Infrared Heating in Food Drying: An Overview

Article *in* Drying Technology · February 2015

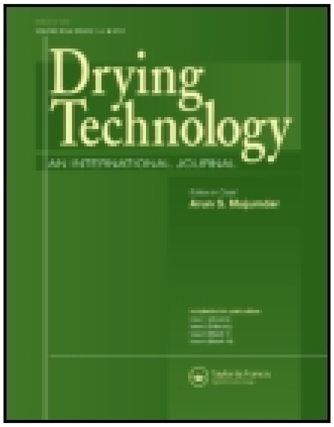
DOI: 10.1080/07373937.2014.951124

Siti Ahmad
Universiti Putra Malaysia

Mohammad Hamiruce Marhaban
Universiti Putra Malaysia

Azura che soh
Universiti Putra Malaysia

This article was downloaded by: [Siti Ahmad]
On: 12 February 2015, At: 23:08
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Click for updates

Drying Technology: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ldrt20

Infrared Heating in Food Drying: An Overview

Muhmmed Hussain Riadh[a], Siti Anom Binti Ahmad[a], Mohd Hamiruce Marhaban[a] & Azura Che Soh[a]
[a] Department of Electrical Engineering, University Putra Malaysia, Seri Kembangan, Malaysia

Accepted author version posted online: 15 Aug 2014.Published online: 20 Dec 2014.

To cite this article: Muhmmed Hussain Riadh, Siti Anom Binti Ahmad, Mohd Hamiruce Marhaban & Azura Che Soh (2015) Infrared Heating in Food Drying: An Overview, Drying Technology: An International Journal, 33:3, 322-335, DOI: 10.1080/07373937.2014.951124

To link to this article: http://dx.doi.org/10.1080/07373937.2014.951124

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Drying Technology, 33: 322–335, 2015
Copyright © 2015 Taylor & Francis Group, LLC
ISSN: 0737-3937 print/1532-2300 online
DOI: 10.1080/07373937.2014.951124

Infrared Heating in Food Drying: An Overview

Muhmmed Hussain Riadh, Siti Anom Binti Ahmad, Mohd Hamiruce Marhaban, and Azura Che Soh
Department of Electrical Engineering, University Putra Malaysia, Seri Kembangan, Malaysia

This article aims to review and analyze the aspects and characteristics related to infrared food drying. Indeed, with a review of 100 relevant publications all dealing with infrared food drying, this article notes that infrared drying has several advantages over other common food drying methods. Shorter drying time, a better final dried product quality, and more energy savings in the process are revealed as the most important advantages of infrared drying over convective heat drying. Infrared dryers can also be easily combined with other drying methods such as hot air, microwave, vibration, and vacuum. This article clearly shows that using 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 Drying quality; Drying time; Energy saving; Food drying; Infrared radiation

INTRODUCTION

Deterioration is the main problem that limits the extension of shelf life for postharvested food materials. Other postharvest 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 foodstuffs is an appropriate solution for some of these postharvest challenges. In the drying process, heat is transferred from the heat source to the material, which causes the evaporation of moisture. Elimination of the moisture content prevents the growth of microorganisms, which causes a reduction in the moisture-mediated deterioration reactions.[1] Consequently, this brings about a minimization of the packing, storage, and shipping costs due to the reduction in the weight and volume.

The quality of the final dried product is a significant factor to be studied in the drying industry. Loss of nutritious substances (e.g., ascorbic acid),[2–5] loss of color,[6,7] and deformation or internal structure[8–10] are some of the negative effects of drying that should be minimized by optimizing the process. Choosing the proper dryer for a particular material, drying within an appropriately limited time, and pretreatment of the material are factors that affect the quality of dried products.

Gratifying the market and industrial demand creates the need to design and develop efficient drying techniques in order to reduce energy use and maintain product quality. In addition, the use of smart drying has expanded, causing the need for more drying methods that decrease the amount of energy required. Thus, there is an urgent need to design dryers with the correct management of energy and high efficiency. The evaporation rate, surrounding heat loss, thermal energy efficiency, and electric, gas, or steam energy consumption are several factors that categorize the energy management of the drying process.

