



P-ISSN: 2349-8528

E-ISSN: 2321-4902

[www.chemijournal.com](http://www.chemijournal.com)

IJCS 2020; 8(3): 327-336

© 2020 IJCS

Received: 11-03-2020

Accepted: 13-04-2020

**Leena Tyagi**

PhD research scholar,  
Department of Processing &  
Food engineering, CTAE,  
MPUAT, Udaipur, Rajasthan,  
India

**GP Sharma**

Professor, Department of  
Processing & Food engineering,  
CTAE, MPUAT, Udaipur,  
Rajasthan, India

**RC Verma**

Professor, Department of  
Processing & Food engineering,  
CTAE, MPUAT, Udaipur,  
Rajasthan, India

**SK Jain**

Professor, Department of  
Processing & Food engineering,  
CTAE, MPUAT, Udaipur,  
Rajasthan, India

**LK Murdia**

Professor, Department of Dairy  
& food Engineering, CDFST,  
MPUAT, Udaipur, Rajasthan,  
India

**SM Mathur**

Professor, Department of Farm  
Machinery, CTAE, MPUAT,  
Udaipur, Rajasthan, India

**Corresponding Author:****Leena Tyagi**

PhD research scholar,  
Department of Processing &  
Food engineering, CTAE,  
MPUAT, Udaipur, Rajasthan,  
India

## Infrared heating in food processing: An overview

**Leena Tyagi, GP Sharma, RC Verma, SK Jain, LK Murdia and SM Mathur**

DOI: <https://doi.org/10.22271/chemi.2020.v8.i3e.9248>

**Abstract**

One of the best methods for the preservation of agricultural product is drying, which consists in removing water from the manufactured goods. One of the best ways to decrease drying time is to provide heat by infrared (IR) radiation. Infrared (IR) heating provides significant advantages over conventional heating, including reduced heating time, uniform heating, reduced quality losses, absence of solute migration in food material, versatile, simple, and compact equipment, and significant energy saving. Infrared heating can be applied to various food processing operations, namely, drying, baking, roasting, blanching, pasteurization, and sterilization. Combinations of IR heating with microwave heating and other common conductive and convective modes of heating have been gaining momentum because of increased energy throughput. This article reviews aspects of IR heating and presents a theoretical basis for IR heat processing of food materials and the interaction of IR radiation with food components. The effect of IR on food quality attributes is discussed in the context of samples and process parameters. Infrared heating for food drying purposes has become more popular in the last decade and its application in the industrial drying of different foodstuffs has been employed widely.

**Keywords:** Infrared heating, mode of heating, effect on food quality

**Introduction**

Food processing such as thermal and non-thermal processes could affect changes in structure and composition of the food (Mercier *et al.*, 2011) [43]. The process of food processing with a thermal method could cause a chemical and organoleptic properties damage and reduce nutrition or nutritional bioavailability. An example of food processing technology with thermal is drying. Drying is one of the food processing methods to prolong shelf life or preserve grains, fruits, vegetables and food in all varieties. The quality of dried fruits depends on the conditions of drying process. One type of drying processes is by using infrared radiation. Infrared drying has been widely implemented in the food process because of its several advantages including to reduce water content in food, low energy consumption short time in processing and also maintain and ensure product quality conditions (Rahmawati *et al.*, 2019) [53]. The advantages of infrared radiation could inhibit the pathogens in products which include mold, yeast, bacteria and spore by controlling some parameters such as power on the heater (Hamanaka *et al.*, 2000) [16], temperature of sample (Sawai *et al.*, 2003) [58], wavelength and the target wave in a wide range (Krishnamurthy *et al.*, 2008) [30], sample thickness (Sawai *et al.*, 2000) [57] and sample water content (Hamanaka *et al.*, 2006) [17]. As with other electromagnetic wavelengths such as microwaves and radio frequencies, infrared radiation has a unique characteristic in the design of its spectral distribution and energy intensity which could be controlled by using optical filters. Furthermore, the unique characteristic of infrared radiation to the product is the heat energy from the emitter only affected the surface of food in a short time without raising the inside temperature of material (Li and Pan, 2014a) [34]. Infrared radiation is divided into three different categories, namely near-IR (NIR) with a spectrum scale in the range of 0.75 – 1.4  $\mu\text{m}$ , mid-IR (MIR) with a spectrum scale in the range of 1.4 – 3  $\mu\text{m}$ , and far-IR with a spectrum scale in the range of 3 – 1000  $\mu\text{m}$  (FIR) (Sakai and Hanzawa, 1994) [55]. The drying of thicker bodies seems to be more efficient using the NIR region, while the drying of thin layers yields better results at the FIR region. In general, FIR radiation is advantageous for food processing because most food components absorb radiative energy in the FIR region (Sandu 1986) [56]. Sheridan and Shilton (2002) [62] evaluated the efficiency of cooking hamburger patties using the MIR and FIR.

They observed a change in the core temperature and a change in the surface temperature with the decrease of the drying time using the MIR; however with FIR the rate of increase of the core temperature was influenced by fat content.

Infrared radiation has a longer wavelength than visible light, but is shorter than terahertz radiation and a microwave. The infrared radiation spectrum has a range of 750 nm up to 100  $\mu\text{m}$  and widely used in food processing in several ways including food processes involving heating processes, spectroscopic measurements of chemical composition (food analytical applications), and measurement of non-contact food temperature.

By exposing an object to infrared (IR) radiation (wavelength of 0.78 to 1000  $\mu\text{m}$ ), the heat energy generated can be absorbed by food materials. Along with microwave, radiofrequency (RF), and induction, IR radiation transfers thermal energy in the form of electromagnetic (EM) waves and encompasses that portion of the EM spectrum that borders on visible light and microwaves (Fig-1). Certain characteristics of IR heating such as efficiency, wavelength, and reflectivity set it apart from and make it more effective for some applications than others. IR heating is also gaining popularity because of its higher thermal efficiency and fast heating rate/response time in comparison to conventional heating. Recently, IR radiation has been widely applied to various thermal processing operations in the food industry such as dehydration, frying, and pasteurization (Sakai and Hanzawa 1994)<sup>[55]</sup>.

Deterioration is the main problem that limits the extension of shelf life for post-harvested food materials. Other post-harvest challenges, in addition to the shelf life, include the packing cost, shipping weights, the nutritional value and the appearance of the products. The drying of foodstuff is an appropriate solution for some of these post-harvest challenges. In the drying process, heat is transferred from the heat source to the material which causes the evaporation of the moisture content. The elimination of the moisture content prevents the growth of microorganisms, which causes a reduction in the moisture-mediated deterioration reaction.

Over the past several years, IR heating has been predominantly applied in the electronics and allied fields with

little practical application in the food processing industry. However, in the last few years significant research efforts have been made in the area of IR heating of foods. The present review is in line with the current developments in the area of IR heating and a base for its widespread upcoming practical applications in food processing. Therefore, the aim of this review is to evaluate existing knowledge in the area of IR heating, provide insight for the relation between product properties and engineering processes, and present an up-to-date view on further research. Along with the sound theoretical background on IR heating, the review also encompasses application of IR heating in food processing operations such as drying, dehydration, blanching, thawing, pasteurization, sterilization, and other miscellaneous food applications such as roasting, frying, broiling, and cooking, as well as in-depth assessment of pathogen inactivation. The effect of IR heating on sensory, physicochemical, nutritional, and micro structural quality of foods and its comparison with other existing common methods of heating such as convection and microwave heating are discussed as well.

