REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

This chapter deals with the review of literature of moringa leaves and beetroot, its health and nutritional benefits. The chapter also deals with ultrasound technology, processing equipment, and its applications in the food industry. Similarly, the chapter deals with the literature reviews on development of infrared dryer, cabinet dryer, heat pump dryer, hybrid drying technologies, drying kinetics, modelling, quality evaluation and economic analysis are also included in this chapter.

2.1 Moringa leaves

Moringa (*Moringa oleifera*), a soft wooded tree has been used for traditional, therapeutic, and industrial purposes and the tree has recently been promoted as a superb native source of highly digestible protein, calcium, iron, vitamin, and carotenoids that can be used in numerous underprivileged nations where undernourishment is an acute problem (Delisle *et al.,* 1997).

The only genus in the Moringaceae family, Moringa is a native plant of Africa and Asia and the most commonly grown species in Northwestern India. It includes thirteen species that range in size from tiny herbs to enormous trees and are found in tropical and subtropical regions. The nutrient-dense pods, edible leaves, and blossoms of *Moringa oleifera* are cultivated for their potential as food, medicine, cosmetic oil, and animal feed. The height of the tree ranged from 5 to 10 m (Padayachee *et al*., 2012).

According to Talhaliani and Kar. (2000), the blooms are a good source of calcium and potassium and can be consumed or used as ingredients for tea. The leaves are an exceptional source of both vitamin C and vitamin A. They are also one of the best plant sources of nutrients and a good source of vitamin B.

According to Subadra *et al.* (1997), the leaves are a good source of protein with minimal amounts of fat and carbohydrates. The sulfur-containing amino acids methionine and cystine, which are frequently lacking in the plant kingdom, cannot be found in leaves

2.1.1 Nutritional aspects of moringa

The leaves of Moringa are abundant in minerals such as calcium, potassium, zinc, magnesium, iron, and copper, and every component of the plant is a storehouse of vital nutrients and antinutrients (Kasolo *et al.,* 2010). *Moringa oleifera* contains vitamins such as beta carotene of vitamin A, vitamin B, including folic acid, pyridoxine, and nicotinic acid, as well as vitamins C, D, and E (Mbikay, 2012).

Moringa is a rich source of minerals that are vital for human growth and development, with calcium being one of the most significant. Moringa powder can provide over 4000 mg of calcium, while 8 ounces of milk can provide only 300–400 mg. Moringa powder can be used as an iron supplement to anemic patients. The iron content of Moringa leaf powder is 28 mg, while 2 mg in beef. Iron content in moringa is reportedly higher than in spinach (Fuglie, 2005).

According to Jongrungruangchok *et al.* (2010) and Moyo *et al.* (2011), the moringa tree is a plant which is high in proteins, fibre, and minerals, all of which are vital for human nutrition. The antioxidant concentration of Moringa leaves is substantially higher than that of fruits with high antioxidant content, including strawberries (Yang *et al.,* 2007).

Compared to traditional iron supplements, a recent study demonstrated that iron from moringa can better modify the expression of iron-responsive genes and overcome iron shortage (Saini *et al.,* 2014). According to Lakshmipriya *et al.* (2016), the leaves of Moringa are said to be abundant in vitamins, minerals, and other vital elements. The leaves extracts are used to boost nursing mother’s breast milk production and cure malnutrition. Similarly, it has prospective uses as an antibacterial, anticancer, anti-inflammatory, and antidiabetic drug.

Moringa leaves are low in calories and can be included in the diet of obese people (Oduro *et al.,* 2008). In addition to anti-cancerous substances like glucosinolates, isothiocyanates, glycoside compounds, and glycerol-1-9-octadecanoate, the plant contains phytochemicals such tannins, sterols, terpenoids, flavonoids, saponins, anthraquinones, alkaloids, and reducing sugar (Berkovich, 2013).

2.1.2 Medicinal properties of moringa

According to Mishra *et al.* (2012), moringa leaves are used to treat intestinal worms, respiratory disorders, joint pain, anaemia, blackheads, pimples, cholera, diarrhoea, bronchitis, lactation diabetes, abnormal blood pressure, swelling chest congestion, conjunctivitis, asthma, fever, scurvy, tuberculosis, epilepsy, sore throat, ear infections, sprain, hypertension, cough, anxiety, headache, hysteria, skin infections, and epilepsy.

According to Lopez (2011), moringa helps children who are undernourished and strengthens the immune system, which helps prevent diseases connected to HIV and AIDS. Additionally, it is utilised in traditional medicine to treat a variety of ailments, including liver dysfunction. Its antibacterial qualities are now being investigated as a bio-enhancer of nutrients and medications .

According to Anwer *et al.* (2007), it has been established that the moringa tree contains a number of chemical compounds with advantageous pharmacological characteristics. They include substances that reduce cholesterol, have anti-ulcer, hypoglycemic, infectious skin-curing, anti-hypertensive, antispasmodic, and anti-cancer effects.

According to Hannan *et al.* (2014), moringa leaf powder promotes neuro-protection and has prospective pharmacological significance for the nutritional and ethnomedical well-being of the nervous system. Similar results were observed in studies conducted by Chumark *et al.* (2008).

2.2 Beetroot

Beetroot (*Beta vulgaris* L) is a root crimson coloured root vegetable having high medicinal properties. It is an annual herb that grows upright and has tuberous root stocks. It is an annual herb that grows upright and has tuberous root stocks. When it comes to antioxidant properties, it is one of the top ten vegetables. It is a great dietary supplement since it contains special phytoconstituents with a number of therapeutic benefits in addition to being high in vitamins, minerals, and nutrients (Yashwantkumar, 2015).

Beetroot is now cultivated in many nations across the world, consumed on an everyday basis as part of a healthy diet, and widely utilized in manufacturing as E162, a food coloring additive (Clifford *et al.,* 2015). Instead of being produced for sugar, beetroot is grown for its culinary applications, such as pickles, salads, and juice. Unlike other fruits, beetroot contains primarily sucrose as its sugar, with trace levels of fructose and glucose (Bevec *et al.,* 2010) .

According to Georgiev *et al.* (2010), high betalain concentrations lend beetroots a vibrant red hue. Despite being utilized as natural colorants in the food business, betalains have drawn more attention recently because of their health advantages for people, particularly their anti-inflammatory and antioxidant properties. The two primary betalains in beetroot are betaxanthins and betacyanins (Gantia *et al.,* 2010).

2.2.1 Nutritional aspects of beetroot.

Red beetroot (*Beta vulgaris L.*) has become a traditional and prevalent vegetable in numerous parts of the world. It has a moderate calorie content, but is particularly high in fibre and sugars. Bioactive substances are the soluble and cell wall-associated phenolics (Kugler *et al.,* 2007; Pradhan *et al.,* 2010).

According to Chaudhary and Shaikh (2020), beetroot is a rich source of folate, manganese, potassium and vitamin C. Vitamin C content is an important nutrient required in the diet of pregnant ladies, as it is a significant source of tissue development and cellular work (Feketek *et al.,* 2012). According to Cappuccio *et al.* (2011), beetroot helps in reducing blood pressure and improving heart health due to the higher concentrations of magnesium present in the sample.

Beetroot is a rich source of vitamin C, calcium, riboflavin, thiamine, copper, selenium etc. Due to the enhanced vitamin C it is used as an human immune system booster. It also helps in enhancing skin health (Wintergerst *et al.,* 2006; Johnston *et al.,* 2014)

2.2.2 Medicinal properties of beetroot

According to Chawla *et al.* (2016), numerous elements of this plant have medical uses, including diuretics, expectorants, carminatives, anti-inflammatory, anti-fungal, anti-oxidant, antidepressants, and antimicrobials. It contains one of the greatest nitrate and sugar concentrations of any plant, making it a natural diet that gives athletes more energy. Beetroot is known to be a powerful antioxidant (Dambalkar *et al.,* 2015)

According to Kapil *et al.* (2015), beetroot contain nitrates which get converted into nitric oxide inside the body, which results in enlargement of blood vessels. The nitrates in beetroot helps in reducing the risk of heart diseases and stroke by lowering the blood pressure (Coles and Clifton, 2012). Hence beetroot juice consumption is a better alternative to reduce hypersensitive issues.

Beetroot juice contains bioactive compound betalain, which has a potential ability to prevent prostate and breast cancer (Kapadia *et al.,* 2011). Beetroot helps in purification of blood (Chaudhary and Shaikh, 2020). According to Helga (2005), beetroot juice contains high amounts of folic acid which helps in preventing neural tube fault in babies. Hence it is included in the diet of pregnant women.

Vitamin A, found in beets, is primarily responsible for maintaining healthy mucous membranes and skin, and promotes the daily renewal of skin cells (Clare Gilbert. 2013). Beetroot extract helps in treatment of inflammation of the kidney (Gamal *et al.,* 2014).

2.3 Ultrasound

Ultrasound is an innovative, nonthermal, and adaptable technology, now commonly employed in the food processing sector. According to Jayasooriya *et al.* (2004), ultrasound is defined as sound waves with frequencies higher than the upper audible range of human hearing (>20 kHz). Bats and dolphins utilize ultrasonography to find their prey in the wild. Ultrasound has the ability to pass through solids, liquids, and gasses. The ultrasound waves travelled longitudinally across the biological structures. A significant quantity of energy is transferred to the material as a result of the compressions and rarefactions they cause in the medium. Ultrasound is employed in the food industry for a variety of reasons (Dolatoszwski *et al.,* 2007).

Ultrasound can be divided into two categories based on its energy intensity and frequency: high power ultrasound and low power ultrasound (Knorr *et al.,* 2004). High frequencies (more than 100 kHz) and low power levels (less than 1 Wcm^{-2}) are used in low power ultrasound (high frequency) applications. Low power ultrasound is frequently employed in the food industry as a nondestructive analytical instrument because of its low energy level, which does not alter the physicochemical characteristics of food materials. Food texture, composition, and physical condition have all been assessed using low power ultrasonography (Fellows, 2000). Low frequencies, typically between 18 and 100 kHz, and high energy intensity (more than 1 Wcm^{-2}) are characteristics of high power ultrasound (low frequency) (McClements, 1995). High-power ultrasound is used for a variety of purposes, including degassing, crystallization, filtration, enhanced drying, microbial and enzyme inactivation, homogenisation, emulsification, defoaming, and meat tenderisation. This is because it causes cavitation in food products, which causes physical, chemical, and mechanical changes (Cho and Irudayaraja, 2003).

