Solar Energy 246 (2022) 234–244

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

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

A R T I C L E I N F O

Keywords:
Magnetron
solar-LPG drying
Drying efficiency
Microwave radiation
Shrimp drying

A B S T R A C T

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).

https://doi.org/10.1016/j.solener.2022.09.048
Received 16 June 2022; Received in revised form 12 September 2022; Accepted 27 September 2022

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

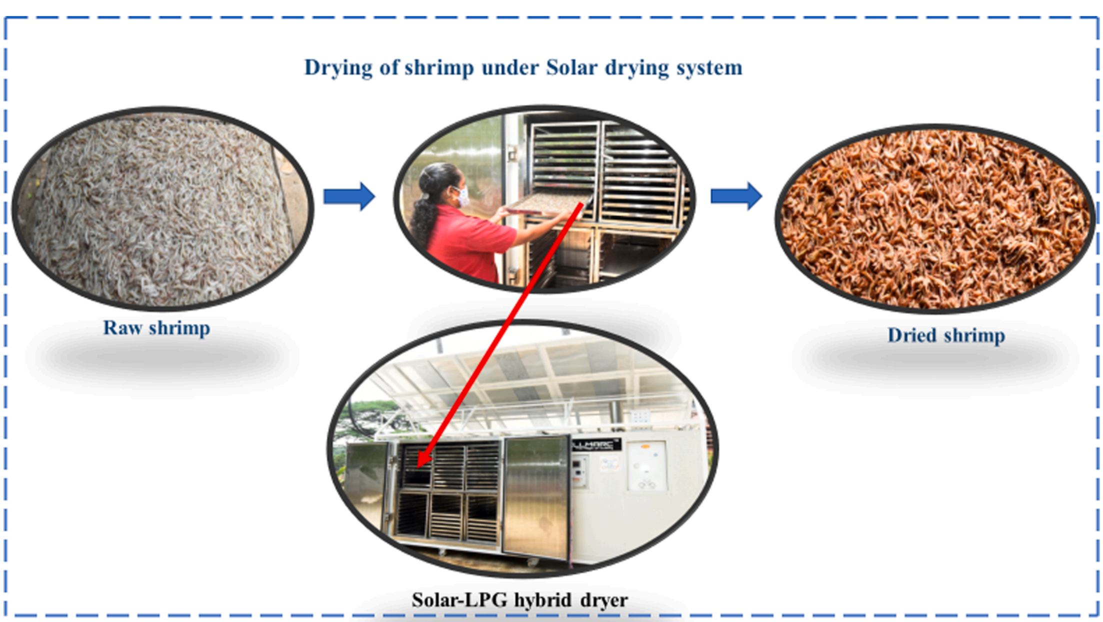

Fig. 1. Drying of shrimp under solar drying system.

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^{0}N, 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:

$$DR = \frac{M_t - M_{t+dt}}{dt} \tag{3}$$

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:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{4}$$

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).

$$MR = \frac{M_t}{M_0} \tag{5}$$

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:

$$\frac{\delta M}{\delta t} = \nabla.\left(D_{eff} \nabla M\right) \tag{6}$$

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.