### Basic laws of infrared radiation

IR radiation is the part of the electromagnetic spectrum that is predominantly responsible for the heating effect of the sun. Since IR radiation is an electromagnetic wave, it has both a spectral and directional dependence. Spectral dependence of IR heating needs to be considered because energy coming out of an emitter is composed of different wavelengths and the fraction of the radiation in each band is dependent on a number of factors such as the temperature of the emitter, emissivity of the lamp, etc. Radiation phenomena become more complicated because the amount of radiation that is incident on any surface does not have only a spectral dependence but also a directional dependence. The wavelength at which the maximum radiation occurs is determined by the temperature of the heater. This relationship is described by the basic laws for blackbody radiation, such as Planck's law, Wien's displacement law, and Stefan–Boltzmann's law (Sakai and Hanzawa, 1994; Dangerskog and Österström, 1979)<sup>[55]</sup>.

**Table 1:** Basic laws pertain to infrared radiation.

Basic laws	Aspects addressed/explanation
<b>Planck's law</b> $E_{b\lambda}(T, \lambda) = \frac{2\pi hc^2}{\lambda^5 [e^{hc_0/\lambda kT} - 1]}$	Gives spectral blackbody emissive power distribution $E_{b\lambda}(T, \lambda)$
<b>Wien's displacement law</b> $\lambda = \frac{2898}{T}$	Gives the total power radiated ( $E_b(T)$ ) at a specific temperature from an infrared source
<b>Stefan– Boltzmann's law</b> $E_b(T) = n^2 \sigma T^4$	Gives the peak wavelength ( $\lambda_{\text{max}}$ ), where spectral distribution of radiation emitted by a blackbody reaches maximum emissive power
<b>Modified Beer's law</b> $H_{\lambda} = H_{\lambda 0} \exp(-\sigma^* \lambda u)$	Gives the transmitted spectral irradiance ( $H_{\lambda}$ W/m <sup>2</sup> · $\mu\text{m}$ ) in non homogeneous systems
$\rho + \alpha + \tau = 1$	<b>Reflectivity (<math>\rho</math>):</b> ratio of reflected part of incoming radiation to the total incoming radiation. <b>Absorptivity (<math>\alpha</math>):</b> ratio of absorbed part of incoming radiation to the total incoming radiation <b>Transmissivity (<math>\tau</math>):</b> ratio of transmitted part of incoming radiation to the total incoming radiation (Fig 2).

k: Boltzmann's constant ( $1.3806 \times 10^{-23}$  J/K),  $n$ : refractive index of the medium ( $n$  for vacuum is 1 and, for most gases,  $n$  is very close to unity),  $\lambda$ : the wavelength ( $\mu\text{m}$ ),  $T$ : source temperature (K),  $c_0$ : speed of light (km/s),  $h$ : Planck's constant ( $6.626 \times 10^{-34}$  J-s),  $\sigma$ : Stefan–Boltzmann constant ( $5.670 \times 10^{-8}$  W m<sup>2</sup>K<sup>4</sup>),  $\lambda_{\text{max}}$ : peak wavelength,  $H_{\lambda 0}$ : incident spectral irradiance (W/m<sup>2</sup> ·  $\mu\text{m}$ ),  $u$ : mass of absorbing medium per unit area (kg/m<sup>2</sup>) and  $\sigma^*_{\lambda}$ : spectral extinction coefficient (m<sup>2</sup>/kg).

(Source: Krishnamurthy K. & Others, 2008)<sup>[30]</sup>

### Irradiation & its propagation during Drying

The IR radiation band of the electromagnetic spectrum encompasses wavelengths from 0.75 to 1000  $\mu\text{m}$  and is

usually subdivided into sections, namely, near-IR (0.75–3  $\mu\text{m}$ ), mid-IR (3.0–25  $\mu\text{m}$ ), and far-IR (25–1000  $\mu\text{m}$ ; Fig-1). This classification is based on vibrational fundamentals and

the interest of physicists (Chantry, 1984) [7]. In general, the food substances absorb FIR energy most efficiently through the mechanism of changes in the molecular vibrational state, which can lead to radiative heating. Water and organic compounds such as proteins and starches, which are the main components of food, absorb FIR energy at wavelengths greater than 2.5  $\mu\text{m}$  (Sakai and Hanzawa 1994) [55]. Sandu (1986) [56] reported that most foods have high transmissivities (low absorptivities) smaller than 2.5  $\mu\text{m}$ .

Chemists tend to define mid-IR from 3.0 to 40  $\mu\text{m}$  because it is where characteristic absorption bands of organic molecules occur. In the electromagnetic spectrum, thermal radiation is mainly considered to be from 0.1 to 100  $\mu\text{m}$  (Incropera and DeWitt, 2002) [23]. IR radiation is propagated essentially like visible light. In food materials, near- and mid-IR radiation is transferred to the molecules by vibration, while the interaction is principally rotational in the far-IR range.

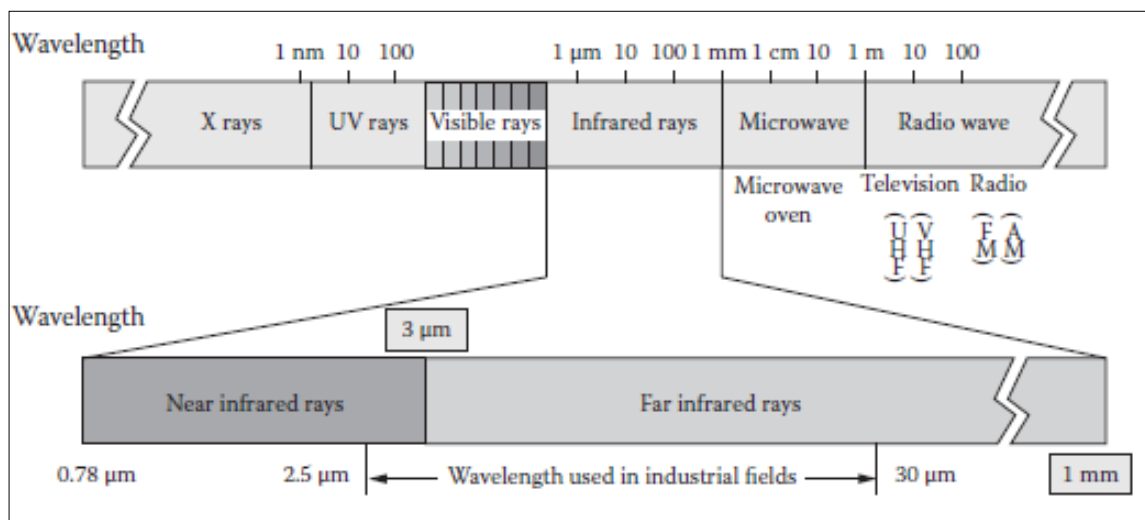


Fig: 1-Electromagnetic wave spectrum.