2.3.1 Ultrasound generation

Joule's discovery of the magnetostriction effect in 1874 served as the foundation for magnetostrictive transducers. When a magnetic field was applied, the ferromagnetic material used to make these transducers changed size in an attempt to produce mechanical vibrations (Raichel, 2000). The system's conversion to acoustic energy is only 60%, which is a very low efficiency. These configurations are essentially restricted to 30 kHz.

Pierre Curie developed the piezoelectric effect in the 1800s, which is the basis for how piezoelectric transducers operate. He claimed that electrical impulses were generated when mechanical pressure was applied to asymmetrical crystals such as quartz and Rochelle salt. On the other hand, applying electrical oscillations to these salts can result in mechanical vibrations. The first practical examination was conducted in 1915 by Paul Langevin (Cruz *et al.,* 2014). Lead zirconate titanate, barium titanate, and lead metaniobate are the most widely utilized piezoelectric materials. The most popular devices are piezoelectric transducers, which use less energy (80% to 90% conversion to acoustic energy).

2.3.2 Ultrasonic processing equipments

The most widely utilized equipment on a laboratory scale is ultrasonic cleaning baths. They are mostly applied to liquid samples submerged in water and are commercially viable (Manson, 1999). In industries, ultrasonic baths are also utilized as batch equipment. Ultrasonic baths work at frequencies and power levels of 40 kHz or less to prevent cavitation-induced cracks or damage to the tank walls. Usually, there are one or more transducers at the bottom of the bath. To achieve optimal energy distribution, the transducers' area of contact with the medium (liquid or water) should be kept at its maximum. In order to prevent cross-contamination, ultrasonic baths are also employed in businesses for cleaning or decontamination, such as when cleaning chicken shackles (Watson, 1998).

The ultrasonic probe device (horn) is another often utilized batch type of equipment. They are transducers of the immersion kind. Usually used to achieve more uniform goods and for more energy-intensive applications. The most crucial element influencing the application's success is the choice of probe. The main elements to be taken into account are the volume of sample to be treated, the distance between the probe's apex and the vessel's bottom, the size and form of the probe, and the manufacturing material. Stainless steel, titanium, or aluminium alloys are typically used in the production of probes. According to Cruz *et al.* (2014), probes come in a variety of shapes, including stepped, tapered, exponential, half wave, full wave, and cylindrical. The two most prevalent types of flow reactors are resonating tubes and liquid whistle reactors. The first kind of emulsification tool is the liquid whistle. A strong pump is used in a liquid whistle to drive the medium through an opening under pressure. After emerging, the medium spreads out into a mixing chamber. A liquid whistle is a very durable instrument because it only has a pump and no other moving parts.

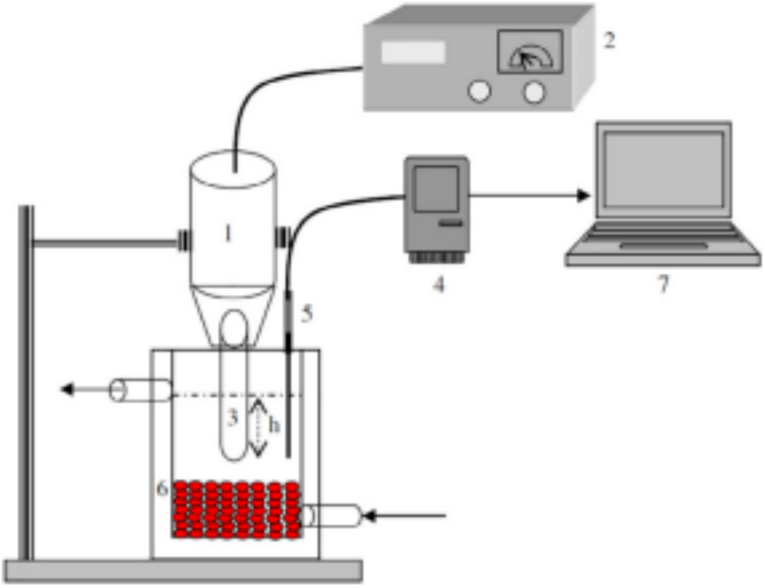

Fig 2.1 Experimental setup for Ultrasound pretreatment: : (1) ultrasound transducer, (2) ultrasonic generator, (3) ultrasound probe (19 mm), (4) data logger, (5) temperature probe, (6) jacketed glass beaker, (7) computer and (h) depth of probe into the water (2.5 cm) (Huang *et al.,* 2020)

2.3.3 Mechanisms of ultrasound processing

Longitudinal waves of ultrasound can travel through the biological material. It causes the medium particles to undergo alternating cycles of rarefaction and compression (Povey and Manson, 1998). Cavitation bubbles are created when the rarefaction cycles surpass the medium's molecules attraction forces when the power is strong enough. Because of corrected diffusion, these bubbles expand across the cycles. The bubbles become unstable and undergo a violent collapse when they reach a crucial size. Cavitation is the process of bubble development, expansion, and collapse. Cavitation alters the medium mechanically, chemically, and biochemically. Microbes and enzymes are destroyed as a result of the localised hot patches it creates. When the cavitation bubbles meet, shock waves are produced. These waves ultimately destroy the cell walls and membranes of microorganisms, inactivating them, and denaturing DNA by sonolyzing water. Microstreaming is another effect of cavitation. A phenomenon known as microstreaming occurs when cavitation bubbles create strong eddy currents and a robust circulatory motion in the medium. Heat and mass transport are facilitated by microstreaming (Zheng and Sun, 2006)

Environmental variables like temperature and pressure also affect microbial inactivation. Ultrasound is typically used in conjunction with other methods to render resistant microorganisms inactive. The following lists the various ways that ultrasonography can be applied:

2.3.3.1 Ultrasonication

This technique applies ultrasound at a low temperature.

2.3.3.2 Thermosonication

Compared to standard heat treatments, this method uses ultrasound in conjunction with moderate heat to achieve more successful microbial inactivation (Manson *et al.,* 1996; Villamiel *et al.,* 1999).

2.3.3.3 Manosonication

Ultrasound and pressure are used in this treatment. Use low temperatures and moderate pressures (100–300 kPa) in most cases (Ercan and Soyal, 2013).

2.3.3.4 Manothermosonication

This technique applies pressure, heat, and ultrasound to the product all at once. Microorganisms with a high tolerance to heat can be rendered inactive using this technique (Chemat *et al.,* 2011).

2.3.4. Application of ultrasound in Food preservation

In the food sector, thermal processes like pasteurization and sterilization are generally used as preservation techniques. Food products are subjected to higher temperatures during thermal treatments, which results in unfavourable alterations. The texture, colour, smell, and nutritional values of food products will alter as a result of cavitation reaction (Roobab *et al.,* 2018). At present, biological materials in fresh form have got more popularity among the consumers. The food processing industry is increasingly searching for non-thermal methods that extend the shelf lives of food products, while maintaining their nutritional value in order to satisfy consumer demands.

2.3.4.1 Application of ultrasound in microbial inactivation

Compared to vegetative cells, spores like *Bacillus* and *Clostridium* are more difficult to inactivate because they are typically more resilient to environmental influences. To inactivate spores, ultrasound is typically used in conjunction with heat and pressure. According to Raso *et al.* (1998), manosonication at 500 kPa for 12 minutes inactivated 99 percent of *B. subtils* (amplitude 117 µm). They also affirmed that sonication amplitude was a crucial consideration. 75% of *B. subtils* was killed by manosonication (20 kHz, 300 kPa) at 90 µm for 42 minutes. When the identical experiment was conducted at 150 µm, 99.9 percent destruction was achieved. More effective microbial killing occurred when the temperature was raised from 70 to 90 °C for 6 minutes under the same experimental circumstances (20 kHz, 300 kPa, 117 µm amplitude).

Pagan e*t al.* (1999) investigated how pH affected sonication treatment. They discovered that the destruction of *Listeria monocytogenes* was more at pH 4 than neutral pH (7) when ultrasonic processing (20 kHz) was performed at 200 kPa.

According to Cabeza *et al.* (2005), the surface of intact eggs can be pasteurised using thermosonication (54 °C for 15 min) to get rid of *S. enteritidis*. Its nutritional and functional qualities, including shelf life, emulsifying and foaming abilities, stability, egg white gel texture, shell breaking resistance, and cooked egg sensory qualities, were unaffected by the treatment.

The amplitude of US waves, treatment duration, product composition, and volume are the main determinants of the extent of microbial annihilation (Ercan and Soyal, 2013). The effectiveness of the process is also determined by the type of microorganism that is present in the food product. According to studies, because of the difference in their surface area, larger cells are far more sensitive to ultrasound than smaller ones. Gramme negative bacteria are significantly more resistant to ultrasound because of their thick cell walls, according to Drakopoulou *et al.* (2009) (gramme positive bacteria have thick peptidoglycan layers in their cell walls). Similarly, due to differences in the structure and chemistry of the cell wall, spores are extremely resistant to ultrasound, particularly when compared to vegetative cells.

A small degree of microbial inactivation (roughly 1.08 log cfu/ml) is revealed by ultrasonography treatment of orange juice (500 kHz, 240 w for 15 min), according to studies conducted by Valero *et al.* (2007). However, there is no negative effect on the juice's quality characteristics, such as limonine content, browning, or colour change. Ultrasound should be used in conjunction with other possible techniques to extend shelf life, according to the microbiological growth seen during storage experiments.

Ferrante *et al.* (2007), discovered that the development and multiplication of *L. monocytogens* in orange juice were inhibited by a combination of ultrasound, mild heat, and an antibiotic agent. Researchers have discovered that $Ca(OH)_2$ and ultrasonic therapy can be used in place of chlorine treatment to inhibit the activity of

Salmonella and E. coli from contaminating lucerne seedlings (Scouten and Beuchat, 2002).

