrooms and reported rehydration ratio in range of 2.18 to 2.46 for various drying temperature (50 – 70 ^{0}C). the authors also concluded that better rehydration characteristics were obtained for samples dried under lower temperatures due to lesser cellular degradation that enabled more absorption of water. A rise in temperature enhanced the drying rate making mushrooms firmer and thus the time for the breakdown of the cell structural components like pectin or cellulose were reduced. Hassan and Medany (2014) published that rehydration ratio was severely affected even by slight variation in mushroom types and in drying temperatures. Jayathunge and Ileperuma (2001) opined that, the higher rehydration ratio observed in their study may probably be due to minimum changes in the structure of proteins and consequently minimum changes in protein functionality at the low drying temperature of 45°C. Kumar *et al.* (2013) recorded that, the mushrooms dried in medium size dryer using pretreatment of 1.0% potassium metabisulphite gave the maximum rehydration ratio and coefficient of rehydration.

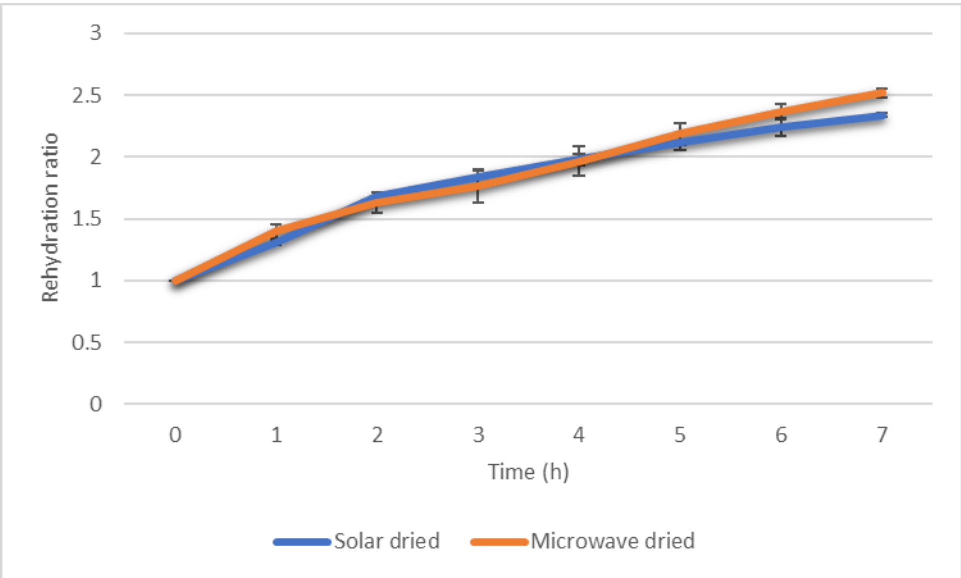


Fig. 4.42 Rehydration ratio of solar and microwave dried oyster mushroom

4.11.7 Shrinkage

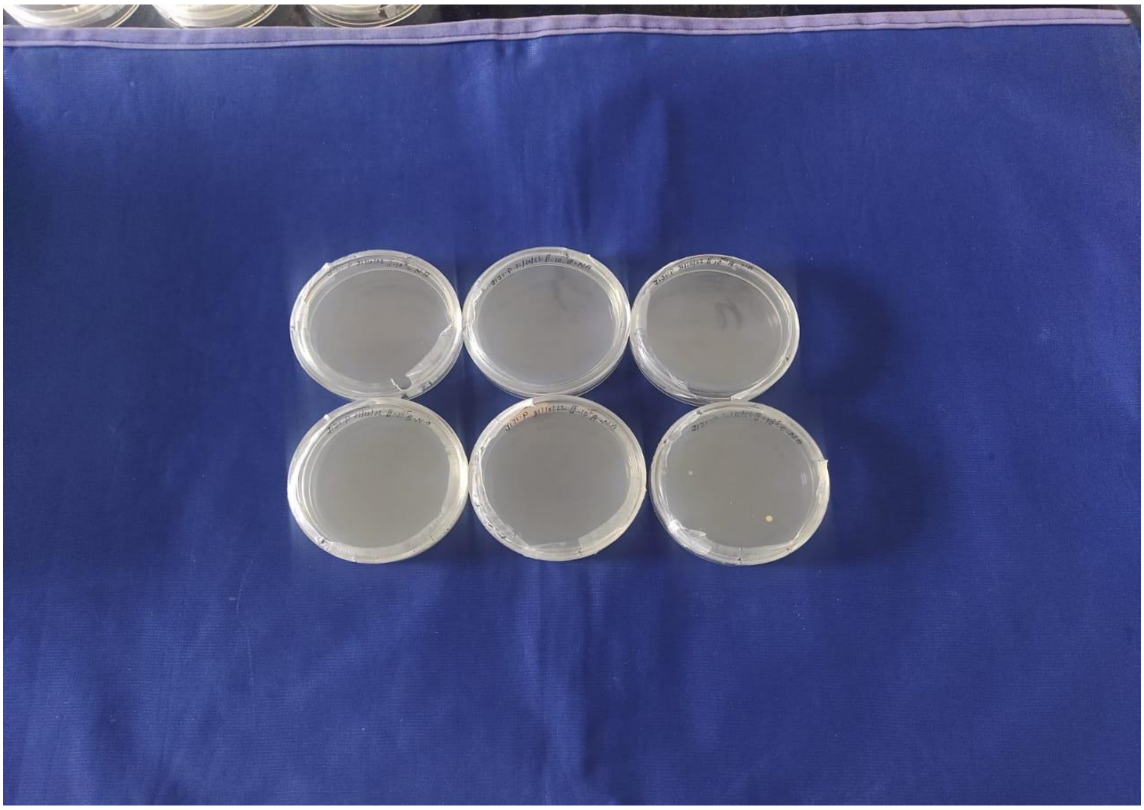
Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extent of shrinkage depends on the method of drying. The shrinkage percentage of SD and MWD shrimp was observed to be 46.42 and 39.64% respectively. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin *et al.*, 2005). The reduction in shrinkage percentage was due to the rapid evaporation of moisture by microwave radiation that created a vapor flux thereby preventing case hardening. Giri and Prasad (2006) reported that the shrinkage ratio obtained during microwave vacuum (150 W, 10 kPa) and air drying (60 ^{0}C) were 0.096 and 0.2323 respectively at a moisture content of 5%. Microwave vacuum drying produced less shrinkage than air drying. The shrinkage has a direct relationship with the way of removal of moisture from the product.

4.11.8 Proximate analysis

Results of proximate analysis of fresh and dried oyster mushroom is shown in Figure 4.44. The moisture content of the fresh oyster mushroom was decreased from 92.35% (w.b) to 8.14% (w.b) in the dryer. Moisture removal was due to the microwave power applied with the assistance of hot air generated in the dryer. Carbohydrate content of dried oyster mushrooms was found to be 47.34%. Tolera and Abera (2017) reported that the average value of crude protein, crude fat, crude fiber, ash, and carbohydrates of the fresh mushroom samples were 28.85, 2.47, 12.87, 9.76 and 48.16% as compared to 25.91, 2.18, 10.41, 10.91 and 42.14% for dried samples. This is in line to the results of present study. Protein content of oyster mushroom increased from 4.57% to 33.21% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried sample. Naknaen *et al*. (2015) reported that all dried mushrooms were found to be good sources of proteins, with contents varying in the ranges of 21.23–28.23 g/100 g dry weight while the fat content was very low (1.47–2.57 g/100 g dry weight). Fat content showed a slight increase from 0.57 to 1.26%. The higher ash content in oyster mushroom was due to the moisture reduction as the ash content is directly related with moisture content and temperature. As moisture content decreases, ash content increases (Adeyeye, 2000).

4.11.9 Microbiological quality

The total plate count of raw oyster mushroom was 3.9 $\times 10^5$ CFU/g of a sample. Drying reduced the TPC value of oyster mushroom to 1.2 $\times$ 10^4 and 3.9 $\times 10^4$ CFU/g respectively under MW and SD drying conditions. Hassan and Medany (2014) reported that drying dramatically reduced TPC for mushroom from 4.9 CFU $\times 10^3$ /g to be ranged from 1.3 – 1.8 CFU $\times 10^3$ /g for P.ostreatus. Lakshmipathy *et. al*. (2013) reported that, open sun-dried mushrooms had a significant higher number of microorganisms than all other dehydrated mushrooms. Higher moisture content of the open dried mushroom compared to other dryers could have influenced the microorganism on the dried mushrooms. The objective of drying is to remove water to a level at which microbial spoilage and deterioration reactions are greatly minimized. TPC of dried mushrooms is shown in Plate 4.9.



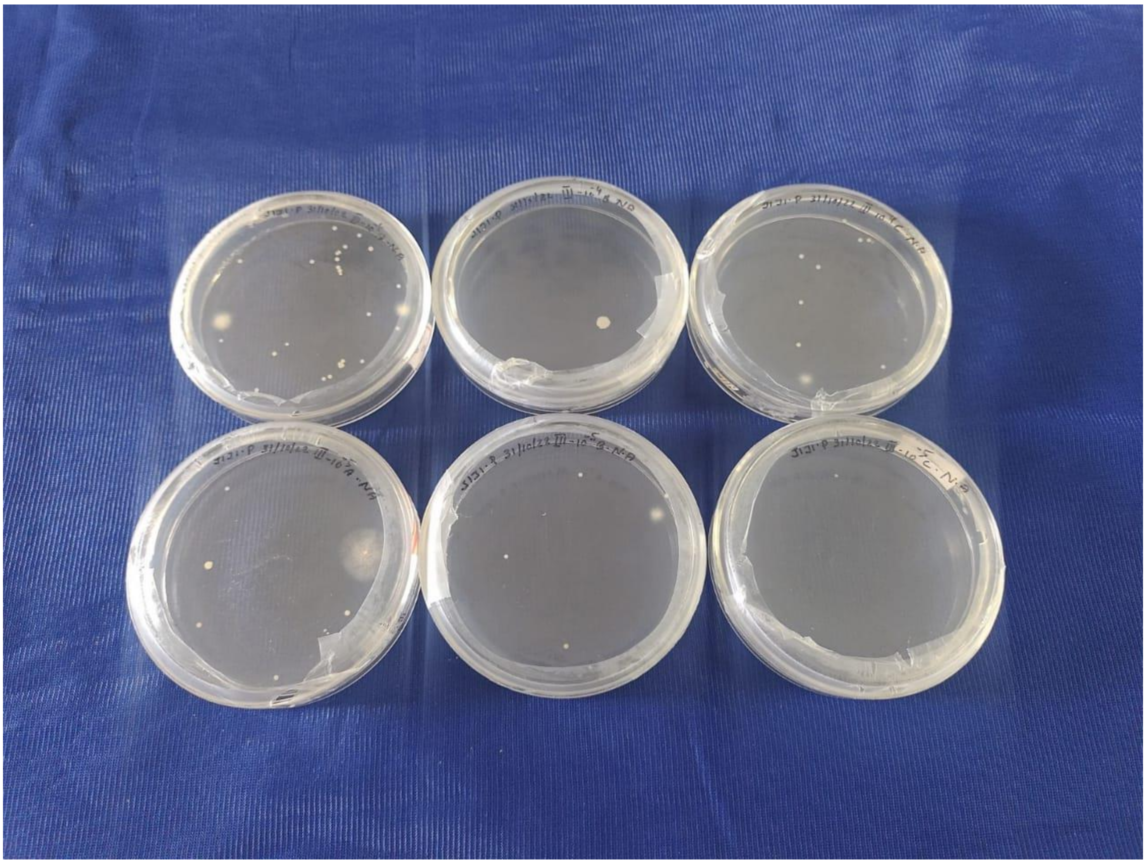


Plate 4.9 Initial and final TPC in dried oyster mushroom samples

4.11.10 Colour change

Solar dried oyster mushrooms were found to be darker (L= 49.61 ± 0.32) compared to microwave dried samples (56.15±0.25). Darkening or browning of dried mushrooms could be attributed mainly to enzymatic browning, Millard reactions, oxidation of phenolic compounds or microbial activities. In this respect, Komanowsky *et al*., (1970) revealed that, mushroom varieties discoloration was proportional to the amount of heat treatment and lower drying temperatures yielded lighter product. Redness of the samples increased from 4.95±0.24 to 5.96±0.46 and blueness increased from 20.85±0.51 to 22.56±0.35. This may be due to the exposure to higher temperatures for longer times. Total colour change (ΔE) determined for SD and MWD samples were 35.31±1.24 and 28.5 ± 1.63 respectively. Celen (2019) evaluated the color of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE respectively at a microwave power of 600 W. It was also observed that higher microwave powers may cause an unstable microwave field that may affect the color quality of products. Authors also reported that Hunter color lab L*, a* and b* values of dried oyster mushrooms to be 58.92, 4.18 and 14.57 respectively which is in line to the results of the present study. Browning index of SD and HAMW dried oyster mushrooms were determined to be 52.50 and 39.30, respectively. Li *et al*., (2020) reported that browning index of microwave oven dried mushrooms varied in range of 55.85 to 75.10. The higher values obtained may be due to the uneven heating achieved in an oven as compared to the microwave dryer. Authors also opined that hybrid technologies with the assistance of microwaves can reduce the colour degradation during drying. Whiteness index of SD and HAMW dried oyster mushrooms were found to be -84.21 and -59.97, respectively. Higher drying temperatures produced more darker products. Mittal *et al*. (2012) reported whiteness index of -40 and -190 for fresh and microwave dried whole mushroom.

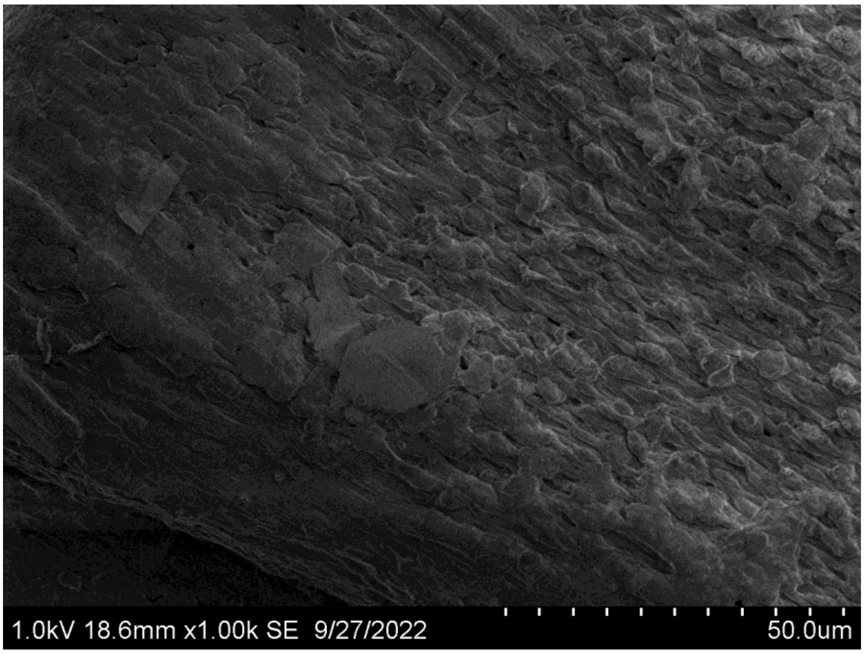
4.11.11 Water activity

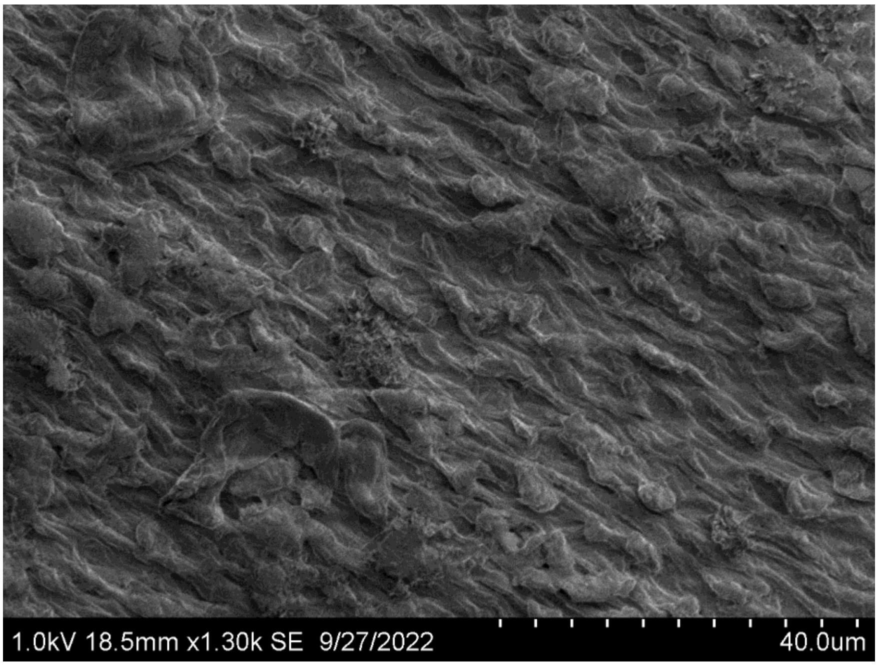
Water activity of value of dried oyster mushroom was determined to be 0.554 and 0.529 under SD and MWD respectively which indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf-life extension of products (Jayaraman and Gupta, 2020).

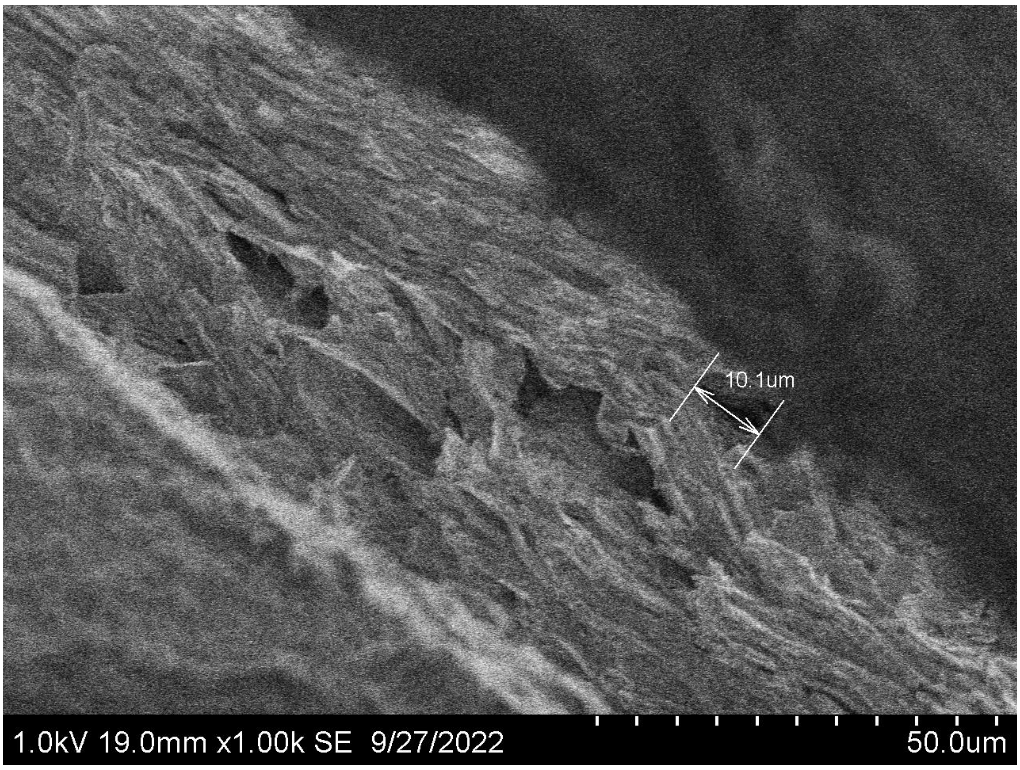
4.11.12 Microstructure analysis

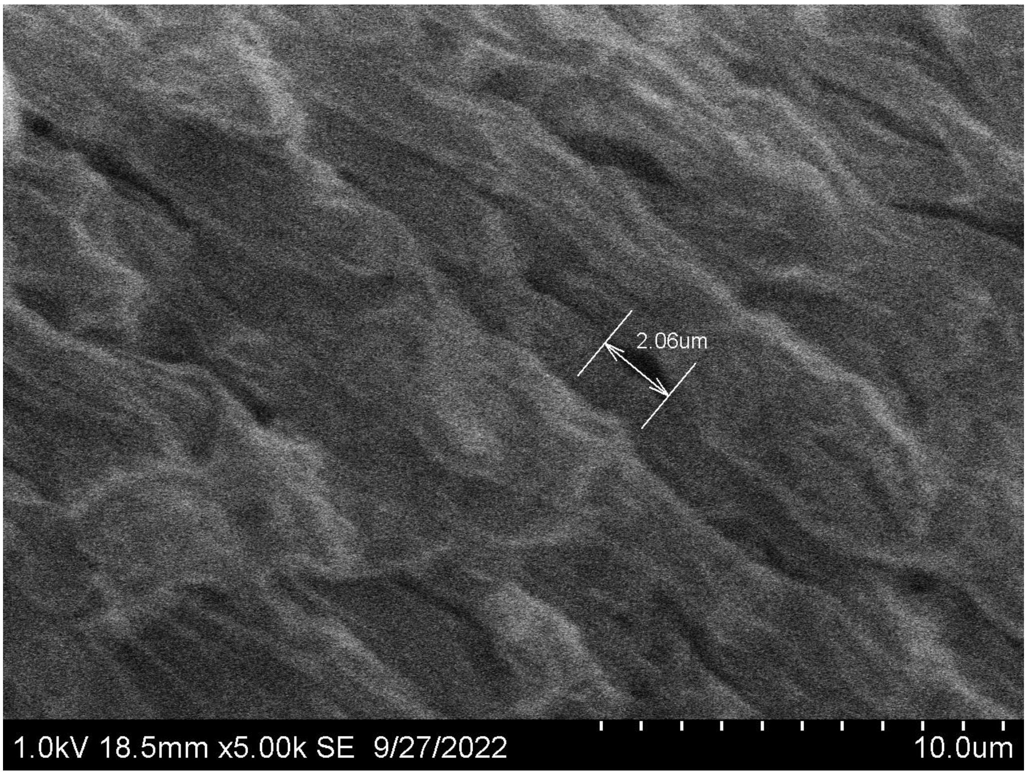
The optimized sample was analysed for microstructure to study the pore size distribution in the dried product. The pore size for microwave dried oyster mushroom samples ranged from 8.65 – 32.4 µm (Fig. 4.43). Scanning electron microscopy analysis of microwave dried oyster mushroom showed the formation of pores of diameters ranging from

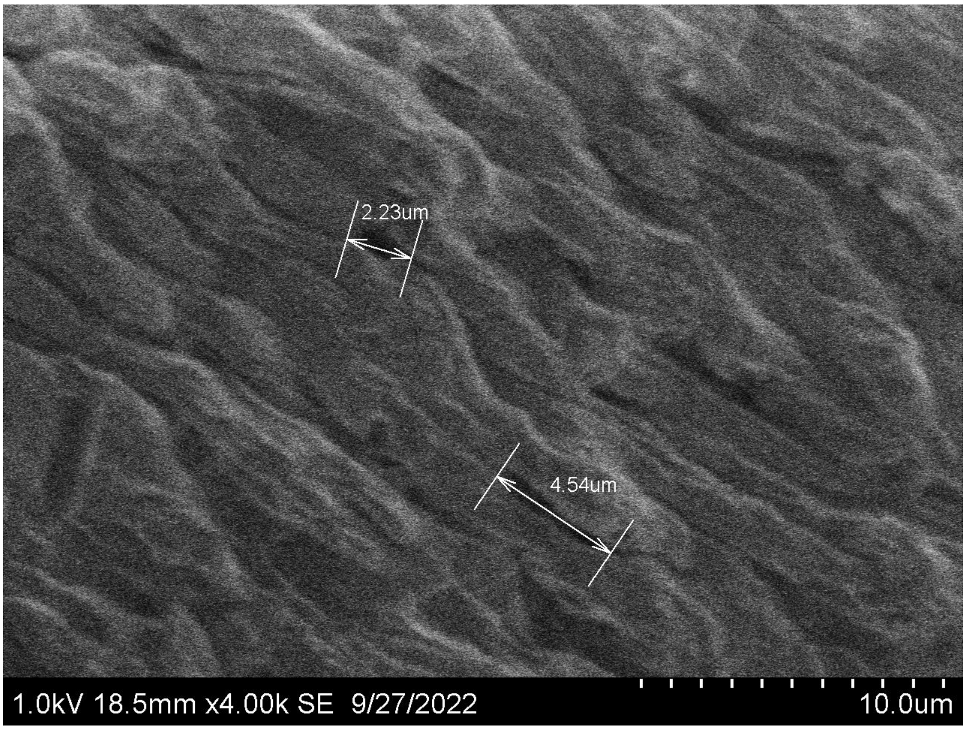
2.06 – 15.7 µm (Fig 4.44). The reason for higher rehydration ratio of hot air assisted microwave dried mushroom can be the presence of these pores. The volumetric heating effects of microwave causes abrupt removal of water molecules which left the internal lattice vacant there by creating pores of varying diameters. Due to longer drying times in solar drying, there was greater diffusion and evaporation happening across the interior to exterior surface of the samples that resulted in more shrinkage and pores of relatively larger sizes as compared to microwave drying.






10.1um
1.0kV 19.0mm x1.00k SE 9/27/2022
50.0um


2.06um
1.0kV 18.5mm x5.00k SE 9/27/2022
10.0um



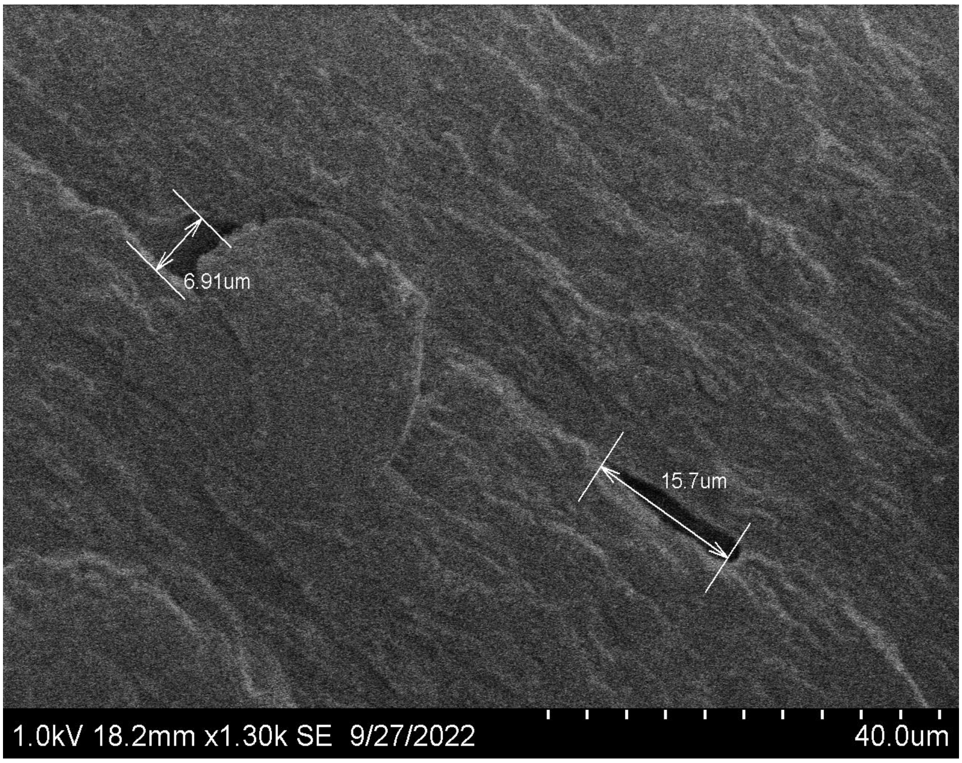
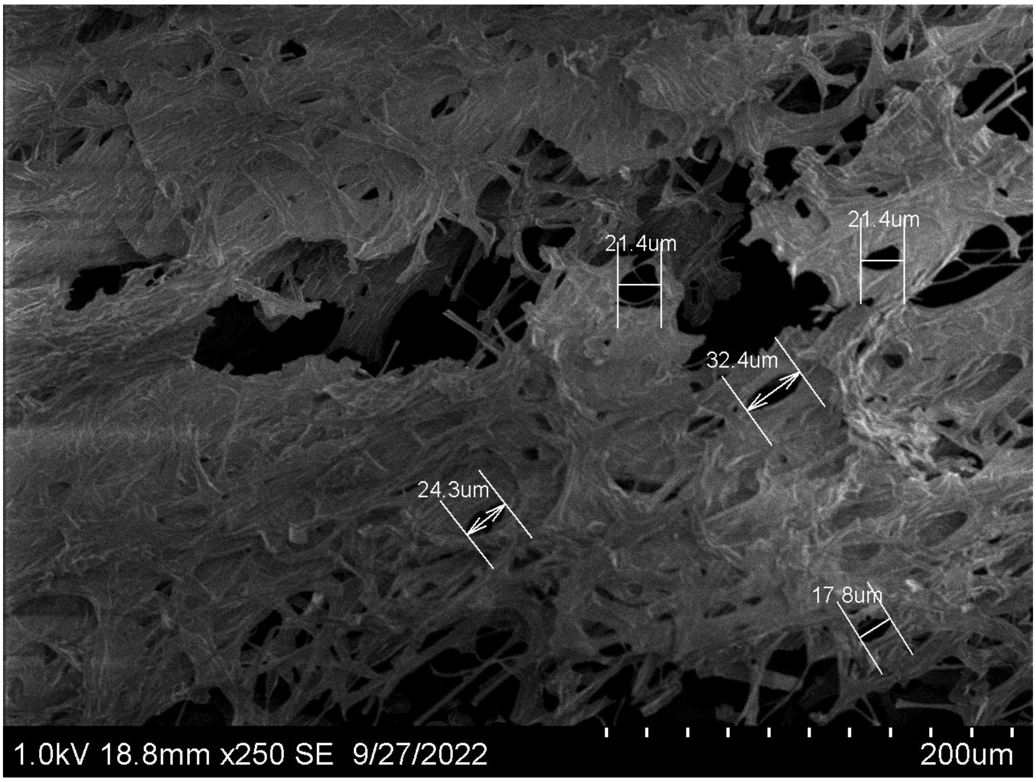
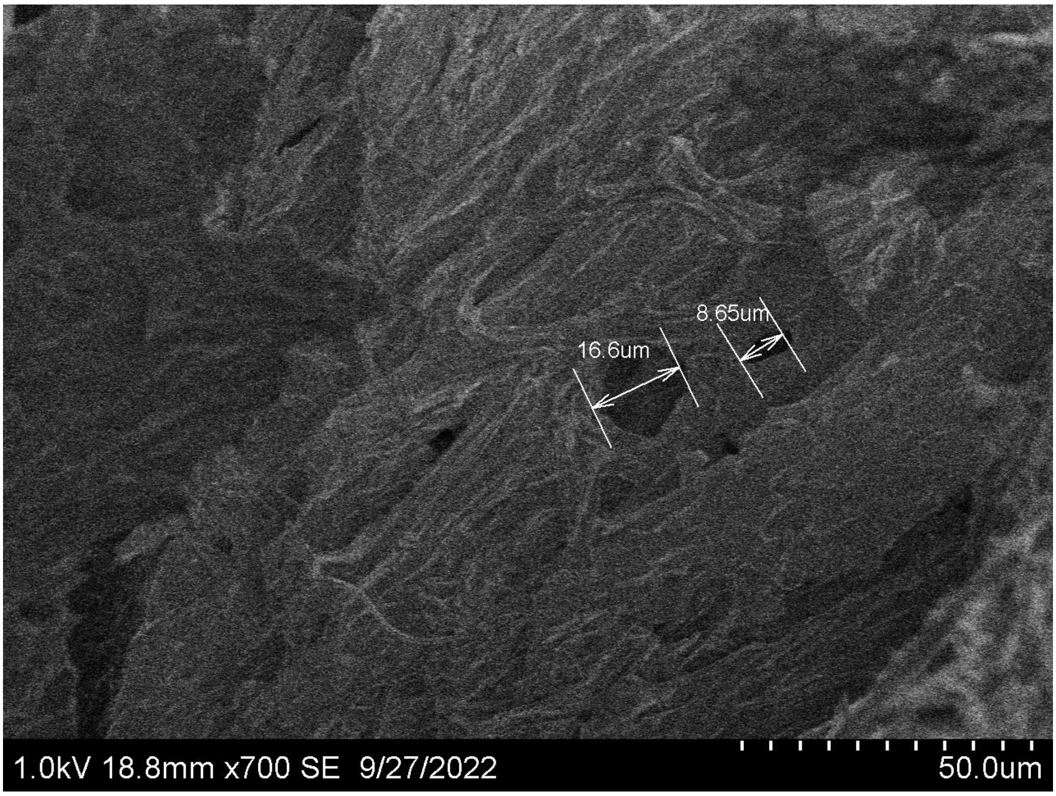


Fig. 4.43 SEM images of HAMW dried oyster mushroom at various resolutions


21.4um
21.4um
32.4um
24.3um
17.8um
1.0kV 18.8mm x250 SE 9/27/2022
200um


8.65um
16.6um
1.0kV 18.8mm x700 SE 9/27/2022
50.0um

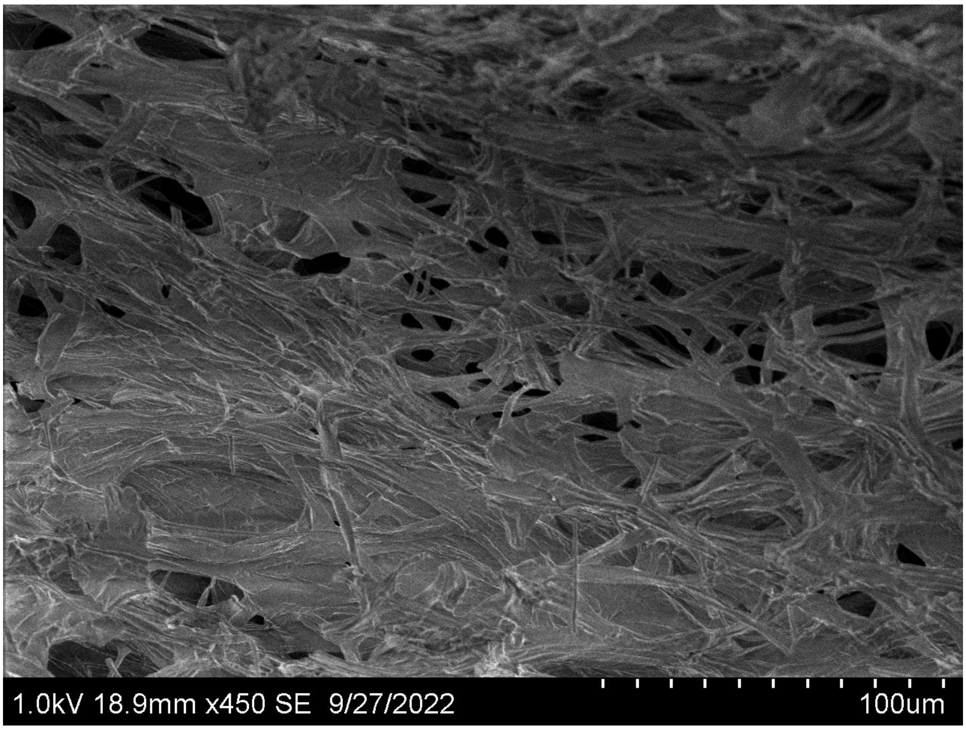


Fig. 4.44 SEM images of solar dried oyster mushroom at various resolutions

4.11.12 Sensory analysis

The scores of sensory evaluations of dried oyster mushroom are depicted in Fig. 4.45. Twenty-five semi-trained panel members comprising research scholars and staff assigned maximum scores to the 'texture' 'overall acceptability' of the SD samples. Whereas for the MWD samples, 'colour' and 'appearance' scored more. Higher drying rates of MWD must have resulted in better colour and appearance due to shorter drying times. Uniformity of the samples led to better overall acceptability for SD mushrooms. Mounir *et al*. (2020) also reported the highest overall acceptability to the intermittent microwave dried shrimp snacks coupled with instant controlled pressure drop treatment. However, market value of dried shrimps is more for solar and microwave dried samples due to the unhygienic practices adopted in traditional sun drying.

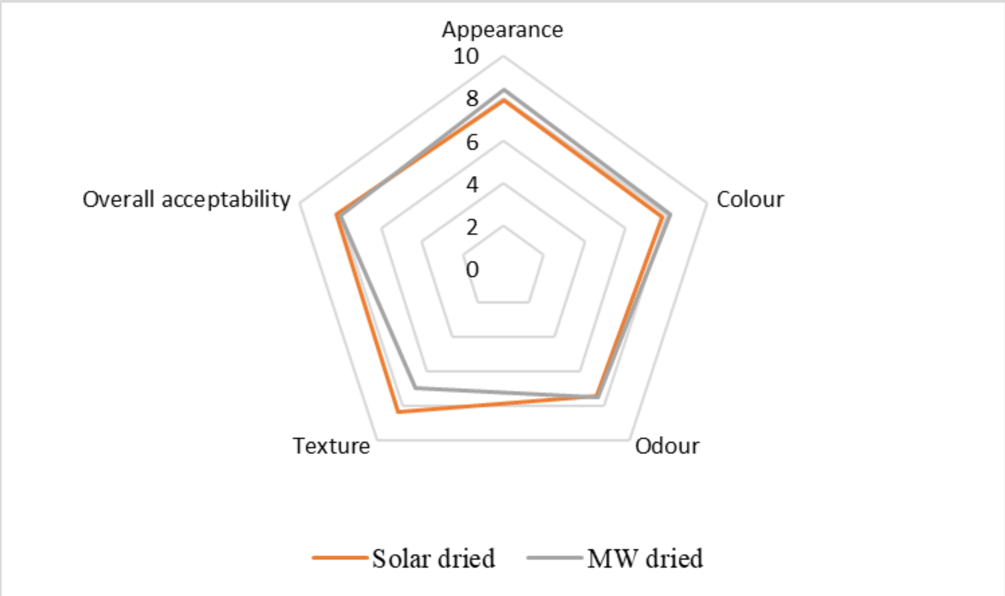


Fig. 4.45 Radar diagram of sensory scores of SD and MWD oyster mushroom

4.12 Economic analysis

Economic analysis was carried out for drying of oyster mushroom in solar-LPG dryer and hot air assisted microwave dryer and is summarized in Table 4.23. The values of economic attributes indicated the economic feasibility of the production of dried oyster mushroom under both drying technologies. However, solar drying is found to be economically more viable than microwave drying technology for the quality production of dried mushrooms. Solar drying was found to have less carbon emissions in terms of electricity usage as 70% of the energy consumption is met with solar radiation. Supplementary heating by LPG is aided only at times of lacunae in availability of solar radiation. Whereas the working of microwave system requires a 1.4 kW magnetron to be run throughout the drying process. But microwave system highly reduced the drying times and thereby the related electricity consumption.

Table 4.23 Economic analysis of solar and microwave drying of oyster mushroom

Sl. No	Parameters	Values	
		Solar -LPG dryer	Hot air assisted microwave dryer
1.	Initial investment (₹)	4,20,000	4,99,000
2.	Operation and maintenance cost (₹) including raw material cost	1,50,000	2,10,000
3.	Salvage value (10% of initial investment) (₹)	42,000	49,000
4.	Life cycle cost (₹)	5,28,000	6,60,000

5.	Annual benefit (₹)*	7,11,000	6,66,150
6.	Benefit-cost ratio	1.11	1.10
7.	Payback period	1.37 years	1.75years

* Dried mushroom output - 10kg/day; price of dried oyster mushroom - ₹ 1500/kg; expenditure - ₹ 1450/day (solar dried) and ₹ 1700/day (microwave dried) ; profit- ₹ 3555/day (solar dried) and ₹3330/day (microwave dried); working days - 200 days/year.