Although there is no complete agreement on where each of the subsets end or start, IR wavelengths from 2.5 to 200  $\mu\text{m}$  are the most commonly used for drying purposes. Water has strong absorption of IR energy around 3, 6, and 12, and 15  $\mu\text{m}$  (Il'asov and Krasnikov, 1991; Datta and Almeida, 2005) [24, 12]. Most ceramic heaters have peak spectral emissivity around 3.0  $\mu\text{m}$ , and this explains why they are commonly used in many situations for drying.

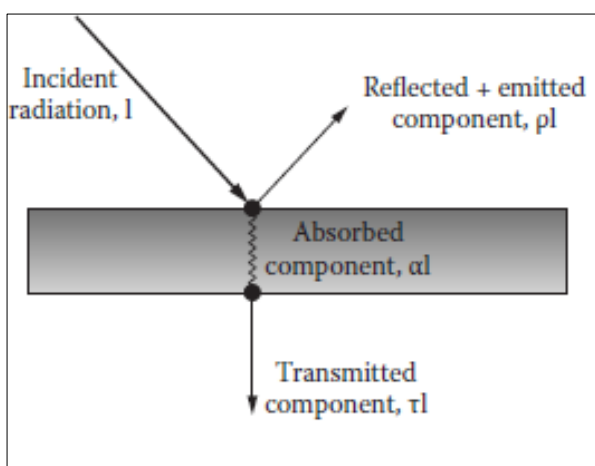


Fig 2: Propagation of IR radiation through absorbing and transmitting medium.

The IR radiation band relevant to heating of foods, and especially drying, was given by Sandu (1986) [56]. Water has very strong absorption of IR radiation at around 2.7–3.3, 6.0, and greater than 12.5  $\mu\text{m}$ . The O-H bonds in water absorb IR energy and start to rotate with the same frequency as the incident radiation. This transformation of IR radiation to rotational energy causes the evaporation of water. When IR radiation strikes a surface, part of it may be reflected ( $\rho$ ),

absorbed ( $\alpha$ ), or transmitted ( $\tau$ ). If the transmissivity is infinitesimal, then the material will reflect or absorb IR depending on the nature of the radiation and the surface characteristics of the material. This is termed *emissivity* ( $\epsilon$ ) and usually ranges from 0 to 1. Blackbody materials absorb all the radiation falling on them and therefore have an emissivity of 1.0 as opposed to completely reflective surfaces ( $\epsilon = 0$ ). Figure 2 illustrates how IR waves are propagated from source to and through a material that is semi transparent.

### Mechanism of Drying

In IR radiation drying, also called thermal radiation drying, heat is transferred to materials to be dried in the form of radiant energy. Artificial radiation drying involves the use of IR radiation generators such as special electric lamps and ceramic or metallic panels heated by electricity or gas. In natural radiation drying (solar drying), radiation from the sun is tapped either directly or indirectly for drying purposes. The major distinguishing feature of IR drying is that it does not require a medium for transmission of energy from source to the target. The materials being dried can themselves be regarded as absorbers of IR radiation. Therefore, to enhance the efficiency of drying, high absorption (and less scattering) of incident IR and coupling of absorbed energy with water in food are important considerations. The scattering of radiation may become significant when particulate materials (~0.1 mm and larger) are being dried. It is also important that the incident energy be uniformly applied on the receiving surface, a situation that requires that the configuration and characteristics of the IR emitter and any reflectors be optimized. These considerations have been applied in the drying of paint and paper for many years because coatings and paper webs are suited to IR drying. An IR source may be enclosed in a chamber with a highly reflective surface to take advantage of the multiple reflections within the enclosure and hence improve energy efficiency.

### Interaction of IR radiation with food components

The effect of IR radiation on optical and physical properties of food materials is crucial for the design of an infrared heating system and optimization of a thermal process of food components. The infrared spectra of such mixtures originate with the mechanical vibrations of molecules or particular molecular aggregates within a very complex phenomenon in overlapping (Halford, 1957) [15].

Due to a lack of information, data on absorption of infrared radiation by the principal food constituents can be regarded as approximate values. Water effect on absorption of incident radiation is predominant over all the wavelengths, suggesting that selective heating based on distinct absorptivities for a target food material can be more effective when predominant energy absorption of water is eliminated. The infrared absorption bands for chemical groups and relevant food components are summarized in Table 2.

**Table 2:** The infrared absorption bands for chemical groups and relevant food components

Chemical group	Absorption wavelength ( $\mu\text{m}$ )	Relevant food component
Hydroxyl group (O-H)	2.7 to 3.3	Water, sugars
Aliphatic carbon-hydrogen bond	3.25 to 3.7	Lipids, sugars, proteins
Carbonyl group (C=O) (ester)	5.71 to 5.76	Lipids
Carbonyl group (C=O) (amide)	5.92	Proteins
Nitrogen-hydrogen group (-NH-)	2.83 to 3.33	Proteins
Carbon-carbon double bond (C=C)	4.44 to 4.76	Unsaturated lipids

(Source: Rosenthal, 1992)

Interactions of light with food material and the crucial optical principles such as regular reflection, body reflection, and light scattering were discussed by Birth (1978) [5]. Regular reflection takes place at the surface of a material. For body reflection, the light enters the material, becomes diffuse due to light scattering, and undergoes some absorption; and the remaining light leaves the material close to where it enters. Regular reflection produces only the gloss or shine of polished surfaces, whereas body reflection produces the colors and patterns that constitute most of the information obtained visually. For materials with a rough surface, both regular and body reflection can be observed. For instance, at NIR wavelength region ( $\lambda < 1.25 \mu\text{m}$ ), approximately 50% of the radiation is reflected back, while less than 10% radiation is reflected back at the FIR wavelength region (Skjoldebrand, 2001) [63]. Most organic materials reflect 4% of the total reflection producing a shine of polished surfaces. The rest of the reflection occurs where radiation enters the food material and scatters, producing different color and patterns (Dagerskog, 1979) [9].

The infrared optical characteristics of different media are also theoretically discussed demonstrating the necessity of the scattered radiation during measurements (Krust and others, 1969). It was experimentally observed that as the thickness of the layer increases, a simultaneous decrease in transmittance and increase in reflection occurs. However, no theoretical explanation of this phenomenon was presented.

### Sources of IR Heating

The main component of IR equipment for heating is the radiator, of which there are various types and shapes. They may be divided into the following main groups

- Gas heated radiators (long waves)
- Electrically heated radiators
  - Tubular/flat metallic heaters (long waves)
  - Ceramic heaters (long waves)
  - Quartz tube heaters (medium, short waves)
  - Halogen tube heaters (ultra short waves).

These 2 types of IR heaters (Gas heated & Electrically heated) generally fit into 3 temperature ranges (Hung and others, 1995) [22]: 343 to 1100 °C for gas and electric IR, and 1100 to 2200 °C for electric IR only. IR temperatures are typically used in the range of 650 to 1200 °C to prevent charring of products. The capital cost of gas heaters is higher, while the operating cost is cheaper than that of electric infrared systems. Electrical infrared heaters are popular because of installation controllability, ability to produce prompt heating rate, and cleaner form of heat. Electric infrared emitters also provide flexibility in producing the desired wavelength for a particular application. In general, the operating efficiency of an electric IR heater ranges from 40% to 70%, while that of gas-fired IR heaters ranges from 30% to 50% (Hung and others, 1995) [22]. The spectral region suitable for industrial process heating ranges from 1.17 to 5.4  $\mu\text{m}$ , which corresponds to 260 to 2200 °C (Sheridan and Shilton, 1999) [60].