Thermal pasteurisation of milk can be replaced with ultrasound treatment, according to experiments conducted by Cameron *et al.* (2009). After a 10-minute sonication process, they discovered that E. Coli and *Listeria monocytogenes* significantly decreased, and milk infected with *Pseudomonas fluorescensin* showed a significant drop after 6 minutes of exposure. According to Odonnell *et al.* (2010), ultrasound treatments had only minor detrimental effects on the quality attributes of fruit juices, including orange, guava, and strawberry. According to Aadil *et al.* (2013), sonication treatment preserved and enhanced the overall quality of grape juices. According to Bevllacqua *et al.* (2014), sonication is a potential method for reducing the growth of rotting yeast in fruit juices, and the duration of treatment and the amount of power used determines the effectiveness of the treatment.

Ultrasound can readily be used in conjunction with other methods to improve the effectiveness of microbial inactivation. Fitriyanti and Narasimhan (2018) found that the E. coli count was significantly lower when ultrasonic treatment was paired with antimicrobial peptide (AMP) Cecropin P1 than when the two treatments were used alone. Additionally, they discovered that the combined treatment was more cost-effective and efficient than the individual treatments. Similarly, Lilliard (1993) used an ultrasound bath to test the efficacy of sonication therapies on Salmonella found in poultry skin. According to his observations, sonication treatment lowers the count by one to one and a half log cycles. However, the count decreased by 2.5 to 4 log cycles when the experiment was conducted again using cold chlorinated water.

In wine processing, *Brettanomyces bruxellensis* is a significant spoiling microorganism. Off-odors are produced as a result of the volatile phenols they create. High power ultrasonic therapy (20 kHz with a diameter probe of 12.7 mm) caused the highest inactivation of *B. bruxellensis* at 43 °C for three minutes, according to Gracin *et al.* (2017).

2.3.4.2 Application of ultrasound in enzyme inactivation

Due to variations in amino acid composition and structural alterations, the mechanism and efficacy of ultrasound-assisted enzyme inactivation vary depending on the enzyme (Ozbek and Ulgen, 2000). According to Lopez and Burgos (1995), lipoxygenase was inactivated by the free radical mechanism through protein denaturation, whereas peroxidase was inactivated by manothermosonication because the enzyme part of the prosthetic heme split. Certain enzymes are also resistant to ultrasound, according to research findings (Sala *et al.*, 1995).

Additionally, researchers discovered that manothermosonication led to the deactivation of enzymes at lower temperatures or within a brief treatment period. According to Vercet *et al.* (2001), the D value for heat treatment of orange juice's pectin methyl esterase at 72 °C was 500 minutes. By using manothermosonication, it was shortened to 1.2 minutes.

Thermal therapies can be replaced with ultrasonication-based combination procedures such as thermosonication, manosonication, and manothermosonication. According to Vercet *et al.* (2002), sonication treatment at 200 kPa and 70 °C results in 100% inactivation of pectin methyl esterase in tomato puree. According to Lopez *et al.* (1998), the D value of enzyme inactivation is decreased when heat is applied during sonication treatment. During sonication, they observed that the D value of pectin methyl esterase dropped from 45 minutes to 0.85 minutes and the D value of polygalactrounase dropped from 20.6 minutes to 0.24 minutes at two different temperatures, 52 °C and 86 °C. The findings of Ercan and Soyals (2013) investigation were similar.They discovered that when temperature and ultrasound were coupled, the rate at which tomato pectin methyl esterase was inactivated rose significantly.

The frequency, power, enzyme type and concentration, pH, and temperature all affect how well ultrasonic inactivates enzymes. Potapovich *et al.* (2003) carried out studies under four distinct conditions to examine the impact of variables like power, pH, frequency, etc.

1) 20 kHz frequency and 48 w/cm^2 power
2) 20 kHz frequency and 62 w/cm^2 power
3) 264 kHz frequency and 0.05 w/cm^2 power
4) 264 kHz frequency and 1 w/cm^2 power

It has been observed that catalase inactivation in a buffer media decreased with increase in enzyme concentration and improves with increased power. Additionally, they noted that as frequency rose, the inactivation rate rose as well because more free radicals were produced. As an alternative to heat treatment, enzymes can be rendered inactive using ultrasound and a combination of approaches.

According to Manas *et al.* (2006), the efficacy of inactivating egg white lysozyme was enhanced when US treatment was coupled with temperature and pressure. Similar findings were made by Villamiel and Dejong (2000), who found that while sonication alone was ineffective at inactivating endogenous milk enzymes like lactoperoxidase, G-glutamyl transpeptidase, and alkaline phosphatase at room temperature, it was effective at denatured proteins when combined with heat (60 to 70 °C). Similarly, Lopez *et al.* (1998) found that utilizing Manosonication to inactivate endo polygalacturonases had a higher rate than heat treatment at 62.5°C.

In nature, all enzymes are typically proteins. Cavitation bubbles are produced in the medium or products by ultrasound. Localized hotspots are produced when these bubbles violently burst. Cavitation also produces microstreaming of liquid and shock waves. The secondary and tertiary structures of the protein undergo structural alterations as a result of all these effects. Enzyme denaturation will result from this.

The biological activity of enzymes is destroyed when free radicals produced by the sonolysis of water combine with protein amino acids (Feng *et al.*, 2011).

2.3.4.3 Application of ultrasound in filtration process

In the food industry, filtration is a crucial unit operation. The traditional approaches necessitate filter cleaning or replacement at specific intervals because of clogging. By using ultrasonic, the filtration system may work more effectively and process materials for longer periods of time without requiring maintenance. The flow is increased by ultrasound energy through the reduction of concentration polarization. This maintains a frictionless filter without changing the permeability of the filter membrane. It keeps the surface friction-free without compromising the filter membrane's permeability. The filter's lifespan is extended by ultrasonically assisted filtration, also known as acoustic filtration. It is frequently used to filter fruit juices and beverages and clean wastewater. Additionally, it is widely used in the dairy industry to separate milk components and process milk and whey products (Zisu and Chandrapala, 2015). According to Koh *et al.* (2012), acoustic filtering lowers the energy needed to process whey solutions with a high solid content.

2.3.4.4 Application of ultrasound in crystallization process

In the food industry, crystallization is a crucial process that creates ice cream, butter, margarine, chocolate, and whipped cream. Ultrasound with a frequency of roughly 20–100 kHz can improve crystallization in a number of ways, including nucleation, monitoring the rate of crystal growth, optimizing the production of tiny, uniformly sized crystals, and preventing surface fouling of freshly formed crystals (Virone *et al.*, 2006). According to Bund and Pandit (2007), by delivering sound energy during the nucleation phase, ultrasonography can be utilized to regulate the crystallization process. According to Ueno *et al.* (2003), sonocrystallization shortens induction periods and speeds up fat nucleation.

2.3.4.5 Application of ultrasound in freezing process

According to Sun and Li (2003), frozen potatoes treated with high power ultrasound have superior cell structure compared to regular frozen potatoes. Cavitation bubbles act as nuclei for crystal formation during ultrasound-assisted freezing, boosting the freezing rate. Because of the high filtering rate, a stable microstructure was achieved under such freezing conditions. The ice crystals are smaller than those created using the traditional process, which lessens the microstructure damage to the product. According to Dette and Janseen (2010), concentrated juices flavour, colour, and aroma are preserved via ultrasonic aided freezing. Ultrasound aided freezing was proven to be beneficial due to its high product quality and quicker freezing time.

2.3.4.6 Application of ultrasound in extraction process

Wu *et al*. (2001) observed that ultrasound-assisted extraction could be used to increase the extraction of thermally unstable chemicals and could be carried out at lower temperatures. According to Halzhou *et al*. (2004) and Zhang *et al*. (2008), the use of power ultrasound during the extraction process increased the amount of edible oil produced from soybean and flax seeds.

Ultrasound aided extraction improves efficiency and preserves the structural and molecular characteristics of hemicellulose, cellulose, xyloglucan, and water-soluble xylan extracted from buckwheat hulls, according to Hromadkova and Ebringerova (2003).

2.3.4.7 Application of ultrasound in drying process

Food can be dehydrated using high-power ultrasound without compromising the product's essential qualities. Compared to traditional methods, ultrasound assisted drying allows products to be dried faster and at a lower temperature while maintaining the product's quality attributes (Garcia *et al*., 2009). Ultrasound can be employed alone or in combination with other energy sources, such as hot air. When working with heat-sensitive goods, like food, high-power ultrasonic dehydration of porous materials can be quite helpful. Because of the increased rate of material drying, high power ultrasonic waves might affect mass transfer processes. Therefore, the use of lower temperatures or shorter processing periods may be possible using ultrasonically aided hot air drying methods. According to Ensminger (1988), the use of ultrasound also accelerates heat transmission by 30–60% between a liquid and a solid heated surface.

The mechanism of the ultrasound-assisted drying process entails a sequence of severe compressions and rarefactions in the food ingredients caused by ultrasonic waves. With each contraction, a very tiny amount is released through the substance's surface, and the hot gas stream subsequently lets the water evaporate. According to Fernandes and Rodrigues (2007), ultrasound therapy of bananas prior to drying creates microscopic channels in the fruit structure, increasing the rate at which water diffuses and shortening the drying time. Additionally, research indicates that ultrasound-pretreated samples, such pineapples and bananas, have better rehydration qualities than untreated samples (Fernandes *et al*., 2008). As a result, this technique can effectively dehydrate fruits and vegetables without compromising their essential nutritious qualities.

2.3.4.8 Application of ultrasound in emulsification

Emulsification is a unit operation that involves the dispersion of two or more immiscible liquids from a combination. Ultrasound provides the energy needed to disperse a liquid phase in tiny droplets in a continuous phase. High liquid velocity liquid jets form as a result of shock waves caused by collapsing cavitation bubbles in the dispersing zone. The emulsion uses stabilizers and emulsifiers (surface active chemicals, surfactants) to prevent coalescence of the newly produced droplets.

In order to create more stable emulsions, ultrasound-assisted emulsification uses less surfactant. These techniques are typically easy to use, economically viable, and may be integrated with current manufacturing systems to improve the end product's quality (Krasulya *et al.*, 2016). According to Riener *et al.* (2009), the use of ultrasound shortened the homogenisation process's duration and temperature. Similarly, Chemat *et al.* (2011) discovered that more compact, uniformly dispersed, and stable emulsions were formed by ultrasonic homogenisation at lower frequency ranges between 16 and 100 kHz.