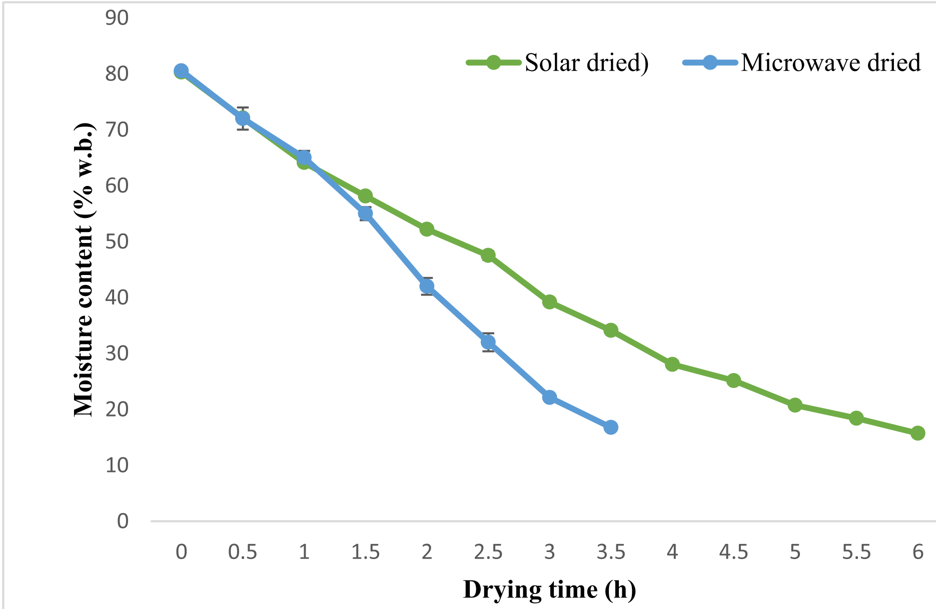

Fig. 3. Drying rate versus drying time for solar and microwave drying of shrimp.

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

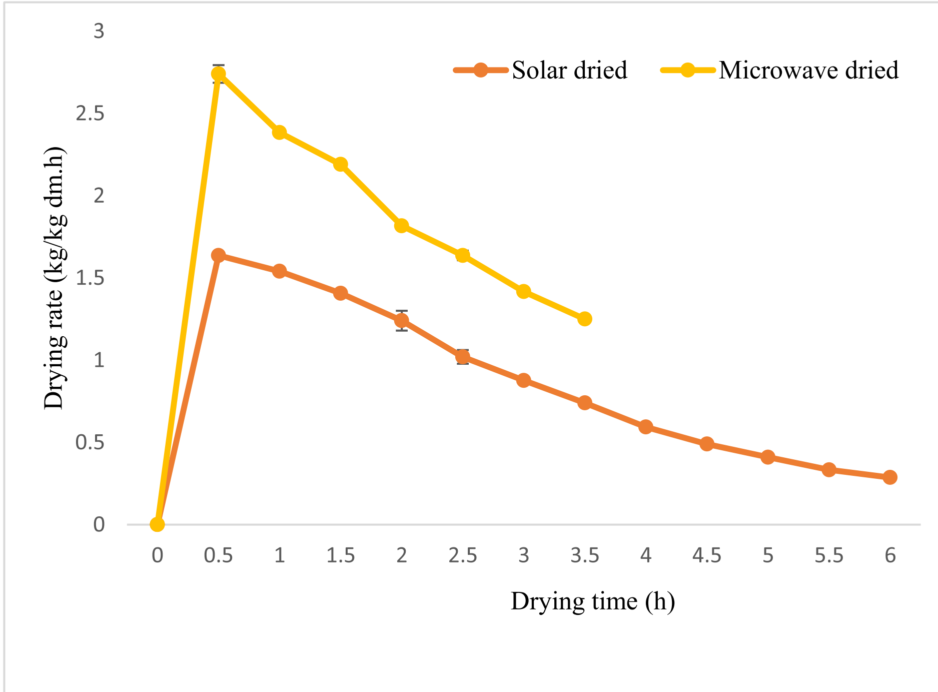

Fig. 4. Moisture content versus drying time for solar and microwave drying of shrimp.

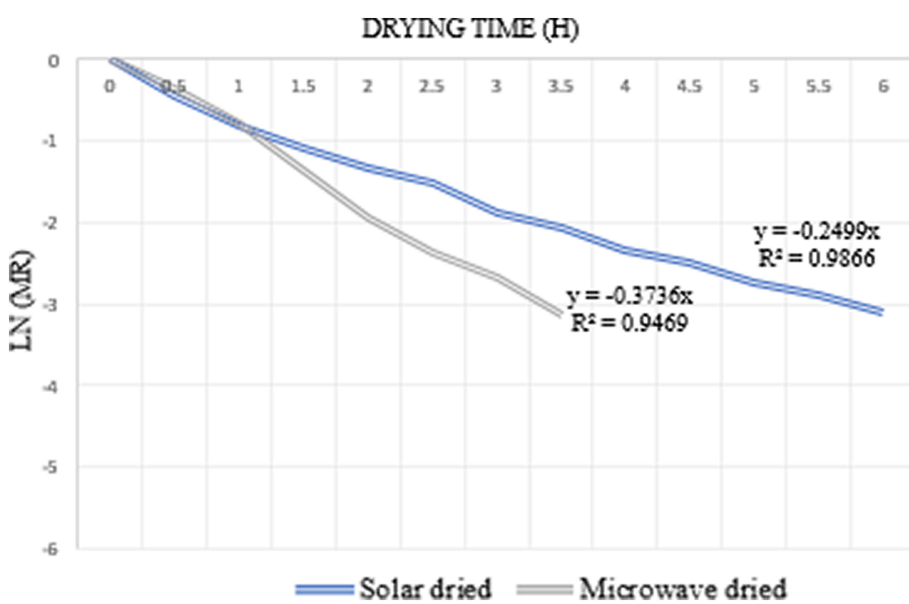

Fig. 5. Plot of LN MR vs drying time.