Comparison of different forms of Infrared wave emitter			
Emitter Type with Spectrum Category			
	Short Wave	Medium Wave	Long Wave
Infrared parameters	Halogen and incandescent lamp	Quartz emitter	Resistance material
Material	Quartz tube with tungsten coil inside sealed	Quartz tube with Fe-Cr-Al alloy as heating element	Steel tube with Fe-Cr-Al alloy as heating element enclosed
Radiation efficiency	High: ~92%	Medium: ~60%	Low: ~40%
Peak wave length	1.2 $\mu\text{m}$	2.2 $\mu\text{m}$	4.0 $\mu\text{m}$
Corresponding radiation temperature	2500 K	1300 K	800 K
Major heating mode	Radiation	Combined radiation and convection	Convection
Response time to 90% output	1 s	30 s	300s
Convergence of Radiation	Possible with good focusing	Fairly possible	Fairly possible

Source: Data adapted from Anonymous, 2009 [3]. <http://www.ercis.lu/default.asp?contentID=680>.



IR rays of wavelength ranging from 0.7 to 1.4  $\mu\text{m}$ , which is closest to the visible spectrum, giving a bright white appearance with the corresponding radiator temperature being around 1300–2600 K. This type of emitter is often considered the most powerful because it can achieve the highest power densities, up to or more than 300  $\text{kWm}^{-2}$ , and are very responsive as they can attain the maximum temperature within a few seconds. They are used extensively for industrial processes such as preheating, metal castings, powder coating, and adhesive bonding. Medium-wave IR emitters emit a radiation spectrum of wavelength ranging from 1.4 to 3.0  $\mu\text{m}$  at radiator temperatures of 850–1200 K and power densities of up to 90  $\text{kWm}^{-2}$ ; they appear as a bright orange glow with a response time of about a minute. Medium wave emitters are extensively used for drying and curing of food product. Long wave IR emitters have a radiation temperature of 500–800 K,

which corresponds to a spectrum of wavelength more than 3.0  $\mu\text{m}$ . It attains a power density up to 40  $\text{kWm}^{-2}$ . The emitter appears dull orange and in many cases is not even perceivable to the human eye. This type of emitter takes more than 5 min to reach its peak emissive power. 4 Long wave IR emitters create a stream of hot air that is useful for processes requiring a combination of convection and IR heating.

Sakai and Hanzawa (1994) [55] reported the penetration depth of the FIR energy did not affect the temperature distribution inside the food. Further, they indicated that FIR energy penetrates very little, almost all the energy being converted to heat at the surface of the food, which was consistent with the study of Hashimoto and others (1993) [18] evaluating FIR heating technique as a surface heating method. Table 4 shows the penetration depth of NIR energy into food products.

**Table 3:** Penetration depth of NIR (0.75 to 1.4  $\mu\text{m}$ ) into food products.

Product	Spectral peak ( $\mu\text{m}$ )	Depth of penetration (mm)
Dough, wheat	1.0	4 to 6
Bread, wheat	1.0	11 to 12
Bread, biscuit, dried	1.0	4
	0.88	12
Grain, wheat	1.0	2
Carrots	1.0	1.5
Tomato paste, 70% to 85% water	1.0	1
Raw potatoes	1.0	6
Dry potatoes	0.88	15 to 18
Raw apples	1.16	4.1
	1.65	5.9
	2.36	7.4

Source: Ginzburg 1969 [14]

### Quality and sensory changes by IR heating

It is crucial and beneficial to investigate the quality and sensory changes occurring during IR heat treatment for commercial success. Several researchers have studied the quality and sensory changes of food materials during IR heating.

Application of infrared radiation in a stepwise manner by slowly increasing the power, with short cooling between power levels, resulted in less color degradation than with intermittent infrared heating (Chua and Chou, 2005) [8]. Reductions in overall color change of 37.6 and 18.1% were obtained for potato and carrot, respectively. The quality of beef produced by infrared dehydration was similar to that of conventional heating as indicated by surface appearance and taste tests (Burgheimer and others, 1971) [6]. Longer infrared heat treatments may darken the color of onion due to browning (Gabel and others, 2006) [13].

Hebbbar and others (2003) [19] suggested that 3 to 4 min infrared heat treatment was adequate for commercially acceptable products, with reduction in yeast cells and acceptable changes in hydroxymethylfurfural and diastase activity. Infrared heating raised the internal temperature of the strawberries not above 50 °C, while the surface temperature was high enough to effectively inactivate microorganisms. Therefore, infrared heating can be used for surface pasteurization of pathogens without deteriorating the food quality (Tanaka and others, 2007) [67].

The evaluation of full-fat flour made from IR-heat treated soybeans maintained freshness similar to fresh flour for 1 y. However, untreated samples resulted in rancidity development (Kouzeh and others, 1982) [27]. Compared to regular freeze-drying, IR-assisted freeze-drying of yam

brought about lower color differences as well as faster dehydration. Furthermore, infrared heating leading to a higher dehydration ratio implies that infrared heating reduces serious product shrinkage (Lin and others, 2007) [36].

IR heat-treated lentils were found to be darker than raw lentils, though there was no visible indication (Arntfield and others, 2001) [4]. Cell walls of lentils were less susceptible to fracture after infrared heat treatment, in addition to having a more open microstructure, thus enhancing the rehydration characteristics (Arntfield and others, 2001) [4].

Although infrared heat-treated turkey samples were slightly darker than the controls after treatments, refrigerated storage for an hour resulted in no significant difference in color values as measured by  $L^*$ ,  $a^*$ , and  $b^*$  values (Huang, 2004) [21]. When menu servings of peas were held at 50 to 60 °C for 2 h by IR lamps, the quality of peas deteriorated and resulted in unacceptable products (Maxcy, 1976) [39]. Bitterness and protein solubility of peas were reduced after IR heat treatment (McCurdy, 1992) [40]. Furthermore, canola seeds had higher dehulling capacity after infrared heating (McCurdy, 1992) [40]. Head rice yield was improved by infrared heating and the whiteness of the rice was maintained (Meeso and others, 2004) [42].

Chlorophyll content of dehydrated onions treated by infrared increased with an increase in irradiation power (Mongpreneet and others, 2002) [45]. Infrared heating provided a more appealing brown color and roasted appearance to deli turkey, in addition to effectively pasteurizing the surface (Muriana and others, 2004) [46]. Infrared heating and jet impingement of bread resulted in rapid drying and enhanced color development, compared to conventional heat treatment (Olsson and others, 2005) [50]. Though the thickness of bread

crust increased faster, a short IR treatment time enabled the formation of thinner crust.

Table 4 briefly summarizes the effect of IR treatment on nutritional quality of various food products. As the literature

review substantiates, IR heating does not change the quality attributes of foods significantly, such as vitamins, protein, and antioxidant activities.