2.3.4.9 Application of ultrasound in degassing

In food processing, degassing is a crucial application. Ultrasound drives gas bubbles that are suspended in liquids to the surface during a degassing procedure, causing the gas to be released. It lowers the dissolved gas content (Juan and Juarez, 2010). The sound waves that propagate from the radiating surface into the liquid media during sonication produce tiny cavitation bubbles. The sequence of little bubbles creates a large overall surface area. The bubbles are evenly distributed throughout the liquid. The dissolved gasses increase the size of the vacuum bubbles by diffusing into them. The acoustic vibrations promote the agglomeration of nearby bubbles, which causes the bubbles to develop quickly. The trapped gas can be released into the atmosphere just below the liquid surface by causing smaller bubbles to emerge through the ultrasonic waves and shaking larger bubbles off container surfaces. Before being bottled, carbonated beverages like beer could be degassed using this technology in the food processing sector. Compared to traditional mechanical agitation, the ultrasound-assisted degassing method reduces the quantity of broken bottles and drink spills.

2.3.4.10 Application of ultrasound in cutting

According to Schneider *et al.* (2009), ultrasound-assisted cutting increases cut precision, lowers cutting energy requirements, and improves the quality of the cut surface. An ultrasonic cutting device typically consists of a generator, a transducer, an amplifier, and a sonotrode, or blade, that can operate at low ultrasonic frequencies between 20 and 100 kHz. Because less mechanical cutting force is needed, the induced oscillation at the sonotrodes cutting edge with a defined amplitude produces faster and more accurate cutting than other conventional technologies like laser cutters and water jet cutters (Rawson, 1998). The cutting blade is composed of sturdy materials including titanium, which is highly innocuous to food. In fact, the cutting board's resistance to friction is reduced by the vibration. Cutting with ultrasound-excited devices is a viable alternative to traditional cutting in situations where the products contain particles that differ in hardness and elasticity from the surrounding mass or when they are composed of layers that exhibit significantly varied mechanical properties.

Ultrasound has numerous advantages in food processing activities. The type and state of the food, frozen or thawed determine the ultrasonic cutting properties (Brown *et al.*, 2005). Foods that are delicate, fatty, sticky, and heterogeneous, such cakes, pastries, bakery goods, and cheeses, are the primary candidates for ultrasound-assisted cutting. This technique also improves hygiene since the vibration keeps the material from sticking to the blade, which stops microorganisms from growing on it. In other words, ultrasonic vibrations allow the blade to "auto-clean" (Rana *et al.,* 2017).

2.3.4.11 Application of ultrasound in meat tenderization

The mechanical process of ultrasonic beef tenderisation is quick and easy. Ultrasonic beef tenderisation is used successfully in industrial production lines and kitchens. The meat's softness, juiciness, flavour, aroma, and appearance all affect its quality. Tenderness is the primary determinant of meat quality, according to consumer purchasing behaviour. The skeletal muscles composition and structure have an impact on meat softness (Jayasooriya *et al.*, 2004). Tenderisation can be accomplished mechanically (e.g. by pounding, piercing), thermally (frying, grilling, braising), or enzymatically.

A cutting-edge mechanical method for tenderising meats like beef, lamb, pork, and poultry is being employed using a high power ultrasound. Tenderness is directly caused by ultrasound-induced cell membrane rupture. Additionally, it triggers the release of cathepsins or Ca^{2+} ions from intercellular storage, which indirectly leads to discomfort (Jayasooriya *et al*., 2004).

Meat tenderisation effectiveness is influenced by temperature, treatment duration, frequency, and intensity. According to Dickens *et al.* (1991), sonication treatment at a frequency of between 22 and 40 kHz improved the softness of the meat. Additionally, Ozuna *et al*. (2013) reported that sonication treatment improved the diffusion of moisture and NaCl. Additionally, the procedure shortened the salting time and enhanced the items' flavour and shelf life.

According to studies, using ultrasonic (25 kHz, 2 W/cm^2) during the rigormortis period enhanced the meat samples' softness and ability to retain water (Dolatowski, 1999; Dolatowski and Tward, 2004). According to research, ultrasonography has the ability to improve meat qualities and boost customer happiness.

2.3.5 Applications of low power ultrasound

Low power ultrasound used in the food industry has high frequencies (more than 100 kHz) and low power levels (less than 1 Wcm^{-2}) (Knorr *et al.,* 2004). Low power ultrasound is frequently employed in the food industry as a nondestructive analytical instrument because of its low energy level, which does not alter the physicochemical characteristics of food materials. Food texture, composition, and physical condition have all been assessed using low power ultrasonography (Fellows, 2000).

A common nondestructive method for analyzing the physicochemical and structural characteristics of food ingredients is low power ultrasound (LPU). It is frequently employed as a sensible technique to investigate the properties of impermeable fluids and to detect foreign substances in food without coming into touch with it (Coupland, 2004).

Longitudinal waves of ultrasound travel through the substance. The characteristics of ultrasound waves include velocity, frequency, amplitude, pressure, and period. Because of absorption and/or scattering mechanisms, the velocity of US waves will alter as they interact with materials (Mc Clements, 2005). The Newton-Laplace equation can be used to compute the change in velocity measurement (Blitz, 1963). Phase transitions, composition, structure, and physical condition are all ascertained using these velocity measurements (Buckin *et al.*, 2002). Finding foreign objects and flaws in processed food items is also helpful (Haeggstrom and Luukkala, 2001; Leemans and destain, 2009).

Acoustic impedance and attenuation coefficient are two additional key variables that may be related to the physical characteristics of food products. According to Dukhin and Goetz (2001), the attenuation coefficient is a feature that can be correlated with bulk viscosity, compressibility, rheology, microstructure, and composition. varied products with varying densities will have varied acoustic impedances. Continuous wave and pulse-echo techniques are the two ways that food items' characteristics are monitored.

In the food sector, low power ultrasonography (LPU) provides a quick and dependable method. The carcass's fat, muscle, and chemical makeup were estimated using low power ultrasonography (Faulkner *et al.*, 1990). It was also used to investigate the fat and moisture content of cod fillets. Using the pulse echo approach, researchers have established a connection between the temperature dependence of ultrasound and fish composition (McClements and Povey, 1987). Benedito *et al.*

(2001) measured ultrasonic velocity in their studies to investigate the composition of raw beef mixes. They looked at how the ultrasonic velocity behaved for varioUS-Components, including protein, fat, meat, and moisture, at various temperatures.

Fruits and vegetables can also be evaluated for quality using low power ultrasonography. Mizrach *et al.* (1991) used the attenuation properties of ultrasound in their tests to investigate the freshness of fruits. They discovered that when the colour of the peel changed from green to yellow, the amplitude of the ultrasonic pulse increased. It can serve as an indicator of fruit ripeness.

One of the key factors influencing the quality of the finished product is the batters physical characteristics. The physical characteristics (density, viscosity, and rheology) of batter and finished goods like cakes, doughnuts, and cupcakes are examined using low power ultrasonography techniques. Salzar *et al.* (2004) measured batter consistency using low power ultrasound. The consistency of several samples was measured by utilizing the relationship between batter consistency and acoustic impedance.

Low power ultrasonography is frequently used to confirm that emulsions, including ice cream, butter, margarine, etc., have crystallized, which is essential for determining the consistency of emulsions. Changes in internal structure, morphological characteristics, and molecular packing are brought about by the emulsion's phase transition. Ultrasound waves can travel at different speeds through solids and liquids. The extent of crystallization and phase shifts can be detected using these ultrasonic velocity measurements (Awad, 2004; Awad *et al.*, 2001; Awad and Sato, 2001). Low power ultrasonography is a nondestructive and efficient method for food product analysis.

2.4 Infrared radiations

Despite being colloquially referred to as "infrared light," infrared is actually electromagnetic radiation (EMR) with longer wavelengths than visible light, making it invisible. It stretches from 700 nanometres (frequency 430 THz), which is the notional red edge of the visible spectrum, to 1 millimetre (300 GHz), yet humans can see infrared radiation as far as 1050 nm using specially pulsed lasers.Infrared radiation makes up the majority of thermal radiation released by items that are close to room temperature. Like all EMR, infrared radiation carries radiant energy and exhibits both wave-like and photon-like behaviour (Gani *et al.,* 2018). The IR heater's energy intensity and spectrum distribution are two important radiative factors to consider when building it. The surface temperature of its heating elements and the application of suitable optical filters can regulate the infrared radiation's spectrum region. When the IR ray emits light in the restricted spectral area between 6 and 11 μm, it is possible to determine the differential energy absorption of protein among numerous important components in the meal complex. Additionally, food items' radiation characteristics change as their water content drops; as a result, their reflectivity rises and their absorptivity falls. Therefore, a thorough understanding of the aforementioned optic-thermal phenomena related to infrared and food products is crucial (Pan *et al.,* 2010). IR has been utilized extensively in the food industry.

Infrared radiation is divided into three types (Rosenthal,1992):

1. Near-IR (NIR) with wavelength ranging from 0.75 to 1.4μm.
2. Mid-IR (MIR) with a wavelength between 1.4 and 3 μm.
3. Far-IR radiation (FIR) with wavelength between 3 and 1000 μm.

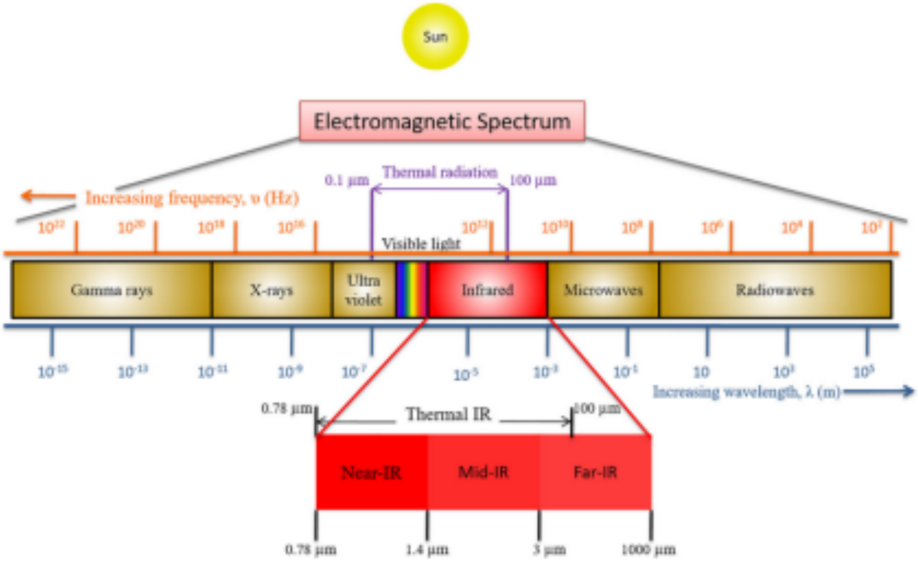

Fig 2.2 Electromagnetic spectrum (Delfiya *et al., 2022*)

As seen in figure 5, the radiation that strikes a certain item is transformed into heat, and the energy can then be absorbed, reflected, or transmitted. Reflectivity (ρ), which is the ratio of the reflected portion of the radiation coming to radiation in the following macro, is one of the three fundamental radiation qualities depicted in this picture. The ratio of the absorbed part of incoming radiation to the total amount of incoming radiation is called absorptivity (α). Emissivity The ratio of the emitted portion of the incoming radiation to the total amount of incoming radiation is known as transmissivity (τ).