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.

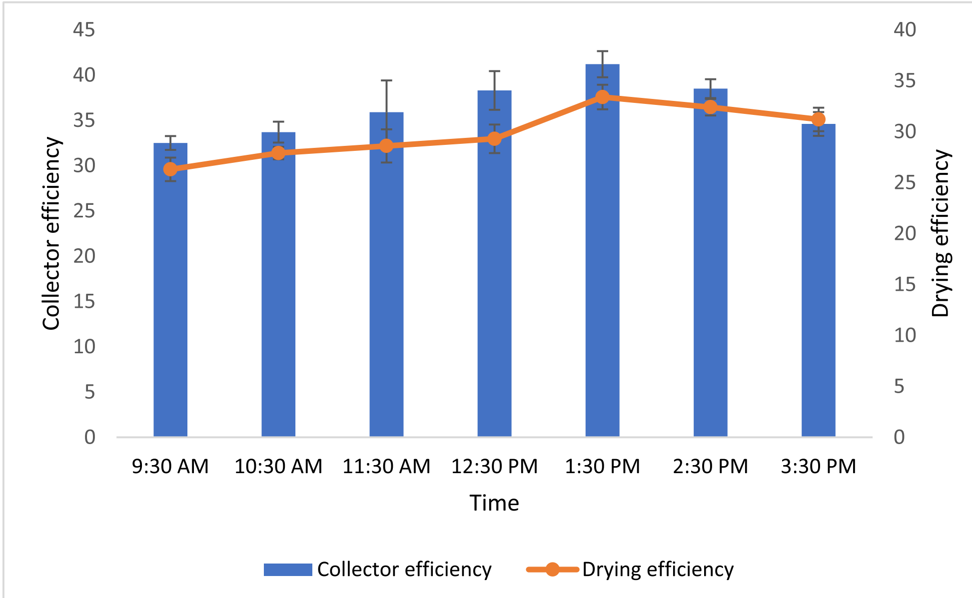

Fig. 6. Instantaneous collector and drying efficiencies during SD of shrimp.

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

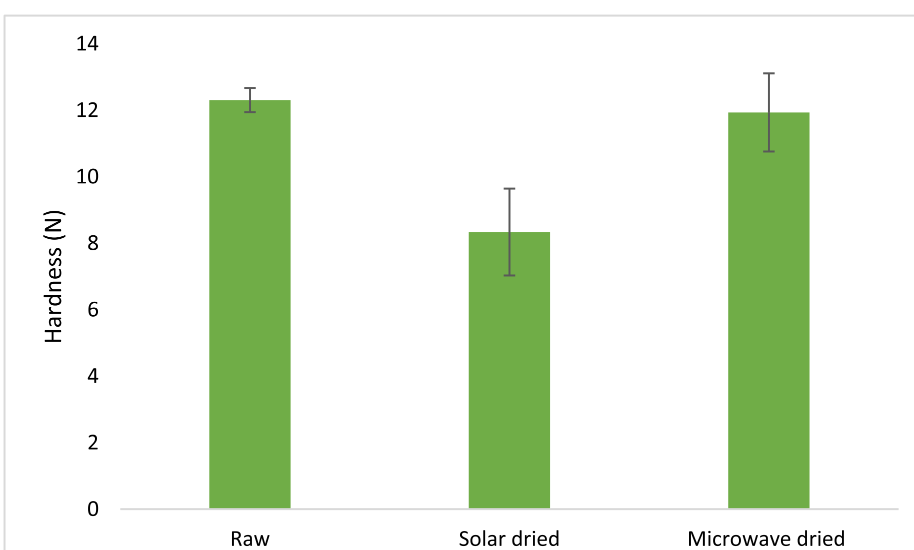

Fig. 7. Hardness values of raw, solar dried and microwave dried shrimp.