4.13 Storage studies on microwave and solar dried oyster mushrooms

Storage studies were carried out for the oyster mushrooms dried under microwave and solar drying conditions to evaluate the shelf stability of the products, which can add to its commercial value. Experiments were done under wo levels of packaging technologies (ambient and vacuum) and three levels of packaging materials (LDPE, polyester polyethylene laminate and metallised polyester). The specifications of the packaging materials are given below:

- LDPE 150 microns
- Polyester polyethylene laminate (Outer layer: polyester, 12 microns and inner layer: LDPE, 60 microns)
- Metallised polyester (Outer layer: polyester, 12 microns; Middle layer: metallised polyester, 12 microns and inner layer: polyethylene, 60 microns)

4.13.1 Storage studies of microwave dried oyster mushrooms in LDPE (150 μ) packaging under ambient conditions

The quality of oyster mushrooms stored in LDPE (150 μ) packages was evaluated with respect to the moisture content, water activity, shrinkage, rehydration ratio, color, total plate count and proximate composition. Table 4.24 shows that the moisture content of oyster mushrooms varied from 8.14 to 8.98 and 9.41% during the 0, 1 and 2 months of storage. There was significant difference ($p<0.5$) between the values of moisture contents during the storage period. The lesser WVTR and OTR of the LDPE films might have resulted in relatively higher moisture absorption during the consecutive months. However, he increases in moisture contents have directly influences the values of water activity during these periods. The water activity values of 0.468, 0.4 and 0.501 were observed during 0, 1 and 2 months of storage. Guillaume *et al*. (2010) also reported that there was a significant increase in weight loss of the oyster mushrooms during storage owing to moisture absorption and that this may lead to depression in the commercial value and deterioration in the market value of the products. Rehydration ratio of dried oyster mushrooms under LDPE packages were 2.49, 2.43 and 2.41. Statistical analysis showed that there was no significant difference ($p<0.5$) between the samples during storage. The shrinkage of the samples was 39.64, 29.12 and 30.31%, which showed a significant difference during the first two months beyond which the value was non -significant. This may be due to the higher rate of moisture absorption in the initial period of storage. Total colour values (ΔE) during storage were 28.5, 29.12 and 30.31 at 0, 1 and 2 months of storage. There was a decrease in the L values throughout the storage due to the browning of the surface of the mushrooms. During the storage the total colour change of the mushrooms were increasing due to the browning of the samples. Due to loss of compartmentalization s and disruption of cell wall, browning was accelerated due to mixing of enzymes and substrates. Major phenomenon responsible for browning in mushrooms are the two distinct mechanisms of phenol oxidation namely activation of tyrosinase, an enzyme of the family of polyphenol oxidase and spontaneous oxidation. Monophenols are oxidised to o-diphenols and then the former is oxidized to quinines, which spontaneously polymerise to form brown, black or red pigments. Nerya *et al.* (2006) published those biochemical changes during the storage of oyster mushrooms led to the brown discolouration due to polyphenol oxidase activity. The texture of the dried mushrooms during storage was determined in terms of hardness. Hardness values as 7.5, 7.16 and 7.13 N during 0, 1 and 2 months of storage. There was a significant difference ($p<0.5$) in the decrease of hardness values. Total plate count values in cfu/ml were taken as the criterion for assessing the shelf life of the dried products. However, TPC values of 1.2×10^5, 2.4×10^5 and 7.3×10^6 were obtained at 0, 1 and 2 months of storage, which concluded that the storage of dried oyster mushrooms were restricted to 2 months under LDPE (150 µ) under ambient conditions. the proximate analysis of dried oyster mushrooms was carried out and the values obtained showed a decrease in carbohydrates, protein, fat and ash as the storage period increased. During the storage there was an increase in the softness of mushrooms which may be due to the changes in the cell membrane. The hardness of all samples declined during storage. The results are in line to the observations made by Jafri *et al.* (2013) for oyster mushrooms. Zivanovic *et al.* (2000) reported that the textural changes in mushrooms are caused by polysaccharide degradation, shrinkage, vacuole disruption and expansion of inter cellular spaces. *Parentelli et al*. (2007) also investigated on the textural changes during storage of mushrooms and reported that there was an increase in cohesiveness with the increase in storage duration. The increase in chitin content and covalent bonds between chitin and glucan might have increased the rigidity of the wall making it more cohesive.

Table 4.24 Storage studies of microwave dried oyster mushrooms in LDPE (150 µ) packaging under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.14± 1.41 [a]	0.529± 0.10 [a]	2.47± 0.10[a]	39.64± 0.32 [a]	28.5±1. 63 [a]	7.25± 0.14 [a]	1.2× 10^{4} [a]	33.21± 0.41[a]	47.37± 0.29 [a]	1.261.31 ±0.14[a]	9.41± 0.46 [a]
1	8.98± 1.23 [b]	0.531± 0.13[b]	2.43± 0.21 [a]	38.71± 0.24[a]	29.12± 1.21 [b]	7.16± 0.40[b]	2.4× 10^{4} [b]	33.12± 0.30 [b]	47.30± 0.26 [a]	1.24±0.1 3[a]	9.40± 0.16[b]
2	9.41± 0.26 [c]	0.544± 0.32[c]	2.41± 0.24 [a]	38.12± 0.41 [b]	30.31± 1.61[b]	1.3±0. 32[c]	7.3× 105[c]	31.10± 0.45[b]	47.12± 0.24[b]	1.21±020 [b]	9.33± 0.31[c]

4.13.2 Storage studies of microwave dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under ambient conditions

The results of changes in the major quality parameters of dried oyster mushrooms under polyester-polyethylene (72 µ) packaging under ambient conditions is shown in Table 4.25 The moisture content varied as 8.14, 8.81. 9.40, 9.9, 10.42, 10.96, 11.32, 11.57, 11.64% during the storage duration of 0,1,2,3,4,5,6,7 and 8 months. There was a significant difference (p<0.5) between the values of moisture contents, however towards the end of storage the difference was less. The higher storage life of 8 months was obtained in the PE PS packaging due to its lower WVTR and OTR compared to the LDPE package. The increase in the moisture contes gradually increased the water activity values from 0.468 to 0.623 during the beginning and end of storage respectively. The consecutive values of water activity at 2, 3, 4, 5, 6 and 7 months were 0.501, 0.523, 0.541, 0.549, 0.563, 0.581 and 0.598, respectively. The rehydration ratio of dried oyster mushroom was 2.49, 2.41, 2.33, 2.29, 2.24, 2.21, 2.18, 2.12 and 2.10 during the consecutive months. A decreased in rehydration ratio can be attributed to the increase in the shrinkage of the samples. The shrinkage values were 39.64, 41.23, 41.54, 41.62, 42.10, 42.41, 42.67, 42.73 and 43.10% during the consecutive storage period. the disruption of the cellular structure due to gain of moisture during storage mad ethe samples smoother and shrinker. Texture of samples in terms of hardness were obtained to be 7.25, 6.93, 6.41, 6.20, 6.13, 6.10, 6.09, 6.08, and 6.02 N, respectively during 0,1,2,3,4,5,6,7 and 8 months of storage. The decrease was more prominent during the initial period of storage due to the increased migration of moisture. The total plate count of the dried oyster mushroom under PE PS laminated packaging in ambient conditions determined the shelf life of the product. The shelf life of the samples was 8 months owing to the TPC count above the acceptable limit during the 8th month of storage (1.3 × 10 ^{6}). Th proximate analysis carried out during storage was in line to the observations of Zivanovic *et al.* (2000) and Parentelli *et al* (2007). There was a decrease in all the nutritional components throughout the storage period. The values of protein, carbohydrates, fat and ash are quantified in Table 4.25.

Table 4.25 Storage studies of microwave dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.14±1.101^{a}	0.529±0.10^{a}	2.47±0.21^{a}	39.64±0.32^{a}	28.5±0.63^{a}	7.25±0.14^{a}	1.2×10$^{4\ a}$	33.21±0.23^{a}	47.37±0.61^{a}	1.26±0.20^{a}	9.41±0.46^{a}
1	8.81±1.13^{b}	0.531±0.11^{b}	2.41±0.11^{a}	41.23±0.14^{a}	29.31±0.59^{b}	6.93±0.12^{b}	2.4×10$^{4\ b}$	33.20±0.29^{a}	47.21±0.32^{a}	1.25±0.15^{a}	9.38±0.16^{b}
2	9.40±0.16^{c}	0.533±0.20^{b}	2.33±0.20^{b}	41.54±0.20^{b}	31.85±0.20^{c}	6.41±0.30^{b}	4.0×10^{4c}	33.12±0.42^{b}	46.38±0.18^{b}	1.20±0.13^{b}	9.31±0.20^{b}
3	9.90±1.23^{c}	0.541±0.14b^{c}	2.29±0.10^{b}	41.62±0.31c	33.63±0.46^{c}	6.20±0.14^{b}	4.9×10$^{4\ b}$	33.00±0.10^{b}	45.41±0.50^{a}	1.19±0.10^{b}	9.29±0.10^{b}
4	10.42±0.14^{c}	0.549±0.31c^{d}	2.24±0.31^{b}	42.10±0.10^{bc}	34.71±0.50^{cd}	6.13±0.12^{c}	6.3×10^{4c}	28.64±0.31^{c}	43.32±0.13^{b}	1.15±0.26^{b}	9.27±0.41^{c}
5	10.96±1.10^{d}	0.563±0.13^{d}	2.21±0.21^{c}	42.41±0.20^{d}	34.88±0.23^{d}	6.10±0.20^{c}	8.1×10^{54}	28.10±0.28^{c}	41.00±0.64^{a}	1.12±0.51^{c}	9.24±0.12^{c}
6	11.32±0.34^{cd}	0.581±0.11^{d}	2.18±0.25^{cd}	42.67±0.32^{d}	35.10±0.62d	6.09±0.30^{d}	1.0×10^{4c}	28.00±0.21^{c}	40.81±0.10^{b}	1.10±0.14^{c}	9.21±0.52^{d}
7	11.57±0.56^{e}	0.598±0.41^{e}	2.12±0.18^{d}	42.73±0.14^{e}	35.10±1.21^{e}	6.08±0.16^{d}	3.5×10$^{4\ b}$	27.90±0.32^{d}	40.20±0.12^{a}	1.08±0.63^{d}	9.18±0.16^{d}
8	11.64±0.80^{de}	0.623±0.20d^{e}	2.10±0.16^{d}	43.10±0.30^{e}	35.300.15^{e}	6.02±0.32^{c}	1.3×10^{5c}	27.90±0.15^{d}	40.12±0.41^{b}	1.21±0.24^{b}	9.16±0.11^{d}

4.13.3 Storage studies of microwave dried oyster mushrooms in metallised polyester (84 µ) packaging under ambient conditions

The storage studies on the quality parameters of dried mushroom observed that the shelf life was limited to 7 months under metallised polyester in ambient conditions. the moisture contents ranged from 8.14 to 11.44% during the beginning and end of storage respectively. The moisture content values during 1, 2, 3, 4, 5, 6, and 7 months of storage were 8.81, 9.23, 9.97, 10.57, 10.92, 11.41 and 11.44^% respectively (Table 4.26). The increase in moisture content was observed throughout the storage period with a significant difference ($p<0.5$). there was a proportional increment in the values of water activity also. The water activity values obtained during 0,1,2,3,4,5,6 and 7 months of storage were 0.468, 0.493, 0.501, 0.544, 0.553, 0.579, 0.600 and 0.621. a water activity value less than or equal to 0.600 is considered to be safe for dried food products. The vales of rehydration ratio ranged from 2.49 during the beginning of storage to 2.41, 2.39, 2.31, 2.29, 2.18, 2.12 and 2.10 at 1, 2,3,4,5,6 and 7 months of storage. However, the increase in moisture contents reduced the rehydration ratio along with the shrinkage of the product. The shrinkage of the dried samples was 39.64,40.12, 40.64, 40.92, 41.31, 41.24, 42.90 and 43.10% respectively during 0,1,2,3,4,5,6 and 7 months of storage, the hardness values of the samples decreased from 7.25 at the beginning of storage to 7.21, 7.17, 7.12, 7.10, 6.95, 6.92, and 6.90 during the consecutive months. The total plate count at the beginning of storage was 1.2×10^5 cfu/ml which was increased to 3.5×10^6, beyond which the product was unfit for consumption. The proximate contents of the samples showed gradual decrease throughout the storage period. However, the critical factor considered in determining the shelf life of the product was the microbial count in terms of TPC.

Table 4.26 Storage studies of microwave dried oyster mushrooms in metallised polyester (84 µ) packaging under MAP conditions

Storage period	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.14±1 .101 ^{a}	0.529± 0.10 ^{a}		39.64± 0.32 ^{a}	28.5±0. 63 ^{a}	7.25± 0.14 ^{a}	1.2× $10^{5\,a}$	33.21± 0.23^a	47.37± 0.61 ^{a}	1.26±0. 0.12^a	9.41±0 .46 ^{a}
1	8.81±0 .56 ^{b}	0.531± 0.11 ^{b}	2.41± 0.11 ^{a}	40.12± 0.12^a	29.13± 0.19 ^{b}	7.21± 0.15^b	2.4× $10^{5\,b}$	33.10± 0.24^a	47.210 ±0.32 ^{a}	1.24±0. 14^a	9.35±0 .16^b
2	9.23±0 .24^c	0.533± 0.20 ^{b}	2.33± 0.20 ^{b}	40.64± 0.16 ^{b}	29.76± 0.31^b	7.17± 0.21 ^{b}	4.0× 10^{5c}	32.98± 0.41^b	46.50± 0.18^b	1.20±0. 20^b	9.31±0 .20^b
3	9.97±0 .34 ^{c}	0.541± 0.14b ^{c}	2.29± 0.10 ^{b}	40.92± 0.57^c	30.15± 0.14 ^{c}	7.12± 0.10^b	4.9× $10^{5\,bc}$	32.51± 0.20 ^{b}	46.20± 0.50 ^{b}	1.17±0. 24^c	9.27±0 .10^c
4	10.57±	0.549±	2.24±	41.31±	31.23±	7.10±	6.3×	32.33±	46.10±	1.10±0.	9.22±0

	0.61^{d}	0.31c^{d}	0.31^{b}	0.15^{c}	0.12^{cd}	0.32^{c}	10^{5d}	0.23^{bc}	0.13^{b}	16^{c}	.41^{d}
5	10.92± 0.55	0.563± 0.13^{d}	2.21± 0.21^{c}	41.24± 0.14^{d}	31.96± 0.13^{d}	6.95± 0.24^{c}	8.1× 10^{5e}	32.10± 0.48^{c}	45.83± 0.64^{c}	1.09±0. 15^{d}	9.18±0 .12de
6	11.41± 0.28^{d}	0.581± 0.11^{d}	2.18± 0.25^{cd}	42.90± 0.22^{d}	32.50± 0.61d	6.92± 0.10^{d}	1.0× 10^{6e}	31.60± 0.20^{cd}	45.47± 0.10^{cd}	0.95±0. 19de	9.15±0 .52^{e}
7	11.44± 0.66^{e}	0.598± 041^{e}	2.12± 0.18^{d}	43.10± 0.13^{e}	32.70± 0.50^{e}	6.908 ± 0.12^{d}	3.5× 10^{6e}	31.40± 0.13^{d}	45.30± 0.12^{d}	0.92±0. 13^{e}	9.10±0 .16^{e}

4.13.4 Storage studies of microwave dried oyster mushrooms in LDPE (150 µ) packaging under vacuum packed conditions

The moisture content of dried oyster mushrooms showed a gradual in LDPE (150 µ) packaging under vacuum packed conditions (Table 4.27). The moisture content ranged from 8.14 at the beginning of storage to 9.23, 10.51 and 11.23% during 1,2 and 3 months of storage. The storage period of dried oyster mushrooms were extended to 3 months under vacuum packed condition which may be due to the absence of oxygen that affected the respiration rates and metabolism of the dried mushrooms. However, the water activity followed the same trend as that of the moisture content. water activity values were 0.468, 0.529, 0.610 and 0.640 during 0,1,2, and 3 months of storage. Rehydration ratio ranged from 2.49 at the beginning of storage to 2.35, 1020 and 2.10 at 1, 2 and 3 months. Towards the end of storage there was no significant difference in the values of rehydration ratio ($p<0.5$). the shrinkage of the samples was 39.64, 40.23, 41.47 and 41.96 % at 0,1,2, and 3 months of storage under vacuum packed conditions in LDPE (150 µ). Total colour change observed were 28.5, 30.58, 31.83 and 31.90 respectively during 0, 1, 2 and 3 months of storage. The prevalence of vacuum conditions has reduced the rate of deterioration in the LDPE packages as compared to the ambient packed samples. The hardness values decreased form 7.25 N to 7.10, 6.90 and 6.42 N during the consecutive storage period. the total plate count in cfu/ml was 3.2×10^{6} at the end of the third month which further concluded that the shelf life of dried oyster mushrooms was limited to 3 months in LDPE (150 µ) packages under vacuum conditions. Further, the determination of carbohydrates, proteins, fats and ash showed a gradual decrease in the consecutive storage periods (Table 4.27).

Table 4.27 Storage studies of microwave dried oyster mushrooms in LDPE (150 μ) packaging under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.14±1.101 ^{a}	0.529±0.13 ^{a}	2.47±0.10 ^{a}	39.64±0.32 ^{a}	28.5±0.63 ^{a}	7.25±0.14 ^{a}	1.2×10^{5} ^{a}	33.21±0.23 ^{a}	47.37±0.61 ^{a}	1.26±0.12 ^{a}	9.41±0.46 ^{a}
1	9.23±0.44 ^{b}	0.558±0.21 ^{b}	2.35±0.14 ^{a}	40.23±0.31 ^{a}	30.58±0.15 ^{b}	7.10±0.21 ^{b}	6.7×10^{5} ^{b}	33.19±0.24 ^{a}	46.54±0.17 ^{a}	1.24±0.15 ^{a}	9.23±0.10 ^{b}
2	10.51±0.56 ^{c}	0.610±0.25 ^{c}	2.20±0.13 ^{b}	41.47±0.12 ^{b}	31.83±0.14 ^{c}	6.90±0.16 ^{c}	9.0×10^{5} ^{c}	33.10±0.41 ^{b}	46.20±0.28 ^{b}	1.19±0.23 ^{b}	9.20±0.10 ^{b}
3	11.23±0.35 ^{d}	0.640±0.32 ^{c}	2.10±0.24 ^{b}	41.96±0.17 ^{c}	31.90±0.23 ^{c}	6.42±0.20 ^{d}	3.2×10^{6} ^{d}	33.00±0.20 ^{b}	45.90±0.16 ^{b}	1.10±0.31 ^{c}	9.15±0.22 ^{c}

4.13.5 Storage studies of microwave dried oyster mushrooms in polyester-polyethylene (72 μ) packaging under vacuum conditions

The studies on quality parameters of dried oyster mushrooms in polyester polyethylene laminated packages under vacuum conditions is shown the Table 4.28. It is clear from the Table that maximum shelf life of ten months was imparted under this packaging conditions. the moisture contents were 8.14, 8.63, 8.79, 8.91, 9.60, 9.82, 10.24, 10.36, 10.41, 10.44 and 10.48% during 0, 1,2,3,4,5,6,7,8,9 and 10 months of storage. It is also relevant from the values that rate of moisture absorption was relatively less as compared to the other packaging conditions which may be due to the combined effects of packaging material and packaging technology. The water activity values were 0.468 at the beginning of storage and 0.471, 0.483, 0.495, 0.510, 0.523, 0.544, 0.0560, 0.564, 570 and 0.574 during consecutive months of storage. This follows a similar trend as that of the variation in the moisture content. The rehydration ratio was 3.49, 2.45, 2.39, 2.32, 2.30, 2.27, 2.25, 2.18, 2.15, 2.14 and 2.12 during 0, 1,2,3,4,5,6,7,8,9 and 10 months of storage. The reduction in values can be attributed to the molecular rearrangements in the vacuoles of the interstitial spaces due to the abrupt moisture migrations. Shrinkage of the samples increased from 39.64 to 46.70% during the beginning and end of storage. The intermediate values of shrinkage were 41.23, 42.41, 4313, 44.00, 44.90, 45.67, 45.20, 45.70 and 44.60% during the consecutive months. The total colour change obtained were 28.5, 29.30, 29.70, 30.20, 30.90, 34.40, 32.50, 33.30, 34.10, 34.60 and 34.90 during 0, 1,2,3,4,5,6,7,8,9 and 10 months of storage. There was a significant difference

($p<0.5$) during the initial periods of storage. The hardness of the samples varied from 7.25 to 7.20, 7.15, 6.97, 6.92, 6.90, 6.85, 6.81, 6.77, 6.70 and 6.65 N at 0, 1,2,3,4,5,6,7,8,9 and 10 months of storage. The storage life of dried oyster mushroom was limited to ten months in PE PS laminated packages under vacuum conditions as the TPC values were exceeding the safe llevel of consumption (6.35 ×10^{6} cfu/ml). the increase in TPC may be due to the absorption of moisture which initiated the microbial growth. The values of water activity also was above the safe level of 0.60 at this condition. However the proximate analysis showed the general trend of gradual decrease during the storage.

Table 4.28 Storage studies of microwave dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under vacuum conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.14±1.101^{a}	0.529±0.10^{a}	2.47±0.21^{a}	39.64±0.32^{a}	28.5±0.63^{a}	7.25±0.14^{a}	1.2×$10^{5\,a}$	33.21±0.20^{a}	47.37±0.61^{a}	1.26±0. 20^{a}	9.41±0.46^{a}
1	8.63±0.59^{b}	0.5311±0.11^{b}	2.45±0.11^{a}	41.23±0.14^{b}	29.30±0.50^{b}	7.20±0.31^{a}	2.4×$10^{5\,b}$	32.90±0.31^{a}	46.32±0.20^{a}	1.25±0.21^{a}	9.24±0.10^{b}
2	8.79±0.67	0.543±0.20^{b}	2.39±0.20^{b}	42.41±0.20^{b}	29.70±0.10^{c}	7.15±0.20^{b}	2.9×10^{5bc}	32.30±0.12^{b}	46.10±0.12^{b}	1.20±0.12^{b}	9.10±0.15^{b}
3	8.91±0.56^{c}	0.5555±0.14b^{c}	2.32±0.10^{b}	43.13±0.31bc	30.20±0.26^{c}	6.97±0.24^{b}	3.1×$10^{5\,bc}$	32.10±0.15^{b}	45.40±0.41^{b}	1.18±0.15^{b}	8.89±0.10^{b}
4	9.60±0.64^{c}	0.560±0.31c^{d}	2.30±0.31^{b}	44.00±0.10^{bc}	30.90±0.51^{cd}	6.92±0.13b^{c}	3.4×10^{5c}	29.90±0.21^{c}	45.21±0.14^{c}	1.15±0.20^{bc}	8.80±0.21^{c}
5	9.82±0.49^{d}	0.563±0.13^{d}	2.27±0.21^{c}	44.90±0.20^{c}	31.40±0.20^{d}	6.90±0.28b^{c}	4.0×$10^{5\,cd}$	29.70±0.25^{c}	44.30±0.46^{c}	1.13±0.14^{bc}	8.76±0.40^{c}
6	10.24±0.58^{cd}	0.564±0.11^{d}	2.25±0.25^{cd}	45.67±0.32c^{d}	32.50±0.60d	6.85±0.31^{c}	4.3×10^{5cd}	28.20±0.14^{c}	41.90±0.20^{d}	1.10±0.34^{c}	8.61±0.1^{d}
7	10.36±0.66d^{e}	0.50±041^{e}	2.18±0.18^{de}	45.20±0.14^{d}	33.30±0.98^{e}	6.81±0.17^{c}	5.7×$10^{5\,d}$	28.00±0.16^{d}	41.20±0.15^{d}	1.09±0.23^{d}	8.59±0.36^{d}
8	10.41±0.41^{e}	0.574±041^{e}	2.15±0.18^{de}	45.70±0.14^{e}	34.10±1.21^{e}	6.77±0.23^{d}	6.3×$10^{5\,de}$	27.60±0.30^{de}	40.30±0.20^{de}	0.93±0.30^{de}	8.53±0.15^{d}
9	10.44±0.60d^{e}	0.5760±041^{e}	2.14±0.18^{e}	46.40±0.14^{e}	34.60±0.21^{e}	6.70±0.21^{de}	8.2×10^{5de}	27.30±0.24^{de}	39.40±0.10^{e}	0.91±0.12^{e}	8.52±0.14^{d}
10	10.48±0.42^{e}	0.584±041^{e}	2.12±0.18^{e}	46.70±0.14^{e}	34.90±0.55^{e}	6.65±0.11^{e}	2.1×$10^{6\,e}$	27.10±0.15^{e}	39.20±0.13^{e}	0.90±0.15^{de}	8.51±0.12^{d}

4.13.6 Storage studies of microwave dried oyster mushrooms in metallised polyester (72 μ) packaging under vacuum conditions

The shelf life of dried oyster mushroom in metallized polyester packages under vacuum conditions were studied and depicted in Table 4.29. The moisture content of the dried samples was 8.14, 8.90, 9.70, 10.50, 11.30 and 12.20% at 0,1,2,3,4,5 and 6 months which showed a significant difference ($p<0.5$) during storage. From this it is clear that PE PS laminated packages offered better results in storage compared to metallized polyester. The water activity values obtained during storage were 0.468, 0.519, 0.532, 0.549, 0.568, 0.611 and 0.623 respectively at 0, 1, 2, 3, 4, 5 and 6 months. The rehydration ratio was determined to be 2.49, 2.38, 2.24, 2.20, 2.17, 2.11 and 2.10 during the consecutive storage periods. Shrinkage of the samples increased from 39.64 to 43.14% respectively during initial and final storage conditions. the intermediate values of shrinkage were 40.23, 141.19, 41.96, 42.34 and 43.10%. the total colour change of the samples was 28.50, 28.93, 29.56, 30.12, 31.23, 21.55 and 31.67 respectively at 0, 1, 2, 3, 4, 5 and 6 months. This was due to the continuous decrease in the L value and increase in and b hunter colour values. The shelf life was limited to six months owing to the unsafe limits of TPC (3.2×10^6 cfu/ml). this shows that apart from packaging conditions, packaging material has a major role in determining the shelf life of the products. The higher atmospheric temperature and relative humidity might have attributed to the absorption of moisture in the packages that finally led to the deterioration of the dried products. The proximate analysis of the dried samples were carried out and is represented in the Table 4.29. Plate 4.10 shows oyster mushroom under vacuum [acakaged condition in various packaging materials.

Table 4.29 Storage studies of microwave dried oyster mushrooms in metallised polyester (84 µ) packaging under vacuum conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.14±1.101^{a}	0.529±0.10^{a}	2.47±0.14^{a}	39.64±0.32^{a}	28.5±0.63^{a}	7.25±0.14^{a}	1.2×10^{5a}	33.21±0.20^{a}	47.37±0.61^{a}	1.26±0. 20^{a}	9.41±0.46^{a}
1	8.90±0.23^{b}	0.539±0.11^{b}	2.38±0.10^{b}	40.23±0.23^{b}	28.93±0.24^{b}	7.14±0.32^{b}	4.3×10^{5b}	33.10±0.25^{a}	47.30±0.31^{a}	1.20±0.15^{a}	9.40±0.26^{b}
2	9.70±0.60	0.542±0.20^{b}	2.24±0.22^{b}	41.19±0.30^{c}	29.56±0.15^{c}	7.15±0.18^{b}	5.61 0^{5c}	32.91±0.10^{b}	47.25±0.22^{b}	1.10±0.20^{b}	9.36±0.10^{c}
3	10.50±0.55^{c}	0.549±0.14b^{c}	2.20±0.15^{b}	41.96±0.15^{c}	30.12±0.20^{c}	7.10±0.15^{c}	6.2×10^{5c}	32.85±0.34^{b}	47.12±0.40^{b}	0.93±0.17^{c}	9.20±0.15^{d}
4	11.30±0.42^{d}	0.568±0.31c^{d}	2.17±0.23^{bc}	42.34±0.12^{d}	31.23±0.16^{cd}	6.88±0.10b^{d}	7.1×10^{5d}	32.60±0.11^{c}	47.10±0.26^{c}	0.90±0.21^{cd}	9.15±0.14^{e}
5	11.90±0.49^{d}	0.611±0.13^{e}	2.11±0.11^{c}	43.10±0.23^{e}	31.55±0.25^{d}	6.82±0.20b^{e}	9.1×10^{5d}	32.50±0.20^{c}	46.95±0.15^{d}	0.89±0.32d	9.12±0.20^{e}
6	12.20±0.35^{e}	0.623±0.11^{e}	2.10±0.15^{d}	43.14±0.20c^{e}	31.67±0.32^{d}	6.80±0.27^{e}	3.2×10^{6e}	32.40±0.24^{c}	46.35±0.22^{d}	0.87±0.14^{e}	9.10±0.15^{e}

Plate 4.10 Oyster mushroom under vacuum packaged conditions

Plate 4.11 Oyster mushroom under packaged under MAP conditions

4.13.7 Storage studies of solar dried oyster mushrooms in LDPE (150 µ) packaging under ambient conditions

Storage studies on solar dried oyster mushrooms in LDPE (150 µ) under ambient conditions were carried out by determining the moisture content, water activity, rehydration ratio, shrinkage, total colour change, texture , microbial load and proximate analysis (Table 4.30). The increase in moisture content from the beginning of storage (8.21%) through the consecutive months (8.90% and 9.56%) was due to the lower water vapour and oxygen permeabilities of LDPE film. There was n increment in the weight of the sample owing to the moisture uptake. The higher relative humidity of the ambient conditions also added for moisture migration. Water activity values of 0.497, 0.512 and 0.531 were obtained during 0, 1 and 2 months of storage. Water activity had a direct relation ship with moisture content as it represented the water available for the growth of microorganisms. Rehydration ratios were calculated during 0(2.21), one (2.27) and two (2.13) months of storage. Shrinkage of the samples at 0, 1 and 2 months were 46.42, 46.50 and 46.75% respectively. The hardness of the sample decreased with the uptake of moisture and reduced from 9.46 N (beginning of storage) to 9.10 N (at the end of storage). The total plate count of 1.3×10^3cfu/ml was the maximum possible limit of shelf stability beyond which the product was found to be unfit for consumption. Hence the shelf life of solar dried oyster mushroom was found to be only two months in LDPE (150 µ) packaging under ambient conditions. proximate analysis of the samples were carried out and a decreases in the nutritional components with respect to storage period was observed ($p<0.5$).

Table 4.30 Storage studies of solar dried oyster mushrooms in LDPE (150 µ) packaging under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.21±1.20 ^{a}	0.554±0.12 ^{a}	2.21±0.19 ^{a}	46.42±0.54 ^{a}	35.31±1.23 ^{a}	9.46±0.54 ^{a}	$3.9\times10^{5\,a}$	31.37±0.45 ^{a}	47.51±0.14 ^{a}	1.31±0.20 ^{a}	8.39±0.12 ^{a}
1	8.90±1.12 ^{b}	0.562±0.10 ^{b}	2.27±0.22 ^{a}	46.50±0.20^{a}	36.42±1.21 ^{b}	9.16±0.10^{b}	$4.3\times10^{5\,b}$	30.48±0.21 ^{b}	46.16±0.41 ^{a}	1.24±0.23^{a}	8.20±0.21^{b}
2	9.56±0.24 ^{c}	0.571±0.30 ^{c}	2.31±0.41 ^{a}	46.75±0.31 ^{b}	38.31±1.23^{b}	9.1±0.21^{c}	1.3×10^{6c}	328.27±0.20^{b}	44.23±0.12^{b}	1.20±0.12^{b}	8.18±0.51^{c}

4.13.8 Storage studies of solar dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under ambient conditions

Quality parameters of solar dried oyster mushrooms were determined in PE-PS packaging material under ambient conditions and is depicted in the Table 4.31. Moisture content of the dried oyster mushroom were 8.21, 8.80, 9.23, 9.64, 10.21, 10.36, 10.93, 11.46 and 11.77% during the storage at 0, 1, 2, 3, 4, 5, 6, 7 and 8 months. The lesser rate of moisture migration to the samples is attributed to the increased barrier properties of PE-PS laminated package. The water activity values obtained during the storage were 0.497, 0.512, 0.543, 0.565, 0.571, 0.584, 0.610, 0.622 and 0.631 respectively during 0,1, 2, 3, 4, 5, 6, 7 and 8 months. The rehydration ratio decreased from 2.21 to 1.93 during the beginning to the end of the storage period with the intermediate values of 2.20, 2.18, 2.15, 2.11, 2.04, 1.98 and 1.94 respectively at 1, 2, 3, 4, 5, 6 and 7 months of storage. The shrinkage of the product was maximum at the end of storage (47.30%) and minimum at the beginning of storage (46.42). there was significant difference ($p<0.5$) in the shrinkage value throughout the storage period. Shrinkage during 1, 2, 3, 4, 5, 6 and 7 months of storage were 46.49, 46.81, 46.84, 46.93, 47.12, 47.14 and 47.27% respectively. The total colour change during storage were 35.31, 36.46, 36.89, 37.12. 37.83, 38.21, 38.35, 38.49 and 38.99 respectively during 0, 1, 2, 3, 4, 5, 6, 7 and 8 months of storage. The texture of the dried oyster mushrooms were determined in terms of its hardness and was found to reduce during the storage period. the hardness values obtained during 0, 1, 2, 3, 4, 5, 6, 7 and 8 months of storage were 9.46, 9.20, 9.10, 8.97, 8.90, 8.84, 8.80, 8.76 and 8.72 N respectively. The TPC values in cfu/ml determined the end of shelf stability and was found to be 4.36×10^6 cfu/ml. hence the shelf life of solar dried oyster mushroom in PE-PS (72 µ) under ambient conditions was limited to 8 months. The proximate analysis of dried oyster mushrooms are shown in the Table and follows a decreasing trend with the storage period. Also, there was a significant difference (p<0.5) between the values of protein, carbohydrates, fat and ash which reduced during storage.

Table 4.31 Storage studies of solar dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under MAP conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.21±1.20 a	0.554±0.12 a	2.21±0.19 a	46.42±0.54 a	35.31±1.23 a	9.46±0.54 a	3.9×10^5 a	31.37±0.45 a	47.51±0.14 a	1.31±0.20 a	8.39±0.12 a
1	8.80±0.59 b	0.562±0.11 b	2.20±0.11 a	46.49±0.20b	36.46±0.50 b	9.20±0.33b	4.1×10^5 b	30.30±0.42b	47.00±0.22 a	1.29±0.15b	8.33±0.20b
2	9.23±0.52	0.563±0.20 b	2.18±0.20 b	46.81±0.22 b	36.89±0.10c	9.10±0.25 c	4.6×10^{5}bc	30.12±0.10b	46.4±0.13b	1.27±0.12bc	8.27±0.17b
3	9.64±0.39 c	0.565±0.14b c	2.15±0.10 b	46.84±0.31bc	37.12±0.26 c	8.97±0.32cd	5.910 5 bc	29.89±0.15 bc	45.90±0.14 b	1.23±0.16bc	8.25±0.12b
4	10.21±0.62 c	0.511±0.31c d	2.11±0.31 b	46.93±0.33c	37.83±0.51cd	8.90±0.15bd	8.1×10^{5}c	29.42±0.20c	45.20±0.14c	1.12±0.18c	8.21±0.23c
5	10.36±0.45d	0.584±0.13 d	2.04±0.21 c	47.12±0.27c	38.21±0.20d	8.84±0.28bd	8.3×10^5 cd	29.14±0.16c	45.12±0.26 c	1.10±0.24d	8.18±0.44c
6	10.93±0.50 cd	0.610±0.11 d	1.98±0.25 cd	47.14±0.32cd	38.35±0.60d	8.80±0.11de	9.7×10^{5}cd	29.12±0.24c	44.80±0.20d	1.09±0.30d	8.12±0.14d
7	11.46±0.61de	0.622±041 e	1.94±0.18 de	47.27±0.15d	38.49±0.98 e	8.76±0.27e	1.2×10^6 d	28.69±0.15d	44.70±0.25d	0.93±0.15de	8.10±0.30d
8	11.77±0.44e	0.631±041 e	1.93±0.18 de	47.30±0.14e	38.99±1.21 e	8.72±0.56e	4.3×10^6 de	28.66±0.12 d	44.50±0.30de	0.89±0.28e	7.80±0.12e

4.13.9 Storage studies of solar dried oyster mushrooms in metallised polyester (84 µ) packaging under MAP conditions

The storage studies on solar dried oyster mushrooms in metallized polyester under ambient packaging conditions were carried out and is depicted in Table 4.32. there was an increase in the moisture contents of the sample from 8.21 during the beginning to 8.31, 9.54, 10.12, 10.24, 10.67, 11.23 and 11.33% during the 1, 2,2 3, 4, 5, 6 and 7 months of storage. The increase in moisture content was more prominent (significant at $p<0.5$) during the initial period of storage. This may be due to the higher water vapour pressure gradient between the ambient conditions and the samples within the package. However, the weight of samples increased due to moisture absorption. The water activity values obtained were 0.497, 0.521, 0.540, 0.535, 0.571, 0.693, 0.610 and 0.653 respectively during beginning and consecutive months of storage. The rehydration ratio obtained during the beginning of storage was 2.21 which reduced to 1.86 at the end of storage. The intermediate values of rehydration ratio at 1, 2, 3, 4, 5, 6 and 7 months of storage were 2.12, 2.08, 1.97, 1.95, 1.92 an d1.87 respectively. The more the abrupt migration of moisture, the more will be the changes in the rehydration ratio. Rehydration ratio is also dependent on the rate of shrinkage of the samples which was obtained as 46.42, 46.81, 47.12, 17.39, 47.40, 48.10, 48.80 and 48.9% respectively during 0, 1, 2, 3, 4, 5, 6 and 7 months of storage. The total colour change of the samples were due to the decrease in the Lightness value and increase in the a and b Hunter colour values. the total colour change obtained were 35.31, 36.42, 37.10, 38.67, 38.10, 38.20, 38.40 and 38.50 respectively during 0, 1, 2, 3, 4, 5, 6 and 7 months of storage. TPC in cfu/ml of the samples were $3.9\times10^{5,}$ 4.4×10^{5}, 5.6×10^{5}, 7.7×10^{5}, 8.1×10^{5}, 9.2×10^{5} and 4.2×10^{6} respectively. Hence the shelf life of solar dried oyster mushrooms we\as limited to 7 months in metallized polyester under ambient conditions. proximate analysis was also carried out and the values are represented in Table 4.31.