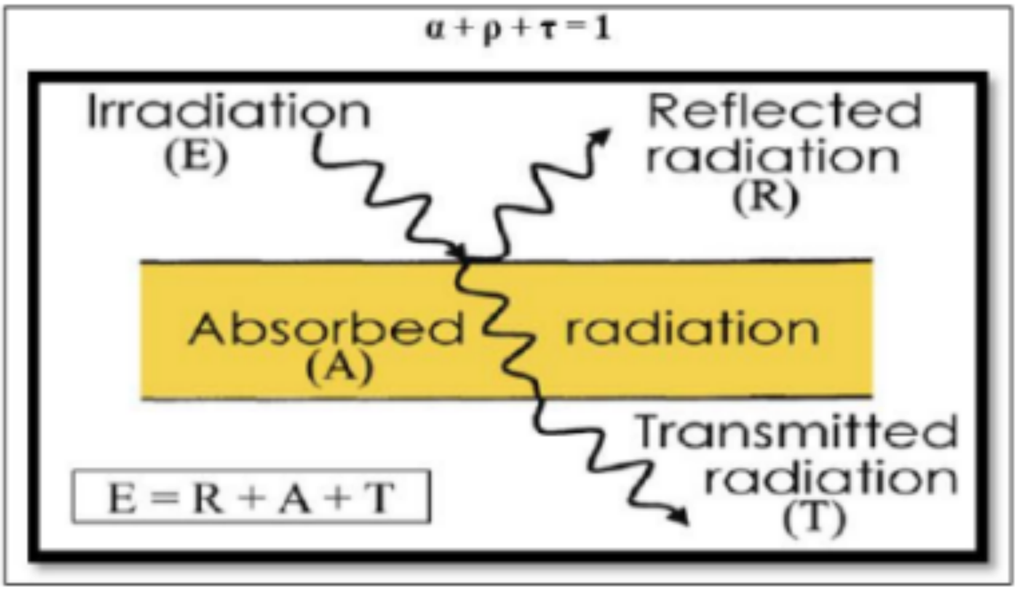

Fig 2.3 Extinction of radiation and total energy (Yadhav *et al.,* 2020)

2.4.1 Mechanism of Infrared treatment in food

One of the elements that determines the effectiveness and success of any food business unit's operations is energy conservation. Convection, radiation, and conduction are the three ways that heat is transferred. Foods are heated to extend their shelf life and enhance their flavour (Lee *et al.,* 2006). At the molecular level, temperature is a measurement of thermal motion. Molecular motion gains energy as the material's temperature rises, and as the temperature rises more, the heated substance undergoes physical and chemical changes. Heat is transported to the substance from the outside by thermal conduction or convection by hot air in conventional heating, which is produced by burning fuel or using electric heaters.

The process of transferring energy from the source to the food depends on the type of cooking; energy will be very close to the food's surface and then heat the food gradually from the hot surface towards the inside, heat is transferred to the food through conduction only, which requires continuous processing of heat; the high temperature and time needed for the food depend on its engineering and thermal properties (Rosenthal, 1992). When heating by radiation, the heat is transferred by convection and conduction; and thermal radiation causes the broiling process.

Since the infrared heating produces heat on the material's surface, the connection between the food molecules heats the inside of the material, causing the temperature to rise from the surface to the center. Indirect heating takes place in the air that comes into contact with the food's surface, however it is not as hot as when heated by convection and conduction. Figure 4, which displays the infrared absorption ranges by food components, demonstrates how the food components interfere with one another when it comes to the absorption of various infrared spectra. Proteins are absorbed by infrared radiation at wavelengths 3–4 and 6–9 µm, whereas water primarily impacts the absorption of incoming radiation at all wavelengths. Sugars absorb at wavelengths of 3 and 7–10 µm, while fats absorb at wavelengths of 3–4, 6, and 9–10 µm. According to Sandu (1986), the water absorption beams are 3, 4.7, 6, and 15.3 µm. Furthermore, the absorption rises as meal thickness increases. Heat emitted by an object is known as infrared radiation. Heat causes a thing to gain energy, which causes its atoms and molecules to move or vibrate and emit infrared heat. When an object is too cold to emit visible light, it will emit infrared. Heat energy is released when infrared waves come into contact with a surface or land on any material. The temperature of the environment has no bearing on this heat energy. Heat from the sun, fire, radiators, and other sources are examples of infrared radiation.

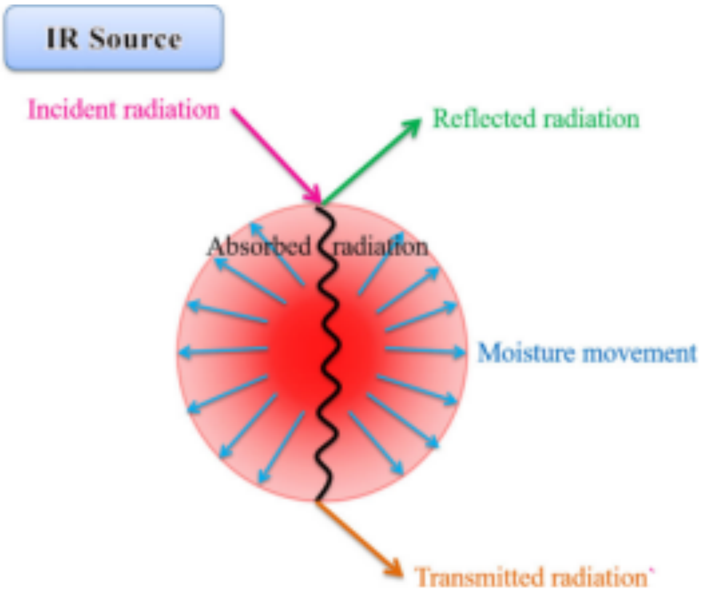

Fig 2.4 Schematic representation of IR heating in food products

(Delfiya *et al., 2022*)

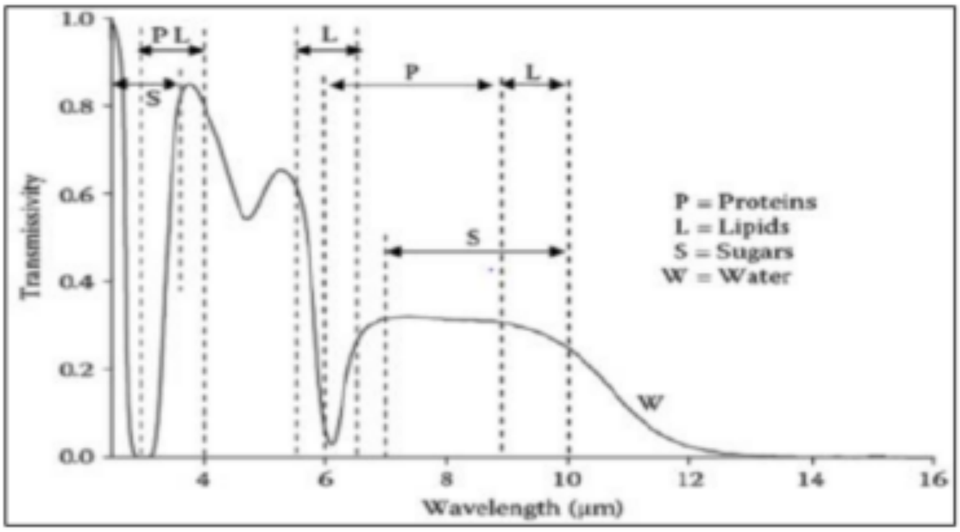

Fig 2.5 Principal absorption bands of the main food components compared with water (Krishnamurthy *et al*., 2008)

Food ingredients can be thought of as complex matrices made up of water, inorganic salts, biological polymers, and various biochemical macromolecules. Certain wavelengths of radiation can be absorbed by the food item during infrared heating, while other wavelengths can be reflected and transmitted. The object's internal heat is produced by the absorbed radiation energy. Proteins, polypeptides, and amino acids all exhibit two prominent absorption bands that are situated at 3–4 and 6–9 mm. Carbohydrates contain two strong absorption bands centered at 3 and 7–10 mm, while lipids have three strong bands at 3–4, 6, and 9–10 mm (Sandu, 1986; Rosenthal, 1992).

2.4.2 Infrared processing equipment

Infrared emitters (Figure 8) are categorised according to their electrical or gaseous type. Infrared radiation is produced by the emitters between 343 and 1100 °C for gas heaters and between 1100 and 2200 °C for electric heaters. The usual infrared temperature generated to keep items from burning is between 650 and 1200 °C (Aboud *et al.,* 2019). Although gas heaters are quite expensive, they have very low operating costs as compared to systems that emit electrically infrared radiation (electric heaters). Due to its clean energy, quick heating rate, and ease of control, infrared electric heaters are more common than gaseous ones. When it comes to providing the wavelength needed for a certain application, infrared emitters are more adaptable.

Electrical infrared emitters are made up of a metal filament that is either empty or loaded with inert gas inside a sealed container. An electric current is passed through a high-resistance wire, such as tungsten filament, iron-chromium wire, or nichrome wire, to heat the filament to a specific temperature using an electric heater. This produces infrared radiation. When the metal wire is heated to the glow temperature, which is 2200 K, infrared radiation of the NIR wavelength, which ranges from 0.7 to 1.4 µm, will be released. Reflector-type emitters, incandescent lamps, quartz tubes, and resistance elements including metallic, ceramic, and non-metallic rods are among the several kinds of electric infrared emitters (Figure 9) (Vidyarthi *et al.,* 2019). The most commonly employed IR emitters in the food industry are ceramic infrared heaters and infrared bulbs.