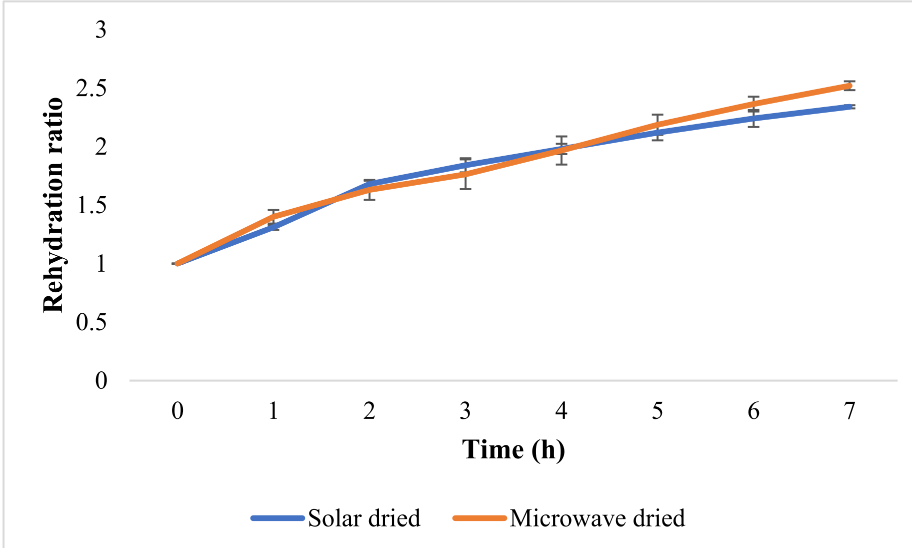

Fig. 8. Rehydration ratio of solar and microwave dried shrimp.

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.

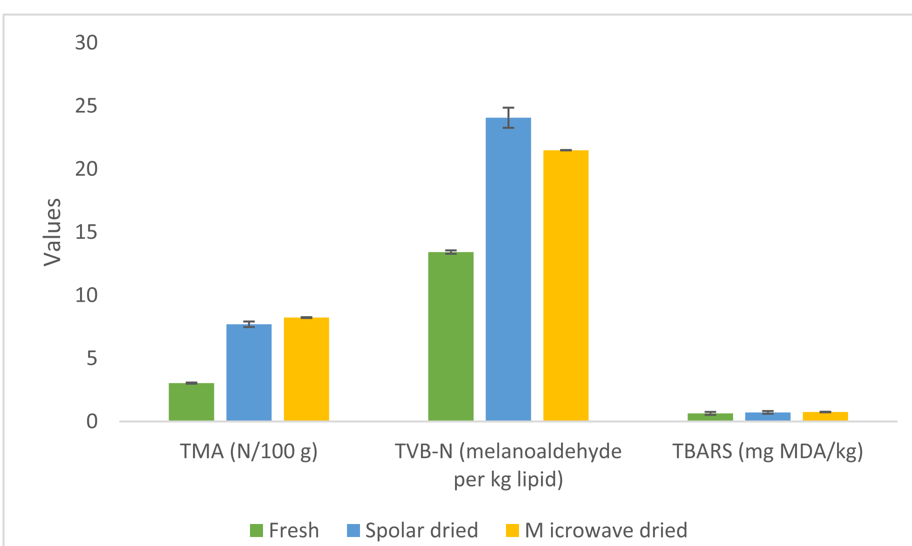

Fig. 9. Biochemical analysis of fresh, solar dried and microwave dried shrimp.