Convection, conduction, and radiation are the main methods of transferring heat energy. Several methods are used in the drying industry, such as sun drying, hot air, microwave, vacuum, and infrared radiation. Sun drying is the most common method adopted for drying fruits and vegetables, whereby the products are dried under the sun's radiation. Hot air dryers work easily by injecting hot air into a chamber and evaporating the moisture content of the material with conduction and convection. In the vacuum drying method, the pressure is reduced and thus the boiling point of water becomes lower; that is, below 100°C. Alternatively, the material can be heated using very high-frequency electromagnetic waves in microwave dryers.

By subjecting the material to infrared radiation, the heating power generated can penetrate into the food materials. Infrared radiation has gained popularity because of its superior thermal efficiency and fast response time/drying rate compared to conventional heating. Infrared radiation heating has been widely applied in recent years to different thermal processing systems in the food industry, such as pasteurization, drying, and frying.[11] The number of published articles related to infrared food drying has increased in the last two decades as a consequence. Table 1 presents drying experiments carried out since 2008 that use infrared radiation heating. However, there is a need for more studies concerning infrared drying.

This article is organized as follows: Firstly, the classification of infrared radiation and its interaction with food is presented. The contribution of the second part deals with

---

Correspondence: Muhmmed Hussain Riadh, Department of Electrical Engineering, University Putra Malaysia, Seri Kembangan 43400, Malaysia; E-mail: 110mhra@gmail.com

TABLE 1
Summary of recent drying experiments since 2008 using infrared radiation heating

Material	Method	Reference
Soil	Temperature-controlled infrared drying	[17]
	Freeze-drying process with infrared radiation heating	[18]
Noodles	Quick boiling by using infrared drying	[19]
Olive	Infrared heating	[20]
Grape	Infrared heating	[21]
Wet olive husk	Infrared heating	[22]
Tiger prawn	Infrared-assisted freeze drying of	[23]
High-moisture paddy	Vibration-assisted infrared (IR) drying	[24]
Soybean grains	Combined near-infrared radiation and fluidized-bed drying	[25]
Sweet potato	Infrared drying	[26]
	Combined convective and far-infrared drying	[27]
Celery	Infrared drying	[28]
Ring-shaped pineapple	Combined far-infrared radiation and hot air drying	[29]
Carrot slices	Infrared radiation	[30]
Biological materials	Convective drying in combination with microwave and IR drying	[31]
Tomato		[3]
Red pepper slices	Infrared radiation	[32]
Longan fruit	Far-infrared radiation-assisted hot air drying	[33]
Whole longan	Combined infrared and hot air	[34]
Rough rice	Infrared radiation heating	[35]
Banana	Sequential infrared radiation heating and freeze drying	[36]
Alumina-silicate mineral cake	Infrared drying	[37]
Ham	Near-infrared spectroscopy	[38]
Carrot	Infrared radiation heating	[9]
Blueberries	Infrared radiation heating	[39]
Banana slices	Combined far-infrared and vacuum drying	[40]
Red bell pepper	Infrared radiation heating	[10]
Mulberry leaves	Combined far-infrared radiation and air convection	[41]
Apple slices	Infrared dry-blanching and dehydration with continuous heating	[42]
Apple slices	Infrared dry-blanching and dehydration with intermittent heating	[43]

the motivation behind using infrared radiation in industrial drying, including the process time, product quality, and energy savings of the drying system. Thirdly, the article analyzes a number of experiments on different food materials that have used infrared heating. Fourthly, the combination of infrared radiation with other drying methods is introduced and discussed with some examples. Finally, the modeling of infrared radiation is reviewed briefly with some examples.

Overall, this article attempts to reveal the significance of infrared drying in industrial food drying processes and demonstrate the need for improvement for this method to be more efficient. Additionally, this article aims to review recent ideas and experiments concerning infrared drying.

INFRARED RADIATION

Infrared radiation (IR) is a part of the electromagnetic spectrum that is predominantly responsible for the heating effect of the sun.[12] IR is an electromagnetic wave that has three categories based on its wavelength: the near-infrared (NIR; 0.78–1.4 μm), middle-infrared (MIR; 1.4–3 μm) and far-infrared (FIR; 3–1,000 μm) (Fig. 1).[13] The transition of infrared radiation through water is at the NIR, which has a short wavelength,[14] whereas at the FIR (longer wavelength) it is absorbed at the surface.[11] The drying of thicker bodies seems to be more efficient using the NIR region, whereas the drying of thin layers yields better results at the FIR region.