Table 4.32 Storage studies of solar dried oyster mushrooms in metallised polyester (84 µ) packaging under MAP conditions

Storage period	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/ Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.21±1.20 ^{a}	0.554±0.12 ^{a}	2.21±0.19 ^{a}	46.42±0.54 ^{a}	35.31±1.23 ^{a}	9.46±0.54 ^{a}	3.9×10$^{5\,a}$	31.37±0.45 ^{a}	47.51±0.14 ^{a}	1.31±0.20 ^{a}	8.39±0.12 ^{a}
1	8.31±0.16^{b}	0.559±0.20 ^{b}	2.12±0.20 ^{b}	46.81±0.32 ^{b}	36.42±0.11^{b}	9.21±0.10 ^{b}	4.4×10^{5b}	31.35±0.40^{a}	46.60±0.28^{b}	1.30±0.25^{b}	8.32±0.23^{b}
2	9.54±0.30 ^{c}	0.560±0.14b ^{c}	2.08±0.13 ^{b}	47.12±0.17^{c}	37.10±0.10 ^{c}	8.56±0.51^{c}	5.6×10$^{5\,c}$	31.30±0.10 ^{b}	46.42±0.52 ^{b}	1.29±0.12^{c}	8.25±0.11^{c}
3	10.12±0.66 ^{d}	0.565±0.31c ^{d}	1.97±0.11 ^{c}	47.39±0.10 ^{c}	38.67±0.22^{cd}	8.12±0.12^{c}	7.7×10^{5cd}	31.00±0.23^{bc}	46.00±0.17^{b}	1.25±0.20^{c}	8.21±0.40^{d}
4	10.24±0.54 ^{d}	0.571±0.30 ^{d}	1.95±0.31 ^{c}	47.40±0.15^{d}	38.10±0.14^{d}	7.90±0.34^{de}	8.1×10^{5d}	30.50±0.41^{c}	45.60±0.60 ^{c}	1.22±0.40^{d}	8.15±0.32^{de}
5	10.67±0.29 ^{de}	0.693±0.12 ^{d}	1.92±0.10 ^{d}	48.10±0.12^{d}	38.20±0.60^{d}	7.65±0.17^{d}	9.2×10^{6de}	29.88±0.32^{cd}	45.40±0.14^{cd}	1.12±0.50^{de}	8.12±0.22^{e}
6	11.23±0.40^{e}	0.610±0.21 ^{e}	1.87±0.41 ^{d}	48.80±0.16^{e}	38.40±0.21 ^{e}	7.41±0.20^{e}	9.8×10^{5e}	29.85±0.10 ^{d}	45.20±0.02^{d}	1.10±0.16^{e}	8.10±0.26^{e}
7	11.33±0.16^{e}	0.653±0.15^{e}	1.86±0.20 ^{d}	48.90±0.11^{e}	38.50±0.22 ^{e}	7.23±0.14^{e}	4.2×10^{6e}	29.80±0.31 ^{d}	45.15±0.10^{d}	0.94±0.23^{e}	7.98±0.15^{e}

4.13.10 Storage studies of solar dried oyster mushrooms in LDPE (150 µ) packaging under vacuum packed conditions

Storage studies on solar dried oyster mushrooms with respect to various packaging materials are represented in the Table 4.33. it is evident from the Table that as storage interval increased, moisture content also increased due to the migration of water vapour from the atmosphere in to the packaging material. However, the rate of migration is depended on the thickness and type of packaging material. The moisture contents of solar dried mushroom were 8.21, 9.11, 10.42 and 11.20% at 0m, 1, 2 and 3 months of storage. Statistical analysis showed a significant difference ($p<0.5$) in the moisture contents due to the lower barrier properties of LDPE package. The water activity of solar dried mushrooms in LDPE package were 0.497, 0.523, 0.667 and 0.698 respectively during 0, 1, 2 and 3 months of storage. The safe limit of water activity for dried products ins 0.600. Rehydration ratio of the solar dried mushroom was initially found to be 2.21 which decreased to 2.18, 2.10 and 1.98 during consecutive months of storage. Shrinkage of the solar dried oyster mushrooms increased from 46.42 to 49.61% during the beginning and end of storage period respectively. Intermediate values of shrinkage were 47.44, 48.52 and 49.61% respectively during the first, second and the third months of storage. The total colour change of the products was witnessed with respect to the decrease in the L vale and increase in the a and b Hunter colour values. the values obtained for total colour change were 35.31, 36.32, 37.41 and 38.21 during 0, 1, 2 and 3 months of storage. The texture of the solar dried oyster mushrooms were determined with respect to their hardness values. the hardness obtained were 9.46, 8.21, 7.99 and 6.30 N during 0, 1, 2 and 3 months of storage. The shelf life of solar dried oyster mushroom in LDPE (150 µ) under ambient conditions were determined with respect to the safe level of microbial count present in the products. Hence at 3-month storage, the microbial count was found to be 2.1×10^{6} which concluded that the safe storage under this packaging was limited to 3 months.

Table 4.33 Storage studies of solar dried oyster mushrooms in LDPE (150 µ) packaging under vacuum packed conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.21±1.20^{a}	0.554±0.12^{a}	2.21±0.19^{a}	46.42±0.54^{a}	35.31±1.23^{a}	9.46±0.54^{a}	3.9×10^{5a}	31.37±0.45^{a}	47.51±0.14^{a}	1.31±0.20^{a}	8.39±0.12^{a}
1	9.11±0.55^{b}	0.562±0.15^{b}	2.18±0.14^{a}	47.44±0.24^{b}	36.32±0.20^{b}	8.21±0.21^{b}	4.2×10^{5b}	30.30±0.25^{b}	45.12±0.21^{b}	1.30±0.23^{a}	8.20±0.11^{b}
2	10.42±0.24^{c}	0.667±0.24^{c}	2.10±0.26^{b}	48.52±0.10^{c}	37.41±0.32^{c}	7.99±0.16^{c}	6.9×10^{5c}	29.54±0.32^{b}	42.32±0.30^{c}	1.25±0.12^{b}	8.18±0.10^{c}
3	11.20±0.62^{d}	0.698±0.20^{a}	1.98±0.15^{c}	49.61±0.12^{d}	38.21±0.30^{c}	6.30±0.14^{d}	2.1×10^{6d}	26.32±0.25^{c}	40.54±0.24^{d}	1.21±0.20^{b}	8.12±0.13^{d}

4.13.11 Storage studies of solar dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under vacuum conditions

Maximum storage life for solar dried oyster mushroom was obtained in PE-PS laminated packages under vacuum packaged conditions. The lower oxygen and water vapour permeability of the PE-PS packages along with the vacuum conditions extended the shelf stability. The moisture contents of the samples at the beginning of storage were 8.21% which decreased to 8.44, 8.56, 8.81, 8.93, 9.59, 10.21, 10.41, 10.63, 11.21 and 11.24% during one to ten months of storage respectively. The increase in moisture content were not abrupt, but gradual establishing the equilibrium conditions. The water activities during 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 months of storage were 0.554, 0.562, 0.564, 0.569, 0.572, 0.580, 0.585, 0.591, 0.594, 0.597 and 0.610 respectively. It is evident from the Table 4.39 that the rise in water activity was gradual which further depended on the rate of moisture migration into the packaging material. The rehydration ratio varied from 2.21 at the beginning of storage of 1.81 at the end of storage. The intermediate values of rehydration ratio were 2.18, 2.12, 2.08, 2.10, 1.98, 1.93, 1.87, 1.85 and 1.82 during 1, 2, 3, 4, 5. 6, 7, 8 and 9 months of storage. The shrinkage of the samples increased during the storage which was due to the lack of cellular rigidity of the samples owing to the changes due to atmospheric conditions. the obtained values of shrinkage were 46.42, 47.18, 47.32, 48.14, 48.26, 48.49, 48.52, 48.61, 48.79, 49.52 and 49.64% respectively during 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 months of storage. The total colour change varied from 35.31 at the beginning of storage to 35.49, 36.32, 36.56, 36.84, 37.36, 38.20, 38.46, 38.93, 39.40 and 39.60 respectively at 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 months of storage. The hardness of samples decreased during storage from 9.46 to 8.75 N. the intermediate values of hardness were 9.40, 9.35, 9.27, 9.15, 9.10, 8.96, 8.85, 8.80 and 8.78 N. The total plate count of the solar dried mushrooms in PE-PS laminate under vacuum packaged conditions were 3.9×10^5, 4.2×10^5, 6.1×10^5, 6.6×10^5, 8.7×10^5, 8.9×10^5, 4.3×10^5, 9.1×10^5, 2.2×10^6 and 3.1×10^6 respectively during, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 months of storage.

Thus, the shelf life of solar dried oyster mushrooms was limited to 10 months in PE-PS laminate under vacuum packed conditions. proximate analysis of the samples were performed during one month intervals and the results were tabulated (Table 4.34).

Table 4.34 Storage studies of solar dried oyster mushrooms in polyester-polyethylene (72 µ) packaging under vacuum conditions

Storage period(months)	Moisture content (%)	Water activity	Rehydra-tion ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.21±1.20^{a}	0.554±0.12^{a}	2.21±0.19^{a}	46.42±0.54^{a}	35.31±1.23^{a}	9.46±0.54^{a}	3.9×10^{5} ^{a}	31.37±0.45^{a}	47.51±0.14^{a}	1.31±0.20^{a}	8.39±0.12^{a}
1	8.44±0.59^{b}	0.562±0.15^{b}	2.18±0.61^{a}	47.18±0.24^{b}	35.49±0.52^{b}	9.40±0.42^{a}	4.2×10^{5} ^{b}	30.32±0.31^{a}	47.30±0.20^{a}	1.29±0.21^{a}	8.31±0.10^{b}
2	8.56±0.67	0.564±0.30^{b}	2.12±0.54^{b}	47.32±0.28^{b}	36.32±0.17^{c}	9.35±0.27^{b}	6.1×10^{5} ^{bc}	30.10±0.12^{b}	47.10±0.14^{b}	1.21±0.16^{b}	8.29±0.19^{b}
3	8.81±0.67	0.569±0.24 b^{c}	2.08±0.17^{b}	48.14±0.33^{bc}	36.56±0.21^{c}	9.27±0.21^{b}	6.6×10^{5} ^{bc}	29.62±0.10^{b}	46.32±0.41^{b}	1.18±0.15^{b}	8.27±0.10^{b}
4	8.93±0.56^{c}	0.577±0.32 c^{c}	2.10±0.43^{b}	48.26±0.50^{bc}	36.84±0.55^{cd}	9.15±0.18^{bc}	8.7×10^{5} ^{c}	29.51±0.26^{c}	46.20±0.14^{c}	1.15±0.20^{bc}	8.22±0.31^{c}
5	9.59±0.64^{c}	0.580±0.43^{d}	1.98±0.22^{c}	48.49±0.25^{c}	37.36±0.25^{d}	9.10±0.20b^{c}	8.9×10^{5} ^{cd}	29.30±0.25^{c}	46.15±0.46^{c}	1.02±0.14^{bc}	8.18±0.40^{c}
6	10.21±0.49^{d}	0.585±0.17^{d}	1.93±0.35^{cd}	48.52±0.32 c^{d}	38.20±0.63^{d}	8.96±0.30	4.3×10^{5} ^{d}	29.10±0.14^{c}	45.30±0.20^{d}	1.04±0.34^{c}	8.15±0.1^{d}
7	10.41±0.58^{cd}	0.591±21^{d}	1.87±0.18^{de}	48.61±0.18^{d}	38.20±0.0^{e}	8.85±0.14^{c}	9.1×10^{5} ^{e}	28.56±0.14^{c}	44.90±0.15^{d}	0.98±0.23^{d}	8.10±0.36^{d}
8	10.63±0.66^{e}	0.594±42^{d}	1.85±0.28^{de}	48.79±0.26^{e}	38.93±0.59^{e}	8.80±0.26^{d}	9.8×10^{5} ^{de}	28.17±0.16^{d}	43.20±0.20^{de}	0.93±0.30^{de}	7.85±0.15^{d}
9	11.21±0.41^{e}	0.597±26^{d}	1.82±0.10^{e}	49.52±0.19^{e}	39.40±0.24^{e}	8.78±0.11^{de}	2.2×10^{6} ^{f}	28.00±0.30^{de}	43.00±0.10^{e}	0.92±0.12^{e}	7.72±0.14^{d}
10	11.24±0.60d^{e}	0.610±15^{e}	1.81±0.24^{e}	49.64±0.26^{e}	39.60±0.50^{e}	8.75±0.33^{e}	3.1×10^{6} ^{f}	28.00±0.24^{de}	42.80±0.13^{e}	0.90±0.15^{de}	7.60±0.12^{d}

4.13.12 Storage studies of solar dried oyster mushrooms in metallised polyester (84 μ) packaging under vacuum conditions

The shelf life of solar dried oyster mushroom in metallized polyester packages under vacuum conditions were studied and depicted in Table 4.35. The shelf life of solar dried oyster mushroom in metallized polyester packages under vacuum conditions were studied showed moisture content of 8.21, 8.59, 9.23, 9.98, 10.12, 10.66 and 11.21% at 0,1,2,3,4,5 and 6 months which showed a significant difference (p<0.5) during storage. From this it is clear that PE PS laminated packages offered better results in storage compared to metallized polyester. The water activity values obtained during storage were 0.554, 0.559, 0.564, 0.573, 0.577, 0.589 and 0.610 respectively at 0, 1, 2, 3, 4, 5 and 6 months. The rehydration ratio was determined to be 2.21, 2.20, 2.15, 2.12, 2.08, 2.05 and 1.97 during the consecutive storage periods. Shrinkage of the samples increased from 46.42 to 48.12% respectively during initial and final storage conditions. the intermediate values of shrinkage were 46.64, 46.98, 47.22, 47.48, 48.10 and 48.12%. The total colour change of the samples was 35.31, 36.42, 36.90, 37.12, 37.63, 38.10, 38.12 respectively at 0, 1, 2, 3, 4, 5 and 6 months. This was due to the continuous decrease in the L value and increase in and b hunter colour values. The shelf life was limited to six months owing to the unsafe limits of TPC (2.2 $\times 10^6$ cfu/ml). this shows that apart from packaging conditions, packaging material has a major role in determining the shelf life of the products. The higher atmospheric temperature and relative humidity might have attributed to the absorption of moisture in the packages that finally led to the deterioration of the dried products. The proximate analysis of the dried samples was carried out and is represented in the Table 4.35.

Table 4.35 Storage studies of solar dried oyster mushrooms in metallised polyester (84 μ) packaging under vacuum conditions

Storage period (months)	Moisture content (%)	Water activity	Rehydration ratio	Shrinkage (%)	Total colour change	Texture/Hardness (N)	Total plate count (cfu/ml)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)
0	8.21±1.20 ^{a}	0.554±0.12 ^{a}	2.21±0.19 ^{a}	46.42±0.54 ^{a}	35.31±1.23 ^{a}	9.46±0.54 ^{a}	3.9×$10^{5\,a}$	34.37±0.45 ^{a}	47.51±0.14 ^{a}	1.31±0.20 ^{a}	8.39±0.12 ^{a}
1	8.59±1.10 ^{b}	0.559±	2.2±0.15 ^{a}	46.64±0.21 ^{a}	36.42±1.10 ^{b}	9.21±0.15 ^{b}	4.2×$10^{5\,b}$	31.30±0.98 ^{b}	47.50±0.52 ^{a}	1.30±0.34 ^{a}	8.30±0.35 ^{b}

		0.10^{b}									
2	9.23±0.90^{c}	0.564±0.21^{c}	2.15±0.12^{a}	46.98±0.20^{b}	36.90±1.54^{b}	9.0±0.67^{c}	5.1×10^{5c}	31.29±0.23^{b}	47.21±0.10^{b}	1.28±0.15^{b}	8.20±0.64^{c}
3	9.98±1.23^{c}	0.573±0.10^{c}	2.12±0.10^{b}	47.22±0.17^{c}	37.12±1.89^{c}	8.90±0.40^{c}	7.6×10$^{5\ d}$	31.50±0.10^{b}	47.10±0.13^{c}	1.25±0.56^{c}	8.18±0.25^{c}
4	10.12±0.85^{d}	0.577±0.13^{d}	2.08±0.21^{b}	47.18±0.10^{a}	37.63±1.5^{d}	8.80±0.35^{d}	8.5×10^{5d}	30.20±0.56^{c}	47.00±0.62^{c}	1.20±0.40^{d}	8.12±0.80^{d}
5	10.66±1.12^{d}	0.589±0.0^{d}	2.05±0.300.20^{b}	48.48±0.87^{d}	38.10±1.6^{e}	8.72±0.26^{d}	9.1×10$^{5\ e}$	30.10±0.50^{c}	46.4±0.50^{d}	1.12±0.29^{e}	8.10±0.10^{d}
6	11.21±1.14^{e}	0.610±0.20^{e}	1.97±0.14^{c}	48.12±0.41^{d}	38.12±1.20^{e}	8.70±0.60^{e}	2.2×0$^{6\ e}$	30.00±0.40^{c}	46.2±0.20^{d}	1.10±0.42^{e}	8.00±0.24^{e}

Naik *et al*. (2005) published that the shelf life of oyster mushrooms were extended to more than three months under vacuum packaged conditions, whereas the shelf life was limited to 2 months under ambient packaged conditions. both studies were done in 75 micro (300 gauge) packages.

During the storage the total colour change of the mushrooms were increasing due to the browning of the samples. Due to loss of compartmentalization s and disruption of cell wall, browning was accelerated due to mixing of enzymes and substrates. Major phenomenon responsible for browning in mushrooms are the two distinct mechanisms of phenol oxidation namely activation of tyrosinase, an enzyme of the family of polyphenol oxidase and spontaneous oxidation. Monophenols are oxidised to o-diphenols and then the former is oxidized to quinines, which spontaneously polymerise to form brown, black or red pigments. Nerya *et al.* (2006) published those biochemical changes during the storage of oyster mushrooms led to the brown discolouration due to polyphenol oxidase activity.

During the storage there was an increase in the softness of mushrooms which may be due to the changes in the cell membrane. The hardness of all samples declined during storage. The results are in line to the observations made by Jafri *et al.* (2013) for oyster mushrooms. Zivanovic et al. (2000) reported that the textural changes in mushrooms are caused by polysaccharide degradation, shrinkage, vacuole disruption and expansion of inter cellular spaces. Parentelli *et al.* (2007) also investigated on the textural changes during storage of mushrooms and reported that there was an increase in cohesiveness with the increase in storage duration. The increase in chitin content and covalent bonds between chitin and glucan might have increased the rigidity of the wall making it more cohesive.

Summary and Conclusion

CHAPTER V
SUMMARY AND CONCLUSION

This section depicts the major findings of the research work involved in development of microwave convective dryer, performance evaluation of the dryer, optimization of the process conditions for shrimp and oyster mushroom, quality evaluation of the dried products, comparison on microwave and solar drying of shrimp and oyster mushroom and storage studies under different packaging materials and packaging conditions of the dried products and economic analysis of drying under hot air assisted microwave and solar drying conditions.

- Hot air assisted microwave drying system comprised of a drying chamber, conveyor belt, magnetron to generate microwaves at frequency of 2450 MHz±50 MHz, hot air generation system with air heater, axial fan and other controls. Drying chamber consisted of a single layer of conveyor belt of dimension 1.5 × 0.5 m, being derived from dryer design calculations with respect to the capacity and product bulk density. Samples being fed manually were conveyed along the belt made of heat resistant Teflon (PTFE) over SS rollers. Magnetron of 1.45 kW rated power, operating at 2450 MHz±50 MHz generated the microwaves for heating the products in the drying chamber.
- Hot air generation system comprised of air heating zone consisted of air inlet duct (0.164 m diameter x 0.175 m length), axial fan (Make: Almonard, 50 W, 1350 rpm), with one air heater of one kilo watt and recirculation system. Ambient air entered into the top of dryer due to the pull of axial fan and is conveyed to the heater assembly by the air deflection valve. The heated air is then uniformly passed through the chamber at determined velocities. The moist air from the chamber is recirculated and blown in to inlet by means of blower and temperature control of heated air was achieved with an automatic thermal cut off arrangement.
- The drying experiments for shrimp were performed according to a second-order Box-Behnken design (BBD) with three factors at three levels: microwave power (600, 800 and 1000 W), air temperature (50, 60 and 70 °C), and air velocity (0.5, 1.0 and 1.5m/s). Drying time, water activity, and rehydration ratio was selected as the response variables. A three-factor, three-level Box-Behnken design (BBD) experimental design was used in optimizing the drying conditions for shrimp in a hot air-assisted microwave

(HAMW) drying system. The quadratic model for predicting the optimum solution was expressed using the following equation:

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_i \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i$$

Where, Y is the response, Xi and Xj are variables (I and j range from 1 to k), 0 is the model intercept coefficient; j, jj and ij are interaction coefficients of linear, quadratic and second-order terms, respectively, k is the number of independent parameters (k=3) and e_i is the error. A lack of fit test was used to evaluate the appropriateness of the selected model.

- The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 centre points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 9.0.0 (Stat Ease Inc., Minneapolis, MN, USA) was used to perform statistical analysis. Analysis of variance (ANOVA) was carried out to check the significance of the model and process variables. Microwave power levels were adjusted from the control panel of the microwave generator. The air temperature inside the drying chamber was measured using a digital temperature indicator. The air velocity was measured using a vane anemometer. Drying experiments were conducted till the moisture content of 12-18 % (w.b.) was reached.
- The synergistic effects of air temperature and microwave power led to a reduction in drying times due to the volumetric heating effects of microwaves supplemented by increased temperature gradient created by hot air. However, the increase in air velocity and temperature reduced the drying times to a certain limit, beyond which air velocity increased the drying times at all temperatures (50-70°C) due to the lesser temperature gradient on the product. Moreover, at the highest microwave power (1000 W) with the intermediate air velocity (1 m/s) lowest drying time of shrimp can be obtained. The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

$$Drying\ time = +3.50 - 0.25 * A - 0.12 * B - 1.25 * C + 0.56 * A^2 + 0.31 * B^2 + 0.56 * C^2 - 0.12 * A * B - 0.38 * A * C - 0.13 * B * C$$

Where, A, B and C denotes air temperature, air velociity and microwave power, respectively.

- As the water activity of the product is directly related to its moisture content, an increase in moisture content has enhanced the water activity of the products. An increase in microwave power and air temperature reduced the water activity due to increased drying rates. The water activity of the samples decreased significantly with increased temperature, probably due to the lower moisture content of samples at higher temperatures. At higher temperatures, food structure becomes more porous which accelerates the loss of water. Also, proteins become denatured due to higher temperature thereby losing their water binding capacity leading to more removal of water and reducing the water activity**.** However, with both thicknesses, aw dramatically decreased with an increase in temperature. Most enzymes and bacteria will be inactive when the food system has water activity below 0.80. To some extent increase in air velocity, enhances the drying rate, and further reduces the drying rate due to evaporative cooling on the surface of the product. The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

$$Water\ activity = +0.54 - 0.14 * A - 0.018 * \mathrm{B} - 1.31 * \mathrm{C} - 0.054 * A^2 + 0.015 * B^2 + 0.59 * C^2 + 0.03 * A * B - 0.24 * A * C - 0.67 * B * C$$

Where, A, B and C denotes air temperature, air velociity and microwave power respectively.

- The rehydration ratio is an important factor indicating the efficiency of the drying process as the rate of rehydration is will be less when the cells and tissues are collapsed or irreversibly damaged. Air temperature, microwave power, and air velocity had a significant effect on the rehydration ratio ($p \leq 0.01$) . The regression coefficient is positive and maximum for microwave power levels, which indicates better rehydration properties of dried shrimp dried at high microwave power levels. This can be attributed to the high internal pressure development at higher microwave power levels. Higher microwave power causes more internal heating that creates a flux of rapidly escaping water vapor, which opens up the pores. This in turn prevents shrinkage and gives better rehydration properties. The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results,

$$Rehydration\ ratio = +2.52 - 0.01*A + 0.080*B + 0.55*C - 0.087*A^2 - 0.1*B^2 - 0.062*C^2 + 0.27*A*C + 0.13*B*C - 0.06\,A*B$$

Where, A, B and C denotes air temperature, air velociity and microwave power respectively.

- The optimization of drying process parameters was done based on Derringer's desirability function. Microwave power (600 – 1000 W), air temperature (50–70 °C) and air velocity (0.5–1.5m/s) were set within the range with minimization of drying time and water activity and maximization of rehydration ratio. Based on the value of maximum desirability (0 to 1), optimum conditions were selected. The methodology of desired function was applied to indicate 61.74 °C air temperature, 922.61 W microwave power and 1.0 m/s air velocity which indicated the drying time, water activity and rehydration ratio of 2.8 h and 0.424 and 2.51, respectively with a desirability value of 0.949
- The predicted values of response variables under optimized conditions were confirmed by performing experiments under optimized conditions under three replications. The average of the values of response variables were used to determine the error percentage. The error percentage obtained for drying time, water activity and rehydration ratio were 3.44%, 3.85% and 0.79% respectively, which further confirmed the acceptability of the selected model under RSM.
- The moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% within 2.9 h of drying. Volumetric heating effect of microwaves can be attributed for the reduction in drying time. Microwave heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Drying rate exhibited maximum value of 2.74 during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation. Dipole rotation arises owing to the presence of water molecules in the sample that tends to change the polarity depending on the rapidly changing electromagnetic field induced by the magnetron. As the moisture content reduces, the magnitude of dipole rotation also reduces and thereby lowering the drying rate.

- Sum of liquid and vapor diffusion during drying is represented by effective moisture diffusivity of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gave the slope value to determine the diffusivity. Effective moisture diffusivity during drying of HAMW of shrimp was determined to be 6.7 x 10^{-7} m^2/s. Effective moisture diffusivity was estimated from the experimental data based on Fick's law of diffusion. This parameter represented the intrinsic mechanism by which moisture transport was facilitated by means of liquid diffusion, vapor diffusion, hydrodynamic flow and other means. The volumetric heating effect of microwaves resulted in higher drying rates and decreased drying times due to higher moisture diffusivity. Thus, moisture diffusivity served as the quantitative parameter at molecular level for explaining drying kinetics.
- HAMW of shrimp was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying were fitted into thin layer drying models by non-linear regression analysis. Page model was identified as the best fit model with higher R^2 value of 0.9984, lower $\chi 2$ value of 0.000134 and RMSE value of 0.01552. To verify the acceptability of the selected Page model, observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9984 which implies that the selected model satisfactorily described the drying behaviour of shrimp under the HAMW dryer.
- Drying efficiency of the dryer under HAMW mode was observed to be 35.71%. This was a result of volumetric hearing effect of microwave radiation combined with convective effect of hot air. The SEC value for HAMW of shrimp was found to be 1.75 kWh/kg. It is understood that as moisture content decreases the energy requirement and specific energy consumption increases due to difficulties in removing water other than free and unbound moisture in the product. But the volumetric heating effect of microwaves in the study tended to fasten the drying process leading to higher drying rates and subsequently lower SEC as compared with convective drying.
- The total value of colour change (ΔE) determined for dried shrimp was 16.95 ± 2.14. The 'L' value of the dried shrimp (41.31 ± 1.63) decreased during drying whereas the 'a' and 'b' values increased from 3.56 ± 1.54 to 14.23± 2.36 and 12.42 ± 0.65 to 19.42 ± 1.61 during the drying process. Darker colour of shrimps can be attributed to the process of Maillard browning reaction that might have occurred during drying. The

development of redness was due to the release of astaxanthin during the breakdown of carotenoproteins. Yellowness of shrimp increased as a consequence of the formation of yellow pigments due to browning reactions during drying.

- Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extend of shrinkage depends on the method of drying. Shrinkage percentage of dried shrimp was observed to be 14.14%. Shorter drying time could be the reason for lesser shrinkage values.
- The structural and cellular degradation occurred within the sample during drying is explained by rehydration ratio. Within the first hour of soaking shrimp in water, a rapid rise was seen in rehydration ratio. Average rehydration ratio was observed to be 2.53. Rehydration ratio of Tilapia fillets increased with MW power and air temperature during HAMW drying of the fish.
- The total plate count of raw shrimp was 3.6×10^6 CFU/g of a sample. Drying reduced the TPC value of shrimp to 2×10^4 CFU/g, which is lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample. This confirms that dried shrimps prepared with hot air assisted microwave dryer was microbiologically safe for consumption.
- The moisture content of the fresh shrimp was decreased from 80.55% (w.b) to 16.5% (w.b) in the dryer. Moisture removal was due to the microwave power applied with the assistance of hot air generated in the dryer. Protein content of shrimp increased from 15.12% to 60.24% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried shrimp. This ensures the maximum retention of fat during drying. The higher ash content in dried shrimp was due to the moisture reduction as the ash content is directly related with moisture content and temperature.
- The optimized sample was analysed for microstructure to study the pore size distribution in the dried product. Scanning electron microscopy analysis of dried shrimp showed the formation of pores of diameters ranging from 1.26 – 10.6 µm. The reason for higher rehydration ratio of hot air assisted microwave dried shrimp can be the presence of these pores. The volumetric heating effects of microwave causes abrupt removal of water molecules which left the internal lattice vacant there by creating pores of varying diameters.

- Solar radiation, ambient temperature and relative humidity (RH) were measured using sensors at each hour of the study. The solar radiation intensity during the experimental conditions was observed to be in range of 320 to 840 W/m^2, ambient temperature varied from 27.5 to 36.5 ^{0}C and RH from 62.45% to 77.24% on a typical day of the experiment. The moisture content of shrimp was reduced from 80.2% to 15.7% (w.b.) within 6 h of drying in the solar dryer. The drying conditions were maintained at temperature, air velocity and RH of 55±1.5 ^{0}C, 1.5 ± 0.25 m/s and 60±0.5 % respectively.
- The drying rate of solar and microwave dried shrimp was found to be 1.63 kg/kgh and 2.74 kg/kgh at the beginning of drying. Drying rate exhibited a maximum value of 2.74 during the initial stages of drying that can be due to the higher moisture content of a sample that created more friction and heat generation due to dipole rotation. In both the studies, the rate of moisture removal decreased with time, and hence drying was under a falling rate period. Effective moisture diffusivity during SD and MWD of shrimp were determined to be 2.3×10^{-10} m^2/s and 6.7×10^{-7} m^2/s respectively.
- The efficiency of the collector was calculated using the whole collector area and solar irradiation received instantaneously during drying. The instantaneous collector efficiency values varied in the range of 32.5 to 41.2%. However, maximum efficiency was related directly to the hours of maximum solar irradiation received which is from 12:30 AM to 2:30 PM. The drying efficiency of the shrimp under MWD mode was observed to be 35.71%. This was a result of the volumetric hearing effect of microwave radiation combined with the convective effect of hot air.
- The textural analysis of dried products is important in determining their palatability. Textural attributes of dried products are generally expressed in terms of hardness indicated by the maximum compressive force needed to crush the product by the molars. Average hardness values of raw, solar dried and microwave dried shrimp obtained from the plots of compressive force (N) versus time (s) were 12.3, 11.93 and 3.3 N respectively.
- The average rehydration ratio was observed to be 2.39 and 2.53 for SD and MWD respectively. solar-dried shrimp exhibited higher values of rehydration ratio more rapidly than hot air-dried samples. Due to the volumetric heating of MW radiation, the moisture movement is fast leaving a porous matrix in the cells which can be accounted for their higher moisture absorption properties.

- The shrinkage percentage of SD and MWD shrimp was observed to be 24.67 and 14.14% respectively. Shorter drying time could be the reason for lesser shrinkage values reduction in shrinkage percentage was due to the rapid evaporation of moisture by microwave radiation that created a vapor flux thereby preventing case hardening.
- The values of TVB-N, TMA and TBARS determined the quality of sea food products. TMA values for fresh, solar dried and microwave dried shrimp were 3.04, 7.7 and 8.23 mg N/100g respectively. TMA was responsible for the unpleasant odour in shrimp. There is no significant difference in TMA values of solar and microwave dried samples. The dried samples were adhering to the permissible values of TVB-N (<50 mgN/100 g). TBARS values showed the extent of lipid oxidation and were determined to be 0.64, 0.72 and 0.75 MDA/kg of lipid for fresh, solar dried and microwave dried samples. The increase in values of all biochemical constituents represented the degree of spoilage due to higher microbial activity.
- The total plate count of raw shrimp was 4.3×10^6 CFU/g of a sample. Drying reduced the TPC value of shrimp to 1.65×10^4 and 2.6×10^4 CFU/g and to for SD and MWD respectively which is significantly ($p< 0.05$) lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample.
- Solar dried shrimp were found to be darker (L= 41.31 ± 1.63) compared to microwave dried samples (49.5±1.28). This may be due to the exposure to higher temperatures for longer times. Total colour change (ΔE) determined for SD and MWD samples were 14.25±1.94 and 16.95 ± 2.14 respectively. Redness of samples increased during both drying methods due to the release of astaxanthin from carotenoids during drying.
- The optimized sample was analysed for microstructure to study the pore size distribution in the dried product. The pore size for solar dried shrimp samples ranged from 4.96 – 22.10 µm. Scanning electron microscopy analysis of microwave dried shrimp showed the formation of pores of diameters ranging from 1.26– 10.30 µm. The reason for higher rehydration ratio of hot air assisted microwave dried mushroom can be the presence of these pores. The volumetric heating effects of microwave causes abrupt removal of water molecules which left the internal lattice vacant there by creating pores of varying diameters. Due to longer drying times in solar drying, there was greater diffusion and evaporation happening across the interior to exterior surface

of the samples that resulted in more shrinkage and pores of relatively larger sizes as compared to microwave drying.

- The values of economic attributes indicated the economic feasibility of the production of dried shrimp under both drying technologies. However, solar drying is found to be economically more viable than microwave drying technology for the quality production of dried shrimp. Solar drying was found to have less carbon emissions in terms of electricity usage as 70% of the energy consumption is met with solar radiation. Supplementary heating by LPG is aided only at times of lacunae in availability of solar radiation. Whereas the working of microwave system requires a 1.4 kW magnetron to be run throughout the drying process. But microwave system highly reduced the drying times and thereby the related electricity consumption.
- The response surface methodology plots of Oyster mushrooms showed that drying time decreased with an increase in air temperature (40 to 60°C) and microwave power (600 to 1000W). Synergistic effects of air temperature and microwave power led to a reduction in drying times due to the volumetric heating effects of microwaves supplemented by increased temperature gradient created by hot air. However, the increase in air velocity and temperature reduced the drying times to a certain limit, beyond which air velocity increased the drying times at all temperatures (40-60°C) due to the lesser temperature gradient on the product. Moreover, at the highest microwave power (1000W) with the intermediate air velocity (1 m/s) lowest drying time of shrimp can be obtained. Similar trends were seen in the interaction reported by Han et al. (2010) for microwave drying of apple slices. The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.
- $$Drying\ time = +3.50 - 0.25 * A - 1.25 * B + 0.12 * C + 0.56 * A^2 + 0.31 * B^2 + 0.56 * C^2 - 0.38 * A * B - 0.12 * A * C - 0.13 * B * C$$

Where, A, B and C denotes air temperature, microwave power and air velocity, respectively.

Water activity of HAMW dried mushrooms ranged from 0.504 to 0.572 under various drying conditions of inlet air temperature, microwave power and air velocity. The effect of air temperature, microwave power, and air velocity on the water activity of the dried product is shown in Fig. 4.23 (a, b, and c) as air velocity increased (0.5 – 1.5 m/s), water activity decreased to a certain limit, further which it increased. As the water activity of the product is directly related to its moisture content, an increase in moisture content has enhanced the water activity of the products. An increase in microwave power and air temperature reduced the water activity due to increased drying rates. The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box-Behnken design.

$$Water\ activity = +0.54 + 3.250E - 0.30 * A - 0.48 * B + 4.750\,E - 0.13 * C - 1.950E - 003 * A^2 + 0.015 * B^2 + 8.050E - 003 * C^2 - 2.500E - 0.15 * A * B + 0.024 * A * C + 9.000E - 0.103 * B * C$$

Where, A, B and C denote air temperature, microwave power and air velocity, respectively.

- Rehydration ratio of HAMW dried mushrooms were in range of 2.21 – 2.51 under various drying conditions of inlet air temperature, microwave power and air velocity. This can be attributed to the high internal pressure development at higher microwave power levels. Higher microwave power causes more internal heating that creates a flux of rapidly escaping water vapor, which opens up the pores. The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results,

$$Rehydration\ ratio = +2.52 - 0.01 * A + 0.080 * B + 0.055 * \boldsymbol{C} - 0.087 * A^2 - 0.1 * B^2 - 0.062 * C^2 - 2.500E - 0.012 * A * B - 0.018 * A * C - 0.033 * B * C$$

Where, A, B and C denotes air temperature, microwave power and air velocity, respectively.

- The optimization of drying process parameters was done based on Derringer's desirability function. Microwave power (600 – 1000 W), air temperature (40–60 °C) and air velocity (0.5–1.5m/s) were set within the range with minimization of drying time and water activity and maximization of rehydration ratio. Based on the value of maximum desirability (0 to 1), optimum conditions were selected. The methodology of desired function was applied to indicate 55.05 °C air temperature, 1000 W microwave power and 0.81 m/s air velocity which indicated the drying time, water activity and rehydration ratio of 5.05 h and 0.532 and 2.49, respectively with a desirability value of 0.830.

- The predicted values of response variables under optimized conditions were confirmed by performing experiments under optimized conditions under three replications. The average of the values of response variables were used to determine the error percentage. The error percentage obtained for drying time, water activity and rehydration ratio were 1.76%, 0.564% and 0.80% respectively, which further confirmed the acceptability of the selected model under RSM.
- Moisture content of Oyster mushroom decreased from 92.35 to 8.42% within 5 h of drying. Volumetric heating effect of microwaves can be attributed for the reduction in drying time. Microwave heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Drying rate exhibited maximum value of 3.47 during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation. Dipole rotation arises owing to the presence of water molecules in the sample that tends to change the polarity depending on the rapidly changing electromagnetic field induced by the magnetron. As the moisture content reduces, the magnitude of dipole rotation also reduces and thereby lowering the drying rate.
- Effective moisture diffusivity during SD and MWD of oyster mushroom were determined to be 2.41×10^{-9} m^2/s and 5.63×10^{-7} m^2/s respectively. Effective moisture diffusivity was estimated from the experimental data based on Fick's law of diffusion. This parameter represented the intrinsic mechanism by which moisture transport was facilitated by means of liquid diffusion, vapor diffusion, hydrodynamic flow and other means. The volumetric heating effect of microwaves resulted in higher drying rates and decreased drying times due to higher moisture diffusivity.
- Logarithmic model was identified as the best fit model with higher R^2 value of 0.9967, lower $\chi 2$ value of 0.000405 and RMSE value of 0.01938 for HAMW drying of Oyster mushroom. To verify the acceptability of the selected Logarithmic model, observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9931 which implies that the selected model satisfactorily described the drying behaviour of oyster mushrooms under the HAMW dryer.

- Drying efficiency of the dryer under HAMW mode was observed to be 23.12%. This was a result of volumetric hearing effect of microwave radiation combined with convective effect of hot air. The SEC value for HAMW of oyster mushroom was found to be 2.71 kWh/kg. Solar drying efficiency of the collector was calculated using the whole collector area and solar irradiation received instantaneously during drying. The instantaneous collector efficiency values varied in the range of 30.9 to 42.4%.
- The L*, a* and b* colour values of fresh mushrooms were determined to be 84.12±0.46, 3.3±0.24 and 15.57±0.62 respectively. The colour values of the microwave dried mushrooms under optimized conditions were recorded as 56.15±0.25 (L*), 4.95±0.24 (a*) and 20.85±0.51 (b*) respectively. The 'L' value of the dried oyster mushroom decreased whereas the 'a' and 'b' values increased during microwave convective drying. Darker color of oyster mushroom can be attributed to the process of Maillard browning reaction that might have occurred during drying. Solar dried oyster mushrooms were found to be darker (L= 49.61 ± 0.32) compared to microwave dried samples (56.15±0.25).
- Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extend of shrinkage depends on the method of drying. The shrinkage percentage of SD and MWD shrimp was observed to be 46.42 and 39.64% respectively. The initial diameter of oyster mushroom samples was in range of 4.9 – 6.4 cm which was reduced to 2.4 – 4.1 cm upon drying.
- The structural and cellular degradation occurred within the sample during drying is explained by rehydration ratio. Within the first hour of soaking mushroom in water, a rapid rise was seen in rehydration ratio. The average rehydration ratio was observed to be 2.21 and 2.47 for SD and MWD respectively. Water activity of value of dried oyster mushroom was determined to be 0.497 and 0.468 under SD and MWD respectively which indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf-life extension of products
- The moisture content of the fresh oyster mushroom was decreased from 92.35% (w.b) to 8.14% (w.b) in the dryer. Moisture removal was due to the microwave power applied with the assistance of hot air generated in the dryer. Carbohydrate content of dried oyster mushrooms were found to be 47.34%. Protein content of oyster mushroom

increased from 4.57% to 33.21% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried sample. Fat content showed a slight increase from 0.57 to 1.26%. The higher ash content in oyster mushroom was due to the moisture reduction as the ash content is directly related with moisture content and temperature.