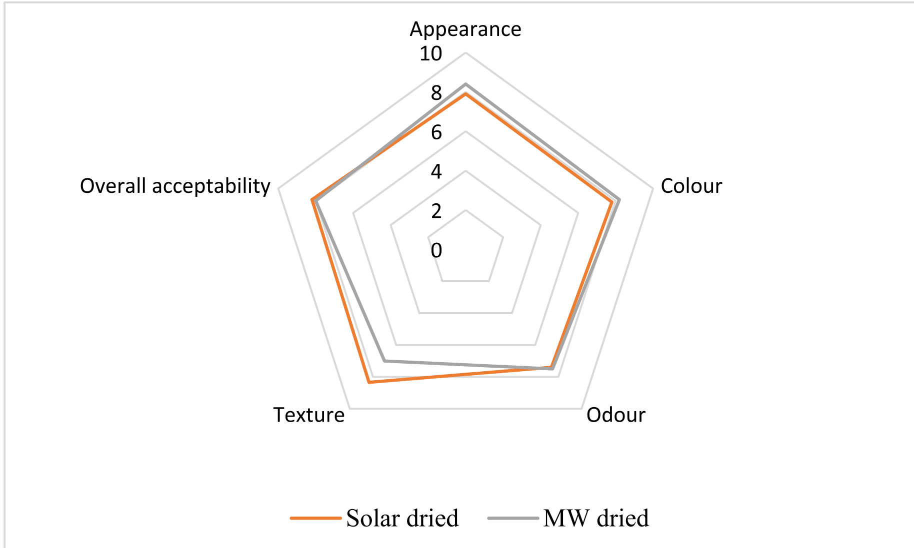

Fig. 10. Radar diagram of sensory scores of SD and MWD shrimp.

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 ± 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.

Acknowledgments

The work was done under Indian Council of Agricultural Research - All India Coordinated Research Projects (AICRP) for Tavanur Centre. Authors would like to acknowledge the Director, ICAR-CIFT, Kochi, Dean, KCAET, Tavanur and Head, Division of Engineering, ICAR-CIFT, Kochi for providing the necessary facilities for the research work.

References

Akonor, P.T., Ofori, H., Dziedzoave, N.T., Kortei, N.K., 2016. Drying characteristics and physical and nutritional properties of shrimp meat as affected by different traditional drying techniques. Int. J. Food Sci. 2016, 1–5.
Alfiya, P. V., Murali, S., Delfiya, D. A., Samuel, M. P. 2018. Empirical modelling of drying characteristics of elongate glassy perchlet (Chanda nama) (Hamilton, 1822) in solar hybrid dryer.
Alfiya, P.V., Murali, S., Delfiya, D.A., Sreelakshmi, K.R., Sivaraman, G.K., Ninan, G., 2022. Kinetics, modelling and evaluation of Bombay duck (Harpodon nehereus) dried in solar-LPG hybrid dryer. Solar Energy 242, 70–78.
Arunsandeep, G., Lingayat, A., Chandramohan, V.P., Raju, V.R.K., Reddy, K.S., 2018. A numerical model for drying of the spherical object in an indirect type solar dryer and estimating the drying time at different moisture levels and air temperature. Int. J. Green Energy. 15, 189–200.
Basunia, M.A., Abe, T., 2001. Design and construction of a simple three-shelf solar rough rice dryer. Am. Med. Association 32 (3), 54–59.
Belessiotis, V., Delyannis, E., 2011. Solar drying. Solar Energy. 85, 665–1691.
Bellagha, S., Amami, E., Farhat, A., Kechaou, N., 2002. Drying kinetics and characteristic drying curve of lightly salted sardine (Sardinella aurita). Dry. Technol. 20 (7), 1527–1538.
Çelen, S., 2019. Effect of microwave drying on the drying characteristics, color, microstructure, and thermal properties of Trabzon persimmon. Foods 8 (2), 84.
Chauhan, Y.B., Rathod, P.P., 2020. A comprehensive review of the solar dryer. Int. J. Ambient Energy. 41 (3), 348–367.
Chavan, B R, Yakupitiyage, A, Kumar, S, 2008. Mathematical modeling of drying characteristics of Indian mackerel (Rastrilliger kangurta) in solar-biomass hybrid cabinet dryer. Dry. technol. 26 (12), 1552–1562. https://doi.org/10.1080/07373930802466872.
Chua, K.J., Chou, S.K., 2003. Low-cost drying methods for developing countries. Trends in Food Sci. Technol. 14 (12), 519–528.
Connell, J. 1980. Control of fish quality: Methods of assessing and selecting for quality. Farnham, Surrey, England: Fishing New Books Ltd.
Conway, E. J. 1962. Microdiffusion analysis and volumetric error. 5th ed. London (UK): Parch Goskey and Sockwood.
Crank, J. 1975. The mathematic of diffusion. 2nd ed. Oxford (UK): Oxford University Press.
Darvishi, H., Azadbakht, M., Rezaeiasl, A., Farhang, A., 2013. Drying characteristics of sardine fish dried with microwave heating. J. Saudi Soc. Agric. Sci. 12 (2), 121–127.
Darvishi, H., Asl, A.R., Asghari, A., Azadbakht, M., Najafi, G., Khodaei, J., 2014. Study of the drying kinetics of pepper. J. Saudi Soc. Agric. Sci. 13 (2), 130–138.
Diemuodeke, O., Momoh, Y., 2011. Design and fabrication of a direct natural convection solar dryer for tapioca. Leonardo El. J. Pract. Technol. 10, 95–104.
Doymaz, İ., İsmail, O., 2011. Drying characteristics of sweet cherry. Food Bioprod. Process. 89 (1), 31–38.
Duan, Z.H., Jiang, L.N., Wang, J.L., Yu, X.Y., Wang, T., 2011. Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. Food Bioprod. Process. 89 (4), 472–476.
Fudholi, A. H. M. A. D., Ruslan, M. H., Othman, M. Y., Sopian, K. A. 2013. Energy consumption of hybrid solar drying system (HSDS) with rotating rack for salted