**Table 4:** Effect of infrared treatment on nutritional quality of food products.

Food product	Parameters effecting nutritional quality	Effect of treatment	Reference
Barley	Germination rate at 55 °C	25% increase by combination of IR heating and convectional heating	Afzal and others (1999) [12]
Wheat	Germination rates (heat treatment for 63 s each)	Convectional heating: 90% to 97% Intermittent IR heating: 80% to 86% Continuous IR heating: 78% to 85%	Uchino and others (2000) [68]
Lentils	Phytic acid content	Untreated: 2.34% High density IR heating (170 °C): 1.06%	Arntfield and others (2001) [4]
Full fat soybeans	Protein solubility	Infrared heating: 84% Spouted bed drying: 82% Extrusion: 73%	Wiriyumpaiwong and others (2004) [70]
Soymilk	Protein digestibility	Untreated: 83.2% IR heat treated (110 to 115 °C): 86.5%	Metussin and others (1992) [44]
Crude canola oil	Phosphorus content	Untreated canola seeds: 46 ppm IR heat treated (123 °C): 273 ppm	McCurdy (1992) [40]
Orange juice	<i>D</i> values for vitamin C degradation at 75 °C	Convectional heating: 27.02 min Ohmic heating: 23.72 min Infrared heating: 23.76 min	Vikram and other (2005) [69]
Peanut hulls	Antioxidant activities (total phenolic compounds in water extract, after 60 min) Radical scavenging activities	FIR irradiation: 141.6 μM FIR heating: 90.3 μM FIR irradiation: 48.83% FIR heating: 23.69%	Lee and others (2006) [32]

#### Applications of IR heating in food processing operations

The application of infrared radiation to food processing has gained momentum due to its inherent advantages over the conventional heating systems. Infrared heating has been applied in drying, baking, roasting, blanching, pasteurization, and sterilization of food products.

**Drying and dehydration:** Infrared heating provides an imperative place in drying technology and extensive research work has been conducted in this area. Application of FIR drying in the food industry is expected to represent a new process for the production of high-quality dried foods at low cost (Sakai and Hanzawa 1994) [55]. The use of IR radiation technology for dehydrating foods has numerous advantages including reduction in drying time, alternate energy source, increased energy efficiency, uniform temperature in the product while drying, better-quality finished products, a reduced necessity for air flow across the product, high degree of process control parameters, and space saving along with clean working environment (Dostie and others 1989; Navari and others 1992; Sakai and Hanzawa 1994; Mongpreneet and others 2002) [47, 55, 45].

Generally, solid materials absorb infrared radiation in a thin surface layer. However, moist porous materials are penetrated by radiation to some depth and their transmissivity depends on the moisture content (Lampinen and others 1991) [31]. Energy and mass balance developed by Ratti and Mujumdar (1995) [52] accounts for the shrinkage of the heated particle and absorption of infrared energy. Theoretical calculations showed that intermittent infrared drying with energy input of 10 W/m<sup>2</sup> becomes equivalent to convective drying in which the heat transfer coefficient would be as high as 200 W/m<sup>2</sup> K.

**Enzyme inactivation:** Infrared heating can be effectively used for enzyme inactivation. Lipooxygenase, an enzyme responsible for deterioration in soybeans, was inactivated 95.5% within 60 s of IR treatment (Kouzeh and others 1982)

[28]. Certain enzyme reactions (involving action of lipases and  $\alpha$  amylases) were affected by infrared radiation at a bulk temperature of 30 to 40 °C (Kohashi and others 1993; Rosenthal and others 1996; Sawai and others 2003) [54, 58]. FIR radiation for 6 min resulted in a 60% reduction in lipase activity, while thermal conduction resulted in 70% reduction.

**Pathogen inactivation:** IR heating can be used to inactivate bacteria, spores, yeast, and mold in both liquid and solid foods. Efficacy of microbial inactivation by infrared heating depends on the following parameters: infrared power level, temperature of food sample, peak wavelength, and bandwidth of infrared heating source, sample depth, types of microorganisms, moisture content, physiological phase of M/Os (exponential or stationary phase), and types of food materials.

**IR heating in other miscellaneous food processing operations:** The usefulness of IR heating has also been demonstrated in various other food processing applications such as roasting, frying, broiling, heating, and cooking meat and meat products, soy beans, cereal grains, cocoa beans, and nuts.

With the growing interest in flame-broiling and rapid cooking methods, conveyerized IR broiling is a unique and innovative method. Khan and Vandermeij (1985) [26] prepared ground beef patties by IR broiling in a conveyerized broiler. The results showed that due to high temperatures and short cooking times, the infrared broiler could produce more servings per hour compared to conventional gas heating. Sakai and Hanzawa (1994) [55] reported on the performance of infrared-based systems with conventional ovens for baking rice crackers and for roasting fish pastes. The comparative study indicated energy savings of 45% to 70% with infrared heating. Abdul-Kadir and others (1990) [1] conducted imbibition studies and cooking tests to evaluate the effect of

IR heating on pinto beans (*Phaseolus vulgaris*) heated to 99 and 107 °C.

Studies on color development during IR roasting of hazelnuts were reported by Ozdemir and Devres (2000)<sup>[51]</sup>. Olsson and others (2005)<sup>[50]</sup> found that infrared radiation and jet impingement, as compared with heating in a conventional household oven, increased the rate of color development of the crust and shortened the heating time of parbaked baguettes during postbaking. Furthermore, the fastest color development was obtained by combining infrared and impingement heating. The rate of water loss increased due to a higher heat transfer rate, but the total water loss was reduced because of a shorter heating time. In general, the formed crust was thinner for IR-treated baguettes.

### IR radiation heating with different dryers

Although IR heating has the advantage of lowering drying time, it is not applicable and suitable for all drying systems because of the limitation in its penetrating power especially in falling rate period. As a result, the combination of IR radiation and other drying methods can be found more efficient and useful to get improved results. Various researchers have carried out IR drying and combined IR-convective drying for food and agriculture products.

### Intermittent IR Drying

Several researchers have studied the intermittent approach of drying using IR heaters in convective dryers. Tan *et al.* (2001)<sup>[66]</sup> carried out the experimentation on IR drying of osmosed fruit products in a heat pump dryer. The application of intermittent IR drying was found to work well for both osmosed and non-osmosed products. Also, it has been observed that the osmotically treated samples of potato and pineapple can undergo less color change than untreated ones during convective drying with intermittent IR heating. Furthermore, the authors improved the process of intermittent IR heating by keeping control over the surface temperature of sample which enabled heater to be put-off at predetermined temperature. Moreover, Sandu (1986)<sup>[56]</sup> reported long ago that intermittent irradiation methods were primarily suited for drying of food products thicker than their depth of penetration to the IR radiation.