- The drying rate of solar and microwave dried oyster mushrooms were found to be 3.47 kg/kgh and 2.14 kg/kgh at the beginning of drying. Drying rate exhibited a maximum value of 3.47 during the initial stages of drying that can be due to the higher moisture content of a sample that created more friction and heat generation due to dipole rotation.
- Drying reduced the TPC value of oyster mushroom to 1.2×10^4 and 3.9×10^5 CFU/g respectively under MW and SD drying conditions. Higher moisture content of the open dried mushroom compared to other dryers could have influenced the microorganism on the dried mushrooms. The objective of drying is to remove water to a level at which microbial spoilage and deterioration reactions are greatly minimized.
- The optimized sample was analysed for microstructure to study the pore size distribution in the dried product. The pore size for microwave dried oyster mushroom samples ranged from 8.65 – 32.4 µm. Scanning electron microscopy analysis of microwave dried oyster mushroom showed the formation of pores of diameters ranging from 2.06 – 15.7 µm. The reason for higher rehydration ratio of hot air assisted microwave dried mushroom can be the presence of these pores. The volumetric heating effects of microwave causes abrupt removal of water molecules which left the internal lattice vacant there by creating pores of varying diameters.
- Result of shelf-life studies of shrimp and oyster mushroom is given in Table 5.1:

Table 5.1 Results of shelf-life studies on shrimp and oyster mushroom under various packaging conditions and packaging materials

S. No.	Product	Ambient			Vacuum		
1.	Shrimp – HAMW dried	LDPE (150 µ)	PE-PS laminate (72 µ)	Metallised PS (84 µ)	LDPE (150 µ)	PE-PS laminate (72 µ)	Metallised PS (84 µ)
2.	Shrimp – Solar dried	< 1 month	3 months	2 months	< 1 month	5 months	3 months
3.	Oyster mushroom – HAMW dried	< 1 month	3 months	2 months	< 1 month	5 months	3 months
4.	Oyster mushroom – Solar dried	1 month	7 months	6 months	2 months	9 months	5 months

Hence it was concluded from the study that microwave drying produced better quality shrimp and oyster mushrooms with respect to shrinkage, rehydration ratio, moisture diffusivity and drying times and hence finds application in the production of bulk quantity of high-quality dried products. This dryer is capable of producing of high-quality dried shrimp and oyster mushroom with economic viability and can be used for commercial production of dried products. The effect of solar and microwave drying on the quality of dried shrimp and oyster mushroom were studied. Drying time reduction of 58.3% was achieved under microwave drying as compared to solar drying of these products under the experimental set up. Biochemical and microbiological analyses of dried shrimp and oyster mushrooms under both drying methods were found to be within safe limits.

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Appendix

Appendix - A

Table A-1 ANOVA and statistical parameters of the model for drying time

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	17.22	9	1.91	10.72	0.002 significant
A	*0.50*	*1*	*0.50*	*2.80*	*0.0182*
B	*12.50*	*1*	*12.50*	*70.00*	*< 0.0001*
C	*0.13*	*1*	*0.13*	*0.70*	*0.0404*
A^2	*1.33*	*1*	*1.33*	*7.46*	*0.0293*
B^2	*0.41*	*1*	*0.41*	*2.30*	*0.1729*
C^2	*1.33*	*1*	*1.33*	*7.46*	*0.0293*
AB	*0.063*	*1*	*0.063*	*0.35*	*0.5727*
AC	*0.56*	*1*	*0.56*	*3.15*	*0.1192*
BC	*0.063*	*1*	*0.063*	*0.35*	*0.5727*
Residual	1.25	7	0.18		
Lack of Fit	*1.25*	*3 0*	*.42*		
Pure Error	*0.000*	*4*	*0.000*		
Cor Total	18.47	16			
C.V. (%)		3.4			
R^2		0.9323			
Adj. R^2		0..8453			

Table A-2 ANOVA and statistical parameters of the model for water activity

ANOVA for Response Surface Quadratic Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	7.126E-003	9	7.917E-004	4.68	0.0271significant
A	*8.450E-005*	*1*	*8.450E-005*	*0.50*	*0.0468*
B	*2.664E-003*	*1*	*2.664E-003*	*15.74*	*0.0054*
C	*1.805E-004*	*1*	*1.805E-004*	*1.07*	*0.0361*
A^2	*1.601E-005*	*1*	*1.601E-005*	*0.095*	*0.7674*
B^2	*1.297E-003*	*1*	*1.297E-003*	*7.66*	*0.0278*
C^2	*2.729E-004*	*1*	*2.729E-004*	*1.61*	*0.2448*
AB	*2.500E-005*	*1*	*2.500E-005*	*0.15*	*0.7121*
AC	*2.209E-003*	*1*	*2.209E-003*	*13.05*	*0.0086*
BC	*3.240E-004*	*1*	*3.240E-004*	*1.91*	*0.2090*
Residual	1.185E-003	7	1.692E-004		
Lack of Fit	*1.113E-003*	*3*	*3.712E-004*	*20.85*	*0.0066*

Pure Error	*7.120E-005*	*4*	*1.780E-005*
Cor Total	8.310E-003	16	
C.V. (%)		2.27	
R^2		0.9122	
Adj. R^2		0.8354	

Table A-3 ANOVA and statistical parameters of the model for rehydration ratio

ANOVA for Response Surface Quadratic Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.20	9	0.022	32.78	< 0.00	significant
A	*1.800E-003*	*1*	*1.800E-003*	*2.72*	*0.00130*	
B	*0.051*	*1*	*0.051*	*77.41*	*< 0.0001*	
C	*0.024*	*1*	*0.024*	*36.59*	*0.0005*	
A^2	*0.032*	*1*	*0.032*	*48.46*	*0.0002*	
B^2	*0.053*	*1*	*0.053*	*80.21*	*< 0.0001*	
C^2	*0.016*	*1*	*0.016*	*24.67*	*0.0016*	
AB	*2.500E-005*	*1*	*2.500E-005*	*0.038*	*0.8514*	
AC	*1.225E-003*	*1*	*1.225E-003*	*1.85*	*0.2157*	
BC	*4.225E-003*	*1*	*4.225E-003*	*6.39*	*0.0394*	
Residual	4.630E-003	7	6.614E-004			
Lack of Fit	*4.150E-003*	*3*	*1.383E-003*	*11.53*	*0.0194*	
C.V. (%)	0.8					
R^2	0.9864					
Adj. R^2	0.9690					

Table A-4 ANOVA for response variables: Drying time (Oyster mushroom)

Model	127.59	9	14.18	11.05	0.0023	significant
A-Air temperature	0.2556	1	0.2556	0.1992	0.0488	
B-Microwave power	120.13	1	120.13	93.63	< 0.0001	
C-Air velocity	2.19	1	2.19	1.71	0.0322	
AB	2.00	1	2.00	1.56	0.2517	
AC	0.2401	1	0.2401	0.1871	0.6783	
BC	0.2352	1	0.2352	0.1833	0.6814	
A^2	2.34	1	2.34	1.82	0.2192	
B^2	0.2179	1	0.2179	0.1699	0.6926	
C^2	0.0767	1	0.0767	0.0598	0.8138	
Residual	8.98	7	1.28			
Lack of Fit	5.25	3	1.75	1.88	0.2742	not significant
Pure Error	3.73	4	0.9320			
Cor Total	136.57	16				
C V %	3.14					
R^2	0.9342					
Adj R^2	0.8497					

Table A-5 ANOVA for response variables: Water activity (Oyster mushroom)

Source	Sum of squares	df	Mean square	f - value	p - value	
Model	112.34	9	12.34	10.52	0.0031	significant
A-Air temperature	0.4831	1	0.4831	0.2561	0.0284	
B-Microwave power	6.40	1	6.40	3.39	0.01080	
C-Air velocity	0.2701	1	0.2701	0.1432	0.0464	
AB	0.2025	1	0.2025	0.1073	0.7528	
AC	3.04	1	3.04	1.61	0.2450	
BC	0.0449	1	0.0449	0.0238	0.8817	
A^2	1.55	1	1.55	0.8216	0.3948	
B^2	1.75	1	1.75	0.9263	0.3679	
C^2	1.77	1	1.77	0.9407	0.3644	
Residual	13.21	7	1.89			
Lack of Fit	5.23	3	1.74	0.8733	0.5254	not significant
Pure Error	7.98	4	2.00			
Cor Total	28.55	16				
C V %	2.62					
R^2	0.8961					
Adj R^2	0.0.846					

Table A-6 ANOVA for response variables: Rehydration ratio (Oyster mushroom)

Source	Sum of squares	df	Mean square	f - value	p - value	
Model	115.38	9	13.54	1.63	0.0029	significant
A-Air temperature	0.6328	1	0.6328	1.39	0.0270	
B-Microwave power	0.2080	1	0.2080	0.4567	0.0409	
C-Air velocity	1.14	1	1.14	2.50	0.0476	
AB	1.70	1	1.70	3.74	0.0944	
AC	0.3969	1	0.3969	0.8714	0.3816	
BC	0.6724	1	0.6724	1.48	0.2637	
A^2	0.1987	1	0.1987	0.4363	0.5300	
B^2	0.2786	1	0.2786	0.6118	0.4597	
C^2	0.0882	1	0.0882	0.1937	0.6731	
Residual	3.19	7	0.4555			
Lack of Fit	1.86	3	0.6207	1.87	0.2751	not significant
Pure Error	1.33	4	0.3315			
Cor Total	8.57	16				
C V %	1.24					
R^2	0.9236					
Adj R^2	0.9012					

Appendix - B

Drying characteristic data during solar drying of shrimp

Moisture content (R1) wb %	Moisture content (R2)wb %	Moisture content (R3)wb %	Moisture content (%w.b.)	Drying rate (R1) (g/g.h)	Drying rate (R2) (g/g.h)	Drying rate (R3) (g/g.h)	Drying rate (g/g.h)
81.65	80.52	79.5	80.55667				0
75.85	72	69	72.28333	2.61	2.72	2.89	2.74
67.23	65	63	65.07667	2.39	2.4	2.36	2.383333
52.94	55	57	54.98	2.21	2.19	2.17	2.19
38.83	42	44	41.61	1.9	1.8	1.75	1.816667
29.42	32	35	32.14	1.61	1.7	1.6	1.636667
23.54	22.12	22.56	22.74	1.38	1.45	1.42	1.416667
16.5	16.75	16.5	16.58333	1.2	1.3	1.25	1.25

Drying characteristic data during solar drying of shrimp

Moisture content (R1) wb %	Moisture content (R2) db %	Moisture content (R3) wb %	Moisture content wb %	Drying rate (R1) (g/g.h)	Drying rate (R2) (g/g.h)	Drying rate (R3) (g/g.h)	Drying rate (g/g.h)
80.33	81.35	79.2	80.29333	1.82			
72.3	71	73	72.1	1.62	1.65	1.64	1.636667
64.36	65	63	64.12	1.53	1.55	1.54	1.54
58.36	59	57	58.12	1.4	1.42	1.4	1.406667
52.6	51	53	52.2	1.12	1.31	1.29	1.24
46.5	49	47	47.5	0.96	1	1.1	1.02
39.5	38	40	39.16667	0.84	0.89	0.9	0.876667
34.3	35	33	34.1	0.71	0.75	0.76	0.74
29.1	28	27	28.03333	0.59	0.6	0.59	0.593333
25.4	24	26	25.13333	0.49	0.5	0.48	0.49
21.2	20	21	20.73333	0.41	0.42	0.4	0.41
18.6	19	17.6	18.4	0.33	0.34	0.33	0.333333
15.66	16.88	14.6	15.71333	0.29	0.29	0.28	0.286667

Effective moisture diffusivity during solar and microwave drying of shrimp

Drying time	Solar dried	Microwave dried
0	0	0
0.5	-0.4553	-0.34828
1	-0.8255	-0.77154
1.5	-1.078	-1.37516
2	-1.347	-1.94771
2.5	-1.505	-2.37516
3	-1.897	-2.67365
3.5	-2.0635	-3.12357
4	-2.347	
4.5	-2.496	
5	-2.745	
5.5	-2.9	
6	-3.1	

Moisture content and drying rate during solar and microwave drying of oyster mushroom

Drying time (h)	Moisture content (% w. b.)		Drying rate (g/gh)	
	Microwave dried dried	Solar dried		
0	92.35	91.24		
0.5	75.85	80.24	3.47	2.42
1	67.23	72.3	2.61	2.1
1.5	52.94	61.27	2.39	1.86
2	38.83	53.49	2.21	1.64
2.5	29.42	46.32	1.9	1.59
3	23.54	36.21	1.61	1.45
3.5	16.5	29.13	1.38	1.39
4	12.56	25.36	1.2	1.25

4.5	9.94	21.62	0.9	1.19
5	8.42	18.75	0.8	1.1
5.5		15.67		1.04
6		13.45		0.9
6.5		11.23		0.87
7		10.24		0.76
7.5		9.45		0.65
8		8.59		0.54
8.5		8.21		0.41

Effective moisture diffusivity during solar and microwave drying of oyster mushroom

Drying time	**Solar dried**	**Microwave dried**
0	0	0
0.5	-0.5267	-0.6354
1	-0.8956	-0.9638
1.5	-1.2687	-1.5987
2	-1.6978	-2.1456
2.5	-2.1569	-2.37516
3	-2.6974	-2.67365
3.5	-2.9634	-3.12357
4	-3.1569	-4.12
4.5	-3.2697	-4.65
5	-3.5412	-4.97
5.5	-3.963	
6	-4.125	
6.5	-4.59	
7	-4.97	
7.5	-5.21	
8	-5.48	
8.5	-5.71	

APPENDIX C

Economic analysis

Total cost of the HAMW dryer = ₹ 4,99,000

Assumptions:

Life span of the dryer	=	10 years
Salvage value, S	=	10%
Depreciation	=	10%
Intrest	=	10%
No. of working days	=	200 days/year
Dried shrimp output	=	10 kg/day
Price of dried shrimp	=	₹ 500/kg
Expenditure (solar drying)	=	₹ 1450/day
Expenditure (microwave drying)	=	₹ 1700/day
Profit (solar drying)	=	₹ 3555/day
Profit (microwave drying)	=	₹3330/day

$$\text{Life cycle cost (LCC)} = \text{Initial investment} + \text{Operation and maintenance cost} - \text{Salvage value}$$

Life cycle benefit is determined as the total annual benefit from the dried product. Benefit cost ratio is the ratio of discounted benefits to the discounted values of all costs and is expressed as

$$Benefit - cost\ ratio = \frac{Life\ cycle\ benefit}{Life\ cycle\ cost}$$

Payback period is the length of time from the beginning of the project before the net benefits return the cost of capital investments.

$$Pay\ back\ period = -Life\ cycle\ cost + Life\ cycle\ benefits = 0$$

Economic analysis of solar and microwave drying of shrimp

Sl. No	Parameters	Values	
		Solar -LPG dryer	**Hot air assisted microwave dryer**
1.	Initial investment (₹)	4,20,000	4,99,000
2.	Operation and maintenance cost (₹) including raw material cost	1,50,000	2,10,000
3.	Salvage value (10% of initial investment) (₹)	42,000	49,000
4.	Life cycle cost (₹)	5,28,000	6,60,000
5.	Annual benefit (₹)*	7,11,000	6,66,150
6.	Benefit-cost ratio	1.4	1.31
7.	Payback period	1.03 years	1.48 years

* Dried shrmp output - 10kg/day; price of dried shrimp - ₹ 700/kg; expenditure - ₹ 1450/day(solar dried) and ₹ 1700/day (microwave dried) ; profit- ₹ 3555/day (solar dried) and ₹3330/day (microwave dried); working days - 200 days/year.

Drying of Oyster mushroom

Life span of the dryer	=	10 years
Salvage value, S	=	10%
Depreciation	=	10%
Interest	=	15%
No. of working days	=	200 days/year
Dried oyster mushroom output	=	20 kg/day
Price of dried shrimp	=	₹ 1500/kg
Expenditure (solar drying)	=	₹ 1450/day
Expenditure (microwave drying)	=	₹ 1700/day
Profit (solar drying)	=	₹ 3555/day
Profit (microwave drying)	=	₹3330/day

Economic analysis of solar and microwave drying of oyster mushroom

Sl. No	Parameters	Values	
		Solar -LPG dryer	Hot air assisted microwave dryer
1.	Initial investment (₹)	4,20,000	4,99,000
2.	Operation and maintenance cost (₹) including raw material cost	1,50,000	2,10,000
3.	Salvage value (10% of initial investment) (₹)	42,000	49,000
4.	Life cycle cost (₹)	5,28,000	6,60,000
5.	Annual benefit (₹)*	7,11,000	6,66,150
6.	Benefit-cost ratio	1.11	1.10
7.	Payback period	1.37 years	1.75years

* Dried mushroom output - 10kg/day; price of dried oyster mushroom - ₹ 1500/kg; expenditure - ₹ 1450/day (solar dried) and ₹ 1700/day (microwave dried) ; profit- ₹ 3555/day (solar dried) and ₹3330/day (microwave dried); working days - 200 days/year.

PROFITABILITY

i. Shrimp under HAMW drying

<u>Assumptions for calculation:</u>

Raw product price	-	Rs. 100/kg
Amount of raw material required	-	30 kg/day
Hygienically Dried product sales	-	Rs. 700/kg
Working Days	-	200
Investment on Fixed Assets	-	Rs. 4,99,000/-

BENEFIT-COST ANALYSIS:

Expenses:

Working Capital for 200 days	-	Rs. 9,40,000/-
Interest on Rs 4.99 lakhs @ 15%	-	Rs. 74,850/-
Depreciation on Dryer 10%	-	Rs. 49,900/-
Total Costs	**-**	**Rs. 10,64,750/-**

Revenue:

Sales Return for One Year		
Rs. 2000 per kg x 700	-	Rs. 14, 00,000/-
Total revenue	**-**	**Rs. 14,00,000/-**
Gross Profit	**-**	**Rs. 3,35,250/-**

B - C ratio = 1.31 (Ist year)

Payback period = Initial investment/Net cash flow = 1.48 years

ii. Shrimp under solar drying

Raw product price	-	Rs. 100/kg
Amount of raw material required	-	30 kg/day
Hygienically Dried product sales	-	Rs. 700/kg
Working Days	-	200
Investment on Fixed Assets	-	Rs. 4,20,000/-

BENEFIT-COST ANALYSIS:

Expenses:

Working Capital for 200 days	-	Rs. 8,90,000/-
Interest on Rs 4.20 lakhs @ 15%	-	Rs. 63,000/-
Depreciation on Dryer 10%	-	Rs. 42,000/-
Total Costs	**-**	**Rs. 9,95,000/-**

Revenue:

Sales Return for One Year		
Rs. 2000 per kg x 700	-	Rs. 14, 00,000/-
Total revenue	**-**	**Rs. 14,00,000/-**
Gross Profit	**-**	**Rs. 4,05,000/-**

B - C ratio = 1.4 (Ist year)

Payback period = Initial investment/Net cash flow = 1.03 years

iii. Oyster mushroom under HAMW drying

Raw product price	-	Rs. 250/kg
Raw material	-	45 kg/day
Hygienically Dried product sales	-	Rs. 1500/kg
Working Days	-	200
Investment on Fixed Assets	-	Rs. 4,99,000/-

BENEFIT-COST ANALYSIS:

Expenses:

Working Capital for 200 days	-	Rs. 20,00,000/-
Interest on Rs 4.99 lakhs @ 15%	-	Rs. 74,850/-
Depreciation on Dryer 10%	-	Rs. 49,900/-
Total Costs	**-**	**Rs. 27,14,750/-**

Revenue:

Sales Return for One Year

Rs. 2000 per kg x 1500 - Rs. 30, 00,000/-

Total revenue	**-**	**Rs. 30,00,000/-**
Gross Profit	**-**	**Rs. 2,85,250/-**

B - C ratio = 1.10 (Ist year)

Payback period = Initial investment/Net cash flow = 1.75 years

i. Oyster mushroom under solar drying

Raw product price	-	Rs. 250/kg
Raw material	-	Rs. 45 kg/day
Hygienically Dried product sales	-	Rs. 1500/kg
Working Days	-	200
Investment on Fixed Assets	-	Rs. 4,99,000/-

BENEFIT-COST ANALYSIS:

Expenses:

Working Capital for 200 days	-	Rs. 25,00,000/-
Interest on Rs 4.99 lakhs @ 15%	-	Rs. 63,000/-
Depreciation on Dryer 10%	-	Rs. 42,000/-
Total Costs	**-**	**Rs. 26,95,000/-**

Revenue:

Sales Return for One Year		
Rs. 2000 per kg x 1500	-	Rs. 30, 00,000/-
Total revenue	**-**	**Rs. 30,00,000/-**
Gross Profit	**-**	**Rs. 3,05,000/-**

B - C ratio = 1.11 (Ist year)

Payback period = Initial investment/Net cash flow = 1.37 years

Abstract

DEVELOPMENT AND EVALUATION OF SEMI-CONTINUOUS MICROWAVE CONVECTIVE DRYER FOR FOOD PRODUCTS

By

Er. Alfiya P. V.

(2019-28-021)

ABSTRACT

Submitted in partial fulfilment of the requirement for the degree

DOCTOR OF PHILOSOPHY

IN

AGRICULTURAL ENGINEERING

(Processing and Food Engineering)

Faculty of Agricultural Engineering and Technology

Kerala Agricultural University

Department of Processing and Food Engineering

KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY

TAVANUR P.O, MALAPPURAM – 679573

KERALA, INDIA

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ABSTRACT

The research work aimed to develop a semi-continuous microwave convective dryer for foods and evaluate the performance of the dryer for drying of shrimp and oyster mushroom. The study also aimed to assess the shelf-life of the dried products under different packaging technologies and packaging materials. The quality of conventionally dried shrimp and oyster mushrooms were compared and evaluated with the hot air assisted microwave (HAMW) dried products. The developed HAMW drying system comprised of a drying chamber, conveyor belt, magnetron to generate microwaves at frequency of 2450 MHz±50 MHz, hot air generation system with air heater, axial fan and other controls.

The drying experiments for shrimp were performed according to a second-order Box-Behnken design (BBD) with three factors at three levels: microwave power (600, 800 and 1000 W), air temperature (50, 60 and 70 °C), and air velocity (0.5, 1.0 and 1.5m/s). Drying time, water activity, and rehydration ratio was selected as the response variables. A three-factor, three-level Box-Behnken design (BBD) experimental design was used in optimizing the drying conditions for shrimp in a hot air-assisted microwave (HAMW) drying system.

The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 centre points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 9.0.0 (Stat Ease Inc., Minneapolis, MN, USA) was used to perform statistical analysis.

The moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% within 2.9 h of drying. HAMW drying of shrimp was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying were fitted into thin layer drying models by non-linear regression analysis. Page model was identified as the best fit model with higher R^2 value of 0.9984, lower $\chi 2$ value of 0.000134 and RMSE value of 0.01552.

Drying efficiency of the dryer under HAMW mode was observed to be 35.71%. This was a result of volumetric hearing effect of microwave radiation combined with convective effect of hot air. The SEC value for HAMW of shrimp was found to be 1.75 kWh/kg. The total value of colour change (ΔE) determined for dried shrimp was 16.95 ± 2.14. The 'L' value of the dried shrimp (41.31 ± 1.63) decreased during drying whereas the 'a' and 'b' values

increased from 3.56 ± 1.54 to 14.23± 2.36 and 12.42 ± 0.65 to 19.42 ± 1.61 during the drying process.

Solar radiation, ambient temperature and relative humidity (RH) were measured using sensors at each hour of the study. The solar radiation intensity during the experimental conditions was observed to be in range of 320 to 840 W/m^2, ambient temperature varied from 27.5 to 36.5 ^{0}C and RH from 62.45% to 77.24% on a typical day of the experiment. The moisture content of shrimp was reduced from 80.2% to 15.7% (w.b.) within 6 h of drying in the solar dryer. The drying conditions were maintained at temperature, air velocity and RH of 55±1.5 ^{0}C, 1.5 ± 0.25 m/s and 60±0.5 % respectively.

The drying rate of solar and microwave dried shrimp was found to be 1.63 kg/kgh and 2.74 kg/kgh at the beginning of drying. Drying rate exhibited a maximum value of 2.74 during

The average rehydration ratio was observed to be 2.39 and 2.53 for SD and HAMW drying respectively. The shrinkage percentage of SD and HAMW shrimp was observed to be 24.67 and 14.14% respectively.

Storage studies of hot air assisted microwave dried and solar dried shrimps were carried out under MAP and vacuum conditions in three types of packaging materials namely LDPE (150 µ), polyester polyethylene laminate (72 µ) and metallised polyester (84 µ). Shelf life of the dried shrimps was quantified with respect to the microbial growth and other quality parameters. Maximum storage life was exhibited for SD and HAMW dried shrimp under polyethylene-polyester laminated (72 µ) packaging material.

The response surface methodology plots of Oyster mushrooms showed that drying time decreased with an increase in air temperature (40 to 60℃) and microwave power (600 to 1000W). Based on the value of maximum desirability (0 to 1), optimum conditions were selected. The methodology of desired function was applied to indicate 55.05 ℃ air temperature, 1000 W microwave power and 0.81 m/s air velocity which indicated the drying time, water activity and rehydration ratio of 5.05 h and 0.532 and 2.49, respectively with a desirability value of 0.830.

Moisture content of Oyster mushroom decreased from 92.35 to 8.42% within 5 h of drying. Volumetric heating effect of microwaves can be attributed for the reduction in drying time. Microwave heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Drying rate exhibited maximum value of 3.47

during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation.

Drying efficiency of the dryer under HAMW mode for oyster mushroom was observed to be 23.12%. The SEC value for HAMW of oyster mushroom was found to be 2.71 kWh/kg. Solar drying efficiency of the collector was calculated using the whole collector area and solar irradiation received instantaneously during drying. The instantaneous collector efficiency values varied in the range of 30.9 to 42.4%.

The L*, a* and b* colour values of fresh mushrooms were determined to be 84.12±0.46, 3.3±0.24 and 15.57±0.62 respectively. The colour values of the microwave dried mushrooms under optimized conditions were recorded as 56.15±0.25 (L*), 4.95±0.24 (a*) and 20.85±0.51 (b*) respectively. The 'L' value of the dried oyster mushroom decreased whereas the 'a' and 'b' values increased during microwave convective drying.

The drying rate of SD and HAMW dried oyster mushrooms were found to be 3.47 kg/kgh and 2.14 kg/kgh at the beginning of drying. Drying rate exhibited a maximum value of 3.47 during the initial stages of drying that can be due to the higher moisture content of a sample that created more friction and heat generation due to dipole rotation. Drying reduced the TPC value of oyster mushroom to 1.2×10^4 and 3.9×10^5 CFU/g respectively under MW and SD drying conditions.

The optimized sample was analysed for microstructure to study the pore size distribution in the dried product. The pore size for microwave dried oyster mushroom samples ranged from 8.65 – 32.4 µm. Scanning electron microscopy analysis of microwave dried oyster mushroom showed the formation of pores of diameters ranging from 2.06 – 15.7 µm.

Storage studies of hot air assisted microwave dried and solar dried oyster mushrooms were carried out under MAP and vacuum conditions in three types of packaging materials namely LDPE (150 µ), polyester polyethylene laminate (72 µ) and metallised polyester (84 µ). Shelf life of the dried oyster mushroom was quantified with respect to the microbial growth and other quality parameters and maximum value of 9 months was achieved for SD and HAMW dried oyster mushroom in polyethylene-polyester (72 µ) laminated packaging material.

സംഗ്രഹം

ഭക്ഷണങ്ങൾക്കായി ഒരു അർദ്ധ-തുടർച്ചയുള്ള മൈക്രോവേവ് സംവഹന ഡ്രയർ വികസിപ്പിക്കാനും ചെമ്മീനും മുത്തുച്ചിപ്പി കൂണും ഉണക്കുന്നതിനുള്ള ഡ്രയറിൻ്റെ പ്രകടനം വിലയിരുത്താനും ഗവേഷണ പ്രവർത്തനങ്ങൾ ലക്ഷ്യമിടുന്നു. വ്യത്യസ്ത പാക്കേജിംഗ് സാങ്കേതികവിദ്യകൾക്കും പാക്കേജിംഗ് മെറ്റീരിയലുകൾക്കും കീഴിൽ ഉണക്കിയ ഉൽപ്പന്നങ്ങളുടെ ഷെൽഫ് ലൈഫ് വിലയിരുത്താനും പഠനം ലക്ഷ്യമിടുന്നു. പരമ്പരാഗതമായി ഉണക്കിയ ചെമ്മീനിൻ്റെയും മുത്തുച്ചിപ്പി കൂണിൻ്റെയും ഗുണനിലവാരം ഹോട്ട് എയർ അസിസ്റ്റഡ് മൈക്രോവേവ് (HAMW) ഉണക്കിയ ഉൽപ്പന്നങ്ങളുമായി താരതമ്യം ചെയ്യുകയും വിലയിരുത്തുകയും ചെയ്തു. ഒരു ഡ്രൈയിംഗ് ചേമ്പർ, കൺവെയർ ബെൽറ്റ്, 2450±50 MHz ആവൃത്തിയിൽ മൈക്രോവേവ് സൃഷ്ടിക്കുന്നതിനുള്ള മാഗ്നെട്രോൺ, എയർ ഹീറ്റർ, ആക്സിയൽ ഫാൻ, ചൂട് എയർ ജനറേഷൻ സിസ്റ്റം എന്നിവ ഉൾപ്പെടുന്നതാണ് വികസിപ്പിച്ച HAMW ഡ്രൈയിംഗ് സിസ്റ്റം.

മൈക്രോവേവ് പവർ (600, 800, 1000 W), വായുവിൻ്റെ താപനില (50, 60, 70 ഡിഗ്രി സെൽഷ്യസ്), വായു വേഗതയും (0.5, 1.0, 1.5m/s) എന്നിങ്ങനെ മൂന്ന് ഘടകങ്ങളുള്ള മൂന്ന് ഘടകങ്ങളുള്ള ഒരു സെക്കൻഡ്-ഓർഡർ ബോക്സ്-ബെൻകെൻ ഡിസൈൻ (ബിബിഡി) അനുസരിച്ചാണ് ചെമ്മീൻ ഉണക്കൽ പരീക്ഷണങ്ങൾ നടത്തിയത്. ഉണങ്ങുന്ന സമയം, ജലത്തിൻ്റെ പ്രവർത്തനം, റീഹൈഡ്രേഷൻ അനുപാതം എന്നിവ പ്രതികരണ വേരിയബിളുകളായി തിരഞ്ഞെടുത്തു. ഹോട്ട് എയർ അസിസ്റ്റഡ് മൈക്രോവേവ് (HAMW) ഡ്രൈയിംഗ് സിസ്റ്റത്തിൽ ചെമ്മീൻ ഉണക്കൽ സാഹചര്യങ്ങൾ ഒപ്റ്റിമൈസ് ചെയ്യുന്നതിന് മൂന്ന്-ഘടക, മൂന്ന്-തല ബോക്സ്-ബെൻകെൻ ഡിസൈൻ (BBD) പരീക്ഷണാത്മക ഡിസൈൻ ഉപയോഗിച്ചു.

ഉണക്കൽ സമയത്തിൻ്റെയും ജല പ്രവർത്തനത്തിൻ്റെയും ഏറ്റവും കുറഞ്ഞ മൂല്യങ്ങൾ, റീഹൈഡ്രേഷൻ അനുപാതത്തിൻ്റെ പരമാവധി മൂല്യം എന്നിവ ഉപയോഗിച്ച് വ്യവസ്ഥകൾ ഒപ്റ്റിമൈസ് ചെയ്യുന്നതിനായി ഒപ്റ്റിമൈസേഷൻ നടത്തി. 5 സെൻ്റർ പോയിൻ്റുകളുള്ള 17 റണ്ണുകൾ അടങ്ങിയതായിരുന്നു ഡിസൈൻ പ്ലാൻ. പ്രോസസ് വേരിയബിളുകളുടെ ഒപ്റ്റിമൽ

അവസ്ഥകൾ ഡിസറബിലിറ്റി ഫംഗ്ഷൻ ഉപയോഗിച്ച് ഉരുത്തിരിഞ്ഞു. സ്റ്റാറ്റിസ്റ്റിക്കൽ വിശകലനം നടത്താൻ ഡിസൈൻ വിദഗ്ധ സ്റ്റാറ്റിസ്റ്റിക്കൽ സോഫ്റ്റ്വെയർ പാക്കേജ് 9.0.0 (സ്റ്റാറ്റ് ഈസ് ഇൻക്., മിനിയാപൊളിസ്, എംഎൻ, യുഎസ്എ) ഉപയോഗിച്ചു.

ഉണങ്ങിയതിന് (HAMW) ശേഷം 2.9 മണിക്കൂറിനുള്ളിൽ ചെമ്മീനിൻ്റെ ഈർപ്പം പ്രാരംഭ മൂല്യമായ 80.55% ൽ നിന്ന് അവസാന മൂല്യം 16.5% ആയി കുറഞ്ഞു. ചെമ്മീൻ ഉണക്കുന്ന സമയത്തിൻ്റെ ഭാഗമായി ഈർപ്പത്തിൻ്റെ ശതമാനം കുറയ്ക്കുന്നതിലൂടെയാണ് HAMW ചെമ്മീൻ ഉണക്കുന്നത്. ഉണങ്ങുമ്പോൾ ലഭിച്ച ഈർപ്പം അനുപാതം നോൺ-ലീനിയർ റിഗ്രഷൻ വിശകലനം വഴി നേർത്ത പാളി ഉണക്കൽ മോഡലുകളിൽ ഘടിപ്പിച്ചിരിക്കുന്നു. ഉയർന്ന R2 മൂല്യം 0.9984, താഴ്ന്ന χ2 മൂല്യം 0.000134, RMSE മൂല്യം 0.01552 എന്നിവയുള്ള മികച്ച ഫിറ്റ് മോഡലായി പേജ് മോഡൽ തിരിച്ചറിഞ്ഞു.

HAMW മോഡിന് കീഴിലുള്ള ഡ്രയറിൻ്റെ ഉണക്കൽ കാര്യക്ഷമത 35.71% ആയി നിരീക്ഷിച്ചു. മൈക്രോവേവ് റേഡിയേഷൻ്റെ വോള്യൂമെട്രിക് ശ്രവണ ഫലവും ചൂടുള്ള വായുവിൻ്റെ സംവഹന ഫലവും ചേർന്നതാണ് ഇത്. HAMW ചെമ്മീനിൻ്റെ SEC മൂല്യം 1.75 kWh/kg ആണെന്ന് കണ്ടെത്തി. ഉണങ്ങിയ ചെമ്മീനിൽ നിർണ്ണയിച്ചിട്ടുള്ള വർണ്ണ മാറ്റത്തിൻ്റെ (ΔE) ആകെ മൂല്യം 16.95 ± 2.14 ആയിരുന്നു. ഉണങ്ങിയ ചെമ്മീനിൻ്റെ 'L' മൂല്യം (41.31 ± 1.63) ഉണങ്ങുമ്പോൾ കുറഞ്ഞു, അതേസമയം 'a', 'b' മൂല്യങ്ങൾ 3.56 ± 1.54 ൽ നിന്ന് 14.23± 2.36 ആയും 12.42 ± 0.65 മുതൽ 19.42 ± 19.42 ലേക്ക് 19.42 ലേക്ക് വർധിച്ചു.

പഠനത്തിൻ്റെ ഓരോ മണിക്കൂറിലും സെൻസറുകൾ ഉപയോഗിച്ച് സൗരവികിരണം, ആംബിയൻ്റ് താപനില, ആപേക്ഷിക ആർദ്രത (RH) എന്നിവ അളക്കുന്നു. പരീക്ഷണ ഘട്ടങ്ങളിൽ സൗരവികിരണത്തിൻ്റെ തീവ്രത 320 മുതൽ 840 W/m2 വരെയും, ആംബിയൻ്റ് താപനില 27.5 മുതൽ 36.5 0C വരെയും RH 62.45% മുതൽ 77.24% വരെയും പരീക്ഷണത്തിൻ്റെ ഒരു സാധാരണ ദിവസത്തിൽ വ്യത്യാസപ്പെട്ടിരിക്കുന്നു. സോളാർ ഡ്രയറിൽ ഉണക്കി 6 മണിക്കൂറിനുള്ളിൽ ചെമ്മീനിൻ്റെ ഈർപ്പം 80.2% ൽ നിന്ന് 15.7% ആയി (w.b.) കുറഞ്ഞു. യഥാക്രമം 55± 1.5 0C, 1.5 ± 0.25 m/s, 60± 0.5 % എന്നിങ്ങനെയുള്ള

താപനില, വായു പ്രവേഗം, RH എന്നിവയിൽ ഉണക്കൽ സാഹചര്യങ്ങൾ നിലനിർത്തി.

സോളാർ, മൈക്രോവേവ് ഉണക്കിയ ചെമ്മീൻ ഉണക്കൽ നിരക്ക് 1.63 കി.ഗ്രാം / കി.ഗ്രാം, 2.74 കി.ഗ്രാം / കി. ഉണക്കൽ നിരക്ക് 2.74 എന്ന പരമാവധി മൂല്യം പ്രദർശിപ്പിച്ചു. SD, HAMW ഉണക്കലിനായി ശരാശരി റീഹൈഡ്രേഷൻ അനുപാതം യഥാക്രമം 2.39 ഉം 2.53 ഉം ആയി നിരീക്ഷിച്ചു. SD, HAMW ചെമ്മീൻ എന്നിവയുടെ ചുരുങ്ങൽ ശതമാനം യഥാക്രമം 24.67, 14.14% ആയി നിരീക്ഷിച്ചു.

എൽഡിപിഇ (150 µ), പോളിസ്റ്റർ പോളിയെത്തിലീൻ ലാമിനേറ്റ് (72 µ), മെറ്റലൈസ്ഡ് പോളിസ്റ്റർ (84 µ) എന്നിങ്ങനെ മൂന്ന് തരം പാക്കേജിംഗ് സാമഗ്രികളിൽ MAP, വാക്വം അവസ്ഥകളിൽ ചൂടുവായുവിൻ്റെ സഹായത്തോടെയുള്ള മൈക്രോവേവ് ഉണക്കിയതും സോളാർ ഉണക്കിയതുമായ ചെമ്മീനുകളുടെ സംഭരണ പഠനങ്ങൾ നടത്തി. ഉണങ്ങിയ ചെമ്മീനുകളുടെ ഷെൽഫ് ആയുസ്സ് സൂക്ഷ്മജീവികളുടെ വളർച്ചയും മറ്റ് ഗുണനിലവാര പാരാമീറ്ററുകളും കണക്കിലെടുത്താണ് കണക്കാക്കുന്നത്. പോളിയെത്തിലീൻ-പോളിസ്റ്റർ ലാമിനേറ്റഡ് (72 µ) പാക്കേജിംഗ് മെറ്റീരിയലിന് കീഴിൽ സോളാർ ഉണക്കൽ (SD), HAMW ഉണങ്ങിയ ചെമ്മീൻ എന്നിവയുടെ പരമാവധി സംഭരണ കാലാവധി പ്രദർശിപ്പിച്ചു.