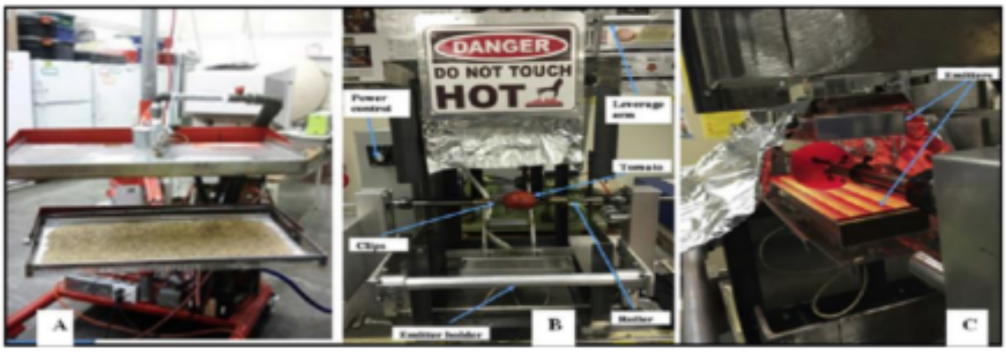

Fig 2.6 Various infrared heating systems (A) Custom-designed catalytic infrared heating unit for rice drying and (B and C) electric IR heating system.

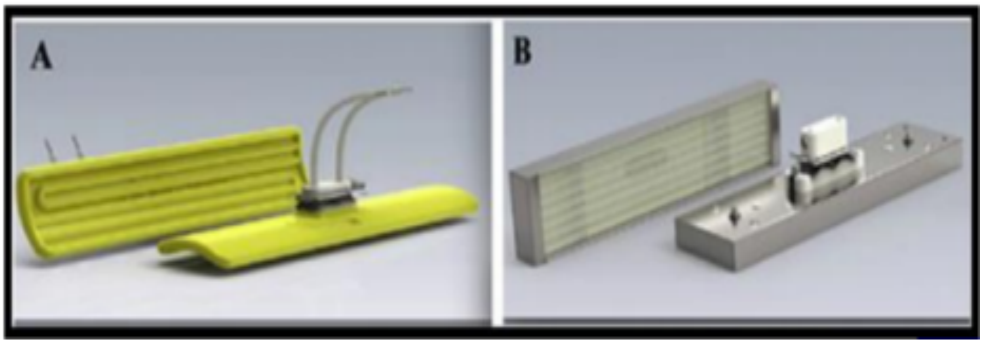

Fig 2.7 Infrared emitters : (A) Ceramic full trough element (B) Pillared quartz element (PQE)

Industrial applications frequently use gaseous infrared emitters powered by natural gas or propane because they are more reliable, durable, and have lower running costs than electrical infrared emitters. Direct or open flame infrared emitters and catalytic flameless infrared emitters are the two varieties of gaseous infrared emitters. Through typical flame burning, the open flame infrared emitters emit infrared radiation. A component of the fire flame may release visible light as part of the combustion process, wasting fuel and energy (MacConnell, 1972).

With no discernible flame, the catalytic infrared emitter radiates heat across a broad spectrum of wavelengths. These emitters typically emit MIR and FIR radiation with a heating-up period ranging from 180 to 300 s, a radiant intensity ranging from 6 to 28 kW and a radiation efficiency ranging from 30% to 75% (Das and Das, 2010). For industrial use, the gaseous infrared emitters come in a variety of sizes. For instance, if the emitter is assumed to be a blackbody, a catalytic infrared emitter with an effective heating area of 30 cm by 30 cm can produce infrared heat with an isothermal surface temperature of the emitter at around 500 C, which translates to a peak wavelength of 3.7 mm (Li *et al.,* 2014).

2.4.3 Applications of Infrared radiations in food processing

The food processing industry uses infrared radiation extensively for a number of unit operations, including baking, heating, blanching, roasting, dehydration, peeling, pasteurisation, drying, dehydrating, and inactivating enzymes and pathogens.

2.4.3.1 Drying and Dehydration

Numerous studies have been carried out in the field of infrared heating, which plays a significant role in drying technology (figures 10 and 11). Traditionally, a hot-air dryer is used to prepare the majority of dried vegetable products. Due to the poor rate of rehydration of dried veggies, this approach is not suitable for use as ingredients in instant foods. Although it is a competitive alternative, the freeze-drying technology is quite costly. It is anticipated that the use of FIR drying in the food business would introduce a novel method for producing inexpensive, high-quality dried goods (Sakai and Hanzawa, 1994).

There are many advantages of employing IR radiation technology to dehydrate food, such as improved energy efficiency, drying time, alternative energy source, consistent product temperature during drying, higher-quality final products, less need for air flow across the product, high process control parameters, space savings, and a clean working environment (Mongpreneet *et al.,* 2002). As a result, FIR drying techniques have been effectively used recently to dry fruit and vegetable products like kiwifruit, sweet potatoes, potatoes, and onions. Tunnel infrared dryers are also used to dry pasta, vegetables, seaweed, and fish flakes. Food analysis now uses infrared drying to determine how much water is in food items. Infrared light is typically absorbed by a thin layer on the surface of solid objects. Nonetheless, radiation can penetrate moist porous materials to a certain depth, and the moisture content affects how transmissible they are. The shrinkage of the heated particle and the absorption of infrared energy are taken into account by the energy and mass balance that Ratti and Mujumdar, (1995) devised. According to theoretical calculations, intermittent infrared drying with a 10 W/m^2 energy input is similar to convective drying, where the heat transfer coefficient can reach 200 W/m^2 K.

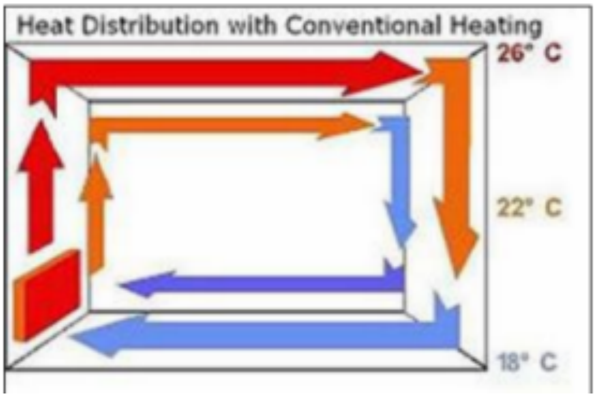

Fig 2.8 Heat distribution with conventional heating (Yadhav *et al.,* 2020)

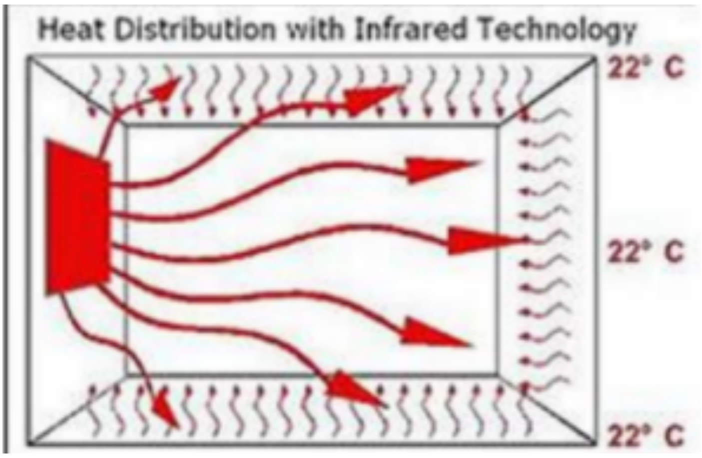

Fig 2.9 Heat distribution with infrared technology (Yadhav *et al.,* 2020)

2.4.3.2 Enzyme Inactivation

Enzyme inactivation can be accomplished with the help of infrared heating. Within 60 seconds of IR treatment, 95.5% of the enzyme lipoxygenase, which causes soybean degradation, was rendered inactive (Kouzeh *et al.,* 1982). At bulk temperatures between 30 and 40 °C, infrared radiation had an impact on specific enzyme processes that involved the action of lipases and α amylases. Lipase activity was reduced by 60% after 6 minutes of FIR radiation and 70% after thermal conduction. Enzymes that cause off flavours to develop in peas before freezing, as well as other enzymes and bacteria in solution, have all been effectively inactivated using FIR. Galindo *et al.* (2005) examined the effects of infrared heating on carrot cell and tissue damage before freezing versus blanching. The potential of FIR energy technology in the frozen carrot sector was demonstrated by the fact that carrot slices heated by FIR radiation only had damaged cells within the first half millimeter from the surface and displayed the texture of raw tissue.

2.4.3.3 Pathogen Inactivation

Mould, spores, bacteria, and yeast can all be rendered inactive in liquid and solid meals by applying infrared heating. The infrared power level, peak wavelength, and bandwidth of the infrared heating source, sample depth, food sample temperature, microorganism types, moisture content, physiological phase of the microorganisms (exponential or stationary phase), and food material types all affect the infrared heating method's ability to inactivate microorganisms. As a result, a number of studies have looked into how these characteristics affect the inactivation of harmful microbes. The impact of power Microbial inactivation results from an increase in the energy produced by infrared heating sources, which raises the overall amount of energy absorbed by bacteria. Because infrared rays heated the surface directly without the use of conductors, the surface temperature rose quickly. The experimental device reached 60, 80, 125, and 195 °C with irradiating powers of 0.5, 1.0, 1.5, and 2.0 kW, while the wheat stack surface reached 45, 65, 95, and 120 °C. Following a 60-second treatment, the corresponding log10 CFU/g total bacteria were 0.83, 1.14, 1.18, and 1.90. correspondingly. Microorganism Types: Because of structural and compositional changes, bacteria, yeasts, and molds may have varying levels of resistance to infrared heating. Spores are typically more resilient than vegetative cells. Spores were triggered after vegetative cells were rendered inactive by infrared heat treatment. Spores will then become inactive as a result of the activation of vegetative cells generated from them. Heat shock spore germination led to an initial rise in the B. subtilis population. Following the treatment, the honey's temperature was increased to 110 °C, which led to a 3.85 log10 CFU/mL microbial reduction (Krishnamurthy *et al.,* 2008)

2.5 Development of an infrared dryer

Hebbar *et al.* (2004) developed a device that combines infrared and hot air heating to dry vegetables. Mid-infrared (MIR) heaters were used for radiative heating in a three-chambered conveyorised drying system. Convective mode heating also included through-flow hot air circulation. The system was built to function independently in combined, hot air, and infrared modes. In addition to using less energy (63%) than hot air heating, the performance evaluation studies showed that drying carrots and potatoes at 80°C with air moving at a speed of 1 m/s and at a temperature of 40 °C shortened the drying time by 48%. Additionally, combination drying outperformed infrared heating alone. According to estimates, the dryer's energy efficiency was 38% for both carrot and potato drying.