### IR-Assisted Hot Air Drying

The qualitative economical evaluation of IR dryer was carried out by Hebber *et al.* (2004)<sup>[20]</sup> for drying of vegetables, potato and carrot in a continuous IR-convective dryer. It has been reported that the combined mode of IR-convective dryer reduces the processing time dramatically (48%), besides consuming less energy (63%) for water evaporation compared to hot air drying. Heat utilization efficiencies were found to be 38.5 and 38.9% for potato and carrot, respectively. The heat and mass transfer phenomena in the drying process of longan fruit leather under a combination of convective and FIR drying was studied by Jaturonglumlert and Kiatsiriroat (2010)<sup>[25]</sup>. The ratio of the heat and mass transfer coefficients on two modes of drying, viz. hot air method and a combination of hot air and IR, was determined. The combined mode of operation was found to show higher heat and mass transfer rates (Nuthong *et al.* 2011)<sup>[49]</sup>. Zare *et al.* (2015)<sup>[72]</sup> studied the energy and quality attributes of combined hot air and IR drying for paddy. A combination of a low-intensity IR radiation (2000 W/m<sup>2</sup>), inlet air temperature (30°C) and moderate values of inlet air velocity (0.15 m/s) was found to effectively improve the final quality of paddy. Xu *et al.*

(2014)<sup>[71]</sup> studied drying of kelp using IR radiation. It was found that the total drying time required for IR drying products was approximately 120 min, reduced by 56% compared to air drying. Sui *et al.* (2014)<sup>[64]</sup> studied three different combinations of drying, viz. IR, convective and sequential IR-convective for wine grape pomace. IR drying was found to have the highest drying rate, which reduced the drying time by more than 47.3% compared with other methods.

### IR-Assisted Vibration Mode of Drying

Although IR drying is very attractive to food drying, its application for the grain drying is limited. The reason being an increase in the grain bed depth can cause the surface layer to be heated rapidly compared to the layers beneath. These limitations can be eliminated using vibrated mode-IR drying. Das *et al.* (2004)<sup>[10]</sup> studied the drying characteristics of high moisture paddy under different vibrating conditions for different levels of irradiation intensity and grain bed depths and proved that the IR radiation is very beneficial in this category too.

### IR-Vacuum Drying

The vaporization can be promoted even at low temperature by application of vacuum to dry the heat-sensitive food products. IR heaters can be successfully applied to accelerate the drying of foodstuff in time-consuming vacuum-drying process. Mongpraneet *et al.* (2002)<sup>[45]</sup> studied IR-vacuum drying of welsh onion using ceramic coated radiator. It has been found that IR can change the quality properties of food sample and significantly affect the chlorophyll content. Recently, Swasdisevi *et al.* (2009)<sup>[65]</sup> modeled combined FIR and vacuum drying for banana slice and validated with experimental results.

### IR-Assisted Microwave Drying

Any electromagnetic radiation can heat the material when absorbed. The microwave or IR radiation both are strongly absorbed by the moist food materials. Moisture accumulation at the food surface during microwave heating is a well-known problem which results in soggy surface instead of crispy. This phenomenon happens because of the inability of the surrounding air to remove the moisture with a rate at which it is coming from the interior to the surface. Thus, the removal of surface moisture can be enhanced by adding external IR source. Datta and Ni (2002)<sup>[11]</sup> studied IR and hot air-assisted microwave heating of foods to obtain the desired surface characteristics of dried product. In order to include the penetration of IR energy into the material resulting in significant internal heating, a multiphase porous model was used to obtain the temperature and moisture profiles in the product.

### IR-Assisted Freeze Drying

Freeze drying is a dehydration operation in which the sublimation of ice is carried out from a frozen product by applying vacuum. Because of the absence of liquid water and low temperature used in the operation, most of the deterioration and microbiological reactions are inhibited. Freeze drying is an expensive process and the cost may be reduced if processing time is effectively shortened. Freeze drying with FIR heating is a novel technique that can reduce the risk of melting of ice because of the heating plate which is in direct contact with the sample tray (Lin *et al.* 2005, 2007)<sup>[35, 36]</sup>. Lin *et al.* (2005)<sup>[35]</sup> studied IR-assisted freeze drying

for sweet potato and an empirical model was developed. IR-assisted freeze drying was found to reduce the drying time when compared to conventional freeze drying. Furthermore, the authors studied the drying of yam slices (a functional food and herbal medicinal ingredients) in freeze dryer assisted with FIR heaters using surface response methodology (Lin *et al.* 2007) [36]. The application of FIR radiation in freeze drying of yam slices was found to reduce the drying time and total color difference. Recently, Senevirathne *et al.* (2010) [59] studied IR drying of citrus press cakes (CPC) and dried samples were evaluated for flavonoid composition and antioxidant activities. When compared with freeze-dried CPC sample, the FIR-dried sample showed almost equal total flavonoid content and antioxidant activities with slightly lower extraction yield. Thus, FIR drying can be a replacement for freeze drying of CPC sample and come forth as an economically beneficent technology.

### IR-Assisted Low-Pressure Superheated Steam Drying

A novel technology combining low-pressure superheated steam with FIR radiation was proposed and studied recently for heat-sensitive products. The effect of various operating parameters on drying kinetics and quality of dried products (in terms of color, shrinkage, rehydration behavior, microstructure and texture) of banana were investigated (Nimmol *et al.* 2007) [48]. The previous studies on IR drying were limited only to finding the drying kinetics and modeling of the process. Furthermore, the effect of IR radiation on the structure of the dried food product has also been investigated. Leonard *et al.* (2008) [33] applied the X-ray microtomography successfully to investigate the affect of FIR radiation on the microstructure of food material. Banana slices were dried in low-pressure superheated steam drying (LPSSD) assisted with FIR, and the total pore volume and pore size distribution of dried banana were determined using X-ray microtomography. FIR radiation was found to modify the structure of dried bananas by increasing their final porosity in both LPSSD-FIR and vacuum-FIR drying. Furthermore, the application of IR radiation can be found for simultaneous blanching and dehydration of food material. Lin *et al.* (2009) [37] presented a novel approach for simultaneous blanching and partial dehydration of apple slices using FIR radiation. In order to predict the temperature and moisture profiles and enzyme inactivation rate, the heat and mass transfer models as well as enzymatic inactivation models were proposed. The model results were found to fit well for thin layer apple slice than the thick ones.

### Advantages of IR heating as compared to conventional heating methods

- High thermal efficiency
- Alternate source of energy
- Fast heating rate
- Shorter response time
- Uniform drying temperature
- High degree of process control
- Cleaner working environment
- Possibility of selective heating

### Disadvantages of IR heating as compared to conventional heating methods

- Low penetration power
- Prolonged exposure of biological materials may cause fracturing

- Not sensitive to reflective properties of coatings

### Conclusions and Future Research Potential

IR heating is a unique process; however, presently, the application and understanding of IR heating in food processing is still in its infancy, unlike the electronics and allied sector where IR heating is a mature industrial technology. It is further evident from this review that IR heating offers many advantages over convection heating, including greater energy efficiency, heat transfer rate, and heat flux that results in time-saving as well as increased production line speed. Table 5 lists advantages and disadvantages of IR heating compared to other thermal processing techniques.

Applications of IR energy for drying purposes have expanded from the earlier industrial applications such as drying of paints, coatings, paper, and wood; to space heating; to processing of food and fiber. Materials containing high moisture can be dried rapidly using IR radiation if they can be spread thinly on a flat surface or presented as thin layers of particles. Selecting IR generators with peak IR emission at wavelengths that match the absorption bands of water in foods is key to achieving high efficiency in IR drying. IR application for drying facilitates very easy heating control, with fast heat-up and cool-down times that are important for energy conservation process management. IR energy has the potential to be applied extensively in the food industry to process high-value and value-added food products, such as fruits, vegetables, spices, juices, and other biomaterials.