ഓയ്സ്റ്റർ കൂണിൻ്റെ പ്രതികരണ ഉപരിതല രീതിശാസ്ത്ര പ്ലോട്ടുകൾ, വായുവിൻ്റെ താപനില (40 മുതൽ 60 ഡിഗ്രി വരെ), മൈക്രോവേവ് പവർ (600 മുതൽ 1000 വാട്ട് വരെ) എന്നിവയിൽ ഉണങ്ങാനുള്ള സമയം കുറയുന്നതായി കാണിച്ചു. പരമാവധി അഭിലഷണീയതയുടെ (0 മുതൽ 1 വരെ) മൂല്യത്തെ അടിസ്ഥാനമാക്കി, ഒപ്റ്റിമൽ വ്യവസ്ഥകൾ തിരഞ്ഞെടുത്തു. 55.05 °C വായുവിൻ്റെ താപനില, 1000 W മൈക്രോവേവ് പവർ, 0.81 m/s വായു പ്രവേഗം എന്നിവ സൂചിപ്പിക്കാൻ ആവശ്യമുള്ള പ്രവർത്തനത്തിൻ്റെ രീതി പ്രയോഗിച്ചു, ഇത് ഉണക്കൽ സമയം, ജലത്തിൻ്റെ പ്രവർത്തനം, 5.05 മണിക്കൂർ, 0.532, 2.49 എന്നിവയുടെ പുനർനിർമ്മാണ അനുപാതത്തെ സൂചിപ്പിക്കുന്നു. 0.830.

മുത്തുച്ചിപ്പി കൂണിൻ്റെ ഈർപ്പം ഉണങ്ങിയതിന് ശേഷം 5 മണിക്കൂറിനുള്ളിൽ 92.35 ൽ നിന്ന് 8.42% ആയി കുറഞ്ഞു. മൈക്രോവേവിൻ്റെ

വോള്യൂമെട്രിക് തപീകരണ പ്രഭാവം ഉണക്കൽ സമയം കുറയ്ക്കുന്നതിന് കാരണമാകാം. മൈക്രോവേവ് ചൂടാക്കൽ വൈദ്യുത ചൂടാക്കൽ രീതിക്ക് കീഴിലാണ്, അതിൽ ഉൽപ്പന്നത്തിൻ്റെ ഈർപ്പം നേരിട്ട് ചൂടാക്കൽ നിരക്കിനെ സ്വാധീനിക്കുന്നു. ദ്വിധ്രുവ ഭ്രമണം മൂലം കൂടുതൽ ഘർഷണവും താപ ഉൽപാദനവും സൃഷ്ടിക്കുന്ന സാമ്പിളിലെ ഉയർന്ന ഈർപ്പം മൂലമാകാം, ഉണക്കലിൻറെ പ്രാരംഭ ഘട്ടത്തിൽ ഡ്രൈയിംഗ് നിരക്ക് പരമാവധി മൂല്യം 3.47 പ്രദർശിപ്പിച്ചു.

ഹോട്ട് എയർ അസിസ്റ്റഡ് മൈക്രോവേവ് ഉണക്കിയതും സോളാർ ഉണക്കിയതുമായ മുത്തുച്ചിപ്പി കൂണുകളുടെ സംഭരണ പഠനങ്ങൾ MAP, വാക്വം അവസ്ഥകളിൽ LDPE (150 µ), പോളിസ്റ്റർ പോളിയെത്തിലീൻ ലാമിനേറ്റ് (72 µ), മെറ്റലൈസ്ഡ് പോളിസ്റ്റർ (84 µ) എന്നിങ്ങനെ മൂന്ന് തരം പാക്കേജിംഗ് മെറ്റീരിയലുകളിൽ നടത്തി. ഉണങ്ങിയ മുത്തുച്ചിപ്പി കൂണിൻ്റെ ഷെൽഫ് ആയുസ്സ് സൂക്ഷ്മജീവികളുടെ വളർച്ചയും മറ്റ് ഗുണനിലവാര പാരാമീറ്ററുകളും കണക്കിലെടുത്ത് പോളിയെത്തിലീൻ-പോളിസ്റ്റർ (72 µ) ലാമിനേറ്റഡ് പാക്കേജിംഗ് മെറ്റീരിയലിൽ SD, HAMW ഉണക്കിയ മുത്തുച്ചിപ്പി കൂൺ എന്നിവയ്ക്ക് 9 മാസത്തെ പരമാവധി മൂല്യം ലഭിച്ചു.

ഓയ്സ്റ്റർ കൂണിൻ്റെ പ്രതികരണ ഉപരിതല രീതിശാസ്ത്ര പ്ലോട്ടുകൾ, വായുവിൻ്റെ താപനില (40 മുതൽ 60 ഡിഗ്രി വരെ), മൈക്രോവേവ് പവർ (600 മുതൽ 1000 വാട്ട് വരെ) എന്നിവയിൽ ഉണങ്ങാനുള്ള സമയം കുറയുന്നതായി കാണിച്ചു. പരമാവധി അഭിലഷണീയതയുടെ (0 മുതൽ 1 വരെ) മൂല്യത്തെ അടിസ്ഥാനമാക്കി, ഒപ്റ്റിമൽ വ്യവസ്ഥകൾ തിരഞ്ഞെടുത്തു. 55.05 °C വായുവിൻ്റെ താപനില, 1000 W മൈക്രോവേവ് പവർ, 0.81 m/s വായു പ്രവേഗം എന്നിവ സൂചിപ്പിക്കാൻ ആവശ്യമുള്ള പ്രവർത്തനത്തിൻ്റെ രീതി പ്രയോഗിച്ചു, ഇത് ഉണക്കൽ സമയം, ജലത്തിൻ്റെ പ്രവർത്തനം, 5.05 മണിക്കൂർ, 0.532, 2.49 എന്നിവയുടെ പുനർനിർമ്മാണ അനുപാതത്തെ സൂചിപ്പിക്കുന്നു. 0.830.

മുത്തുച്ചിപ്പി കൂണിനുള്ള HAMW മോഡിൽ ഡ്രയറിൻ്റെ ഉണക്കൽ കാര്യക്ഷമത 23.12% ആയി നിരീക്ഷിച്ചു. മുത്തുച്ചിപ്പി കൂണിൻ്റെ HAMW ൻ്റെ SEC മൂല്യം 2.71 kWh/kg ആണെന്ന് കണ്ടെത്തി. കളകൂറുടെ സോളാർ ഡ്രൈയിംഗ്

കാര്യക്ഷമത മുഴുവൻ കളക്ടർ ഏരിയയും ഉണങ്ങുമ്പോൾ തൽക്ഷണം ലഭിക്കുന്ന സൗരവികിരണവും ഉപയോഗിച്ച് കണക്കാക്കി. തൽക്ഷണ കളക്ടർ കാര്യക്ഷമത മൂല്യങ്ങൾ 30.9 മുതൽ 42.4% വരെ വ്യത്യാസപ്പെട്ടിരിക്കുന്നു.

കൂണുകളുടെ എൽ*, എ*, ബി* വർണ്ണ മൂല്യങ്ങൾ യഥാക്രമം 84.12±0.46, 3.3±0.24, 15.57±0.62 എന്നിങ്ങനെയാണ് നിശ്ചയിച്ചിരിക്കുന്നത്. ഒപ്റ്റിമൈസ് ചെയ്ത സാഹചര്യങ്ങളിൽ മൈക്രോവേവ് ഉണക്കിയ കൂണുകളുടെ വർണ്ണ മൂല്യങ്ങൾ യഥാക്രമം 56.15±0.25 (L*), 4.95±0.24 (a*), 20.85±0.51 (b*) എന്നിങ്ങനെ രേഖപ്പെടുത്തിയിട്ടുണ്ട്. ഉണക്കിയ മുത്തുച്ചിപ്പി കൂണിൻ്റെ 'L' മൂല്യം കുറഞ്ഞു, അതേസമയം മൈക്രോവേവ് സംവഹന ഡ്രൈയിംഗ് സമയത്ത് 'a', 'b' മൂല്യങ്ങൾ വർദ്ധിച്ചു.

SD, HAMW ഉണക്കിയ മുത്തുച്ചിപ്പി കൂണുകളുടെ ഉണക്കൽ നിരക്ക് 3.47 കി.ഗ്രാം / കി.ഗ്രാം, 2.14 കി.ഗ്രാം / കി. ദ്വിധ്രുവ ഭ്രമണം മൂലം കൂടുതൽ ഘർഷണവും താപ ഉൽപാദനവും സൃഷ്ടിച്ച സാമ്പിളിലെ ഉയർന്ന ഈർപ്പം കാരണം ഉണക്കലിൻ്റെ പ്രാരംഭ ഘട്ടത്തിൽ ഡ്രൈയിംഗ് നിരക്ക് 3.47 എന്ന പരമാവധി മൂല്യം പ്രദർശിപ്പിച്ചു. ഉണക്കൽ മുത്തുച്ചിപ്പി കൂണിൻ്റെ ടിപിസി മൂല്യം യഥാക്രമം 1.2 × 104, 3.9 × 105 CFU/g എന്നിങ്ങനെ മെഗാവാട്ട്, SD ഉണക്കൽ സാഹചര്യങ്ങളിൽ കുറച്ചു.

ഒപ്റ്റിമൈസ് ചെയ്ത സാമ്പിൾ, ഉണങ്ങിയ ഉൽപ്പന്നത്തിലെ സുഷിരത്തിൻ്റെ വലിപ്പം വിതരണത്തെക്കുറിച്ച് പഠിക്കാൻ മൈക്രോസ്ട്രക്ചറിനായി വിശകലനം ചെയ്തു. മൈക്രോവേവ് ഉണക്കിയ മുത്തുച്ചിപ്പി മഷ്റൂം സാമ്പിളുകളുടെ സുഷിരത്തിൻ്റെ വലുപ്പം 8.65 - 32.4 μm വരെയാണ്. മൈക്രോവേവ് ഉണക്കിയ മുത്തുച്ചിപ്പി കൂണിൻ്റെ ഇലക്ട്രോൺ മൈക്രോസ്കോപ്പി വിശകലനം സ്കാനിംഗ് 2.06 മുതൽ 15.7 μm വരെ വ്യാസമുള്ള സുഷിരങ്ങളുടെ രൂപീകരണം കാണിച്ചു.

ഹോട്ട് എയർ അസിസ്റ്റഡ് മൈക്രോവേവ് ഉണക്കിയതും സോളാർ ഉണക്കിയതുമായ മുത്തുച്ചിപ്പി കൂണുകളുടെ സംഭരണ പഠനങ്ങൾ MAP, വാക്വം അവസ്ഥകളിൽ LDPE (150 μ), പോളിസ്റ്റർ പോളിയെത്തിലീൻ ലാമിനേറ്റ് (72 μ), മെറ്റലൈസ്ഡ് പോളിസ്റ്റർ (84 μ) എന്നിങ്ങനെ മൂന്ന് തരം പാക്കേജിംഗ്

മെറ്റീരിയലുകളിൽ നടത്തി. ഉണങ്ങിയ മുത്തുച്ചിപ്പി കൂണിൻ്റെ ഷെൽഫ് ആയുസ്സ് സൂക്ഷ്മജീവികളുടെ വളർച്ചയും മറ്റ് ഗുണനിലവാര പാരാമീറ്ററുകളും കണക്കിലെടുത്ത് പോളിയെത്തിലീൻ-പോളിസ്റ്റർ (72 µ) ലാമിനേറ്റഡ് പാക്കേജിംഗ് മെറ്റീരിയലിൽ SD, HAMW ഉണക്കിയ മുത്തുച്ചിപ്പി മഷ്റൂമിന് 9 മാസത്തെ പരമാവധി മൂല്യം നേടി.

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Development and evaluation of hot air-assisted microwave dryer for shrimp (*Metapenaeus dobsoni*)

Palli V. Alfiya[1] | **Gourikutty K. Rajesh**[2] | **Subramaniam Murali**[1] | **Dhanapaul S. Aniesrani Delfiya**[1] | **Manoj P. Samuel**[1] | **Manadan V. Prince**[2]

[1]Engineering Division, ICAR-Central Institute of Fisheries Technology, Cochin, India

[2]Department of Processing and Food Engineering, Kelappaji College of Agricultural Engineering and Technology, Tavanur, India

Correspondence
Palli V. Alfiya, Engineering Division, ICAR-Central Institute of Fisheries Technology, Cochin 682 029, India.
Email: alfiya.sam@gmail.com

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Abstract

The study aimed to develop a hot air-assisted continuous microwave (HAMW) drying system and evaluate the drying of shrimp under microwave radiation. The drying system comprised of a drying chamber with a conveyor belt of dimension 1.5 × 0.5 m, magnetron of 1.45 kW to generate microwaves at frequency of 2450 ± 50 MHz, hot air generation system with air heater of 1 kW and axial fan of 50 W and other controls. Moisture content of shrimp was reduced from 80.55% to 16.5% within 3.5 h of drying. Volumetric heating effect of microwaves resulted in reduction of drying times. Effective moisture diffusivity of microwave-dried shrimp was found to be 6.7×10^{-7} m^2/s. Page model was the suitable fit for the data under study ($R^2 = 0.998454$, RMSE = 0.0.01552 and χ^2 = 0.000134). The drying efficiency and specific energy consumption for hot air-assisted microwave drying of shrimp were calculated to be 35.71% and 1.75 kWh/kg, respectively. Water activity, rehydration ratio and shrinkage of the dried shrimp samples were 0.552%, 2.51% and 14.14%, respectively, with maximum color retention. Proximate and microbiological analysis of fresh and dried shrimp were carried out and were found to be under safe limits. The developed HAMW drying system was found to be suitable for shrimp drying under controlled conditions.

Practical applications

Hot air-assisted microwave (HAMW) drying system was developed to cater drying of shrimp under controlled conditions with lower drying times. Specific energy consumption (1.75 kWh/kg), drying efficiency (35.71%) and effective moisture diffusivity (6.7×10^{-7} m^2/s) during drying was found to be superior to convective drying. Evaluation of quality parameters of dried shrimp such as rehydration ratio (2.51), shrinkage (14.14%), water activity (0.552) and total plate count (2×10^4 CFU/g) was falling under acceptable limits. The study suggests HAMW drying system as a potential means of drying shrimps for large-scale commercial production.

1 | INTRODUCTION

Shrimp is a major commercial seafood in the world and belongs to the phylum arthropod with extended abdomen (Oosterveer, 2006). Owing to the relatively higher water and protein content of shrimps, they are subjected to rapid deterioration soon after harvest. Natural sun drying was practiced as an economic method for drying of fish and shrimps. Since the method has several drawbacks such as longer duration, weather uncertainties, infestation by predators and lack of control, convective drying is adopted commercially for dried shrimp production (Jain & Pathare, 2007). But the existing convective drying systems for shrimp often result in inferior product quality due to longer drying time requirement and non-uniform drying. Drying under microwave (MW) was found to lower drying time and enhance energy efficiency (Soysal et al., 2006). MW drying of shrimp increased drying efficiencies to about 22.54% and reduced specific energy consumption (SEC) to about 28.94%, on increasing MW power from 200 to 500 W (Farhang et al., 2011).

Application of MW radiation for food product drying has been reported in various literatures. Mohd Rozainee and Ng (2010) reported that drying time for catfish slices was reduced to 75% using MW as compared to hot air (HA) drying. Also, there were significant reduction in the SEC and shrinkage of foods under MW convective drying. Darvishi et al. (2013) studied the implication of microwave assisted hot air dryingb (MWHA) on rate of drying, effective moisture diffusivity (EMD) and energy for drying Sardine fish at four varying MW powers of 200, 300, 400 and 500 W and at constant air velocity. Moisture percent of the samples reduced to 0.01 (dry basis) with a reduction in drying time (9.5 to 4.25 min) as power increased. Wu & Mao, 2008, investigated the influence of HA and MW drying on nutritional properties of grass carp (Ctenopharyngodon idellus) fillets. MW drying showed an increase in protein contents since it had less effect on the amino acid composition of grass carp fillets. MW heating of shrimp at 1.3 kW and 2450 MHz was found to retain better color and texture compared to conventional methods (Tsai et al., 2021). Dong et al. (2021) evidenced that MW heating at 1 kW and 2450 MHz showed potential impact on reducing the allergenicity of shrimps. Mounir et al. (2020) published that MW drying of shrimp with intermittent pressure drop removed 90% of moisture within 10 min and exhibited better quality attributes compared to convective dried samples.

Drying involves complex mass, heat and momentum transport followed by intermolecular transformation (Kudra & Mujumdar, 2002). Hence, drying process needs to be effectively designed and optimized. This can be achieved by mathematical modeling using thin layer drying equations that are practical and give adequately fair results on prediction of drying time. Moisture removal during drying can be projected by modeling of drying kinetics (Alfiya et al., 2019). Drying kinetics describe the changes in moisture regime in the product with time. Various models defining the drying rate curve are proposed based on the factors that affects the drying process (Pacheco-Aguirre et al., 2015).

Post-harvest loss of agricultural and marine products is attributed to be an important factor for the food crisis in the world, where around 10% of the total population does not have enough food to consume (Chauhan & Rathod, 2020). Shrimp, being a highly perishable product, is subjected to immediate spoilage soon after harvest. The drying of commodities reduces the post-harvest loss thereby enhancing shelf life by lowering the moisture content present in the foods (VijayaVenkataRaman et al., 2012). But the existing drying systems for shrimp often results in inferior product quality due to long drying time requirement and non-uniform drying.

The combination of HA and MW is an innovative method to improve the effectiveness of drying with better retention of the quality of products. MW is an electromagnetic wave with a frequency in the range of 0.3–300 GHz and a wavelength in the range of 1 m to 1 mm, respectively. These waves are capable of rotating bipolar molecules, and due to high friction produced by changing polarity of molecules, they produce heat in bipolar materials such as water (Kouchakzadeh & Shafeei, 2010). Application of MWs in drying process causes reduced energy consumption and improves quality of dried products (Andrés et al., 2004). Due to fast mass transferring in this method, removal of emerging moisture from product is difficult, and this result in condensation of steam inside the container (Sharmaa et al., 2009). To overcome this difficulty, combined MW-HA flow drying, pulsed MWs and also combined MW-vacuum drying can be used in drying process (Gunasekaran, 1999). Hybrid drying offers many advantages over conventional drying in terms of reduced drying time, reduced energy usage and improved product quality. Furthermore, most of the existing drying techniques are utilizing high energy or leading to carbon emissions. Hence, it is contemplated to develop technologies which are green, clean and affordable to MSMEs and fisherfolks. Thus, design and development of semi-continuous HAMW dryer for shrimp is planned in this study. However, the MW-based heating systems mentioned in literatures were meant for batch scale production to process very few quantities of products. However, food processing industries are targeting on conveyor type systems that aids in continuous production reducing the material handling and enabling them to meet the consumer demands. Presently, HAMW heating systems are not available for drying fish /fishery products, under continuous/semi-continuous processing method for drying large quantity of products. Hence, the study was aimed to develop a HAMW drying system for marine products. The study was undertaken to develop a HAMW dryer and to carry out performance evaluation of the dryer with shrimp samples. Hence, in this study, an attempt was made to develop a hot air assisted microwave dryer and to evaluate the performance of the dryer with shrimp samples.

2 | MATERIAL AND METHOD

2.1 | Materials

Raw shrimps (*Metapenaeus dobsoni*) were purchased from Chaliyam Fish Harbor of Calicut, Kerala. The shrimps were counting around 350–380 nos./kg and were thoroughly cleaned with potable water. The length, width and thickness of shrimp were determined to be 45 ± 1.5, 24 ± 1.3 and 9 ± 0.6 mm, respectively. Moisture percentage of shrimp was found to be 80.55 ± 1.54 (% w. b.) by gravimetric method (AOAC, 1990).

2.2 | Methods

2.2.1 | Design calculations

HAMW dryer was developed for drying of shrimp with an initial moisture level of around 75–80% w. b. Following assumptions were considered in dryer design (Table 1).

TABLE 1 Hot air-assisted microwave dryer design assumptions

Factors	Specifications
Capacity	1 kg fresh shrimp/h 0.6 kg/h moisture removal
Product type	Shrimp
Moisture percentage (initial)	75%–80% w. b.
Moisture percentage (final)	10%–15% w. b.
Drying air temperature	60–70°C
Air flow rate	1 m/s
Air temperature (ambient)	30–33°C
Air relative humidity (ambient)	70%–75%
Latent heat of vaporization of water at drying temperature	2260 kJ/kg
Specific heat capacity of air at constant pressure	1 kJ/ kg°C
Air density	1.225 kg/m^3
Specific heat of shrimp	3.65 kJ/kg°C
Specific heat of water	4.2 kJ/kg°C
Drying time	3 h

Thermodynamic equilibrium calculation for energy balance

Energy balance in drying was calculated by the equation (Exell, 1980):

$$M_w L = m_a C_p (T_i - T_f) \tag{1}$$

where M_w: mass of water to be removed, kg; L: LH of vaporization, kJ/kg °C; T_i: Initial temperature of air, °C; T_f: Final temperature of air, °C; m_a: Mass of air, kg; C_p: Specific heat capacity of air at constant pressure, kJ/kg °C.

Amount of water to be removed from product

Amount of water evaporated was calculated as:

$$M_w = \frac{W_i (M_i - M_f)}{100 - M_f} \tag{2}$$

where W_i: Product weight initially, kg; M_i, M_f: Initial and final content of moisture in of the sample, % w. b.

HA requirement for drying

Air requirement for drying was calculated as:

$$M_a = \frac{M_w L}{C_p (T_i - T_f)} \tag{3}$$

Flow rate of air is given as:

$$\text{Mass flow rate of air} \left(\frac{\text{kg}}{s}\right) = \rho \times V_a \tag{4}$$

$$\text{Volumetric flow rate of air } (V_a) \left(\frac{\text{m}^3}{s}\right) = A \times V \times n \tag{5}$$

where V_a: Volumetric flow rate of air, m^3/s; ρ: Air density, kg/m^3; A: Area of air passage duct, m^2; V: Air velocity, m/s and n: Number of air passage ducts.

Heat energy required for evaporation

Heat requirement for evaporation is the total of sensible heat required to raise the temperature of sample, sensible heat of water and latent heat of vaporization of water at specific temperature and it can be determined as:

$$Q_{Total} = Q_{sensible,product} + Q_{sensible,water} + Q_{Latent} \tag{6}$$

Sensible heat needed to raise the sample temperature:

$$Q_{sensible,product} = W_d C_{pp} (T_{fp} - T_{ip}) \tag{7}$$

where $Q_{sensible,product}$: Sensible heat of sample, kJ; W_d: Bone dry weight of product, kg; C_{pp}: Product-specific heat, kJ/kg °C (3.65 kJ/kg °C); T_{ip}: Product temperature (initial), °C; T_{fp}: Temperature of product, (final), °C.

Sensible heat for raising water temperature is estimated as:

$$Q_{sensible,water} = W_w C_{pw} (T_{fp} - T_{ip}) \tag{8}$$

where $Q_{sensible,water}$: Sensible heat of water (kJ); W_w: Mass of moisture in product, kg; C_{pw}: Specific heat of water, kJ/kg °C.

Latent heat (LH) needed is represented as:

$$Q_{Latent} = M_w L \tag{9}$$

where Q_{Latent}: LH of water evaporation, kJ; M_w: Mass of water evaporated from sample, kg; L: LH of vaporization of water, kJ/kg.

2.2.2 | Dryer components

Drying chamber

Drying chamber consisted of a single layer of conveyor belt of dimension 1.5 × 0.5 m, being derived from dryer design calculations with respect to the capacity and product bulk density. Samples being fed manually were conveyed along the belt made of heat-resistant Teflon (PTFE) over SS rollers. Magnetron of 1.45 kW rated power, operating at 2450 ± 50 MHz generated the MWs for heating the products in the drying chamber. A solid diagram of the HAMW drying system (Enerzi Microwave Systems, India) is shown in Figure 1 (SOLIDWORKS 3D CAD).

HA generation system

The air heating zone consisted of air inlet duct (0.164 m diameter × 0.175 m length), axial fan (Make: Almonard, 50 W, 1350 rpm), with one air heater of one kilowatt and recirculation system. Ambient air entered into the top of dryer due to the pull of axial fan and is conveyed to the heater assembly by the air deflection valve. The heated air is then uniformly passed through the chamber at determined velocities. The moist air from the chamber is recirculated and blown into inlet by means of blower, and temperature control of heated air was achieved with an automatic thermal cutoff arrangement. Top, front and side views of the HA generation system are depicted in Figure 3.

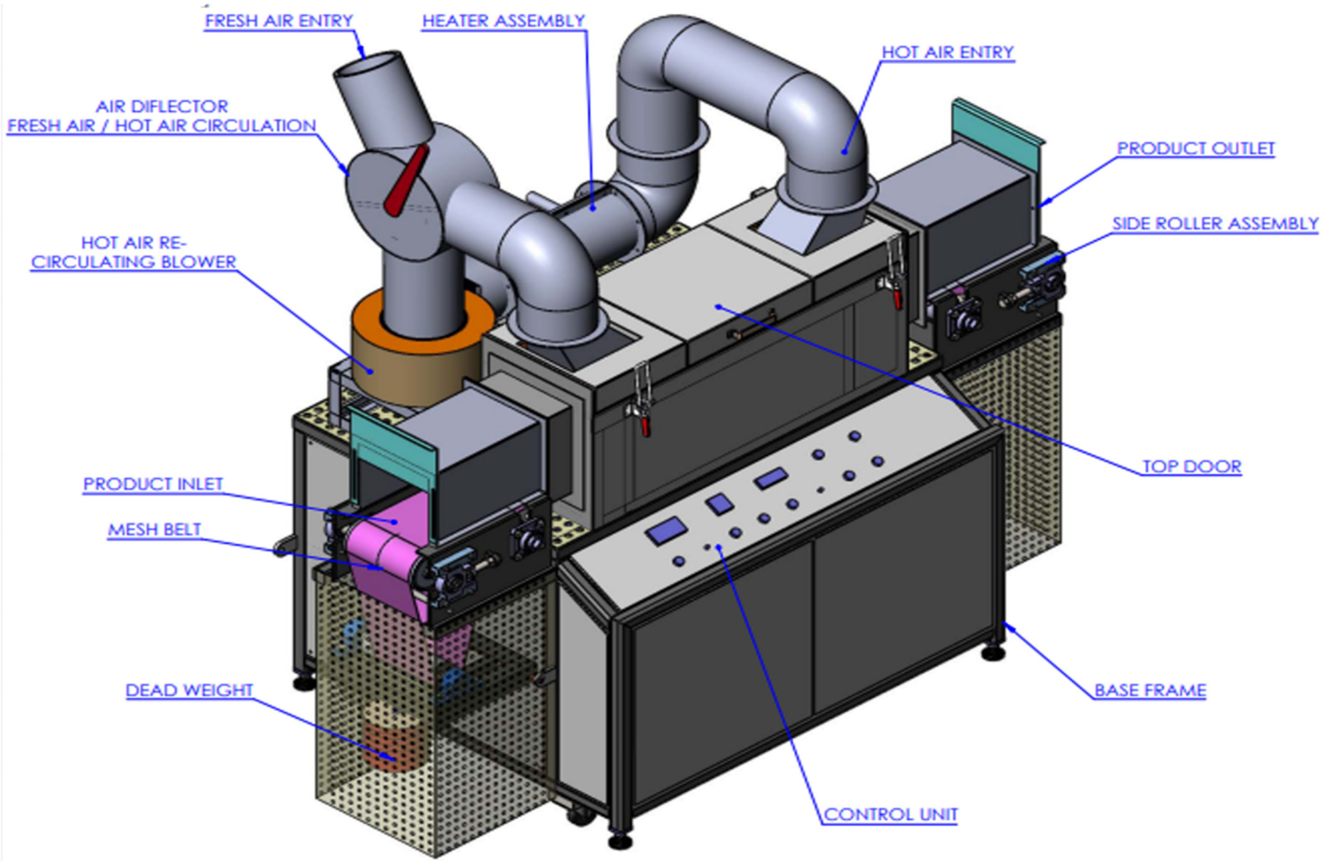

FIGURE 1 Hot air-assisted microwave dryer—Solid diagram (courtesy: Enerzi microwave systems Pvt. Ltd., Belgaum, India).

2.2.3 | Drying procedure

Performance evaluation of HAMW drying system was carried out using shrimp under MW power of 1000 W and HA temperature of 60–65°C. Drying was continued up to 12%–18% w.b. moisture content. Drying studies were conducted in triplicates. For each drying experiment, 1000 g of cleaned samples was taken and fed to the conveyor. A handheld infrared thermometer (METRAVI, Kolkata, India) was used to measure chamber and shrimp temperature during drying. Relative humidity of air ranged from 67 ± 1% to 36 ± 1% during drying. Based on the preliminary experiments, MW power levels were optimized for the desired temperature range for drying of shrimps. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28 ± 2°C). Weight loss of the shrimp was measured in every 30 min of drying operation. The experimental setup of HAMW dryer and graphical abstract of shrimp during HAMW drying is shown in Figures 2 and 3, respectively.

Moisture content

Weight of water in the product is represented by moisture content and can be calculated as dry and wet basis values, as given below:

$$M_w = \frac{W_I - W_F}{W_I} \tag{10}$$

$$M_d = \frac{W_I - W_F}{W_F} \tag{11}$$

where M_d, M_w are dry and wet basis moisture, respectively; W_I is the sample weight before drying (kg), W_F is the sample weight after drying (kg).

Drying rate

Amount of moisture removed in terms of time is described by drying rate and is determined as follows (Sodha et al., 1987):

$$DR = \frac{M_t - M_{t+dt}}{dt} \tag{12}$$

where DR, the drying rate, is obtained as kg of water per kg dry mass per h, M_t is moisture content at time t (kg water/kg dry mass), M_{t+dt} is moisture content at time, $t + dt$ (kg water/kg dry mass and dt is the difference in time, h.

Moisture ratio

Moisture ratio was determined as below:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{13}$$

where MR stands for moisture ratio, M_0, M_e and M_t are the percent moisture contents initial, equilibrium and at time, t (in % db),

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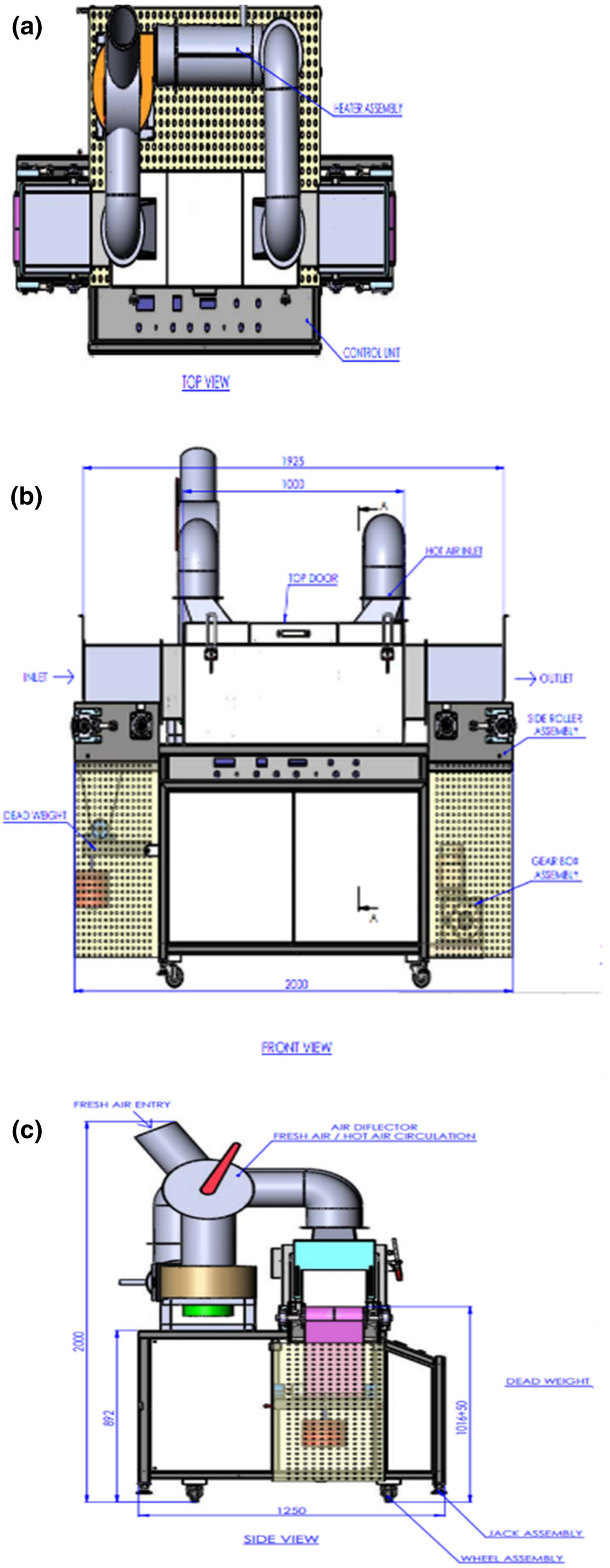

FIGURE 2 Hot air generation system (a) top view, (b) front view and (c) side view (courtesy: Enerzi microwave systems Pvt. Ltd., Bangalore, India).

FIGURE 3 Hot air-assisted microwave dryer.

respectively. Above equation takes the form as equation (16) by omitting the term M_e, as it is very small comparable with M_0 and M_t values (Sacilik et al., 2006).

$$\mathrm{MR} = \frac{M_t}{M_0} \tag{14}$$

EMD

Diffusion, which is the major driving force for moisture removal in drying, is expressed by EMD that determine the overall mass transfer process. It is the rate of movement of moisture and gives insight to the migration of water during drying and hence needed for optimization process. Movement of water inside hygroscopic material during falling rate drying is given by Fick's law as:

$$\frac{\delta M}{\delta t} = \nabla.\left(D_{\mathrm{eff}}\,\nabla M\right) \tag{15}$$

where M denotes moisture content of the sample in kg water/kg dry matter, t stands for drying time in s, and D_{eff} represents the EMD in m^2/s.

It was assumed that shrimp for drying were cylindrical in shape for the diffusivity calculation. For an infinite cylinder (where the moisture diffusion takes place in radially outward direction only), the assumptions considered for calculating diffusivity were (Crank, 1975):

- Uniform distribution of moisture initially in the ample
- Symmetric mass transfer with reference to cylindrical center
- Surface mass transfer resistance is very less compared with internal resistance to mass transfer
- Shrinkage of product is negligible with constant diffusion coefficient

For cylindrical material, Crank's solution for equation (17) is given by:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{4}{b_n^2} \exp\left(- \frac{D_{eff} b_n^2 t}{r^2} \right) \quad (16)$$

Taking the initial term, diffusivity is calculated as (Zogzas & Maroulis, 1996):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{4}{b_n^2} \exp\left(- \frac{D_{eff} b_n^2 t}{r^2} \right) \quad (17)$$

In the above equation, r represents mean radius of sample in meters, n denotes positive integer, and b_n are the root of Bessel's function (2.405, 5.52, 8.654 ……). For $n > 1$, solution is obtained as (Lopez et al., 2000):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{4}{b_1^2} \exp\left(- \frac{D_{eff} b_1^2 t}{r^2} \right) \quad (18)$$

where b_1 is 2.405.

The simplified form of equation (20) in logarithmic form is written as:

$$\ln(MR) = A - B \times t \quad (19)$$

Here, B represents the slope of line and is related to moisture diffusivity as:

$$B = \frac{b_1^2 D_{eff}}{r^2} \quad (20)$$

Thus, moisture diffusivity is determined from the slope obtained from plot of linear regression of ln (MR) with time (Equation 23)

$$D_{eff} = - \frac{B\, r^2}{b_1^2} \quad (21)$$

Mathematical modeling of drying behavior

Drying data were substituted in thin layer drying equations (Table 2) to predict behavior, control parameters and improve efficiency. The solutions to the values of model constants and non-linear regression analysis were executed by MATLAB (R2021b) software (Alfiya et al., 2018). The prediction on the model of best fit was done with respect to higher coefficient of determination (R^2) and lower percentage root mean square (RMSE) and reduced chi-square (χ^2).

Drying efficiency

The efficiency of MW drying was calculated as the ratio of heat utilized for vaporization of water to the heat provided by the dryer (Soysal et al., 2006).

$$\eta = \frac{Mw \times L}{P \times t} \quad (22)$$

where η is the HAMW drying efficiency (%); P is the MW power (W); m_w is the mass of water evaporated (kg); L is the LH of vaporization of water (2257 kJ/kg); and t is the drying time (s).

SEC

SEC is determined using the following equation and is expressed as kWh/kg of water evaporated (Wang & Sheng, 2006).

$$SEC = \frac{E_T}{M_W} \quad (23)$$

where E_T is the total energy (kWh) and M_W is mass of water evaporated (kg).

Color

Colorimetric values (L^*, a^*, b^*) were measured to find out the color changes of shrimp and were performed using a colorimeter (Hunterlab, Colorflex: EZ). Conventionally, the Hunter color scale is represented by L^* for lightness or darkness ($L^* = 0$ for darkness and $L^* = 100$ for whiteness), a^* for redness or greenness ($a^* > 0$ for redness and $a^* < 0$ for greenness) and b^* for yellowness or blueness ($b^* > 0$ for yellowness and $b^* < 0$ for blueness). The total variation ΔE is given as:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (24)$$

where L^*, a^*, b^* and L_0, a_0, b_0 indicated the color parameters for dried and raw samples, respectively. More variation from control is represented by higher ΔE values.

Shrinkage

The volume changes in foods during drying are expressed in terms of shrinkage. Difference in volume of samples before and after drying was estimated by comparing the dimensions of sample in three directions using Vernier caliper (accuracy of ±0 0.05 mm) before and after drying. Equation to calculate shrinkage is given as (Tirawanichakul et al., 2008):

$$\text{Shrinkage}\,(\%) = \frac{D_{Initial} - D_{Final}}{D_{Initial}} \times 100 \quad (25)$$

where $D_{Initial}$ and D_{Final} are geometric mean diameter of shrimp before and after drying, respectively.