Sadin *et al.* (2014) developed a laboratory-scale infrared and hot air dryer, with operational control over several parameters such drying chamber temperature, input air temperature, air flow rate, and distance from the infrared source. Different combinations of these parameters were used to dry the tomato thin layers. According to experimental findings, drying times were 60, 75, and 116 minutes for temperatures of 60, 70, and 80 °C, respectively. The amount of operational infrared power has a direct correlation with drying. Additionally, two air velocities of 0.6 and 1.1 m s-1 required 109 and 95 minutes, respectively, to dry. Due to a higher rate of moisture evaporation from the product's surface at low speeds, raising the drying air velocity shortened the drying time. The findings indicated that drying time would increase as the drying chamber's distance from the infrared source increased because less heat would be delivered to the product. The temperatures of 80 and 60 °C were associated with the minimum and greatest drying times, respectively. Additionally, there was a direct correlation between the drying rate and the incoming air's temperature and velocity.

For turmeric slices, a hot air dryer with infrared assistance has been developed by jeevarathinam *et al.* (2022). An infrared heating source, heating coils, and a blower were used in the development of the dryer. With a blower capacity of 6.06 m3/min, the total power needed for the hot air drying and infrared drying was 36.35 kWh and 2.25 kW, respectively. Turmeric slices (5 mm thick) were dried using infrared drying (IRD), hot air drying (HAD), and infrared-assisted hot air drying (IRHAD) at various drying temperatures of 50°C, 60°C, and 70°C while maintaining a constant air velocity of 2 m/s and a bed thickness of 25 mm. The IRHAD method at 70°C was found to have the highest drying efficiency of 25.22% and the lowest specific energy consumption of 1.24 kWh/kg, making it the best drying method for turmeric slices.

Delfiya *et al.* (2022) develop a continuous infrared radiation (IR) drying system with hot air (HA) assistance. They use IR mode (4500 W, 1.5 m/s), HA mode (45 °C, 1.5 m/s), and a combination of IR-HA mode (4500 W, 45 °C, 1.5 m/s) to dry the prawn samples. Under the HA, IR, and IR-HA modes of drying, the prawn samples achieved a final moisture content of 15.12%, 11.66%, and 11.98% (w.b.) and a drying efficiency of 8.78%, 15.65%, and 36.25% in 21.5 hours, 3 hours, and 2 hours, respectively. The IR-HA method of drying prawns was shown to be effective in this investigation, with the lowest drying time of 2 hours, the highest colour retention, the water activity of 0.57, the shrinkage of 7.27, the rehydration ratio of 2.40, and the specific energy consumption of 1.80 kWh/kg. Therefore, for drying prawns, the IR-HA drying mode is better than both the HA and IR drying modes.

Nowak and Lewicki (2004) designed a laboratory drier enabling the use of both convection or infrared energy for drying. Near-infrared radiators with a peak wavelength of 1200 nm were installed. The infrared dryer's energy efficiency ranged from 35% to 45%. Slices of apples were dried using convection and infrared radiation in comparable circumstances. The distance between emitters, the air velocity, and the heat-irradiated surface all affected the kinetics of infrared drying. Both the distance and the air velocity have an inverse relationship with drying kinetics. It was discovered that water evaporation occurs on both apple slice sides. But until 80% of the water is gone from the material, the heat-irradiated surface evaporates a lot more water than the one that isn't heated by infrared energy. When it comes to the flux of evaporated water, the top and bottom surfaces of the apple slice are identical at the end of the drying process. When infrared energy is used for heating, the process time can be reduced by up to 50%, according to a comparison between infrared drying and convective drying conducted under similar conditions.

The commonly used conventional dryers are cabinet dryer, heat pump dryer, fluidized bed dryer, freeze dryer etc. In this study the comparison of the developed dryer was done with the conventional dryers such as cabinet and heat pump dryers.

2.6 Cabinet drying of food products

Green leafy veggies were preserved by Satwase *et al.* (2013). There are several applications for *Moringa oleifera* leaves in daily life. The leaves of *Moringa oleifera* are used to make a variety of dishes, including soups, sauces, and medications. In the current study, attempts have been made to make *Moringa oleifera* powder using the drying techniques of oven, cabinet, shadow, and sun drying. To reduce drying losses, the drying process was carried out at 60°C. The cabinet-dried sample produced superior results than the others and retained the most nutrients, followed by the samples that were shade-, sun-, and oven-dried. The rehydration ratio was computed for 60, 45, and 30 minutes at 55°C, 65°C, and 75°C, respectively. Compared to other samples, the cabinet-dried sample had a higher rehydration ratio. According to the study, drumstick leaves might be dehydrated using the cabinet tray drying method.

To determine changes in the product's weight without taking it out of the dryer, a laboratory scale cabinet dryer was developed by Jabeen *et al.,* 2015 with a weighing balance attached. The impact of process variables (temperature and thickness) on the potato drying kinetics was investigated through experiments. The drying process exhibited non-linear behaviour and was marked by a decrease in the moisture ratio over time. Drying in this experiment was primarily controlled by a diffusion mechanism, as evidenced by the fact that no constant rate drying period was attained during the process and that the entire drying process took place in the falling rate period. A slower rate of moisture removal was obtained after an initial faster drying rate. There was an increase in drying rate and a decrease in drying time.

Fresh fenugreek leaves were blanched in water at 80°C, steam, and water containing three chemicals: potassium metabisulphite (0.5%), magnesium oxide (0.1%), and sodium bicarbonate (0.1%). The leaves were then dried in a cabinet dryer at 40°C and 50°C and 1.1 m/s air velocity, respectively (Bishnoi *et al.,* 2020). Numerous metrics, including ascorbic acid, total chlorophyll, β-carotene content, moisture content, moisture ratio, and rehydration ratio, were measured in the samples. After drying at 40°C, the water-added chemical-blanched samples outperformed the other two treated samples in terms of many quality measures and highest nutrient retention. The drying behaviour of the fenugreek leaves was predicted using five mathematical models for thin layer drying. The Midilli model performed the best when appropriate statistical parameters were examined for each model; as a result, it was used in this study to forecast how fenugreek leaves would dry under the conditions mentioned above.

Chokphoemphun *et al.* (2024) dried potato slices in a cabinet dryer at two distinct drying temperatures and three different hot air velocities. It was discovered that the moisture content change in each drying tray and the shrinkage in each coordinate of the potato slices varied even when the hot air temperature and air velocity were the same. By contrasting it with the drying model, the experiment's moisture ratio was assessed. With the coefficient of determination falling between 0.962 7 and 0.9933, the results demonstrated a high degree of confidence.

2.7 Heat pump drying of food products

S. Prasertsan and Saen-saby (1998) used a heat pump dryer to dry bananas and sawn rubber wood. While the compressor power remained relatively constant, the moisture extraction rates (MER) and specific moisture extraction rates (SMER) of drying wood and bananas dropped off quickly as the drying duration increased. The maximum average MER and SMER were 2.854 kg/h and 0.572 kg/kWh, respectively, of wood with a final moisture content below 10%. When the drying load was at its maximum, banana drying produced the highest average MER of 2.710 kg/h. The SMER for that was 0.540 kg/kWh. According to economic assessments, the HPD had the lowest operating costs when compared to a direct-fired dryer, an electrically heated hot air dryer, and the heat pump dryer.

A heat pump dryer was developed by Fatouh *et al.* (2006) in order to study the drying properties of different herbs. According to experimental data, the drying air with a temperature of 55 °C and a velocity of 2.7 m/s achieves the highest drying rate, while a high surface load of 28 kg/m^2 produces the smallest drying rate. When the air temperature is 55 °C, the air velocity is 2.7 m/s, and the dryer surface load is 28 kg/m^2, the maximum dryer productivity of roughly 5.4 kg/m^2h is achieved. It was discovered that little, stemless herbs require less specific energy and little drying time. Parsley has the lowest specific energy consumption (3684 kJ/kgH_20), followed by spearmint (3982 kJ/kgH_20) and Jew's mallow (4029 kJ/kgH_20), according to a comparison of the drying properties of several herbs. Lastly, surface load, drying air velocity, and drying air temperature have all been linked to dryer productivity.

Pal *et al.* (2010) carried out controlled thin-layer drying studies for green sweet peppers in a hot air dryer at 45°C and a heat pump dryer at 30, 35, and 40°C with relative humidities ranging from 19 to 55%. As the drying time increased, the sweet pepper slices' moisture content decreased rapidly. The drying curve showed a steeper slope as the temperature rose, indicating an increase in drying rate. Green sweet peppers were primarily dried during the falling-rate period. With a greater coefficient of determination and a lower root mean square error, the Page equation was shown to be more effective than the Lewis equation in explaining the thin-layer drying of green sweet pepper. Compared to hot air drying at 45°C, drying in a heat pump dryer at 40°C took less time and had a greater drying rate and specific moisture extraction rate because the drying air in a heat pump dryer had a lower relative humidity even if its temperature was lower. Heat pump-dried samples with greater rehydration ratios and sensory scores were found to retain more of their ascorbic acid and total chlorophyll content. As the drying air temperature increased from 30 to 45°C, the quality parameters displayed a decreasing trend. It is suggested that green sweet peppers be dried in a heat pump dryer at 35°C in consideration of the energy usage and quality characteristics of dehydrated products.