Sakai and Hanzawa[11] indicated that there is greater heat sink into food using the NIR compared to the FIR, whereas the rate of color development is greater using FIR heating. Shilton et al.[15] evaluated the efficiency of cooking hamburger patties using MIR and FIR. They observed a change in the core temperature and a change in the surface temperature with the decrease of the drying

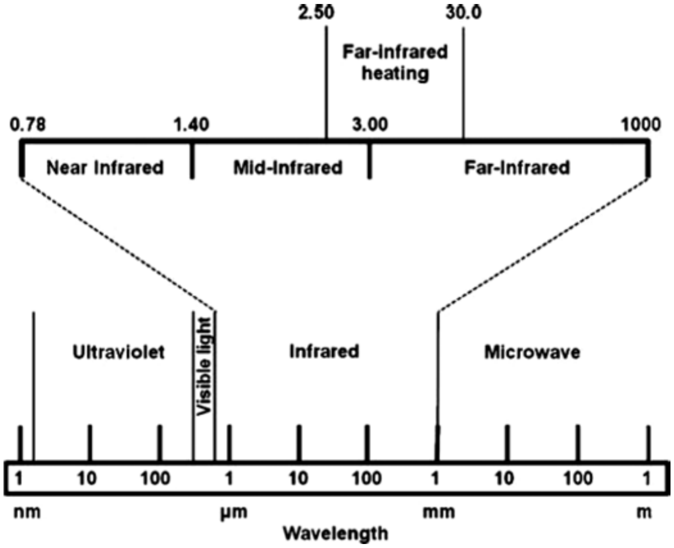


FIG. 1. Electromagnetic wave spectrum.[30]

TABLE 2
Depth of penetration of NIR (0.75 to 1.4 µm) into food products[32]

Product	Spectral peak (µm)	Depth of penetration (µm)
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, 70–85% water	1.0	1
Raw potatoes	1.0	6
Dry potatoes	0.88	15 to 18
Ram apples	1.16	4.1
	1.65	5.9
	2.36	7.4

time using MIR; however, with FIR the rate of increase of the core temperature was influenced by the fat content.

In terms of the NIR, Nowak and Lewicki[16] designed a laboratory dryer that worked either with infrared energy or with hot air in order to dry apple slices using NIR with a wavelength of 1,200 nm. Hashimoto et al.[17] also used NIR to study and compare the infrared drying characteristics of wet, porous (full of pores) material with convective drying characteristics. FIR drying processes have also been effectively utilized in recent years to dry vegetable and fruit products, such as sweet potatoes,[18] potatoes,[19,20] onions,[21–24] apples,[16,25] and kiwifruit.[26]

The penetration of NIR and FIR radiation into sweet potato was studied by Hashimoto and Kameoka.[27] The results demonstrated that FIR penetrates to a depth between 0.26 and 0.36 mm into the material, and the corresponding values for the NIR were 0.38 to 2.54 mm. Agreeing with Hashimoto et al.'s[28] study, Sakai and Hanzawa[11] indicated that most of the FIR energy was converted to heat at the surface of the material. The penetration depth of the NIR radiation into some food products is illustrated in Table 2.

As shown in Fig. 2, when subjecting the foodstuff to infrared radiation, the latter is reflected, absorbed, or scattered (no scattering or reflecting for black body). Table 3 shows the IR absorption group for pertinent foodstuff components and chemical groups. In another study, Christina[30] showed that less than 10% of the radiation is reflected back with FIR, whereas it is approximately 50% with NIR. Years earlier, Dagerskog[31] claimed that the rest of the reflection occurs when the radiation goes through the material and scatters as well as produces different patterns and colors. Before Dagerskog, the optical properties of dissimilar media were also hypothetically discussed by Krust and Mcquistan.[32]

APPLICATION OF INFRARED HEATING IN FOOD DRYING

Among industrial dryers, infrared dryers are used very frequently to handle the significant operation of drying in chemical engineering. Infrared radiation has been deployed in the food and other industries for a long time. Drying by infrared radiation is energy proficient if the drying process is efficiently tuned.