silver jewfish. In Proceedings of the 7th WSEAS International Conference on Renewable Energy Sources (RES'13) (pp. 294-298).
Hassan, M., 2016. Energy consumption and mathematical modeling of microwave drying of date. Misr J. Agric. Eng. 33 (1), 151–164.
IS 14950. (2001). Indian standard. fish-dried and dry silted specification. New Delhi (India).
Jain, D., Pathare, P.B., 2007. Study the drying kinetics of open sun drying of fish. J. Food Eng. 78 (4), 1315–1319.
Jayaraman, K. S., Gupta, D. D. 2020. Drying of fruits and vegetables. In Handbook of industrial drying (pp. 643-690). CRC Press.
Kaveh, M., Golpour, I., Gonçalves, J.C., Ghafouri, S., Guiné, R., 2021. Determination of drying kinetics, specific energy consumption, shrinkage, and colour properties of pomegranate arils submitted to microwave and convective drying. Open Agric. 6 (1), 230–242.
Lin, T.M., Durance, T.D., Scaman, C.H., 1999. Physical and sensory properties of vacuum microwave dehydrated shrimp. J. Aquat. Food Prod. Technol. 8 (4), 41–53.
Lingayat, A.B., Chandramohan, V.P., Raju, V.R.K., Meda, V., 2020. A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights. Appl. Energy. 258, 114–1005.
Lopez, A., Iguaz, A., Esnoz, A., Virseda, P., 2000. Thin-layer drying behaviour of vegetable wastes from wholesale market. Dry. Technol. 18 (4–5), 995–1006.
López-Vidaña, E.C., Méndez-Lagunas, L.L., Rodríguez-Ramírez, J., 2013. Efficiency of a hybrid solar–gas dryer. Sol. energy 93, 23–31.
Mohd Rozainee, T., Ng, P.S., 2010. Microwave assisted hot air convective dehydration of fish slice: drying characteristics, energy aspects and colour assessment. In: In World EngIneerIng Congress 2010-Conference on Advanced Processes and Materials, pp. 41–46.
Moriarty, P., Honnery, D., 2019. Global renewable energy resources and use in 2050. Managing Global Warming 221–235.
Mounir, S., Amami, E., Allaf, T., Mujumdar, A., Allaf, K., 2020. Instant controlled pressure drop (DIC) coupled to intermittent microwave/airflow drying to produce shrimp snacks: process performance and quality attributes. Dry. Technol. 38 (5–6), 695–711.
Murali, S., Amulya, P.R., Alfiya, P.V., Delfiya, D.A., Samuel, M.P., 2020. Design and performance evaluation of solar-LPG hybrid dryer for drying of shrimps. Renew. Energy. 147, 2417–2428.
Murali, S., Delfiya, D.A., Kumar, K.S., Kumar, L.R., Nilavan, S.E., Amulya, P.R., Alfiya, P. V., Samuel, M.P., 2021. Mathematical modeling of drying kinetics and quality characteristics of shrimps dried under a solar–LPG Hybrid Dryer. J. Aquat. Food Prod. Technol. 30 (5), 561–578.
Murali, S., Alfiya, P.V., Delfiya, D.A., Harikrishnan, S., Kunjulakshmi, S., Samuel, M.P., 2022. Performance evaluation of PV powered solar tunnel dryer integrated with a mobile alert system for shrimp drying. Sol. Energy 240, 246–257.
Muriana, F.J., Ruiz-Gutierrez, V., Gallardo-Guerrero, M.L., Minguez-Mosquera, M.I., 1993. A study of the lipids and carotenoprotein in the prawn. Penaeus japonicus. J. Biochem. 114 (2), 223–229.