2.8 Hybrid drying technology

Hybrid drying is the combination of two or more methodologies to enhance the quality of the dried product with less energy consumption. Szadzinska *et al.* (2019), conducted ultrasound and microwave assisted intermittent drying of red beetroot. The study inferred that the periodical microwave radiation together with ultrasound reduced the total drying time, improved the drying rate and decreased in energy consumption as compared to the hot air drying method. The study concluded that the pretreatment resulted in higher retention of betalain and attractive appearance compared with convective method

Alfiya *et al.* (2022), developed a hot air assisted microwave dryer for shrimp. The study concluded that microwave drying produced better quality shrimp with respect to shrinkage, rehydration ratio, moisture diffusivity and drying times. The drying efficiency and SEC for HAMW drying of shrimp was 35.71% and 1.75 kWh/kg, respectively indicating that the hybrid drying is a better alternative to conventional dryers.

Delfiya *et al.* (2022), developed a hot air assisted continuous infrared drying (HA-IR) system for shrimps. Shrimp dried in HA-IR reduces drying time, shrinkage and energy consumption, whereas increased rehydration ratio. Hence the hot air assisted infrared drying system was superior to infrared and other conventional methods.

2.9 Response surface methodology in food drying

Response surface methodology is a statistical software which helps in mathematical modeling and designing of experiments. It helps in optimizing the effect of process variables.

Erbay and Icier (2009) optimized the drying conditions of olive leaves in a tray drier using response surface methodology, with the desirability function serving as the methodology. The variables under investigation were total phenolic content (PC), antioxidant activity loss (AC), final moisture content (MC), and energetic efficiency (η). The optimisation parameters were air temperature (40–60 °C), air velocity (0.5–1.5 m/s), and process time (240–480 min).

Using a response surface approach, the drying parameters were optimized according to the dried okra's quality and particular energy consumption. Three variables were used in the drying experiments: air temperature (40–70 °C), air velocity (1–2 m/s), and microwave power level (0.5–2.5 W/g) using a central composite rotatable design. Colour change, rehydration ratio, and textural hardness were used to assess the quality of the dried okra. All responses were well fitted by a second-order polynomial model, and high R^2 values (>0.8) were consistently noted. According to Kumar *et al.* (2014), the ideal drying parameters for okra microwave-convective drying were 1.51 m/s air velocity, 52.09 °C air temperature, and 2.41 W/g microwave power. These parameters also resulted in the lowest energy usage and the highest product quality.

In order to optimise the drying process in terms of the physical (moisture content, water activity, total colour change, firmness, and rehydration power) and chemical (total phenols, total flavonoids, monomeric anthocyanins, ascorbic acid content, and antioxidant activity) properties of dried samples, Sumic *et al.* (2016) used Box–Behnken experimental design with response surface methodology. As independent variables, temperature (48–78 °C), pressure (30–330 mbar), and drying time (8–16 h) were examined. A second-order polynomial model was fitted to the experimental data, and the model's fitness and ideal drying conditions were ascertained using regression analysis and analysis of variance.

Using a desired function, Majdi *et al.* (2019) used RSM to state an optimal system for convective drying of apple slices. The dependent variables, which include drying time, energy consumption, and shrinkage, are found to interact with the independent parameters, which include air temperature (T = 70–90 °C), air velocity (V = 4-5 m/s), and apple slice geometry (G = circular, square, and triangle). The ideal drying conditions for apple slices are thought to be the lowest possible drying time, energy usage, and shrinkage. Analysis of variance is used to determine model compatibility and ideal drying conditions for a second-order polynomial model that adapts experimental results. According to the maximum desirability function, the ideal parameters for the combined optimized responses were square geometry, an intake velocity of 5 m/s, and an inlet temperature of 90 °C (D=0.781).

2.10 Drying kinetics and modeling

Drying kinetics is the study of moisture removal from a substance in terms of time. The modeling involves the procedure for optimizing the drying behaviour in terms of simulation and mathematical equations.

One important component influencing drying kinetics during food drying has been identified as air temperature. Krokida *et al.* (2003) found a direct correlation between drying temperature and the drying constant, equilibrium moisture content, and moisture diffusivity. The impact of air temperature on drying kinetics has been the subject of numerous investigations. Abano *et al.* (2011) explained the drying kinetics using three empirical models: the Page, Logarithmic, and Henderson and Pabis models.

Tomato slices were dried at various air temperatures, and inconsistent drying at high temperatures was noted, highlighting the significance of diffusion as a key physical mechanism for moisture removal. In a different investigation of how sample size and air conditions affect produce drying kinetics According to Krokida *et al.* (2003), the samples' drying kinetics at two ambient temperatures and increased temperatures were predicted by the first-order drying kinetics. Additionally, they noticed a clear correlation between air temperature and moisture loss, as well as an inverse link with the sample's moisture equilibrium.According to Tzempelikos *et al.* (2014), drying time has been found to be impacted by drying air temperatures and air velocity. Additionally, they found that drying temperature and air velocity had an inverse relationship with drying time.

According to Borges *et al.* (2011), the drying kinetics are affected by the form.Produce cut into disc and cylindrical forms was dried in a tray drier, and it was found that the drying rate of the disk-shaped produce was noticeably higher than that of the cylindrical-shaped produce. Additionally, they noted that the fruit benefits from temperature and that blanching had an impact on the produce. Additionally, it was revealed that air temperature and velocity had a significant impact on drying time.

Kipack (2017) investigated how different microwave power levels (90, 180, 360, 600, and 800 W) affect drying kinetics, rehydration properties, and energy consumption in *Mytilus edulis*. For microwave power levels of 90, 180, and 360 W, respectively, the ideal drying times were found to be 16, 5, and 2 minutes. However, the best drying periods were 80 and 60 seconds, respectively, at 600 and 800 W microwave power levels. The experimental findings show that the variation in microwave power levels has a minor impact on the drying kinetics, rehydration properties, and energy consumptions. The experimental data was subjected to seven distinct thin-layer drying models that are often employed in the literature. The findings shown that the Weibull model best explains the experimental data of *Mytilus edulis* drying kinetics (R^2: 0.998135–0.999929, χ 2: 0.000029–0.000401, and RMSE: 0.004172–0.018733). It was found that the effective moisture diffusivity ranged from 2.74×10^{-8} to 4.79×10^{-7} m2/s. 95.131 kW/kg was determined to be the activation energy using a modified Arrhenius-type equation. The most efficient microwave power level, taking into account the least amount of energy used, was 360 W.

2.11 Quality evaluation of dried food products

The flow of moisture in fish products is known as effective moisture diffusivity, and it depends on the pace of drying. Unlike drying rate, which is directly related to the pressure gradient that results from a temperature gradient between the material and the air, effective moisture diffusivity is related to the moisture velocity within the material, whereas drying rate is the moisture vaporising rate to air (Azzouz *et al.,* 2002; Aghbashlo *et al.,* 2008).

Vishwanathan *et al.* (2010) conducted quality evaluation of the product, comparing samples that were hot air dried and hot air assisted infrared (IR) drying of potatoes and carrots. In addition to increasing product quality, the combination mode (hot air assisted IR) drying methods synergistic effect of hot air and IR cut processing time by almost 48% when compared to hot air drying alone. For combined mode dried products, a higher rehydration ratio and lower browning index values are noted. Photomicrographs of dehydrated potatoes and carrots demonstrated that the combined mode dried products had superior product structure. Compared to the hot air-dried sample, the carotenoid retention in the IR-dried carrot was higher by 17%. The drying properties during mixed mode drying were influenced by the processing parameters, such as air temperature and velocity. Combined mode drying results in higher water effective diffusivity values.

Tian *et al.* (2016) assessed how key characteristics and volatile components of whole shiitake (*Lentinus edodes)* mushrooms were affected by hot air, vacuum, microwave, and microwave vacuum drying methods. The relative content of sulphur compounds and the total free amino acid content of dried goods increased significantly ($p < 0.05$) as a result of these four drying techniques. Larger quantities of taste-active amino acids were preserved by microwave vacuum drying, which also enhanced colour and nutrition retention. Additionally, the observed high rehydration ratio can be explained by the homogeneous honeycomb network produced by microwave vacuum drying in conjunction with the dried materials' less collapsed structure.

The food sector uses infrared (IR) radiations for a variety of processes, including roasting, drying, pasteurisation, blanching, peeling, and removing antinutrients from legumes. To increase process speed and improve results, IR drying can be used in conjunction with other drying techniques such as hot air, hoover, microwave and freeze drying. A thorough explanation is given of how process factors affect energy usage, drying time, drying rate, and dried product quality. Sakare *et al.* (2020) also describe model calculations for heat and mass transmission as well as for the penetration depth of infrared in food products.

2.12 Economic analysis of dried food products

The performance and financial evaluations of a solar-assisted heat pump fluidised bed dryer combined with a biomass furnace for rice drying were examined by Yahya *et al.* (2018). The rice's moisture content dropped from 32.85% (dry basis) to 16.29% (dry basis) in 22.95 minutes while maintaining an average temperature of

80.9°C and relative humidity of 8.14%. The drier operated at a mass flow rate of 0.1037 kg/s. With an average of 0.24 kg/kWh, the specific moisture extraction rate ranged from 0.13 kg/kWh to 0.40 kg/kWh.

Functional and economic research on grape drying under solar drying conditions were conducted by Srivasthava *et al.* 2021. Because direct sunlight damages the texture and colour of raisins, the indirect solar dryer produces higher-quality raisins than the direct kind. Although the initial expenditure for mixed-mode and hybrid dryers was 15–25% higher than that of an indirect solar dryer, the drying time was reduced by 30–40%. The Two-term & Midilli model was proven to be the most effective mathematical model for predicting the drying behaviour of grapes.

According to Qu *et al.* (2022), traditional open sun drying is the most widely used food preservation method among local farmers because it requires less cash and little labour. This approach is time-consuming, unsanitary, and extremely energy-intensive.

Using microwave-assisted drying (MAD), Kusuma *et al.* (2023) assessed the drying kinetics of basil leaves in order to calculate the drying rate, moisture content, moisture ratio, and economic analysis at different microwave power levels (136, 264, 440, and 616 W). The economic analysis of microwave versus oven drying is covered in this paper, which hasn't been covered in any other research. Five thin layer models were used by the authors to assess each condition: Henderson and Pabis, Midilli *et al.,* Hii *et al.*, Verma *et al.*, and Diffusion Approximation. The optimal drying kinetics model was identified using the following statistical parameters: Mean Square Error (MSE), Chi-square (X^2), Sum of Square Error (SSE), Root Mean Square Error (RMSE), and Coefficient of Correlation (R^2).