In recent years, infrared drying has become a significant technique in the drying industry because of its numerous advantages, such as the energy savings, lower drying time, high-quality dried products, intermittent energy source, easy control of the process parameters, uniform temperature distribution, and clean operational environment, as well as space savings.[11,37–39] In addition to these benefits,

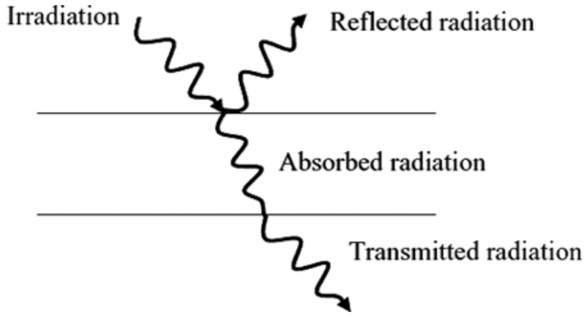


FIG. 2. Extinction of radiation (absorption, reflection, and transmission).[36]

TABLE 3
Infrared absorption bands for chemical groups and relevant food component[132]

Chemical group	Absorption wavelength (μm)	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

there are other advantages, such as the easy integration of the IR with convective, conductive, vibration, freeze, vacuum, and microwave technologies; low capital cost and the low cost of energy; the simplicity of the required equipment; fast transient response; versatility; and easy installation of the infrared dryer, all of which means that the infrared dryer has emerged as a popular dehydration method.[1,25,34,40,41]

Infrared Dryer

Infrared drying has become more popular in recent years because of its advantages, such as its low drying time, the reasonable quality of the final dried product, and its greater energy savings capability, in addition to its lower price compared to microwave and vacuum drying methods. When IR is used to dry or heat a material, it is absorbed by the solid material in its surface layer. Nevertheless, radiation penetrates to some depth in moist, porous materials; their ability to transmit depends on the moisture content.[33]

The energy efficiency of infrared dryers relates directly to the absorption characteristics of the material, which determines the economic feasibility of the dryer.[34] Infrared drying is a dehydration method that has high energy efficiency. This means that the energy savings with an IR dryer is greater than that of convectional and other drying methods.[25] Considering the distance between the heating source and the material, the air flow velocity and temperature, and the velocity of the material sheet (if a continuous IR dryer) can significantly influence the energy efficiency.[16]

In the transfer of heat with high efficiency, the absorption of the infrared radiation should be direct and total. This concept will occur only when there is no absorbing medium between the energy source and the product. The transfer of IR energy is done without heating the surrounding air and no heating medium is needed between the source of the energy and the material in IR dryers. Therefore, because there is rapid and uniform heating and because the IR radiation penetrates directly into the inner layer of the material without heating the surrounding air, the energy consumption of infrared drying is lower compared to other techniques.[27,35,36]

To summarize and analyze other researchers' experiments, it can be concluded that an increase in the infrared power level leads to a reduction in the drying time, whereas an increase in the air velocity causes an increase in the drying time and energy consumption. By increasing the air velocity, the surface layer becomes cool and causes a longer drying time. Thus, the air velocity should be adjusted to ensure better results. The infrared power level should also be adjusted because an increase in power may cause quality losses. In addition, there other factors that have not been addressed by researchers. Selective heating by infrared radiation, the distribution of the infrared radiation and its absorption by the material, the color of the inside of the dryer chamber and the material's initial color, the distance between the emitters and the material, and the number and size of the valves used for fresh air injection to the dryer and wet air extraction from the chamber can also influence the drying time, energy consumption, and quality of the final dried product.

Drying Kinetics and Mathematical Modeling

The drying time depends on several factors; for example, the water mass of the material, the total mass, and the thermal characteristics of the material.[36] One of the main parameters that can improve the drying time is the ability of infrared radiation to penetrate and directly transfer heat to a certain depth of the materials.[42] The power density in infrared drying can also be 6–10 times higher than in convection drying.[33] Applying a high power density to the material can significantly reduce the drying time.