Rehydration ratio

To determine the rehydration ratio of dried shrimp, 5 g of sample was soaked in 200 ml distilled water at room temperature. Weight of the samples was taken at every 30-min interval, until constant value was obtained (Doymaz & İsmail, 2011).

$$\text{Rehydration ratio} = \frac{\text{Weight of rehydrated sample}\,(g)}{\text{Weight of dried sample}\,(g)} \quad (26)$$

Microbial analysis

Microbiological quality of the dried shrimp was tested for total plate count (TPC) as per the standard procedures of Food and Drug Administration (FDA), Bacteriological Analytical Manual (US Food and Drug Administration, 2020). Ten grams of the shrimp sample

TABLE 2 Modeling of drying data

S. No.	Model name	Equation	R^2	RMSE	Reduced χ^2	Constants
1	Logarithmic (Moradi et al., 2020)	$MR = \frac{M-Me}{Mo-Me} = ae^{-kt} + c$	0.9954	0.02853	0.000466	$a = 1.086$ $b = 0.7624$ $c = 0.0688$
2	Henderson and Pabis (Arslan et al., 2010)	$MR = \frac{M-Me}{M0-Me} = ae^{-kt}$	0.9979	0.01698	0.000405	$a = 1.01$ $b = 0.9793$
3	Modified page (Karacabey & Buzrul, 2017)	$MR = \frac{M-Me}{Mo-Me} = e^{(-kt)^n}$	0.9979	0.01698	0.000367	$a = 1.01$ $b = 0.9698$
4	Two-term exponential (Toğrul & Pehlivan, 2004)	$MR = \frac{M-Me}{Mo-Me} = a*\exp(-k1*t) + b*\exp(-k2*t)$	0.9972	0.02973	0.001144 0.000362	$a = 14.32$ $b = 13.32$ $k1 = 0.7225$ $k2 = 0.7075$
5	Wang and Singh (Wang et al., 2005)	$MR = \frac{M-Me}{Mo-Me} = 1 + at + bt^2$	0.9887	0.04396	0.000324	$a = 0.6979$ $b = 0.1253$
6	Verma et al. (Yaldýz & Ertekýn, 2001)	$MR = \frac{M-Me}{Mo-Me} = ae^{-kt} + (1-a)e^{-gt}$	0.9977	0.01919	0.000378	$a = 0.1973$ $b = 0.9468$ $g = 0.9664$
7	**Page (Roy et al., 2022)**	$MR = \frac{M-Me}{Mo-Me} = e^{-kt^n}$	**0.9984**	**0.01552**	**0.000134**	$a = 0.9592$ $b = 1.052$
8	Newton (Benseddik et al., 2018)	$MR = \frac{M-Me}{Mo-Me} = e^{-kt}$	0.9977	0.01622	0.000412	$a = 0.9704$

Bold values indicates the best fit moodel for drying under study.

was aseptically cut into a sterile Petri dish and blended with 90ml of sterile normal saline (NS) in a stomacher and made two-fold serial dilution up to 10^{-6}. For TPC on Total Plate Count Agar, one ml of the appropriate dilutions was pipetted and pour plated with the corresponding medium in duplicate plates. These plates were allowed to set, inverted and incubated at 37°C for 18–24h. The diluted plates contained colonies ranging from 25–250 numbers. The experiments were done in triplicates, and the average value was recorded.

Water activity

Water activity of dried shrimp was determined using Aqualab Series 3 L water activity meter, Decagon Devices, Inc. Pullman, Washington, DC) at 28±°C.

Proximate analysis

Fresh shrimp and shrimp dried under were examined for its proximate composition like moisture, crude protein, crude fat and ash (AOAC, 1990).

Sensory evaluation

Dried shrimp samples were evaluated for sensory parameters like appearance, texture, color, odor and overall acceptability (Chavan et al., 2008). Sensory analysis was carried out using 9-point hedonic scale with 9 – like extremely, 8 – like very much, 7 – like moderately, 6 – like slightly, 5 – neither like nor dislike, 4 – dislike slightly, 3 – dislike moderately, 2 – dislike very much and 1 – dislike extremely. The evaluation was done by 25 semi-trained panel members. The members were the staff and researchers of ICAR-CIFT who were general fish consumers and were able communicate and report variations in the sample (Figure 4).

3 | RESULTS AND DISCUSSION

3.1 | Drying rate and moisture content during drying

Figure 5 shows the variation in moisture content and drying rate with respect to drying time for shrimp under HAMW drying conditions. It is evident from the graph that moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% within 3.5 h of drying. Volumetric heating effect of MWs can be attributed for the reduction in drying time. MW heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Mohd Rozainee and Ng (2010) made laboratory studies on MW heating and published that moisture content of sardine fish was reduced from 2.76 to 0.01 (dry basis) within 4.25min under MW power of 500W. Lin et al. (1999) reported that drying of shrimps from a moisture level of 83% to 20% was achieved within 60min in MW-assisted vacuum dryer, which is only 25% of the time required for HA drying of the same. Darvishi et al. (2012) also reported that at MW powers of 200, 300, 400 and 500W, time taken to dry shrimp from moisture levels of 3.103% (d.b.) to 0.01% (d.b.) was 11.75, 7, 4.75 and 4 min, respectively. Lower drying times are also related to higher drying rates of shrimp under HAMW treatment. Drying rate exhibited maximum value of 2.74 during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation. Dipole rotation arises owing to the presence of water molecules in the sample that tends to change the polarity depending on the rapidly changing electromagnetic field induced by the magnetron. As the moisture content reduces, the magnitude of dipole rotation also

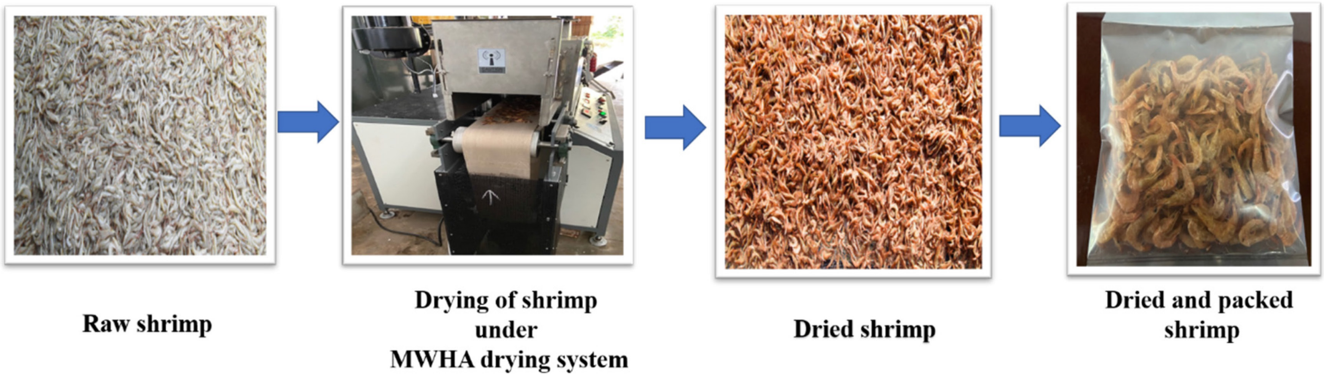

FIGURE 4 Graphical abstract of shrimp drying under HAMW drying system.

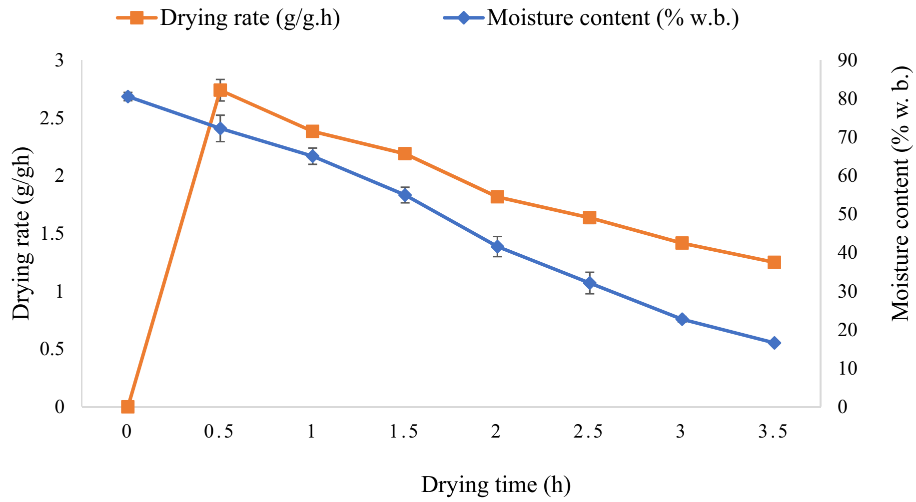

FIGURE 5 Variation in drying rate and moisture content during HAMW drying of shrimp.

reduces and thereby lowering the drying rate. As moisture removal rate is less towards the end, drying occurred under falling rate period. Olatunde et al. (2017) concluded that higher core temperature of materials together with the consistent direction of heat transfer and moisture diffusion enhanced the drying rate in MW drying.

3.2 | EMD

Sum of liquid and vapor diffusion during drying is represented by EMD of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gave the slope value to determine the diffusivity (Figure 6). EMD during drying of HAMW of shrimp was determined to be 6.7×10^{-7} m^2/s. EMD was estimated from the experimental data based on Fick's law of diffusion. This parameter represented the intrinsic mechanism by which moisture transport was facilitated by means of liquid diffusion, vapor diffusion, hydrodynamic flow and other means. The volumetric heating effect of MWs resulted in higher drying rates and decreased drying times due to higher moisture diffusivity. Thus, moisture diffusivity served as the quantitative parameter at molecular level for explaining drying kinetics. Kaveh et al. (2021) opined that MW drying exhibited higher values of diffusivity compared to convective drying based on his study on drying of pomegranate arils. Darvishi et al. (2014) studied MW drying effects on mulberry and reported diffusivities in range of 1.06×10^{-8} to 3.45×10^{-8} m^2/s as the MW power was varied from 100 to 500 W. MW drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s and 4.63×10^{-6} m^2/s under varying operating conditions (Çelen, 2019).

3.3 | Evaluation of drying models

HAMW of shrimp was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying was fitted into thin layer drying models by non-linear regression analysis (Table 2). Page model was identified as the best fit model with higher R^2 value of 0.9984, lower χ^2 value of 0.000134 and RMSE value of 0.01552 (Table 2). To verify the acceptability of the selected page model, observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9984 which implies that the selected model satisfactorily described the drying behavior of shrimp under the HAMW dryer

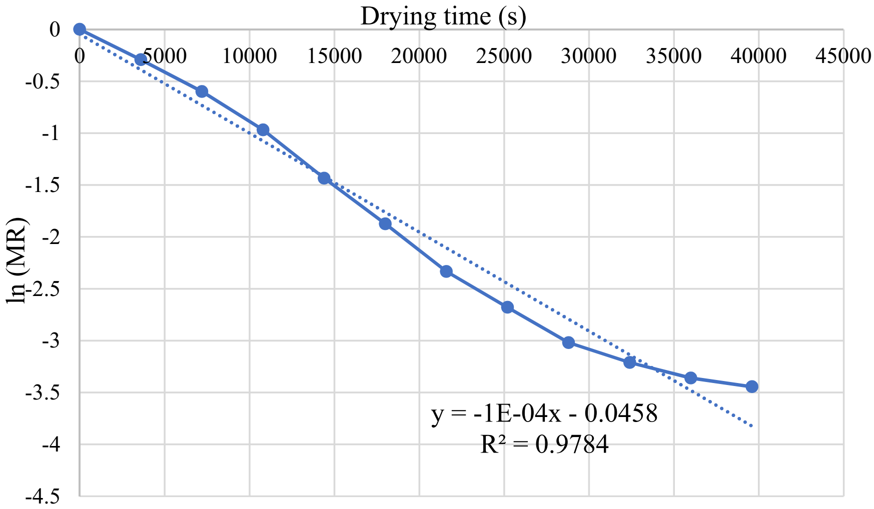

FIGURE 6 Plot of ln (MR) against time for HAMW drying of shrimp.

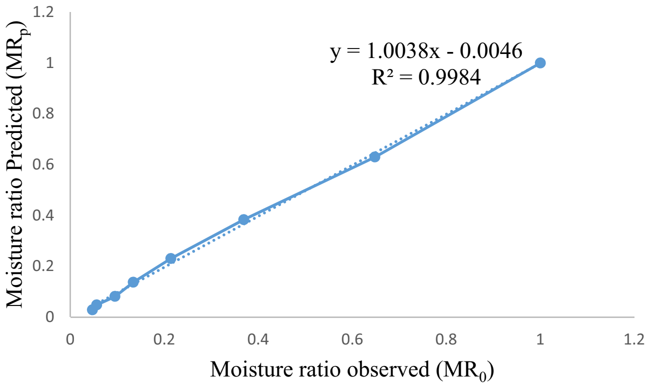

FIGURE 7 Best fit page model.

(Figure 7). Similar study was published by Murali et al. (2021) for drying of shrimp in solar-LPG hybrid dryer.

3.4 | Drying efficiency

Drying efficiency of the dryer under HAMW mode was observed to be 35.71%. This was a result of volumetric hearing effect of MW radiation combined with convective effect of HA. Hassan (2016) published that since MWs act only on polar molecules, MW drying efficiency decreased with time and increased with moisture content of sample during studies on MW drying of date. Maximum drying efficiency of 32% was recorded with a SEC of 7.15 MJ/kgH_2O. Zarein et al. (2015) observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W, respectively, during drying of apple slices in laboratory scale MW dryer.

3.5 | SEC

The SEC value for HAMW of shrimp was found to be 1.75 kWh/kg. Sharma and Prasad (2006) reported SEC of 26.32 MJ/kg for drying of garlic under MW power of 40 W and HA temperature of 70°C. MW and convective drying of pomegranate arils were calculated to have SEC of 35.42 and 145.12 kWh/kg (Kaveh et al., 2021). It is understood that as moisture content decreases, the energy requirement and SEC increases due to difficulties in removing water other than free and unbound moisture in the product. But the volumetric heating effect of MWs in the study tended to fasten the drying process leading to higher drying rates and subsequently lower SEC as compared with convective drying. As moisture content of product decreased, the MW energy absorbed by the shrimp also reduced leading to higher SEC during later stages of drying. SEC in MW drying was observed to have 70% more energy savings as compared to convective drying (Sadi & Meziane, 2015).

3.6 | Color change

The total value of color change (Δ*E*) determined for dried shrimp was 16.95 ± 2.14. The "L" value of the dried shrimp (41.31 ± 1.63) decreased during drying, whereas the "a" and "b" values increased from 3.56 ± 1.54 to 14.23 ± 2.36 and 12.42 ± 0.65 to 19.42 ± 1.61 during the drying process. Darker color of shrimps can be attributed to the process of Maillard browning reaction that might have occurred during drying. The development of redness was due to the release of astaxanthin during the breakdown of carotenoproteins. Yellowness of shrimp increased as a consequence of the formation of yellow pigments due to browning reactions during drying. Çelen (2019) evaluated the color of persimmon dried using MW radiation and obtained values of 13.25 and 24.320 for Δ*L* and Δ*E*, respectively, at MW power of 600 W. It was also observed that higher MW powers may cause unstable MW field that may affect the color quality of products. Taib and Ng (2011) also showed that in MW drying of catfish slices, HA treatment imparted brighter color to dried products shifting towards red and yellow.

3.7 | Shrinkage

Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extend of shrinkage depends on the method of drying. Shrinkage percentage of dried shrimp was observed to be 14.14%. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin et al., 2005). Reduction in shrinkage percentage was due to the rapid evaporation of moisture by MW radiation that created a vapor flux thereby preventing case hardening. Giri and Prasad (2007) reported that MW vacuum drying of mushrooms resulted in dried products with very less shrinkage compared to HA-dried samples. MW-dried herbs exhibited lesser shrinkage and better retention of biochemical constituents as reported by Kathirvel et al. (2006). The reason for a lower percentage of shrinkage was due to controlled drying of shrimp which has resulted in the rapid removal of moisture and thus created an internal porous structure in the dried shrimp.

3.8 | Rehydration ratio

The structural and cellular degradation occurred within the sample during drying is explained by rehydration ratio. The values of rehydration ratio of dried shrimp with respect to time are shown in Figure 8. Within the first hour of soaking shrimp in water, a rapid rise was seen in rehydration ratio. Average rehydration ratio was observed to be 2.51. Rehydration ratio of Tilapia fillets increased with MW power and air temperature during HAMW drying of the fish (Duan et al., 2011). Akonor et al. (2016) also reported similar range of rehydration ratio for shrimp. Initially, a high rate of rehydration was observed which may be due to the porosity of the samples. However, after the first hour, rehydration is slowed down for the next four hours, and thereafter, the process reached equilibrium at the end of 7 h. Hence, the rehydration ratio of 2.51 for the dried shrimp shows that less structural damage could have occurred in the product during drying.

3.9 | Water activity

In this study, water activity value of dried shrimp was determined to be 0.552 that indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf-life extension of products (Jayaraman & Gupta, 2020).

3.10 | Microbiological quality

The TPC of raw shrimp was 3.6×10^6 CFU/g of a sample. Drying reduced the TPC value of shrimp to 2×10^4 CFU/g, which is lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample (IS 14950 2001). This confirms that dried shrimps prepared with HAMW dryer were microbiologically safe for consumption. A similar result of microbial reduction was reported by Murali et al. (2021) for shrimp drying.

3.11 | Proximate and biochemical analysis

Results of proximate analysis of fresh and dried shrimp are shown in Figure 9. The moisture content of the fresh shrimp was decreased from 80.55% (w.b) to 16.5% (w.b) in the dryer. Moisture removal was due to the MW power applied with the assistance of HA generated in the dryer. Similar result was reported by Tein et al. (1999) for drying shrimp from 83% to 20% moisture levels under vacuum-assisted MW drying system. Protein content of shrimp increased from 15.12% to 60.24% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried shrimp. Rasul et al. (2018) reported similar increase in protein content of dried silver carp during drying. This ensures the maximum retention of fat during drying. The higher ash content in dried shrimp was due to the moisture reduction as the ash content is directly related to moisture content and temperature. As moisture content decreases, ash content increases (Adeyeye, 2000). Akonor et al. (2016) reported ash content increase in shrimp during drying due to moisture reduction and concentration of chemical components.

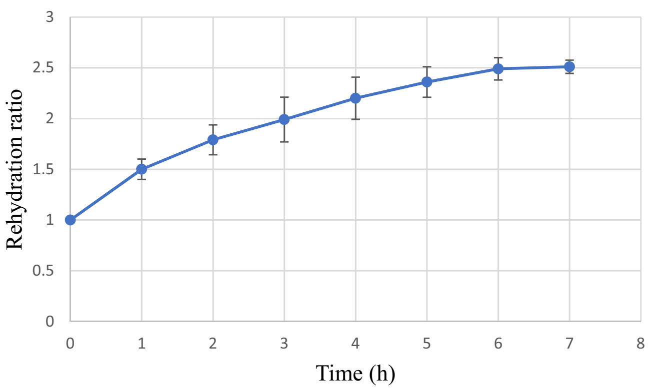

FIGURE 8 Rehydration ratio of dried shrimp as a function of time.

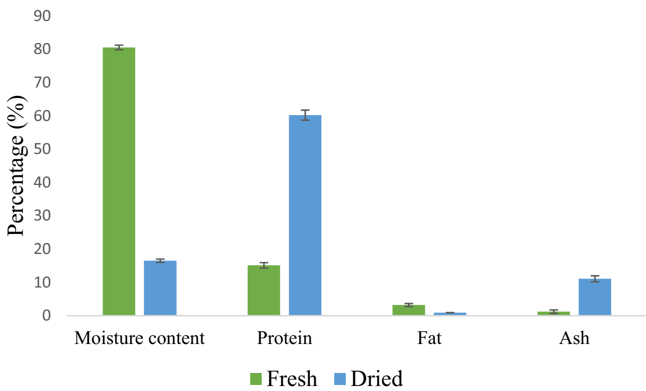

FIGURE 9 Proximate composition of fresh and HAMW dried shrimp.

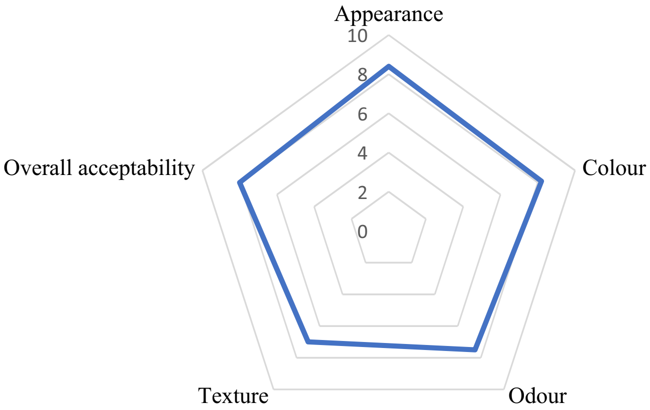

FIGURE 10 Radar diagram for sensory evaluation of dried shrimp.

3.12 | Sensory evaluation

The scores of sensory evaluation of dried shrimp are depicted in Figure 10. Twenty-five semi-trained panel members comprising of research scholars and staff assigned maximum score to "overall acceptability" of the samples. This can be due to the degree of uniformity in the samples, final moisture content and better color retention of the samples. Mounir et al. (2020) also reported highest overall acceptability to the intermittent MW dried shrimp snacks coupled with instant controlled pressure drop treatment.

4 | CONCLUSIONS

MW drying produced better quality shrimp with respect to shrinkage, rehydration ratio, moisture diffusivity and drying times and hence finds application in the production of bulk quantity of high-quality dried shrimp. The developed HAMW drying system was found to be suitable for shrimp drying under controlled conditions. The shrimp samples were dried to a final moisture content of 16.5% within 3.5 h of drying. EMD of MW dried shrimp was found to be 6.7×10^{-7} m^2/s. Logarithmic model was the suitable fit for the data under study (R^2 = 0.9984, RMSE = 0.0.01552 and χ^2 = 0.000134). The drying efficiency and SEC for HAMW drying of shrimp were calculated to be 35.71% and 1.75 kWh/kg, respectively. The total value of color change (ΔE) determined for dried shrimp was 16.95 ± 2.14. Water activity, rehydration ratio and shrinkage of the dried shrimp samples were 0.552%, 2.51% and 14.14%, respectively. Proximate and microbiological analysis of fresh and dried shrimp were carried out and were found to be within safe limits. This dryer is capable of producing high-quality dried shrimp with economic viability and can be used for commercial production of dried shrimp. Development of a pilot scale prototype of the existing system can reduce drying times and thereby the related electricity consumption making it more energy saving and environment friendly with reduced greenhouse gas emissions as compared to a conventional electrical dryer.

AUTHOR CONTRIBUTIONS

Palli V. Alfiya developed the original concept, performed formal analysis and methodologies, prepared the original draft and contributed to reviewing and editing. Gourikutty K. Rajesh contributed to the administration, supervision, provision of resources, curation of data, reviewing and editing. Subramaniam Murali contributed to formal analysis, reviewing and editing. Dhanapaul S. Aniesrani Delfiya contributed to formal analysis, reviewing and editing. Manoj P. Samuel contributed to administration and supervision. Manadan V. Prince contributed to administration and supervision.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Palli V. Alfiya https://orcid.org/0000-0001-7790-5500

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ORIGINAL ARTICLE

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Process optimization for drying of Shrimp (*Metapenaeus dobsoni*) under hot air-assisted microwave drying technology using response surface methodology

P. V. Alfiya[1] | G. K. Rajesh[2] | S. Murali[1] | D. S. Aniesrani Delfiya[1] | Manoj P. Samuel[1] | M. V. Prince[2] | K. P. Sudheer[3]

[1]Engineering Division, ICAR-Central Institute of Fisheries Technology, Cochin, Kerala 682029, India

[2]Department of Processing and Food Engineering, Kelappaji College of Agricultural Engineering and Technology, Tavanur, Kerala 679573, India

[3]Department of Agricultural Engineering, Kerala Agricultural University, Vellanikkara, Thrissur, Kerala 680656, India

Correspondence
P. V. Alfiya, Engineering Division, ICAR-Central Institute of Fisheries Technology, Cochin, Kerala 682029, India.
Email: alfiya.pv@icar.gov.in

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Indian Council of Agricultural Research

Abstract

The study was carried out to optimize the drying conditions of shrimp in the hot air-assisted microwave drying system using response surface methodology. The drying experiments were performed using a Box–Behnken design with air temperature (50–70°C), air velocity (.5–1.5 m/s), and microwave power level (600–1000 W) as independent variables and drying time, water activity, and rehydration ratio as independent variables. The obtained response variables were fitted into the various regression equations to predict a suitable model. The methodology of desired function was applied to indicate 61.74°C air temperature, 922.61 W microwave power, and 1.0 m/s air velocity which offered a reduced drying time of 2.8 h, the water activity of .424 and improved rehydration ratio of 2.51, respectively with a desirability value of .949. The moisture content, drying efficiency, shrinkage, and total color change were determined for the samples obtained under optimized conditions and were observed as 16.5% (w.b), 35.71%, 14.14%, and 16.95 ± 2.14, respectively. Scanning electron microscopy analysis of dried shrimp showed the formation of pores of diameters ranging from 3.17 to 10.6 μm. The process parameters optimized under the study for hot air-assisted microwave drying can be used for the production of good-quality dried shrimps.

Practical applications

Generally, fish and fish products are dried in the open sun or solar dryers in most developing countries. The traditional methods offer the least process controls with maximum energy and manpower demand to meet the ever-growing industry requirements with increased awareness of the safety and quality of the dried products. The hot air-assisted microwave (HAMW) drying system developed under the study could have complete control over the process parameters without compromising the quality of the dried product. The study suggests the HAMW drying system as a potential means of drying technique for large-scale commercial production of dried shrimps.

KEYWORDS
diffusivity, drying rate, microwave radiation, moisture ratio, rehydration ratio

1 | INTRODUCTION

Shrimp is popular seafood with high protein content belonging to the group of crustaceans (Akonor et al., 2016). Shrimps are perishable in nature due to their higher moisture contents and microbial load (70%–80%), which makes drying an inevitable step in the preservation process. Traditionally, sun drying is practiced as the most convenient and economic method for drying fish and shrimp (Alfiya et al., 2019; Murali et al., 2019). However, due to the inherent drawbacks of open sun drying, the convective hot air drying method is being accepted as commercial practice for drying shrimp and fish (Jain & Pathare, 2007). Convective drying is the most adopted drying method mainly due to its convenience, lack of skilled labor requirement, and less economic inputs (Hiranvarachat et al., 2011). The convective drying technique also comes with the issue of prolonged drying and non-uniform temperature distribution. Also, convective drying has the major disadvantage of decreasing the nutrient contents in foods and increasing the energy consumption for the drying process (Miraei Ashtiani et al., 2022). The demand for dried shrimp in domestic and export markets has led researchers to standardize the drying process for shrimp that would yield products with superior quality at lower energy consumption.

Microwave-based drying systems are found to instantly heat the product and reduce the drying times significantly in the drying process. Microwave drying is one of the novel drying technologies that reduces the drying time by volumetric heating effects of microwaves in the frequency range of 915–2450 MHz. In microwave drying, as heating advances within the material, internal pressure increases causing moisture from cells to reach the surface of the products (Miraei Ashtiani et al., 2022). In order to reduce the intensity of heating by the microwaves and to carry away the moisture from the surface of the products, an external hot air supply at desired air velocities is needed (Miraei Ashtiani et al., 2018). Hence, microwave heating systems are combined with hot air circulation for instant moisture removal from the product and reduce the drying times significantly in the drying process.

Darvishi et al. (2013) studied the effect of microwave and hot air (MWHA) combination on the drying rate, effective moisture diffusivity, and energy demand for drying Sardine fish at MW powers of 200–500 W. The moisture content of the Sardine was reduced to .01 (dry basis) with a reduction of drying time from 9.5 to 4.25 min with the increase in the microwave power. The influence of hot air and MW drying on the nutritional properties of grass carp (*Ctenopharyngodon idellus*) fillets were investigated by Wu and Mao (2008). They reported that microwave drying showed an increase in protein contents since it had less effect on the amino acid composition of grass carp fillets. Microwave drying of shrimp increased drying efficiencies to about 22.54% and reduced specific energy consumption to about 28.94%, by increasing MW power from 200 to 500 W (Farhang et al., 2011). Drying under the microwave (MW) was found to lower drying time and enhance energy efficiency (Soysal et al., 2006).

The response surface methodology (RSM) is used as a tool for the optimization of process conditions that govern the effect of each variable and its interactions. It involves an experimental approach, mathematical procedures, and statistical implication which offer the user to make an efficient empirical exploration of the targeted unit (Murali et al., 2017). Ikrang and Umani (2019) optimized the process conditions for drying catfish using an electrical dryer using RSM. Temperature (50–70°C), the thickness of the sample (10–20 mm), salt concentration (0%–20%), and drying time (480–600 min) were the independent parameters. The moisture content of the dried products under optimized conditions (Temperature: 63.43°C, thickness: 14.81 mm, salt concentration: 9.07%, and drying time: 600 min) was 2.64% (w.b.). Shi et al. (2008) evaluated the horse mackerel (*Trachurus japonicus*) drying under a heat pump dryer using RSM and obtained the optimum conditions of drying air temperature of 30°C, drying air velocity of 1.5 m/s and NaCl content in the osmotic solution of 9.9%.

The sustainability of food processing operations lies in the material handling capacity of the equipment and the types of machinery involved. Most of the microwave-based heating systems mentioned in the literature up to date were meant for batch-scale production to process very few quantities of samples. As the food industry targets more conveyor-type systems with continuous production lines, the optimization of process parameters needs to be evaluated. With this background, the drying of shrimp under a hot air-assisted continuous microwave dryer was studied in this paper. Hence, the study aimed to investigate the effect of drying parameters such as microwave power, air temperature, and air velocity on the quality of dried shrimp and to optimize the drying conditions based on the drying time, water activity, and rehydration ratio of the dried product. The study also aimed to investigate the total color change, rehydration ratio, and microstructure of the optimized product.

2 | MATERIALS AND METHODS

2.1 | Materials

Shrimps (*Metapenaeus dobsoni*) required for the study were received from Calicut Fishing Harbor, Kerala. About 350–380 counts of shrimp in a kilogram, were carefully washed with potable water. The length, width, and thickness of shrimp were found to be 45.73 ± 1.4, 23 ± 1.1, and 9.02 ± 0.63 mm, respectively.

2.2 | Hot air-assisted microwave technology

The drying of shrimp was carried out in a continuous hot air-assisted microwave drying unit established at KCAET, Tavanur. A schematic diagram of the drying unit is shown in Figure 1. The drying unit consists of a drying chamber, microwave generator, hot-air provision, exhaust, fan, and control unit. The drying chamber is provided with only a layer of heat-resistant Teflon conveyor belt with dimensions of 1.5 m × 0.5 m. The operation of Magnetron of 1.45 kW power at 2450 MHz generated microwave energy for heating the products spread as a thin layer in the conveyor. The hot air assistance was

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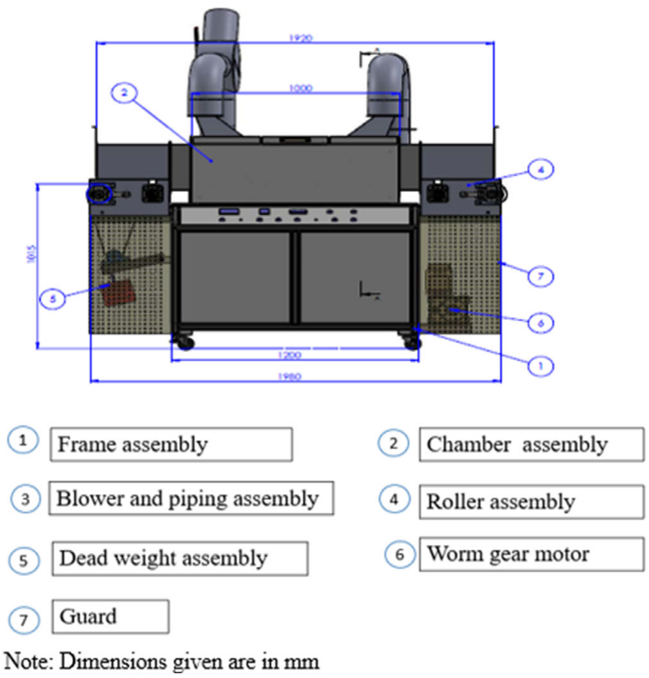

FIGURE 1 Hot air-assisted microwave dryer for shrimp drying.

provided with a 1 kW heating element, an air inlet duct, and an axial fan with a recirculatory section. Fresh inlet air is taken into the top of the dryer with the help of an axial fan and the air deflection valve. The heated air is then uniformly passed over the products at a desired air flow rate. The exit moist air is recirculated into the chamber inlet using a fan and temperature control system for maximum energy savings.

2.3 | Drying experiments using response surface methodology

The drying experiments were performed according to a second-order Box–Behnken design (BBD) with three factors at three levels: microwave power (600, 800, and 1000 W), air temperature (50°C, 60°C, and 70°C), and air velocity (0.5, 1.0, and 1.5 m/s). Drying time, water activity, and rehydration ratio were selected as the response variables. The levels were selected based on literature reviews (Darvishi et al., 2012; Farhang et al., 2011; Lee et al., 2021). A three-factor, three-level BBD experimental design was used in optimizing the drying conditions for shrimp in a hot air-assisted microwave (HAMW) drying system. The quadratic model for predicting the optimum solution was expressed using the following equation:

$$Y=\beta_0+\sum_{j=1}^{k}\beta_j X_j+\sum_{j=1}^{k}\beta_{jj}X_j^2+\sum\nolimits_i\sum_{<j=2}^{k}\beta_{ij}X_iX_j+e_i \qquad (1)$$

where Y is the response, X_i and X_j are variables (i and j range from 1 to k), 0 is the model intercept coefficient; j, jj, and ij are interaction coefficients of linear, quadratic, and second-order terms, respectively, k is the number of independent parameters ($k=3$) and e_i is the error. A lack of fit test was used to evaluate the appropriateness of the selected model.

The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 center points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 13.0 version (Stat Ease Inc., Minneapolis, MN) was used to perform statistical analysis. Analysis of variance (ANOVA) was carried out to check the significance of the model and process variables. The experimental runs were carried out as per the design details provided in Table 1. Microwave power levels were adjusted from the control panel of the microwave generator. The air temperature inside the drying chamber was measured using a digital temperature indicator. The air velocity was measured using a vane anemometer. Drying experiments were conducted till the moisture content of 12%–18% (w.b.) is reached. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28 ± 2°C). The weight loss of the shrimp was measured every 30 min of the drying operation.

2.4 | Drying time

It is the time taken for reducing the moisture content of the shrimp to the desired moisture level in the HAMW drying system. It is generally denoted by the number of hours.

2.5 | Water activity

The water activity of dried shrimp was determined using an Aqualab Series 3 L water activity meter, Decagon Devices, Inc., Pullman, Washington, DC at 28°C.

2.6 | Rehydration ratio

To determine the rehydration ratio of dried shrimp, 5 g of the sample was soaked in 200 mL of distilled water at room temperature. Weights of the samples were taken at every 30-min interval until a constant value was obtained (Doymaz & İsmail, 2011).

$$\text{Rehydration ratio}=\frac{\text{Weight of rehydrated sample (g)}}{\text{Weight of dried sample (g)}} \qquad (2)$$

2.7 | Moisture content

The weight of water in the product was represented by moisture content and can be calculated as dry and wet basis values, as given below:

TABLE 1 Drying time and moisture content under various drying conditions.

Run	Air temperature (°C), Factor: 1	Microwave power (W), Factor: 2	Air velocity (m/s), Factor: 3	Drying time (h), response: 1	Water activity, response: 2	Rehydration ratio, response:3
1	50 (−1)	600 (−1)	1.00 (0)	6	.579	2.23
2	60 (0)	800 (0)	1.00 (0)	3.5	.531	2.51
3	50 (−1)	800 (0)	0.50 (−1)	4	.56	2.32
4	60 (0)	800 (0)	1.00 (0)	3.5	.54	2.52
5	60 (0)	600 (−1)	0.5 (−1)	5.5	.574	2.2
6	50 (−1)	800 (0)	1.50 (+1)	5	.521	2.49
7	70 (+1)	800 (0)	0.50 (−1)	5	.521	2.29
8	60 (0)	1000 (+1)	1.50 (+1)	3	.572	2.43
9	50 (−1)	1000 (+1)	1.00 (0)	4	.524	2.41
10	60 (0)	1000 (+1)	0.50 (−1)	3	.543	2.41
11	70 (+1)	600 (−1)	1.00 (0)	5	.589	2.24
12	60 (0)	600 (−1)	1.50 (+1)	6	.567	2.35
13	60 (0)	800 (0)	1.00 (0)	3.5	.541	2.52
14	70 (+1)	800 (0)	1.50 (+1)	4.5	.576	2.39
15	70 (+1)	1000 (+1)	1.00 (0)	2.5	.524	2.41
16	60 (+1)	800 (0)	1.00 (0)	3.5	.539	2.54
17	60 (+1)	800 (0)	1.00 (0)	3.5	.541	2.52

Note: Figures in the parenthesis signify the coded values.

$$M_w = \frac{W_I - W_F}{W_I} \quad (3)$$

$$M_d = \frac{W_I - W_F}{W_F} \quad (4)$$

where M_d, M_w are dry and wet basis moisture, respectively; W_I is the sample weight before drying (kg), W_F is the sample weight after drying (kg).

2.8 | Drying efficiency

The efficiency of M_W drying was calculated as the ratio of heat utilized for the vaporization of water to the heat provided by the dryer (Soysal et al., 2006).

$$\eta = \frac{M_W \times L}{P \times t} \quad (5)$$

where η is the HAMW drying efficiency (%); P is the M_W power (W); m_w is the mass of water evaporated (kg), and L is the LH of vaporization of water (2257 kJ/kg), t is the drying time (s).

2.9 | Color

Colorimetric values (L^*, a^*, b^*) were measured to find out the color changes of shrimp and were performed using a colorimeter (Hunterlab, Colorflex: EZ). Conventionally, the Hunter color scale is represented by L^* for lightness or darkness ($L^* = 0$ for darkness and $L^* = 100$ for whiteness), a^* for redness or greenness ($a^* > 0$ for redness and $a^* < 0$ for greenness) and b^* for yellowness or blueness ($b^* > 0$ for yellowness and $b^* < 0$ for blueness). The total variation ΔE, is given as:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (6)$$

where L^*, a^*, b^*, and L_0, a_0, b_0 indicated the color parameters for dried and raw samples, respectively. More variation from control is represented by higher ΔE values.

2.10 | Shrinkage

The volume changes in foods during drying are expressed in terms of shrinkage percentage. The difference in the volume of samples before and after drying was estimated by comparing the dimensions of the sample in three directions using a Vernier caliper (accuracy of ±.05 mm). The percentage of shrinkage was calculated as described by Tirawanichakul et al. (2008),

$$\text{Shrinkage}(\%) = \frac{D_{\text{Initial}} - D_{\text{Final}}}{D_{\text{Initial}}} \times 100 \quad (7)$$

where D_{Initial} and D_{Final} is the geometric mean diameters of shrimp before and after drying, respectively.

TABLE 2 ANOVA and statistical parameters of the model for response variable drying time.

ANOVA for response surface quadratic model					
Analysis of variance table (partial sum of squares)					
Source	Sum of squares	*DF*	Mean square	*F*	Prob > *F*
Model significant	17.22	9	1.91	10.72	0.002
A	.50	1	.50	2.80	.1382
B	12.50	1	12.50	70.00	<.0001
C	.13	1	.13	.70	.4304
A^2	1.33	1	1.33	7.46	.0293
B^2	.41	1	.41	2.30	.1729
C^2	1.33	1	1.33	7.46	.0293
AB	.063	1	.063	.35	.5727
AC	.56	1	.56	3.15	.1192
BC	.063	1	.063	.35	.5727
Residual	1.25	7	.18		
Lack of fit	1.25	3.0	.42		
Pure error	.000	4	.000		
Cor total	18.47	16			
C.V. (%)		3.4			
R^2		.9323			
Adj. R^2		.8453			

2.11 | Microstructure analysis

The texture of a food product is a function of micro and macrostructure properties. The microstructure of dried shrimp was analyzed by using the scanning electron microscopy technique (Model: HITACHI SV6600). The analysis was done at a working distance of 8.5–8.8 mm and an accelerating voltage of 15.0 kV. The samples were mounted on metal stubs with double-sided adhesive tape coated with gold.