Nabnean, S., Janjai, S., Thepa, S., Sudaprasert, K., Songprakorp, R., Bala, B.K., 2016. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renew. Energy. 94, 147–156.
Niamnuy, C., Devahastin, S., Soponronnarit, S., 2007. Effects of process parameters on quality changes of shrimp during drying in a jet-spouted bed dryer. J. Food Sci. 72 (9), E553–E563. https://doi.org/10.1111/j.1750-3841.2007.00516.
Oosterveer, P., 2006. Globalization and sustainable consumption of shrimp: consumers and governance in the global space of flows. Int. J. Consum. Stud. 30 (5), 465–476.
Patil, R., Gawande, R., 2016. A review on solar tunnel greenhouse drying system. Renew. Sustainable Energy Rev. 56, 196–214.
Rodziewicz., Tadeusz., Zaremba., Aleksander., Wacławek., Maria., 2016. Photovoltaics: Solar energy resources and the possibility of their use. Ecol. Chem. Eng. S. 23 (1), 9–32.
Sacilik, K., Keskin, R., Elicin, A.K., 2006. Mathematical modelling of solar tunnel drying of thin layer organic tomato. J. Food Eng. 73 (3), 231–238.
Sampaio, G.R., Bastos, D.H., Soares, R.A., Queiroz, Y.S., Torres, E.A., 2006. Fatty acids and cholesterol oxidation in salted and dried shrimp. Food Chem. 95 (2), 344–351.
Sankat, C. K., Mujaffar, S. 2004. Sun and solar cabinet drying of salted shark fillets. In Proceeding of the 14th International Drying Symposium. Vol. 100, 1584-1591.
Sengar, S.H., Khandetod, Y.P., Mohod, A.G., 2009. Low cost solar dryer for fish. Afr. J. Environ. Sci. Technol. 3 (9).
Singh, D., Singh, A.K., Singh, S.P., Poonia, S., 2017. Economic analysis of parabolic solar concentrator-based distillation unit. Indian J. Eco. Dev. 13 (3), 569–575.
Soysal, Y., Öztekin, S., Eren, Ö., 2006. Microwave drying of parsley: modelling, kinetics, and energy aspects. Biosyst. Eng. 93 (4), 403–413.
Sukhatme, S.P., Nayak, J.K., 2008. Solar energy: principles of thermal collection and storage. Tata Mc Graw-Hill, New Delhi 2008, 23–24.
Tapaneyasin, R., Devahastin, S., Tansakul, A., 2005. Drying methods and quality of shrimp dried in a jet-spouted bed dryer. J. Food Process Eng. 28 (1), 35–52.
Tarladgis, B.G., Watts, B.M., Younathan, M.T., Dugan, L., 1960. A distillation method for the quantitative determination of malonaldehyde in rancid foods. J. Am. Oil Chemists' Soc. 37 (1), 44–48.
Tirawanichakul, S., Phatthalung, W.N., Tirawanichakul, Y., 2008. Drying strategy of shrimp using hot air convection and hybrid infrared radiation/hot air convection. Walailak J. Sci. & Tech. 5 (1), 77–100.
Vijaya, V.S., Iniyan, S., Goic, R., 2012. A review of solar drying technologies. Renew. Sustain. Energy Rev. 16 (5), 2652–2670.
Zarein, M., Samadi, S.H., Ghobadian, B., 2015. Investigation of microwave dryer effect on energy efficiency during drying of apple slices. J. Saudi Soc. Agric. Sci. 14 (1), 41–47.
Zhang, J.Y., Liu, S.L., Wang, Y., Ding, Y.T., 2011. Chemical, microbiological and sensory changes of dried Acetes chinensis during accelerated storage. Food Chem. 127 (1), 159–168.
Zogzas, N.P., Maroulis, Z.B., 1996. Effective moisture diffusivity estimation from drying data. a comparison between various methods of analysis. Dry. Technol. 14 (7–8), 1543–1573.