The transfer of IR energy from the heating source to the material surface is performed without heating the surrounding air. The quantity of the heat that is delivered to the material comprises almost all of the heat coming from the source, resulting in less drying time.[43] On the other hand, infrared emitters have low thermal inertia, meaning that as soon as the power is turned on, the heat is delivered without any delay and the heating stops immediately when the power is turned off.[36] In addition, the control of heat delivery in IR dryers can be done either manually or electronically.[36] The on–off timing of the infrared lamps can also be controlled easily by the appropriate temperature setting, which can reduce the drying time.[44]

Nowak and Lewicki[16] indicated that the drying time of an infrared dryer is much faster than that of a hot air dryer for apple slices. Doymaz[45] observed that the drying time decreases and the effective diffusivity increases with an increase in the infrared power level. Nasiroglu and Kocabiyik[46] observed the same effect for red pepper and they examined the air velocity to demonstrate its effect on the drying time. It was revealed that the increase in the infrared power and the decrease in the air velocity caused a reduction in the thickness changes and drying time. Using infrared radiation, the increase in the infrared power level and the decrease in the air velocity are parameters that have been mentioned by researchers to reduce the drying time. The smart control of the off timing of IR lamps, the adjustment of the distance between the heat source and the material, and the temperature of the medium inside the dryer can also be effective in decreasing the drying time without major quality losses. Jezek et al.[47] determined the moisture content, dehydration rate, diffusion content, and mass content of dry matter in celery. Carrot slices were dried by Kocabiyik and Tezer[48] using three levels of infrared power (300, 400, and 500 W) with velocities of 1.0, 1.5, and 2.0 ms^{-1}. They investigated the effect of process variables on the drying kinetics of carrots; for example, the specific energy consumption, drying time, and quality parameters of dried carrot.

Modeling of the infrared heating of food products is a significant approach in the drying industry due to its ability to predict the infrared system performance.

To evaluate the performance of parameters in drying models, nonlinear regression techniques were adopted by several researchers.[25,49–53] A model is considered to be good and acceptable based on the following: the coefficient of determination (R^2), which should be near one; the modeling efficiency, which should be higher; and the mean bias error, root mean square error (RMSE), chi square (χ^2), and the sum of residuals, which should be lower.

A mathematical model of mass and heat transfer for vacuum far-infrared drying of potato slices was introduced by Yunhong et al.[124] on the basis of energy and diffusion equations. The finite difference method is used to mathematically simulate the sample temperature and moisture content in different drying conditions. Comparison results show that the model fits well the changes in sample temperature and moisture content at different times of drying, with the values of the coefficient of determination close to 1.0 and the relative error values less than 10%.

The Page model, a diffusion model based on spherical grain shape, an exponential model, and an approximation of the diffusion model are four mathematical drying models that were shown by Abe and Afzal[54] to identify the thin-layer infrared drying characteristics of rough rice. They indicated that the Page model was the most acceptable for describing the thin-layer of rough rice under infrared drying. Likewise, Das and Bal[55] also stated that the Page model sufficiently fitted the drying characteristics of high-moisture paddy. Togrul[25] studied the characteristics of the infrared drying of apple in order to develop new appropriate models. To clarify the behavior of apple drying, 10 different drying models (Page, Newton, modified Page, Henderson and Pabis, Wang and Singh, diffusion approach, logarithmic, modified Page equation-II, simplified Ficks diffusion equation, and Midilli equation) were developed and validated. Variation of the moisture ratio with time could be explained very well by the model developed by Midilli and Yapar[56] A set of three-dimensional equations, moisture transfer, and heat and pressure equations using infrared radiation was developed by Ranjan et al.[12] to control the volume formulation. Simulation showed that the three-dimensional model can predict the moisture contents and temperature better than the two-dimensional mass and heat transfer model. The mathematical model describing drying of a layer of seeds was presented by Rudobashta et al.[125] in which the energy for water evaporation is supplied through infrared irradiation in the oscillatory mode. The mathematical model comprising the analytical solution of the problem of combined heat and mass transfer allows to analyze the dynamics of oscillating infrared heating of a plate (a layer) under drying conditions.