3 | RESULTS AND DISCUSSION

3.1 | Model fitting

Response surface methodology was used to optimize the process conditions of shrimp in a hot air-assisted continuous microwave dryer. Drying time varied for shrimp under hot air-assisted microwave conditions varied from 2.5 to 6 h, water activity from 0.521 to 0.589, and rehydration ratio from 2.2 to 2.54 The actual measured values were fitted into various regression models to select the appropriate model. ANOVA was done to test the lack of fit and to determine the significance of the selected model and its coefficients (Tables 2–4). Results showed that the model selected for responses was significant. This means that the selected model is appropriate to represent the relationship between responses and factors. To evaluate the model adequacy, R^2, Adj R^2, and coefficient of variation (CV) values were calculated. The coefficient of variation (%) for drying time, water activity, and rehydration ratio were 3.4, 2.27 and .8 respectively. A very low *p*-value (<.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequate precision values of all responses are above 4.0 which indicates the existence of adequate model difference. Also, a low PRESS value for responses indicates model suitability. The desirability function was applied to obtain the optimized values for each dependent variable.

The values of R^2, Adj R^2, and coefficient of variation (CV) values were determined to evaluate the adequacy of the selected model. The R^2 is the measure of the degree of fit and was obtained as .9323, .9122 and .9864 for drying time, water activity and rehydration ratio, respectively and the corresponding adjusted R^2 values were .8453, .8354, and .9690, respectively. A very low value of the coefficient of variation (3.7, 2.17, and 0.8) indicated greater reliability of the experimental data. Therefore, a very low *p*-value (<.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequacy precision values of all responses are above 4.0 which indicates the existence of adequate model difference. The model suitability is also indicated by a low PRESS value for response.

3.2 | Effect of process parameters on drying time

The RSM plots showing the interactions between air temperature, microwave power, and air velocity on drying time are shown in Figure 2a–c. It is evident from the figure that drying time decreased

TABLE 3 ANOVA and statistical parameters of the model for water activity.

ANOVA for response surface quadratic model					
Analysis of variance table (partial sum of squares)					
Source	**Sum of squares**	***DF***	**Mean square**	***F***	**Prob > *F***
Model significant	7.126E−003	9	7.917E−004	4.68	0.0271
A	8.450E−005	1	8.450E−005	.50	0.5027
B	2.664E−003	1	2.664E−003	15.74	0.0054
C	1.805E−004	1	1.805E−004	1.07	0.3361
A^2	1.601E−005	1	1.601E−005	.095	0.7674
B^2	1.297E−003	1	1.297E−003	7.66	0.0278
C^2	2.729E−004	1	2.729E−004	1.61	0.2448
AB	2.500E−005	1	2.500E−005	.15	0.7121
AC	2.209E−003	1	2.209E−003	13.05	0.0086
BC	3.240E−004	1	3.240E−004	1.91	0.2090
Residual	1.185E−003	7	1.692E−004		
Lack of fit	1.113E−003	3	3.712E−004	20.85	0.0066
Pure error	7.120E−005	4	1.780E−005		
Cor total	8.310E−003	16			
C.V. (%)		2.27			
R^2		0.9122			
Adj. R^2		0.8354			

TABLE 4 ANOVA and statistical parameters of the model for rehydration ratio.

ANOVA for response surface quadratic model						
Analysis of variance table (partial sum of squares)						
Source		**Sum of squares**	***DF***	**Mean square**	***F***	**Prob > *F***
Model significant		.20	9	.022	32.78	<0.00
A	1.800E−003	1	1.800E−003	2.72	.1430	
B	.051	1	.051	77.41	<.0001	
C	.024	1	.024	36.59	.0005	
A^2	.032	1	.032	48.46	.0002	
B^2	.053	1	.053	80.21	<.0001	
C^2	.016	1	.016	24.67	.0016	
AB	2.500E−005	1	2.500E−005	0.038	.8514	
AC	1.225E−003	1	1.225E−003	1.85	.2157	
BC	4.225E−003	1	4.225E−003	6.39	.0394	
Residual	4.630E−003	7	6.614E−004			
Lack of fit	4.150E−003	3	1.383E−003	11.53	.0194	
C.V. (%)		.8				
R^2		.9864				
Adj. R^2		.9690				

with an increase in air temperature (50–70°C) and microwave power (600–1000 W). Synergistic effects of air temperature and microwave power led to a reduction in drying times due to the volumetric heating effects of microwaves supplemented by increased temperature gradient created by hot air. However, the increase in air velocity and temperature reduced the drying times to a certain limit, beyond which air velocity increased the drying times at all temperatures (50–70°C) due to the lesser temperature gradient on the product. Moreover, at the highest microwave power (1000 W) with the intermediate air velocity (1 m/s) lowest drying time of shrimp can be obtained. Similar

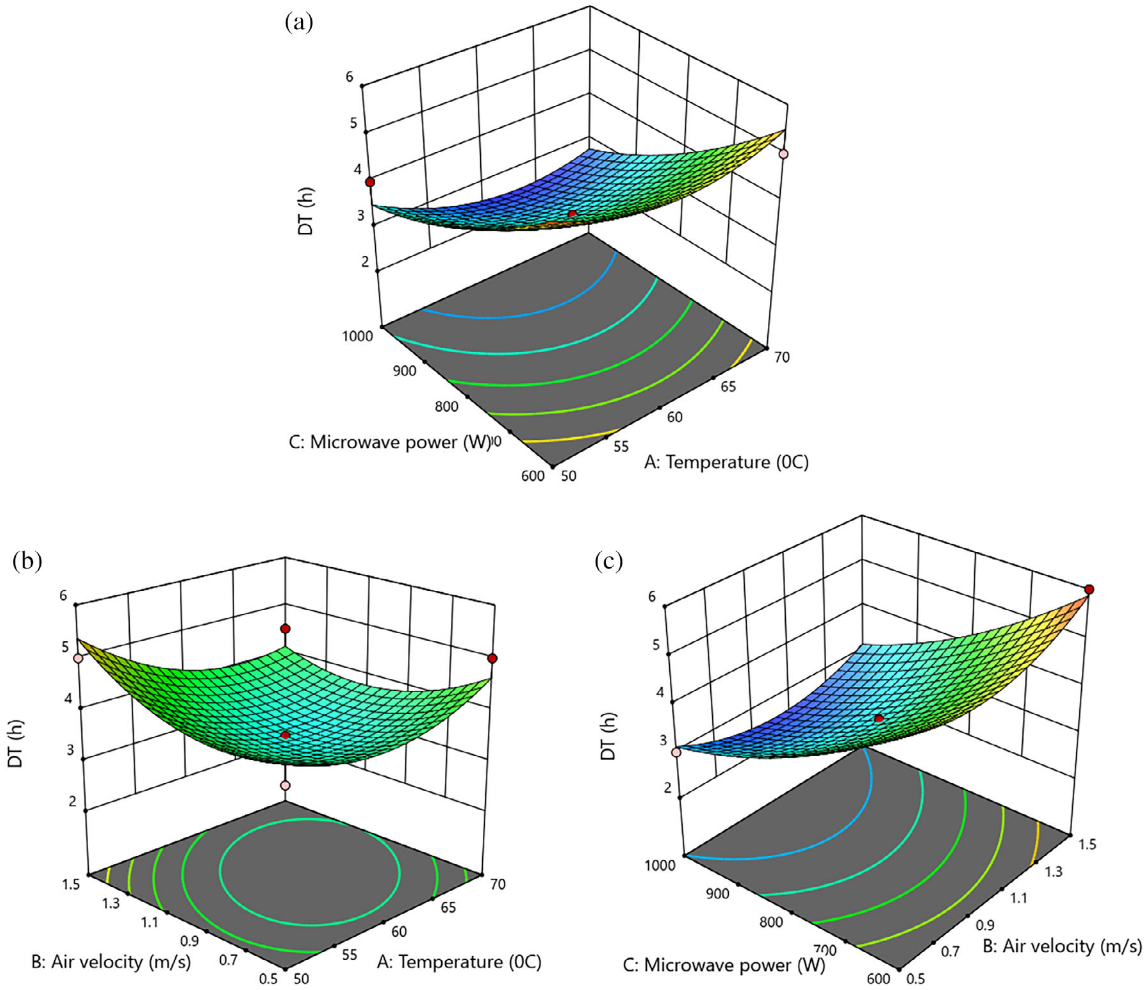

FIGURE 2 Effect of process parameterson drying time (DT).

trends were seen in the interaction reported by Han et al. (2010) for microwave drying of apple slices.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box–Behnken design.

$$\text{Drying time} = +3.50 - 0.25*A - 1.25*B + 0.12*C + 0.56*A^2 + 0.31*B^2 + 0.56*C^2 - 0.12*A*B - 0.38*A*C - 0.13*B*C \quad (8)$$

where *A*, *B*, and *C* denotes air temperature, microwave power, and air velocity, respectively.

3.3 | Effect of process parameters on water activity

The effect of air temperature, microwave power, and air velocity on the water activity of the dried product is shown in Figure 3a–c as air velocity increased (0.5–1.5 m/s), water activity decreased to a certain limit, further which it increased. As the water activity of the product is directly related to its moisture content, an increase in moisture content has enhanced the water activity of the products. An increase in microwave power and air temperature reduced the water activity due to increased drying rates. The water activity of the samples decreased significantly with increased temperature, probably due to the lower moisture content of samples at higher temperatures. At higher temperatures, food structure becomes more porous which accelerates the loss of water. Also, proteins become denatured due to higher temperature thereby losing their water binding capacity leading to more removal of water and reducing the water activity (Azizpour et al., 2016). However, with both thicknesses, aw dramatically decreased with an increase in temperature. Most enzymes and bacteria will be inactive when the food system has water activity below .80. To some extent increase in air velocity, enhances the drying rate, and further reduces the drying rate due to evaporative cooling on the surface of the product (Kilic, 2009). The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box–Behnken design

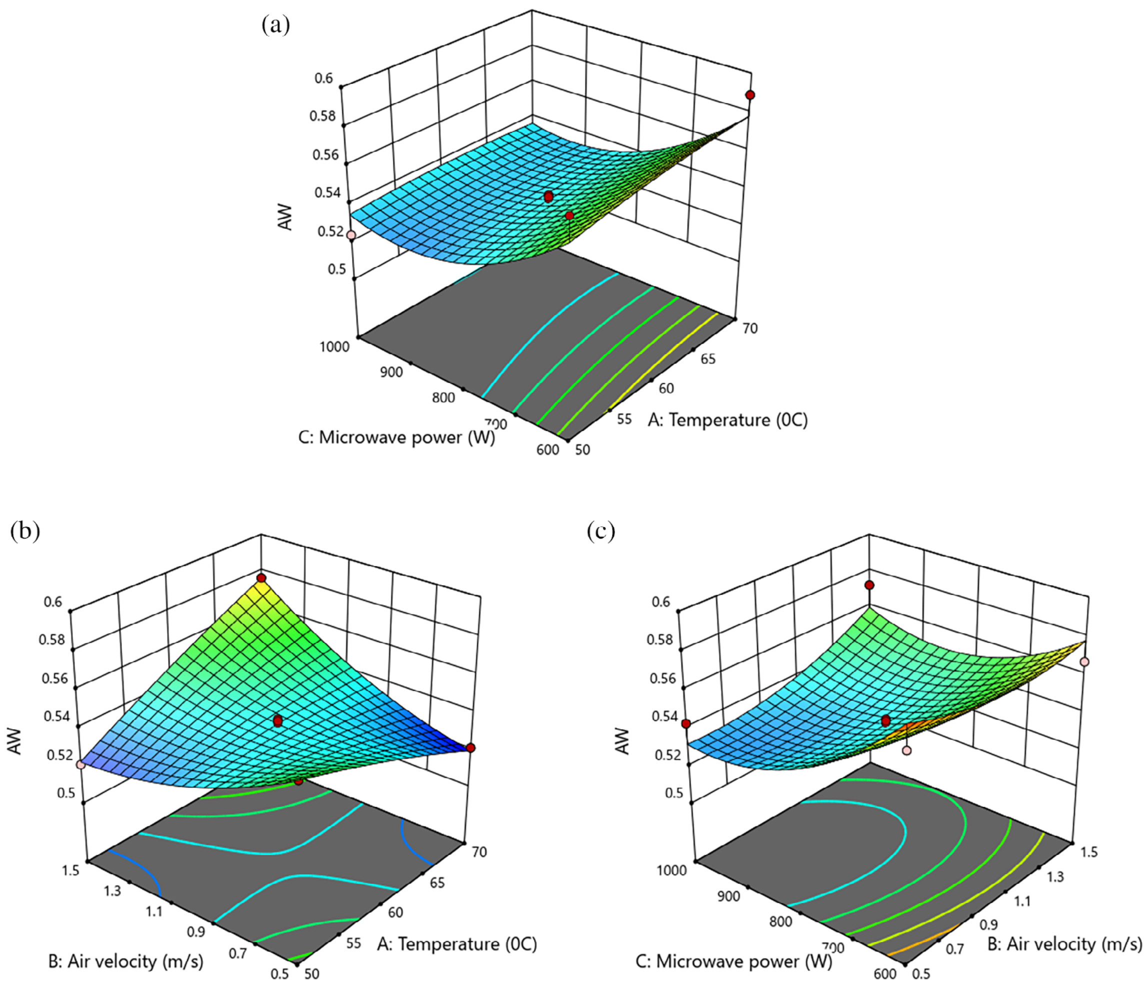

FIGURE 3 Effect of process parameters on water activity (AW)

$$\text{Water activity} = +.54 + 3.250E-003*A - .018*B + 4.750E-003*C - 1.950E-003*A^2 + 0.015*B^2 + 8.050E-003*C^2 - 2.500E-003*A*B + .024*A*C + 9.000E-003*B*C \quad (9)$$

where *A*, *B*, and *C* denote air temperature, microwave power, and air velocity, respectively.

3.4 | Effect of process parameters on rehydration ratio

The rehydration ratio is an important factor indicating the efficiency of the drying process as the rate of rehydration is will be less when the cells and tissues are collapsed or irreversibly damaged (Bozkir et al., 2019). Air temperature, microwave power, and air velocity had a significant effect on the rehydration ratio ($p \leq .01$) (Figure 4a–c). The regression coefficient is positive and maximum for microwave power levels, which indicates better rehydration properties of dried shrimp dried at high microwave power levels. This can be attributed to the high internal pressure development at higher microwave power levels. Higher microwave power causes more internal heating that creates a flux of rapidly escaping water vapor, which opens up the pores. This in turn prevents shrinkage and gives better rehydration properties (Giri & Prasad, 2007). Duan et al. (2011) reported that the rehydration ratio increased with increasing the duration of microwave drying at constant microwave power and also that the rehydration ratio increased with an increase in microwave power at constant time. Qin et al. (2020) observed that microwave combined with hot-air drying could reduce the irreversible structural damage in drying grass carp fillets and further, the rehydration rate increased along with microwave drying time.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results,

$$\text{Rehydration ratio} = +2.52 - .01*A + .080*B + .055*C - .087*A^2 - .1*B^2 - .062*C^2 - 2.500E-003 * - .018*A*C - .033*B*C \quad (10)$$

where *A*, *B*, and *C* denotes air temperature, microwave power, and air velocity, respectively.

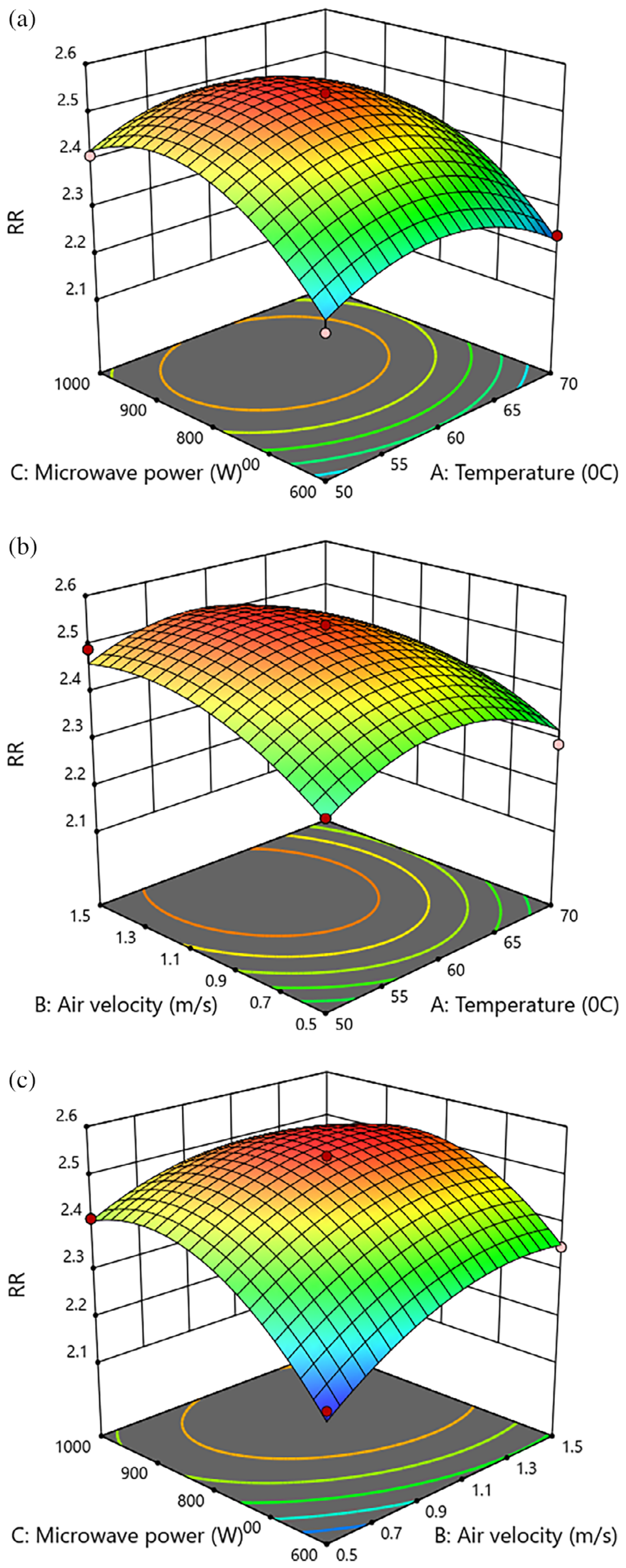

FIGURE 4 Effect of process parameterson rehydration ratio (RR).

3.5 | Determination of optimized conditions

The optimization of drying process parameters was done based on Derringer's desirability function. Microwave power (600–900 W), air temperature (50–70°C) and air velocity (0.5–1.5 m/s) were set within the range with minimization of drying time and water activity and maximization of rehydration ratio. Based on the value of maximum desirability (0–1), optimum conditions were selected. The methodology of desired function was applied to indicate 61.74°C air temperature, 922.61 W microwave power and 1.0 m/s air velocity which indicated the drying time, water activity, and rehydration ratio of 2.8 h and .424 and 2.51, respectively with a desirability value of .949 (Figure 5).

3.6 | Moisture content during drying

The experiments were conducted in the HAMW drying unit at the optimized condition. The moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% (w.b.) within 3.5 h of drying. The volumetric heating effect of microwaves can be attributed to the reduction in drying time. Microwave heating falls under the dielectric heating method wherein the moisture content of the product directly influences the heating rate. Mohd Rozainee and Ng (2010) made laboratory studies on microwave heating and published that the moisture content of sardine fish was reduced from 2.76 to .01 (dry basis) within 4.25 min under microwave power of 500 W. Lin et al. (1999) reported that drying of shrimps from a moisture level of 83% to 20% was achieved within 60 min in a microwave-assisted vacuum dryer, which is only 25% of the time required for hot-air drying of the same. As the moisture removal rate is less toward the end, drying occurred under the falling rate period. Olatunde et al. (2017) concluded that the higher core temperature of materials together with the consistent direction of heat transfer and moisture diffusion enhanced the drying rate in microwave drying.

3.7 | Drying efficiency

The drying efficiency of the HAMW unit was determined for the experiments conducted on the optimized values and was observed to be 35.71%. This was a result of the volumetric hearing effect of microwave radiation combined with the convective effect of hot air. Hassan (2016) reported that microwaves act only on polar molecules, microwave drying efficiency decreased with time and increased with the moisture content of date samples during microwave drying. Maximum drying efficiency of 32% was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein et al. (2015) observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W, respectively during the drying of apple slices in a laboratory-scale MW dryer.

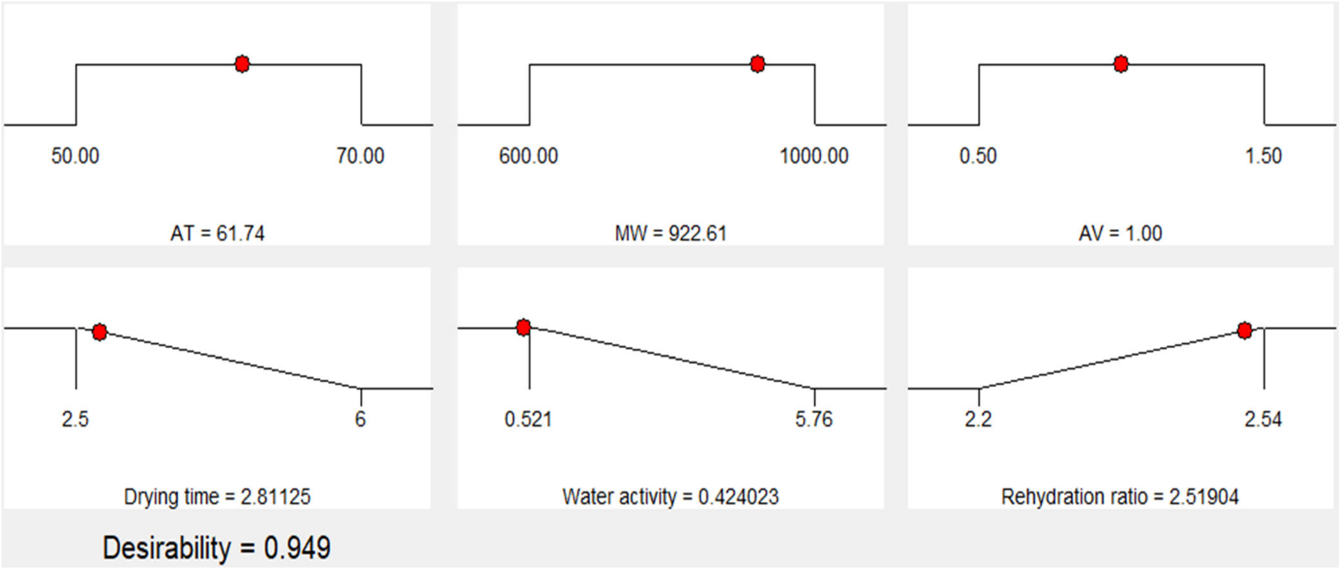

FIGURE 5 Desirability ramps for the optimized conditions of shrimp drying under a hot air-assisted microwave drying system.

FIGURE 6 Color variation in hot air-assisted microwave drying of shrimp.

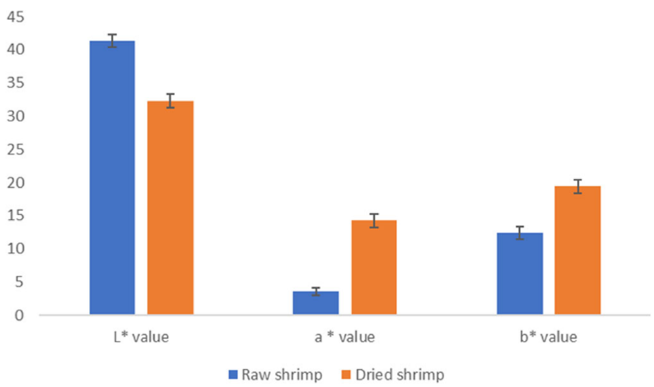

FIGURE 7 Photograph of shrimp before (a) and after drying (b) under a hot air-assisted microwave drying system.

3.8 | Color change

The total value of color change (ΔE) determined for dried shrimp was 16.95 ± 2.14. The "L" value of the dried shrimp (41.31 ± 1.63) decreased during drying whereas the "a" and "b" values increased from 3.56 ± 1.54 to 14.23 ± 2.36 and 12.42 ± 0.65 to 19.42 ± 1.61 during the drying process (Figure 6). The darker color of shrimps can be due to the Maillard reaction. Photographs of shrimp before and after drying is shown in Figure 7. Celen (2019) evaluated the color of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE, respectively at a microwave power of 600 W. It was also observed that higher microwave powers may cause unstable microwave fields that may affect the color quality of

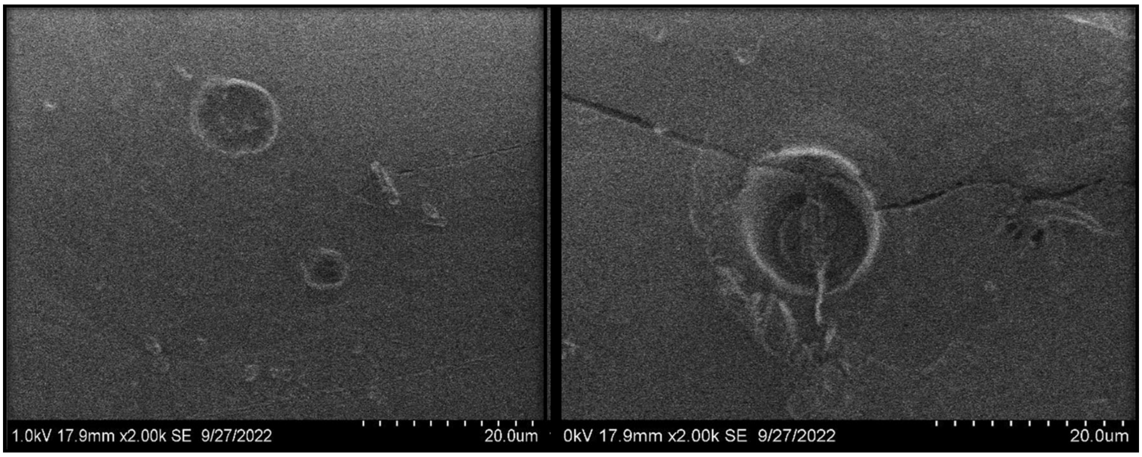

FIGURE 8 Microstructural observations in hot air assisted microwave dried shrimp.

products. Taib and Ng (2011) also showed that in microwave drying of catfish slices, hot air treatment imparted brighter color to dried products shifting toward red and yellow.

3.9 | Shrinkage

During the drying of food, moisture is removed from the product which results in a change in the volume of the product. This volume change is reflected as shrinkage (%) in the dried products. Under the study, the shrinkage percentage of dried shrimp was found to be 14.14%. The lesser shrinkage observed in the samples could be due to shorter drying time with the controlled drying conditions as reported by Murali et al. (2019, 2021). Reduction in shrinkage (%) was also due to the quick evaporation of moisture from the product by microwave heating that created a vapor flux preventing case hardening issue. MW vacuum drying of mushrooms resulted in dried products with very less shrinkage compared to hot air-dried samples (Giri & Prasad, 2007). Similarly, Kathirvel et al. (2006) observed that MW-dried herbs exhibit lesser shrinkage and higher retention of biochemical constituents.

3.10 | Microstructure analysis

The optimized sample was analyzed for microstructure to study the pore size distribution in the dried product. Scanning electron microscopy analysis of dried shrimp showed the formation of pores of diameters ranging from 3.17 to 10.6 μm (Figure 8). The reason for the higher rehydration ratio of hot air-assisted microwave-dried shrimp can be the presence of these pores. The volumetric heating effects of a microwave cause abrupt removal of water molecules which left the internal lattice vacant thereby creating pores of varying diameters. Mounir et al. (2020) studied the porosity and microstructure of shrimp snacks and concluded that higher porosity improved the functional behavior and drying process and quality attributes of the products.

4 | CONCLUSIONS

Process optimization for drying Shrimps (*M. dobsoni*) under hot air-assisted microwave drying technology using a BBD of RSM was employed in this study. The drying experiments were performed using air temperature (50–70°C), air velocity (0.5–1.5 m/s), and microwave power level (600–1000 W) as independent variables and drying time, water activity, and rehydration ratio as independent variables. The methodology of desired function was applied to indicate 61.74°C air temperature, 922.61 W microwave power, and 1.0 m/s air velocity which offered a reduced drying time of 2.8 h, the water activity of .424 and improved rehydration of 2.51, respectively with a desirability value of .949. At the optimized conditions. The moisture content, drying efficiency, shrinkage, and total color change were determined for the samples obtained under optimized conditions and were observed as 16.5%, 35.71%, 14.14%, and 16.95 ± 2.14, respectively. It can be concluded from the study that process parameters optimized under the study for hot air-assisted microwave drying can be used for the production of good quality dried products at the commercial scale.

AUTHOR CONTRIBUTIONS

P. V. Alfiya: Conceptualization, Investigation, Data curation, Formal analysis, Writing - original draft. **G. K. Rajesh**: Resources, Methodology, Supervision, Project administration, Review and editing. **S. Murali:** Methodology, Review and editing. **D. S. Aniesrani Delfiya:** Methodology, Review and editing. **Manoj P. Samuel:** Supervision, Project administration. **M. V. Prince**: Supervision, Project administration. **K. P. Sudheer:** Supervision, Project administration.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

P. V. Alfiya https://orcid.org/0000-0001-7790-5500
S. Murali https://orcid.org/0000-0001-6614-2202
D. S. Aniesrani Delfiya https://orcid.org/0000-0003-4259-4380
K. P. Sudheer https://orcid.org/0000-0001-9981-2356

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Quality evaluation of solar and microwave dried shrimps – A comparative study on renewable and dielectric heating methods

P.V. Alfiya [a,*], G.K. Rajesh [b], S. Murali [a], D.S. Aniesrani Delfiya [a], Manoj P. Samuel [a], M.V. Prince [b]

[a] Engineering Division, ICAR-Central Institute of Fisheries Technology, Cochin 682 029, India

[b] Department of Processing and Food Engineering, Kelappaji College of Agricultural Engineering and Technology, Tavanur 679573, India

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ABSTRACT

The study investigated the quality of shrimp dried under solar and microwave drying conditions. Microwave drying shortened the drying times to 58.3 % as compared to solar drying with increased drying rates. Effective moisture diffusivities of solar and microwave dried shrimp were 2.3×10^{-10} m^2/s and 6.7×10^{-7} m^2/s respectively. Drying and collector efficiency was in the range of 26.3 – 33.4 % and 32.5 – 41.2 % respectively for solar drying whereas the efficiency under microwave drying was 35.7 %. Textural attributes of solar-dried shrimp were superior to microwave-dried samples. The rehydration ratio and shrinkage of solar and microwave dried samples were 2.39 and 24.67 % and 2.51 and 14.14 % respectively. Biochemical and microbiological analyses of dried shrimp under both drying methods were found to be within safe limits. Economic analysis of solar and microwave dried shrimp showed that solar drying is more economically viable than microwave drying for the production of dried shrimp.

1. Introduction

Post-harvest loss of agricultural and marine products is attributed to be an important factor for the food crisis in the world, where around 10 % of the total population does not have enough food to consume (Chauhan and Rathod, 2020). The drying of commodities reduces the post-harvest loss thereby enhancing shelf life by lowering the moisture content present in the foods (Vijayavenkataraman, 2012). Drying by exposure to the sun is an ancient method of preserving foods. It is rather an economic procedure for perishable food products specially to avoid a seasonal glut in markets. Open sun drying involves spreading the materials on the ground over a mat, tray, or concrete in thin layers and thus exposing them to direct solar irradiation and wind power (Lingayat et al., 2020). Though the method is highly economic; the risk of damage by predators, product degradation due to uncontrolled drying temperatures, climatic variations, and non-uniform drying are the various drawbacks associated (Arunsandeep et al., 2018). Solar dryers are intended to sustain controlled conditions inside the dryer for air velocity, temperature, and humidity to improve the efficiency of the process.

Solar drying systems are mainly classified depending upon the heating modes and the solar heat utilization method (Belessiotis and Delyannis, 2011). The classification of these in to active (forced circulation) and passive (natural circulation) dryers is with respect to the pattern of air flow.The classification of these in to active (forced circulation) and passive (natural circulation) dryers is with respect to the pattern of air flow. The former works well with crops of higher water content and require more investment than passive dryers (Chua and Chou, 2003). Here, products are dried with the help of forced air circulation aided by a fan or blower (Patil and Gawande, 2016).

The basic parts of a solar drying system are a collector to harness solar irradiation, a drying chamber with trays for keeping the products, air circulation and a control system (Basunia, 2001). Murali et al (2020) evaluated the performance of the solar-LPG hybrid dryer evaluated using shrimps (*Metapenaeus dobsoni*). The moisture content of fresh shrimp was reduced from 76.71 % (w.b) to 15.38 % (w.b) within 6 h of drying. The maximum water temperature at the collector outlet was 73.5 °C during the experiments. They reported that the solar system supplied 73.93 % of heat energy and the remaining energy was supplied by an LPG heater. The quantity of water to be removed, the flow rate of air and insolation of the region are the major factors to be considered for designing solar-based dryer for agricultural products (Diemuodeke et al., 2011).

The advent in research in the arena of food drying has come up with

* Corresponding author.
E-mail address: alfiya.pv@icar.gov.in (P.V. Alfiya).

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Nomenclature

A_c	Solar water collector area (m^2)
a*, a_0	Redness/greenness of dried and raw samples respectively
b*, b_0	Yellowness/blueness of dried and raw samples respectively
$D_{initial}$	Initial diameter of the sample before drying (m)
D_{final}	Final diameter of the sample after drying (m)
Δ E	Total color change
η	Efficiency (%)
L*, L_0	Lightness value of dried and raw samples respectively
E_{pb}	Energy supplied by pump and blower (W)
E_{sc}	Energy supplied by solar collector (W)
HAMW	Hot air assisted microwave
I	Average incident solar radiation (W/m^2)
LH	Latent heat of vaporization of water (kJ/kg)
M_w	Mass of water to be removed from the product (kg)
m_w	Mass flow rate of water (kg/h)
MDA	Melonaldehyde
TBARS	Thiobarbituric acid (N/100 g)
TMA	Trimethyl amine (N/100 g)
TVBN	Total volatile base nitrogen (mg malonaldehyde/kg of lipid)
TPC	Total plate count
TPA	Total plate count agar
T_{ci}	Temperature of water in the inlet of collector (K)
T_{co}	Temperature of water in the outlet of collector (K)
P	Microwave power (W)
RH	Relative humidity (%)

dielectric drying as a major technology resulting in lower drying times. Dielectric heating consists of radio frequency (RF) and microwave (MW) heating. Microwaves are non-ionizing electromagnetic radiation in the frequency range of 300 MHz – 300 GHz with a wavelength of 1 mm-1 m. Microwaves penetrate the material until moisture is located and heats the material volumetrically thereby facilitating a higher diffusion rate and pressure gradient to expel moisture from inside of the material. The two main mechanisms of microwave heating are dipole rotation and ionic polarization. In the former, water molecules try to follow the electric field which alternates at a very high frequency (2450 MHz) resulting in friction and heat generation inside the food material whereas, in the latter, the ions migrate under the influence of the electric field and generate heat. A dielectric drying system comprises a dielectric wave generator, an adaptor or matching device with generator and load, a wave applicator and handling devices.

Dried shrimp is widely consumed as a main dish and utilized as a major ingredient in sauces and soups for their pleasant taste and flavor (Akonor et al. 2016). Oosterveer (2006) reported that a solar drying system is economical and easy to operate besides producing a superior quality dried product. Murali et al. (2021) assessed the quality characteristics of shrimp (*Metapenaeus dobsoni*) under a solar-LPG hybrid dryer Sengar et al. (2009) studied the drying characteristics of prawn in a low-cost solar dryer and reported a collector efficiency of 70.97 %. Mohd and Ng (2010) reported that drying time for catfish slices was reduced to 75 % using the microwave as compared to hot air (HA) drying. Darvishi et al. (2013) studied the implication of MWHA on the rate of drying, effective moisture diffusivity (EMD) and energy for drying Sardine fish at four varying MW powers of 200 W, 300 W, 400 W and 500 W. The desirable quality characteristics of the dried shrimp are lower shrinkage, higher rehydration rate, reddish color, and about 20 % of moisture content (Niamnuy et al., 2007).

Energy from the sun serves as the vital and inexhaustible form of energy available for the earth and its inhabitants (Rodziewicz et al., 2016). It is the only form of renewable energy with massive applications as compared with other energy sources, with annual global insolation estimated at 5600 ZJ (Moriarty and Honnery, 2019). Conventional dryers utilizing energy from the burning of fossil fuels or electricity are commercially not recommended owing to higher energy consumption, environmental impacts, and cost of operation (Alfiya et al., 2022). Hence, dryers utilizing renewable energy sources were found to be viable and effective for the long-term production of dried products with higher energy efficiency and lower unit cost of production. One of the major drawbacks associated with solar dryers is the higher time requirement for drying which may cause case hardening during the drying of high moisture foods. Longer drying times in solar dryers often affect the quality of dried product as it forms a crust layer that prevent

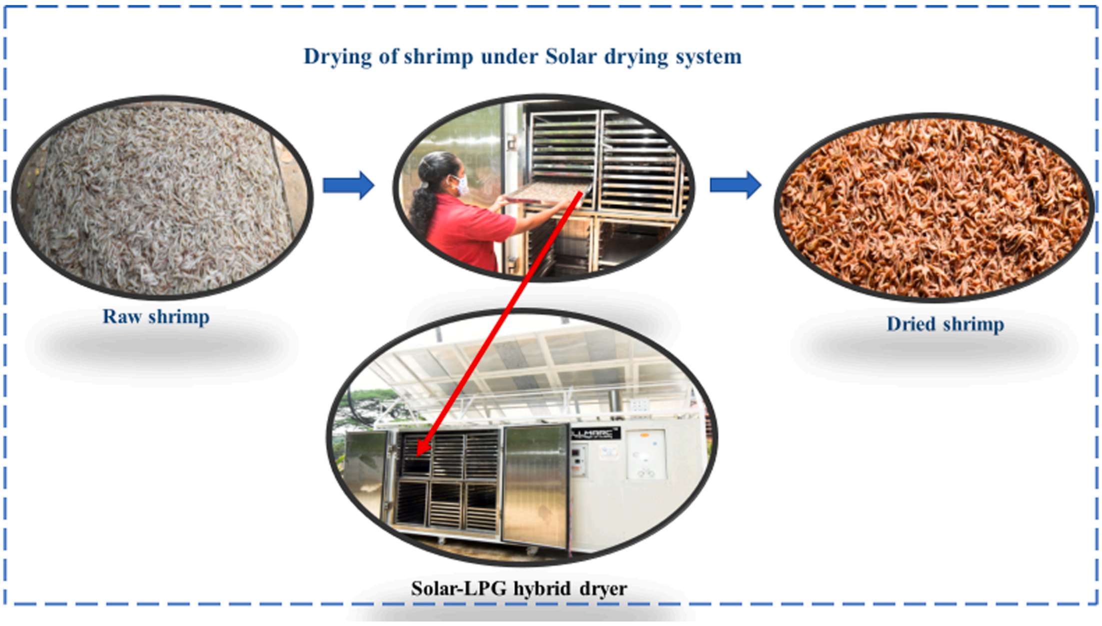

Fig. 1. Drying of shrimp under solar drying system.