IR heating is attractive primarily for surface heating applications. In order to achieve energy optimum and efficient practical applicability of IR heating in the food processing industry, combination of IR heating with microwave and other common conductive and convective modes of heating holds great potential. It is quite likely that the utilization of IR heating in the food processing sector will augment in the near future, especially in the area of drying and minimal processing.

### References

1. Abdul-Kadir, Bargman T, Rupnow J. Effect of infrared heat processing on rehydration rate and cooking of *Phaseolus vulgaris* (var. Pinto). *J Food Sci.* 1990; 55(5):1472-3.
2. Afzal TM, Abe T, Hikida Y. Energy and quality aspects of combined FIR-convection drying of barley. *J Food Eng.* 1999; 42:177-82.
3. Anonymous. 2009. <http://www.ercis.lu/default.asp?contentID=680> (accessed August 13, 2009).
4. Arntfield SD, Scanlon MG, Malcolmson LJ, Watts BM, Cenkowski S, Ryland D *et al.* Reduction in lentil cooking time using micronization: comparison of 2 micronization temperatures. *J Food Sci.* 2001; 66(3):500-5.
5. Birth GS. The light scattering properties of foods. *J Food Sci.* 1978; 43:916-25.
6. Burgheimer F, Steinberg MP, Nelson AI. Effect of near infrared energy on rate of freeze drying of beef spectral distribution. *J Food Sci.* 1971; 36(1):273-6.
7. Chantry GW. *Long-Wave Optics: Principles.* London: Academic Press, 1984, 1.
8. Chua KJ, Chou SK. A comparative study between intermittent microwave and infrared drying of bioproducts. *Int J Food Sci Technol.* 2005; 40:23-39.



9. Dagerskog M, O' sterstro'm L. Infra-red radiation for food processing I. A study of the fundamental properties of infra-red radiation. *Lebens Wissen Technol.* 1979; 12(4):237-42.
10. Das I, Das SK, Bal S. Drying performance of a batch type vibration aided infrared dryer. *J Food Eng.* 2004; 64:129-133.
11. Datta A, Ni H. Infrared and hot air assisted microwave heating of foods for control of surface moisture. *J. Food Eng.* 2002; 51:355-364.
12. Datta AK, Almeida M. Properties relevant to infrared heating of foods. In *Engineering Properties of Foods* (3rd ed.), 2005.
13. Gabel MM, Pan Z, Amaratunga KSP, Harris LJ, Thompson JF. Catalytic infrared dehydration of onions. *J Food Sci.* 2006; 71(9):E351-7.
14. Ginzburg AS. Application of infrared radiation in food processing, chemical and process engineering series. London, U.K.: Leonard Hill, 1969.
15. Halford RS. The influence of molecular environment on infrared spectra. *Ann New York Acad Sci.* 1957; 69:63-9.
16. Hamanaka D, Uchino T, Furuse N, Han W, Tanaka S. Effect of the wavelength of infrared heaters on the inactivation of bacterial spores at various water activities. *International Journal of Food Microbiology.* 2006; 108(2):281-285.
17. Hamanaka D, Dokan S, Yasunaga E, Kuroki S, Uchino T, Akimoto K. The Sterilization Effects of Infrared Ray on The Agricultural Products Spoilage Microorganisms (part I). *ASAE Annual Meeting Presentation*, 2000, 1-9.
18. Hashimoto A, Sawai J, Igarashi H, Shimizu M. Irradiation power effect on pasteurization below lethal temperature of bacteria. *J Chem Eng Japan.* 1993; 26(3):331-3.
19. Hebbar HU, Nandini KE, Lakshmi MC, Subramanian R. Microwave and infrared heat processing of honey and its quality. *Food Sci Technol Res.* 2003; 9:49-53.
20. Hebber HU, Vishwanathan KH, Ramesh MN. Development of combined infrared and hot air dryer for vegetables. *J Food Eng.* 2004; 65:557-563.
21. Huang L. Infrared surface pasteurization of turkey frankfurters. *Innov Food Sci Emerg Technol.* 2004; 5:345-51.
22. Hung JY, Wimberger RJ, Mujumdar AS. Drying of coated webs. In: Mujumdar AS, editor. *Handbook of industrial drying*. 2<sup>nd</sup> ed. New York: Marcel Dekker Inc, 1995, 1007-38.
23. Incropera FP, DeWitt DP. *Fundamentals of Heat and Mass Transfer*. New York: John Wiley & Sons, 2002.
24. Il'yasov SG, Krasnikov VV. *Physical Principles of Infrared Radiation of Foodstuffs*. New York: Hemisphere Publishing Corp, 1991.
25. Jaturonglumlert S, Kiatsirirot T. Heat and mass transfer in combined convective and far-infrared drying of fruit leather. *J Food Eng.* 2010; 100:254-260.
26. Khan MA, Vandermeij PA. Quality assessment of ground beef patties after infrared heat processing in a conveyorized tube broiler for foodservice use. *J Food Sci.* 1985; 50:707-9.
27. Kouzeh KM, van Zuilichem DJ, Roozen JP, Pilnik W. A modified procedure for low temperature infrared radiation of soybeans.II. Inactivation of lipoxygenase and keeping quality of full fat flour. *Lebensm Wiss Technol.* 1982; 15(3):139-42.
28. Kouzeh KM, van Zuilichem DJ, Roozen JP, Pilnik W. A modified procedure for lowtemperature infrared radiation of soybeans.II. Inactivation of lipoxygenase and keeping quality of full fat flour. *Lebensm Wiss Technol.* 1982; 15(3):139-42, 567-88.
29. Krust PW, Kohashi M, Akao K, Watanabe T. Nonthermal effects of a ceramics radiation on xanthine oxidase activity. *Biosci Biotechnol Biochem.* 1993; 57:1999-2004.
30. Krishnamurthy K, khurana HK, Jun S, Irudayaraj J, Demirci A. Infrared Heating in Food Processing: An Overview. *Comprehensive reviews in food science and food safety.* 2008; 7:2008.
31. Lampinen MJ, Ojala KT, Koski E. Modeling and measurements of dryers for coated paper. *Drying Technol.* 1991; 9(4):973-1017.
32. Lee SC, Jeong SM, Kim SY, Park HR, Nam KC, Ahn DU. Effect of far-infrared radiation and heat treatment on the antioxidant activity of water extracts from peanut hulls. *Food Chemistry.* 2006; 94:489-93.
33. Leonard A, Blacher S, Nimmol C, Devahastin S. Effect of far-infrared assisted drying on microstructure of banana slices: An illustrative use of X-ray micro tomography in microstructural evaluation of a food product. *J Food Eng.* 2008; 85:154-162.
34. Li X, Pan Z. Dry-peeling of Tomato by Infrared Radiative Heating: Part I. Model Development. *Food and Bioprocess Technology.* 2014a; 7(7):1996-2004.
35. Lin YP, Tsen JH, King VA. Effects of far-infrared radiation on the freeze-drying of sweet potato. *J Food Eng.* 2005; 68:249-255.
36. Lin YP, Lee TY, Tsen JH, King An-Erl V. Dehydration of yam slices using FIR-assisted freeze-drying. *J Food Eng.* 2007; 79:1295-301.
37. Lin YL, Li SJ, Zhu Y, Bingol G, Pan Z, Mchugh TH. Heat and mass transfer modeling of apple slices under simultaneous infrared dry blanching and dehydration process. *Dry. Technol.* 2009; 27:1051-1059.
38. Rao MA, Rizvi SSH, Datta AK. (Eds.). Boca Raton, FL: CRC Press, 209-237.
39. Maxcy R. Fate of post-cooking microbial contaminants of some major menu items. *J Food Sci.* 1976; 41:375-8.
40. McCurdy SM. Infrared processing of dry peas, canola, and canola screenings. *J Food Sci.* 1992; 57(4):941-4.
41. McGlauchlin LD, Mcquistan RB. *Elements of infra-red technology*. New York: John Wiley & Sons Inc, 1962.
42. Meeso N, Nathakaranakule A7, Madhiyanon T, Soponronnarit S. Influence of FIR irradiation on paddy moisture reduction and milling quality after fluidized bed drying. *J Food Eng.* 2004; 65(2):293-301.
43. Mercier S, Villeneuve S, Mondor M, Des Marchais LP. Evolution of porosity, shrinkage and density of pasta fortified with pea protein concentrate during drying. *LWT-Food Science and Technology*, 2011; 44(4)::883-890.
44. Metussin R, Alli I, Kermasha S. Micronization effects on composition and properties of tofu. *J Food Sci.* 1992; 57(2):418-22.
45. Mongpreneet S, Abe T, Tsurusaki T. Accelerated drying of welsh onion by far infrared radiation under vacuum conditions. *J Food Eng.* 2002; 55:147-56.
46. Muriana P, Gande N, Robertson W, Jordan B, Mitra S. Effect of prepackage and postpackage pasteurization on postprocess elimination of *Listeria monocytogenes* on deli turkey products. *J Food Prot.* 2004; 67(11):2472-9.

47. Navari P, Andrieu J, Gevaudan A. Studies on infrared and convective drying of nonhygroscopic solids. In: Mujumdar AS, editor. *Drying 92*. Amsterdam: Elsevier Science, 1992, 685-94.
48. Nimmol C, Devahastin S, Swasdisevi T, Soponronnarit S. Drying of banana slices using combined low-pressure superheated steam and far-infrared radiation. *J Food Eng.* 2007; 81:624-633.
49. Nuthong P, Achariyaviriya A, Namsanguan K, Achariyaviriya S. Kinetics and modeling of whole longan with combined infrared and hot air. *J. Food Eng.* 2011; 102:233-239.
50. Olsson EEM, Trägårdh AC, Åhrné LM. Effect of near-infrared radiation and jet impingement heat transfer on crust formation of bread. *J Food Sci.* 2005; 70(8):E484-91.
51. Ozdemir M, Devres O. Analysis of color development during roasting of hazelnuts using response surface methodology. *J Food Eng.* 2000; 45:17-24.
52. Ratti C, Mujumdar AS. Infrared drying. In: Mujumdar AS, editor. *Handbook of industrial drying*. New York: Marcel Dekker, 1995, 567-88.
53. Rahmawati L, Saputra D, Sahim K, Priyanto G. Optimization of infrared drying condition for whole duku fruit using response surface methodology. *Potravinarstvo Slovak Journal of Food Sciences.* 2019; 13(1):462-469.
54. Rosenthal I, Rosen B, Berstein S. Surface pasteurization of cottage cheese. *Milchwiss.* 1996; 51(4):198-201.
55. Sakai N, Hanzawa T. Applications and advances in far-infrared heating in Japan. *Trends Food Sci Technol.* 1994; 5:357-62.
56. Sandu C. Infrared radiative drying in food engineering: a process analysis. *Biotechnol Prog.* 1986; 2(3):109-19.
57. Sawai J, Sagara K, Kasai S, Igarashi H, Hashimoto A, Kokugan T *et al.* Far-infrared irradiation-induced injuries to *Escherichia coli* at below the lethal temperature. *Journal of Industrial Microbiology and Biotechnology.* 2000; 24(1):19-24.
58. Sawai J, Sagara K, Hashimoto A, Igarashi H, Shimizu M. Inactivation characteristics shown by enzymes and bacteria treated with far-infrared radiative heating. *Int J Food Sci Technol.* 2003; 38:661-7.
59. Senevirathne M, Kim SH, Kim YD, Oh CK, Oh MC, Ahn CB *et al.* Effect of far-infrared radiation drying of citrus press-cakes on free radical scavenging and antioxidant activities. *J Food Eng.* 2010; 97:168-176.
60. Sheridan P, Shilton N. Application of far-infrared radiation to cooking of meat products. *J Food Eng.* 1999; 41:203-8.
61. Shilton N, Mallikarjunan P, Sheridan P. Modeling of heat transfer and evaporative mass losses during the cooking of beef patties using far-infrared radiation. *Journal of Food Engineering.* 2002; 55:217-222.
62. Sheridan PS, Shilton NC. Determination of the thermal diffusivity of ground beef patties under infrared radiation oven shelf cooking. *J Food Eng.* 2002a; 52:39-45.
63. Skjoldbrand C. Infrared heating. In: Richardson P, editor. *Thermal technologies in food processing*. New York: CRC Press, 2001.
64. Sui Y, Yang J, Ye Q, Li H, Wang H. Infrared, convective, and sequential infrared and convective drying of wine grape pomace. *Dry. Technol.* 2014; 32:686-694.
65. Swasdisevi T, Devahastin S, Sa-Adchom P, Soponronnarit S. Mathematical modeling of combined far-infrared and vacuum drying of banana slice. *J Food Eng.* 2009; 92:100-106.
66. Tan M, Chua KJ, Mujumdar AS, Chou SK. Effect of osmotic pre-treatment and infrared radiation on drying rate and color changes during drying of potato and pineapple. *Dry. Technol.* 2001; 19:2193-2207.
67. Tanaka F, Verboven P, Scheerlinck N, Morita K, Iwasaki K, Nicolai B. Investigation of far infrared radiation heating as an alternative technique for surface decontamination of strawberry. *J Food Eng.* 2007; 79:445-52.
68. Uchino T, Hamanaka D, Hu W. Inactivation of microorganisms on wheat grain by using infrared irradiation. *Proceedings of Intl. Workshop Agricultural Engineering and Agro- Products Processing Toward Mechanization and Modernization in Agriculture and Rural areas*, 2000.
69. Vikram VB, Ramesh MN, Prapulla SG. Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods. *J Food Eng.* 2005; 69:31-40.
70. Wiriyampaiwong S, Soponronnarit S, Prachayawarakorn S. Comparative study of heating processes for full-fat soybeans. *J Food Eng.* 2004; 65:371-82.
71. Xu BG, Zhang M, Bhandari B. Temperature and quality characteristics of infrared radiation-dried kelp at different peak wavelengths. *Dry. Technol.* 2014; 32:437-446.
72. Zare D, Naderi H, Ranjbaran M. Energy and quality attributes of combined hot-air/infrared drying of paddy. *Dry. Technol.* 2015; 33:570-582.