Fig. 2. Drying of shrimp under microwave drying system.

diffusion of water from interior of the products to the surface. In order to reduce the duration of drying, dielectric based drying systems like microwave heating has been evolved. However, partial loss of sensory attributes and higher power requirements restrict the adoption of microwave drying for large-scale production. Though exhaustive literature is available with respect to solar and microwave drying in specific, there are no available research papers investigating the comparison of the effect of these technologies on foods. Hence, this study is taken up with the objective of evaluating the quality of shrimps dried under the renewable (solar) and dielectric (microwave) drying technologies. The quality aspects such as moisture content, drying rate, moisture diffusivity, drying efficiency, rehydration ratio, shrinkage, biochemical and microbiological aspects, water activity, color and texture of the dried products is evaluated and compared under both drying conditions.

2. Material and method

Raw shrimps (*Metapenaeus dobsoni*) were purchased from Kallamukku Harbor of Cochin, Kerala. The shrimps were counting around 340–360 nos./kg and were thoroughly cleaned with potable water. The length, width, and thickness of shrimp were determined to be 45 ± 1.5, 24 ± 1.3, and 9 ± 0.6 mm respectively. The moisture percentage of shrimp was found to be 80.55 ± 1.54 (% w. b.) by the gravimetric method (AOAC 1990).

2.1. Drying conditions

Shrimp were dried under two drying conditions namely solar drying (Solar LPG hybrid dryer, ICAR-CIFT, Cochin) and microwave drying (Microwave dryer, KCAET, Tavanur). Solar drying experiments were conducted during January – February 2022 at ICAR-CIFT, Cochin, India (9.9822^0N, 76.2424 ^{0}E). was done under optimum drying temperature of 50–55 ^{0}C inside the drying chamber was maintained by sunshine and LPG backup heating system whereas MW drying was carried out under microwave power of 1000 W. Drying was continued up to 12–18 % w.b. moisture content. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28 ± 2 °C). Weight loss of the shrimp was measured every 30 min of the drying operation. A graphical representation of the drying process is depicted in Figs. 1 and 2.

2.2. Drying studies

2.2.1. Moisture content

The weight of water in the product is represented by moisture content and can be calculated as dry and wet basis values, as given below:

$$M_w = \frac{W_I - W_F}{W_I}$$

$$M_d = \frac{W_I - W_F}{W_F}$$

where $M_{d,}$ M_w are dry and wet basis moisture respectively; W_I is the sample weight before drying (kg), W_F is the sample weight after drying (kg).

2.2.2. Drying rate

The amount of moisture removed in terms of time is described by drying rate and is determined as follows:

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (3)$$

where DR, the drying rate is obtained as kg of water per kg dry mass per h, M_t is moisture content at time t (kg water/kg dry mass), M_{t+dt} is moisture content at time, t + dt (kg water/kg dry mass and dt is the difference in time, h.

2.2.3. Moisture ratio

The moisture ratio was determined as below:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (4)$$

where MR stands for moisture ratio, M_0, M_e and M_t are the percent moisture contents initial, equilibrium and at a time, t (in % db), respectively. The above equation takes the form as equation (5) by omitting the term M_e, as it is very small compared with M_0 and M_t values (Sacilik et al. 2006).

$$MR = \frac{M_t}{M_0} \quad (5)$$

2.2.4. Effective moisture diffusivity

Diffusion, which is the major driving force for moisture removal in drying is expressed by effective moisture diffusivity that determines the overall mass transfer process. It is the rate of movement of moisture and gives insight into the migration of water during drying and hence is needed for the optimization process. The movement of water inside hygroscopic material during falling rate drying is given by Fick's law as:

$$\frac{\delta M}{\delta t} = \nabla.\left(D_{eff} \nabla M\right) \quad (6)$$

where M denotes moisture content of the sample in kg water/kg dry matter, t stands for drying time in s, and D_{eff} represents the effective moisture diffusivity in m^2/s.

It was assumed that shrimp for drying were cylindrical for the diffusivity calculation. For an infinite cylinder (where the moisture diffusion takes place in a radially outward direction only), the assumptions considered for calculating diffusivity were (Crank, 1975):

- Uniform distribution of moisture initially in the ample
- Symmetric mass transfer regarding the cylindrical center
- Surface mass transfer resistance is very less compared with internal resistance to mass transfer

- Shrinkage of product is negligible with a constant diffusion coefficient

For cylindrical material, Crank's solution for equation (7) is given by:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{4}{b_n^2}exp\left(-\frac{D_{eff}b_n^2 t}{r^2}\right) \quad (7)$$

Taking the initial term, diffusivity is calculated as (Zogzas et al., 1996):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty}\frac{4}{b_n^2}exp\left(-\frac{D_{eff}b_n^2 t}{r^2}\right) \quad (8)$$

In the above equation, r represents mean radius of the sample in metres, n denotes a positive integer and b_n are the roots of Bessel's function (2.405, 5.52, 8.654……). For $n > 1$, the solution is obtained as (Lopez et al. 2000):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{4}{b_1^2}exp\left(-\frac{D_{eff}b_1^2 t}{r^2}\right) \quad (9)$$

Where b_1 is 2.405.

The simplified form of equation (9) in logarithmic form is written as:

$$\ln(MR) = A - B \times t \quad (10)$$

Here, B represents the slope of the line and is related to moisture diffusivity as:

$$B = \frac{b_1^2 D_{eff}}{r^2} \quad (11)$$

Thus, moisture diffusivity is determined from the slope obtained from plot of linear regression of ln (MR) with time (equation (12)).

$$D_{eff} = -\frac{Br^2}{b_1^2} \quad (12)$$

2.3. Drying efficiency

2.3.1. Solar collector efficiency

The efficiency of the collector is determined as the ratio of energy absorbed by water in the collector tubes to the incident solar energy (Sukhatme and Naik 2008). The equation for collector efficiency is given as:

$$Collectoreficiency = \frac{m_w \times c_{pw} \times (T_{co-}T_{ci})}{A_c \times I} \times 100 \quad (13)$$

Where, m_w is the mass flow rate of water (kg/s), C_{pw} is the specific heat water (kJ/kgK), T_{ci} and T_{co} are the temperatures of water collector at inlet and outlet respectively (K), A_c is the solar water collector top surface area (m^2) and I is the average incident solar irradiation (W/m^2).

2.3.2. Solar drying efficiency

The efficiency of drying shrimp in a solar-LPG hybrid drying system was calculated by taking the sum of energy observed by the solar collector, consumed by a blower/pump/fan and supplemented by an LPG water heater (Nabnean et al., 2016). The LPG utilized was determined as the change in weight of the LPG cylinder before and after the study (Lopez et al., 2013). The amount of LPG consumed was expressed in terms of calorific value in MJ. Drying efficiency is the ratio of energy required to the energy supplied for removing water from the product (Murali et al., 2020).

$$Dryingefficiency(\%) = \frac{Energyrequired(M_w \times L_H)}{Energysupplied(E_{lpg} + E_{sc} + E_{pb})} \times 100 \quad (14)$$

Here, M_w denotes the water to be removed (kg), L_H, the latent heat of vaporization of water (kJ/kg) and E_{lpg}, E_{sc} and E_{pb} and are the energy supplied by LPG burner, solar collector, pump and blower (in W).

2.3.3. Microwave drying efficiency

The efficiency of MW drying was calculated as the ratio of heat utilized for vaporisation of water to the heat provided by the dryer (Soysal et.al., 2006).

$$\eta = \frac{Mw \times L}{P \times t} \quad (15)$$

where where η is the HAMW drying efficiency (%); P is the MW power (W); m_w is the mass of water evaporated (kg), and L is the latent heat of vaporization of water (2257 kJ/kg), t is the drying time (s).

2.4. Texture analysis

A texture analyzer (model: TA plus) was used to evaluate the texture of raw and shrimp dried under solar and MW conditions. The maximum shear force needed to compress the sample was recorded at a crosshead speed of 5 mm/s.

2.5. Rehydration ratio

The structural and cellular that degradation occurred within the sample during drying is explained by the rehydration ratio. To determine the rehydration ratio of dried shrimp, 5 g of sample was soaked in 200 ml distilled water at room temperature. The weight of the samples was taken at every 30-minute interval, until a constant value was obtained (Doymaz and Ismail, 2011).

$$Rehydrationratio = \frac{Weightofrehydratedsample(g)}{Weightofdriedsample(g)} \quad (16)$$

2.6. Shrinkage

The volume changes in foods during drying is expressed in terms of shrinkage. Differences in volume of samples before and after drying were estimated by comparing the dimensions of the sample in three directions using a Vernier caliper (accuracy of ± 0 0.05 mm) before and after drying. The equation to calculate shrinkage is given (Tirawanichakul et al., 2008):

$$Shrinkage(\%) = \frac{D_{Initial} - D_{Final}}{D_{Initial}} \times 100 \quad (17)$$

Where, $D_{initial}$ and D_{final} are diameters of sample before and after drying.

2.7. Biochemical analysis

Biochemical analysis of raw and dried shrimp samples was determined for TMA (trimethyl amine), TVB-N (total volatile basic nitrogen) and TBARS (thiobarbituric acid). TMA and TVB-N were estimated in terms of mg N/100 g (Conway, 1962) and TVBN in mg malonaldehyde/kg of lipid (Tarladgis et al., 1960).

2.8. Microbial analysis

The microbiological quality of the dried shrimp was tested for Total Plate Count (TPC) as per the standard procedures of the Food and Drug Administration (FDA), Bacteriological Analytical Manual. Ten grams of the shrimp sample was aseptically cut into a sterile Petridish and blended with 90 ml of sterile normal saline (NS) in a stomacher and made twofold serial dilution up to 10^{-6}. For total plate count on Total Plate Count Agar (TPA), one ml of the appropriate dilutions was pipetted and pour plated with the corresponding medium in duplicate plates. These plates were allowed to be set, inverted and incubated at 37 °C for 18–24 h. The diluted plates contained colonies ranging from 25 to 250 numbers. The experiments were done in triplicates and the average value was recorded.

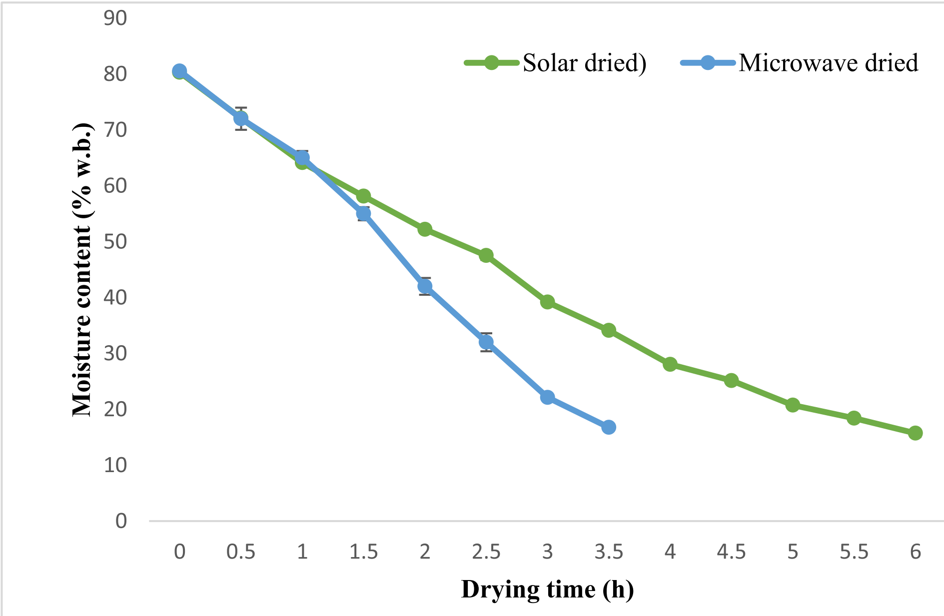

Fig. 3. Drying rate versus drying time for solar and microwave drying of shrimp.

2.9. Colour

Colorimetric values (L*, a*, b*) were measured to find out the color changes of shrimp and were performed using a colorimeter (Hunterlab, Colorflex: EZ). Conventionally, the Hunter color scale is represented by L* for lightness or darkness (L* = 0 for darkness and L* = 100 for whiteness), a* for redness or greenness (a* > 0 for redness and a* < 0 for greenness) and b* for yellowness or blueness (b* > 0 for yellowness and b* < 0 for blueness). The total variation ΔE, is given as:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (18)$$

where L*, a*, b* and L_0, a_0, b_0 indicated the color parameters for dried and raw samples, respectively. More variation from control is represented by higher ΔE values.

2.10. Water activity

Water activity is an indication of the microbial stability of foods. The water activity of dried shrimp was determined using Aqualab Series 3L water activity meter, Decagon Devices, Inc. Pullman, Washington, DC) at 28±^{0}C.

2.11. Sensory evaluation

Dried shrimp samples were evaluated for sensory parameters like appearance, texture, color, odor and overall acceptability (Chavan et al. 2008). Sensory analysis was carried out using the 9-point hedonic scale with 9 – like extremely, 8 – like very much, 7 – like moderately, 6 – like slightly, 5- neither like nor dislike, 4 – dislike slightly, 3 – dislike moderately, 2 – dislike very much and 1 – dislike extremely. The evaluation was done by 25 semi-trained panel members. The members were the staff and researchers of ICAR-CIFT who were general fish consumers and were able to communicate and report variations in the sample.

2.12. Economic analysis

Economic attributes such as life-cycle cost, annual benefit, benefit cost ratio and payback period were determined to find out the economic feasibility of the drying shrimp under solar and microwave conditions. Life cycle cost is the sum of all costs associated with the dryer in its lifetime and considers the money value at present instant of time (Singh et al. 2017) and is calculated as follows:

$$\text{Life cycle cost (LCC)} = \text{Initial investment} + \text{Operation and maintenance cost} - \text{Salvage value} \quad (19)$$

Payback period is the length of time from the beginning of the project before the net benefits return the cost of capital investments.

3. Result and discussion

3.1. Moisture content and drying rate

Solar radiation, ambient temperature and RH were measured using sensors at each hour of the study. The solar radiation intensity during the experimental conditions was observed from to be in range of 320 to 840 W/m^2, ambient temperature varied from 27.5 to 36.5 ^{0}C and RH from 62.45 % to 77.24 % on a typical day of the experiment. The moisture content of shrimp was reduced from 80.2 % to 15.7 % (w.b.) within 6 h of drying in the solar dryer. The drying conditions were maintained at temperature, air velocity and RH of 55 ± 1.5 ^{0}C, 1.5 ± 0.25 m/s and 60 ± 0.5 % respectively (Fig. 3). Initially, moisture evaporated from the shrimp as if from a free water surface due to the temperature difference between the drying medium (hot air) and the product. As drying progressed, moisture removal took place due to the vapor pressure gradient. Similar results were reported by Alfiya et al. (2018) for drying glassy

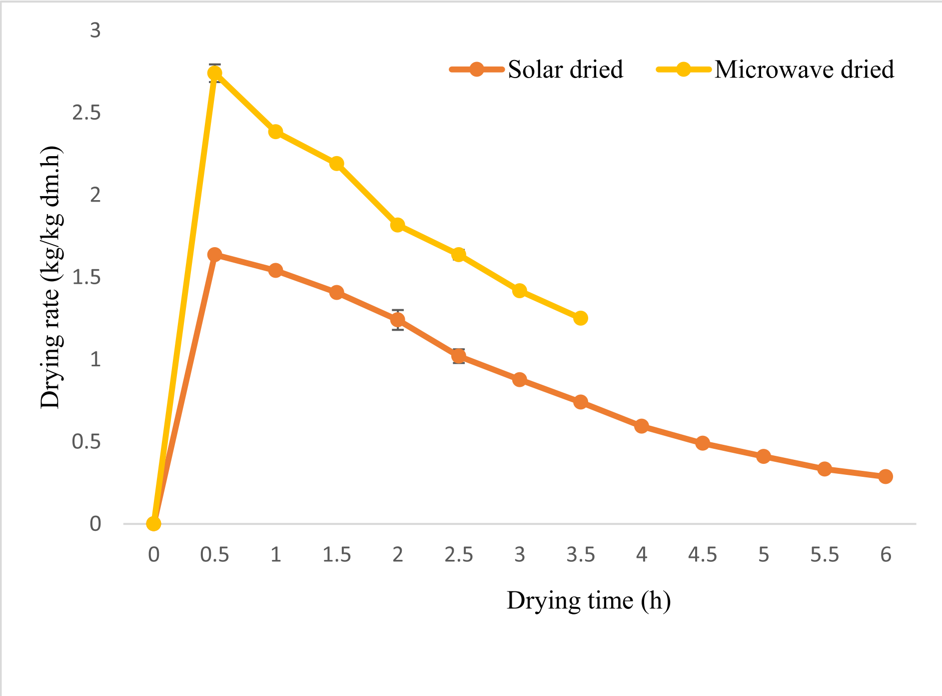

Fig. 4. Moisture content versus drying time for solar and microwave drying of shrimp.

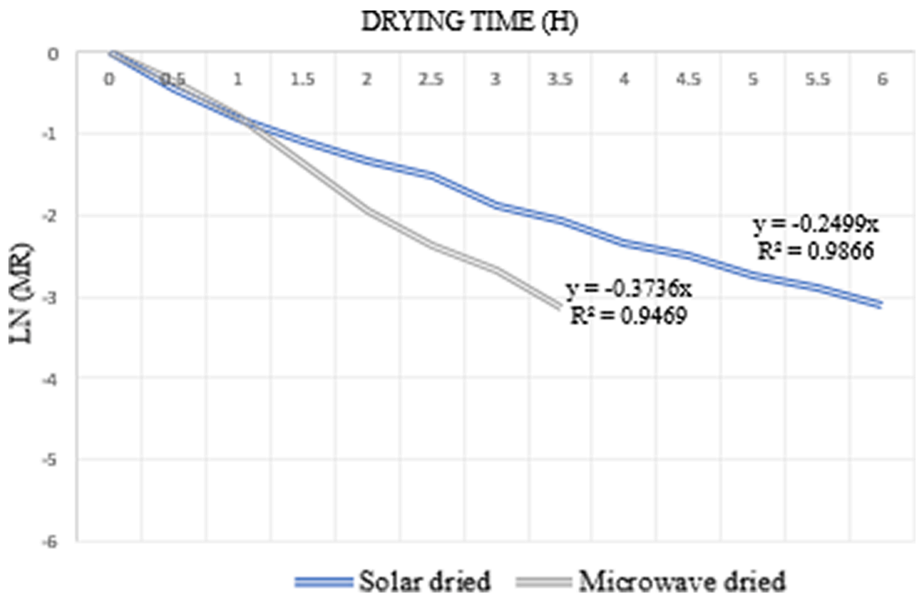

Fig. 5. Plot of LN MR vs drying time.

perchlet in the solar-electrical hybrid dryer. Sankat and Mujaffar (2004) also reported that as drying proceeded, the implication of air flow was less as compared to the temperature of the drying medium during drying of shark fillets in a solar cabinet dryer. It is evident from Fig. 3 that during MW drying moisture content of shrimp decreased from an initial value of 80.55 % to a final value of 16.5 % within 3.5 h of drying. The volumetric heating effect of microwaves can be attributed to the reduction in drying time. Microwave heating falls under the dielectric heating method wherein the moisture content of the product directly influenced the heating rate. Lin et al (1999) reported that drying of shrimps from a moisture level of 83 % to 20 % was achieved within 60 min in microwave assisted vacuum dryer, which is only 25 % of the time required for hot air drying of the same. Lower drying times are also related to higher drying rates of shrimp under MW treatment.

The drying rate of solar and microwave dried shrimp was found to be 1.63 kg/kgh and 2.74 kg/kgh at the beginning of drying (Fig. 4). Drying rate exhibited a maximum value of 2.74 during the initial stages of drying that can be due to the higher moisture content of a sample that created more friction and heat generation due to dipole rotation. In both the studies, the rate of moisture removal decreased with time, and hence drying was under a falling rate period. Bellagaha et al. (2002) reported that the drying rate increases with air flow rate but is affected by the formation of crust on the surface of fish during the studies on the drying of sardine.

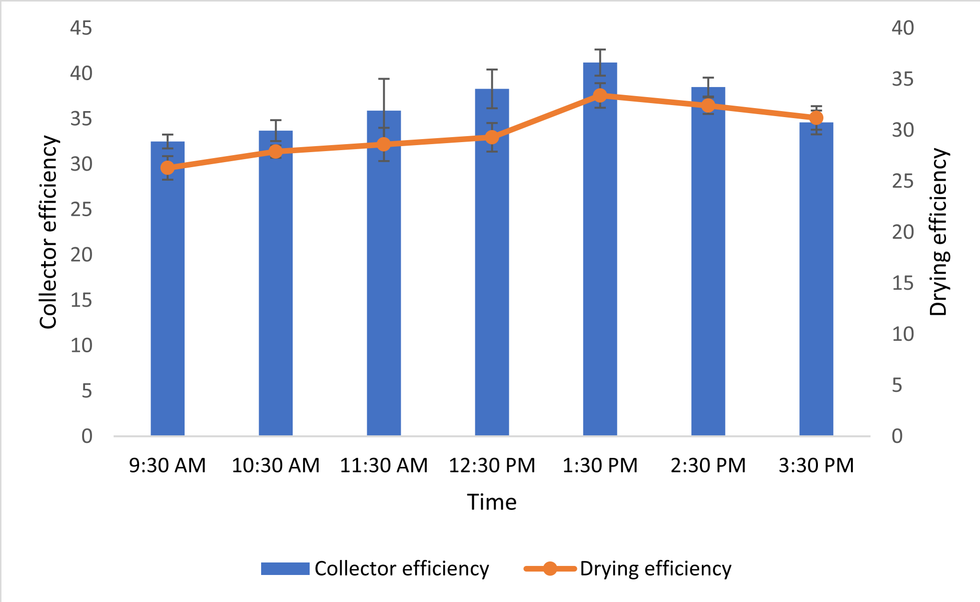

Fig. 6. Instantaneous collector and drying efficiencies during SD of shrimp.

3.2. *Effective moisture diffusivity*

The sum of liquid and vapor diffusion during drying is represented by effective moisture diffusivity of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gave the slope value to determine the diffusivity (Fig. 5). Effective moisture diffusivity during SD and MWD of shrimp were determined to be 2.3×10^{-10} m^2/s and 6.7×10^{-7} m^2/s respectively. Kaveh et al. (2021) opined that microwave drying exhibited higher values of diffusivity compared to convective drying based on his study on drying of pomegranate arils. Darvishi et al. (2014) studied microwave drying effects on mulberry and reported diffusivities in the range of 1.06×10^{-8} to 3.45×10^{-8} m^2/s as the microwave power was varied from 100 to 500 W. Microwave drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s and 4.63×10^{-6} m^2/s under varying operating conditions (Celen, 2019). Moisture diffusivity during sun drying of shrimp was found to be 11.11×10^{-10} m^2/s (Jain and Pathare, 2007). Murali et al (2021) reported effective moisture diffusivity value of 1.04×10^{-9} m^2/s for drying of shrimp in solar LPG dryer.

3.3. *Drying efficiency*

The efficiency of the collector was calculated using the whole collector area and solar irradiation received instantaneously during drying. The instantaneous collector efficiency values varied in the range of 32.5 to 41.2 %. However, maximum efficiency was related directly to the hours of maximum solar irradiation received which is from 12:30 AM to 2:30 PM (Fig. 6). Efficiency of solar collectors was found to vary to the tune of 21–69 % in the drying of osmotically dehydrated cherry tomatoes (Nabnean et al., 2016). The efficiency of shrimp drying was determined by considering the energy supplied by the collector, pump, blower, exhaust and water heater for LPG. The efficiency of drying varied from 26.3 to 33.4 % (Fig. 6), achieving a maximum at 1:30 PM. Maximum available irradiation that enhanced the outlet temperature of water in the collector reduced the LPG consumption for drying at this stage. The values of drying efficiency were in concurrence with the

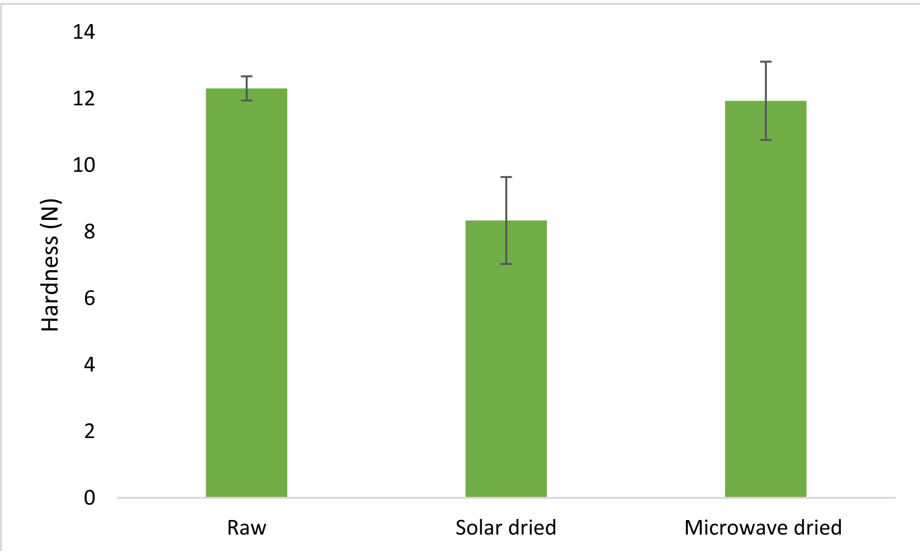

Fig. 7. Hardness values of raw, solar dried and microwave dried shrimp.

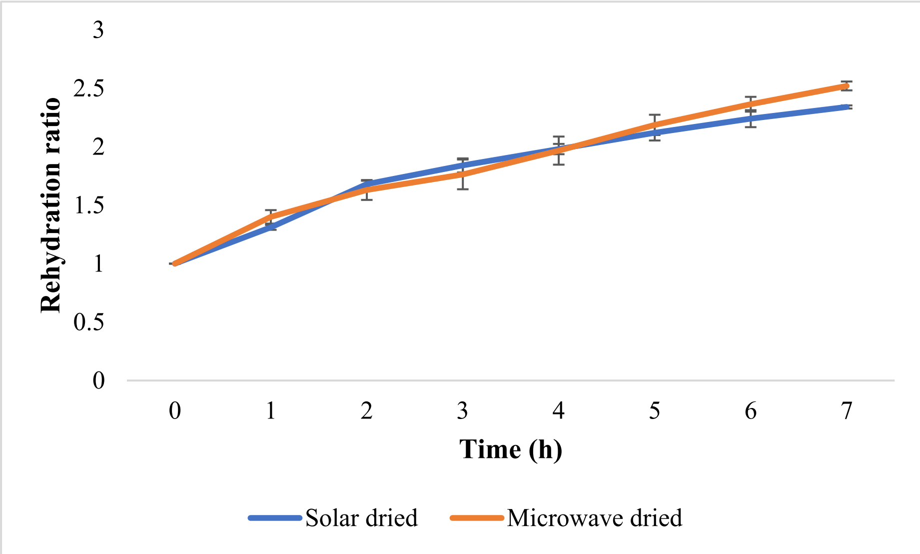

Fig. 8. Rehydration ratio of solar and microwave dried shrimp.

reports of Fudholi et al., 2013 for salted drying of silver jaw fish using solar hybrid dryer. Murali et al (2022) published a drying efficiency of 20.22 % for solar drying of shrimps under controlled conditions.

The drying efficiency of the shrimp under MWD mode was observed to be 35.71 %. This was a result of the volumetric hearing effect of microwave radiation combined with the convective effect of hot air. Hassan (2016) published that since microwaves act only on polar molecules, microwave drying efficiency decreased with time and increased with moisture content of sample during studies on microwave drying of dates. Maximum drying efficiency of 32 % was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein et al. (2015) observed efficiencies of 54.34 % and 17.42 % at MW powers of 600 and 200 W respectively during the drying of apple slices in a laboratory scale MW dryer.

3.4. Texture analysis

The textural analysis of dried products is important in determining their palatability. Textural attributes of dried products are generally expressed in terms of hardness indicated by the maximum compressive force needed to crush the product by the molars. Average hardness values of raw, solar dried and microwave dried shrimp obtained from the plots of compressive force (N) versus time (s) were 12.3, 3.3 and 11.93 N respectively (Fig. 7). Hardness of the products should increase as the moisture content decreases. Since the final moisture levels of solar dried and microwave dried shrimp were in the same range, solar dried were found to be less hard than microwave dried shrimp. Niamuy et al. (2007) reported that higher drying temperature resulted in lesser hardness value of shrimp. As drying time was more in solar dried samples, the exposure to higher temperatures might have resulted in less hard products. Tapaneyasin et al. (2005) also opined that the texture of shrimp dried at lower temperatures was superior during their studies on jet spouted drying of shrimp at 100 and 120 ^{0}C, wherein the former was found to be easy to crush and palatable. He reported a maximum shear force of 1038 kN/m^2 and 1139 kN/m^2 for shrimps dried at 100 and 120 ^{0}C respectively. There were also investigations made by Lin et al. (1999) on shrimp drying showing that microwave-dried shrimp had lower texture scores, though they retained color and appearance very well.

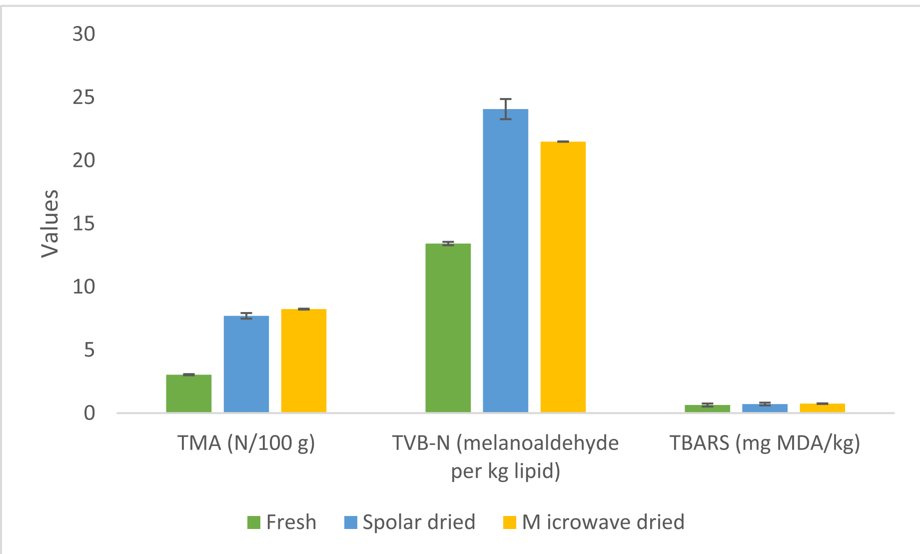

Fig. 9. Biochemical analysis of fresh, solar dried and microwave dried shrimp.

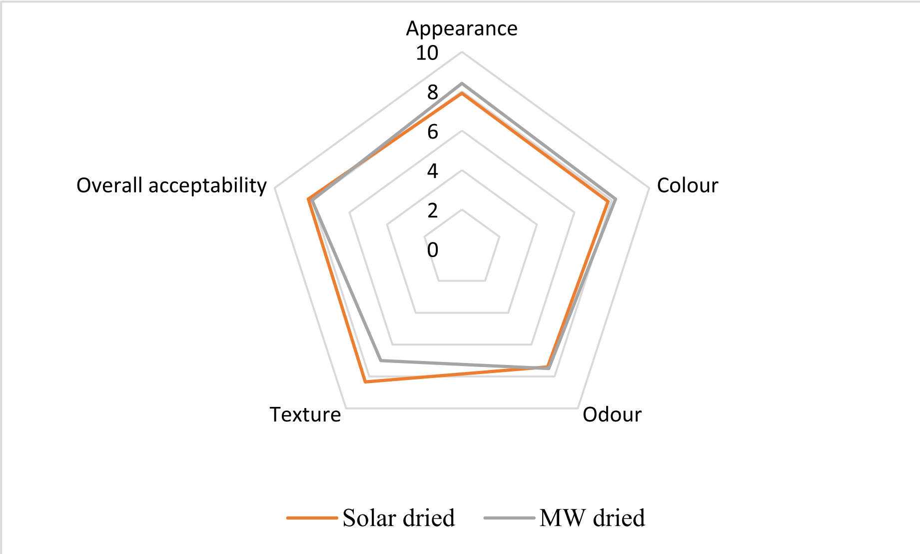

Fig. 10. Radar diagram of sensory scores of SD and MWD shrimp.

3.5. Rehydration ratio

The values of rehydration ratio of SD and MWD shrimp with respect to time is shown in Fig. 8. Under both drying methods, within the first hour of soaking shrimp in the water, a rapid rise was seen in the rehydration ratio. The average rehydration ratio was observed to be 2.39 and 2.51 for SD and MWD respectively. Akonor (2016) reported that solar-dried shrimp exhibited higher values of rehydration ratio more rapidly than hot air-dried samples. Due to the volumetric heating of MW radiation, the moisture movement is fast leaving a porous matrix in the cells which can be accounted for their higher moisture absorption properties. The rehydration ratio of Tilapia fillets increased with MW power and air temperature during hot air aided microwave drying of the fish (Duan et al., 2011).

3.6. Shrinkage

Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extent of shrinkage depends on the method of drying. The shrinkage percentage of SD and MWD shrimp was observed to be 24.67 and 14.14 % respectively. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin et al., 2005). The reduction in shrinkage percentage was due to the rapid evaporation of moisture by microwave radiation that created a vapor flux thereby preventing case hardening.

3.7. Biochemical analysis

The values of TVB-N, TMA and TBARS determined the quality of sea food products. TMA values for fresh, solar dried and microwave dried shrimp were 3.04, 7.7 and 8.23 mg N/100 g respectively. TMA was responsible for the unpleasant odor in shrimp. There is no significant difference in TMA values of solar and microwave dried samples. Zhang et al. (2011) observed TMA for dried *A. chinensis* varied from 7.93 ± 1.21 to 16.06 ± 2.01 during its storage. TVB-N for fresh shrimp increased from 13.42 mgN/100 g to 24.06 and 21.49 mg/100 g respectively when it was dried under solar and microwave radiation. However, the dried samples were adhering to the permissible values of TVB-N (<50 mgN/100 g) (Connell, 1980). TBARS values showed the extent of lipid oxidation and were determined to be 0.64, 0.72 and 0.75 MDA/kg of lipid for fresh, solar dried and microwave dried samples. Sampaio et al. (2006) also opined that owing to lipid oxidation, TBARS values of shrimps increased with time after harvest. The increase in values of all biochemical constituents represented the degree of spoilage due to higher microbial activity. Similar results were published by Murali et al., 2021 for drying of shrimp in solar-LPG dryer. The attainment of final moisture content is in same range for both solar and microwave dried products, which might be the reason that there is no significant difference in the biochemical analysis of these samples (Fig. 9).

3.8. Microbiological quality

The total plate count of raw shrimp was 4.3×10^6 CFU/g of a sample. Drying reduced the TPC value of shrimp to 1.65×10^4 and 2.6×10^4 CFU/g and to for SD and MWD respectively which is significantly ($p < 0.05$) lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample (IS 14950 2001). A similar result of microbial reduction was reported by Murali et al. (2021) for shrimp drying.

3.9. Color change

Solar dried shrimp were found to be darker ($L^*= 41.31 \pm 1.63$) compared to microwave dried samples (49.5 ± 1.28). This may be due to the exposure to higher temperatures for longer times. Total color change (ΔE) determined for SD and MWD samples were 14.25 ± 1.94 and 16.95 ± 2.14 respectively. Redness of samples increased during both drying methods due to the release of astaxanthin from carotenoids during drying (Muriana et al., 1993). Similar results of color change were also reported by Akonor et al., 2016 for solar drying of shrimp. Celen (2019) evaluated the color of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE respectively at a microwave power of 600 W. It was also observed that higher microwave powers may cause an unstable microwave field that may affect the color quality of products. Taib and Ng (2011) also showed that in microwave drying of catfish slices, hot air treatment imparted brighter color to dried products shifting towards red and yellow.

3.10. Water activity

In this study, the water activity value of dried shrimp was determined to be 0.552 and 0.554 under SD and MWD respectively which indicated the product to be stable microbiologically. Oxidative and

Table 1
Economical analysis of solar and microwave drying of shrimp.

Sl. No	Parameters	Values	
		Solar -LPG dryer	Hot air assisted microwave dryer
1.	Initial investment (₹)	4,20,000	4,99,000
2.	Operation and maintenance cost (₹) including raw material cost	1,50,000	2,10,000
3.	Salvage value (10 % of initial investment) (₹)	42,000	49,000
4.	Life cycle cost (₹)	5,28,000	6,60,000
5.	Annual benefit (₹)*	7,11,000	6,66,150
6.	Benefit-cost ratio	3.4	2.9
7.	Payback period	1.2 years	1.8 years

* Dried shrmp output – 10 kg/day; price of dried shrimp - ₹ 500/kg; expenditure - ₹ 1450/day(solar dried) and ₹ 1700/day (microwave dried); profit- ₹ 3555/day (solar dried) and ₹3330/day (microwave dried); working days – 200 days/year.

enzymatic reactions were suppressed by lowering water activity leading to shelf life extension of products (Jayaraman and Gupta, 2020).

3.11. Sensory analysis

The scores of sensory evaluations of dried shrimp are depicted in Fig. 10. Twenty-five semi-trained panel members comprising research scholars and staff assigned maximum scores to the 'texture' 'overall acceptability' of the SD samples. Whereas for the MWD samples, 'color' and 'appearance' scored more. Higher drying rates of MWD must have resulted in better color and appearance due to shorter drying times. Uniformity of the samples led to better overall acceptability for SD shrimp. Mounir et al. (2020) also reported the highest overall acceptability to the intermittent microwave dried shrimp snacks coupled with instant controlled pressure drop treatment. However, market value of dried shrimps is more for solar and microwave dried samples due to the unhygienic practices adopted in traditional sun drying.

3.12. Economic analysis

Economic analysis was carried out for drying of shrimp in solar-LPG dryer and hot air assisted microwave dryer and is summarized in Table 1. The values of economic attributes indicated the economic feasibility of the production of dried shrimp under both drying technologies. However, solar drying is found to be economically more viable than microwave drying technology for the quality production of dried shrimp. Solar drying was found to have less carbon emissions in terms of electricity usage as 70 % of the energy consumption is met with solar radiation. Supplementary heating by LPG is aided only at times of lacunae in availability of solar radiation. Whereas the working of microwave system requires a 1.4 kW magnetron to be run throughout the drying process. But microwave system highly reduced the drying times and thereby the related electricity consumption.

4. Conclusions

The effect of solar and microwave drying on the quality of dried shrimp were studied. Drying time reduction of 58.3 % was achieved under microwave drying as compared to solar drying of shrimp under the experimental set up. Drying and collector efficiency was in range of 26.3 – 33.4 % and 32.5 – 41.2 % respectively for solar dried whereas the efficiency under microwave drying was 35.7 %. Textural attributes of solar dried shrimp were superior to microwave dried samples. Effective moisture diffusivities of solar and microwave dried shrimp were2.3 $\times 10^{-10}$ m^2/s and 6.7 $\times 10^{-7}$ m^2/s respectively. The rehydration ratio and shrinkage of solar and microwave dried samples were 2.39 and 24.67 % and 2.51 and 14.14 % respectively. Biochemical and microbiological analyses of dried shrimp under both drying methods were found to be within safe limits. However, solar dried shrimps exhibited more redness in color values as compared to microwave dried samples. Though microwave drying produced better quality shrimp with respect to shrinkage, rehydration ratio, moisture diffusivity and drying times, solar drying finds application in the production of bulk quantity of dried shrimp as the intervention of microwaves requires expertise and more investment. Economic feasibility analysis of solar and microwave dried shrimp showed that former is more economically viable for the production of dried shrimp. However, a combination of solar-assisted microwave generation systems for drying applications may resolve the energy costs in radiation-based food drying applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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