Islam et al.[130] presented results of a simple diffusion-based model to predict the drying performance of a pilot-scale twin-drum dryer. Numerical results were compared with experimental data obtained from biological sludge. The agreement of model predictions with the pilot-scale experimental data was satisfactory. The validated model was used to predict the performance of a drum dryer subjected to heat input by convection and radiation along with conduction through the drum wall. It was shown that dryer output can be enhanced significantly by increasing the film thickness and applying radiant heating in the initial period of drying. Drum dryers are commonly used for production of a flaky dry powder from thick suspensions. In another study, Islam et al.[131] developed a liquid diffusion model to quantitatively assess the influence of various operating parameters of engineering interest in drying of heat-sensitive materials. Heat of wetting, temperature, and moisture-dependent effective diffusivity and thermal conductivity; changes in product density; and drying-induced ideal shrinkage of the product were considered in the model. Numerical results were reported on drying of potato slices to demonstrate how the moisture and temperature profiles as well as drying performance were affected by multimode heat input. They stated that drying time decreased with a decrease in product thickness and relative humidity and an increase in drying air temperature and velocity. However, the effects of these parameters became less significant if other modes of heat input were combined with convection.

Linear, power, exponential, Arrhenius, and logarithmic models are mathematical structures for the drying models that describe the variation in the constant and coefficient withtemperature.[25,50,53,57]

The numerical methods used to solve the system of equations are finite difference, finite element, and finite volume or control volume method. It is often not easy to choose which solution will give the best results and which will need the least amount of time.[12,58] However, Turner and Perre[59] proposed that if the solution area shows a simple rectangular domain, then it is preferred to employ the traditional finite difference method.

To model the moisture movement in the food material, Fick's second diffusion equation has been used widely by researchers.[49–51,53] If the main mechanism is assumed as diffusive in nature, this equation interprets the experimental results. Using an Arrhenius-type equation can express the values of the effective diffusivity determined and the correlation between the drying conditions.

The transient temperature diffusion in a multilayer composite, semitransparent or transparent, emitting and absorbing area subjected to a thermal radiation heat flux was investigated by Tsai and Nixon.[60] The governing condition with the initial and boundary conditions, considering the effects of thermal conduction and radiation inside each layer and convection on both external surfaces, was solved by a hybrid numerical algorithm, employing a fourth-order Runge-Kutta method and a finite difference method for the time variable and space variable respectively. Dagerskog[31] could successfully predict the temperature distribution of beef slices during infrared drying and developed a model based on the combination of convection heating and infrared radiation. Using the finite difference method, the heat conduction equations were solved numerically.

Several models have been described for mass transfer by several researchers.[14,35,61,62] The difference between the partial pressure of the interface and the drying air medium has been applied to express the mass transfer.[14] Neglecting the convective heat transfer between the elementary surfaces during far-infrared drying, the radiation heat that reaches the elementary surface is the sum of the main radiation heat from the source and the radiation heat that is reflected from the other surrounding elementary surfaces.[10] In the last two decades, a number of researchers have presented models for the heat transfer.[3,7,10,63] The approximate differential equations for mass and heat transfer have considerable similarities. Because Fourier's law for heat and Fick's law for mass are both linear approximations to transport conserved quantities in a flow field, they are very similar.[64]

Diffusion traits in relation to the radiation intensity and slab thickness were investigated by applying the finite element method in order to highlight the transfer of heat into the food system.[20] Because of the predominant energy absorption of water, Sakai and Hanzawa[11] supposed that the greatest amount of radiation power would be absorbed at the material surface. Based on this supposition, a governing equation and boundary conditions to describe the heat transfer derived from the energy balance in the system were solved by employing Galerkin's finite element method.

In order to determine the moisture ratio of the material being dried, several researchers[25,49–52] used the moisture ratio equation, which is the ratio of moisture content at any given time (M_t) over the initial moisture content (M_o). The value of the equilibrium moisture content (M_e) is very small compared to (M_o) and (M_t) and is numerically set to zero. The view factor has been introduced in order to compute the exchange of radiation between any two surfaces.[4,7]

Transport Properties in IR Food Drying

The principles of heat transfer concern many processes and unit operations in the food industry: baking, drying, freezing, and refrigeration all rely on at least one of three heat transfer modes, which are convection, conduction, and radiation.

Numerous models have been developed concerning mass transfer.[14,35,61,62] The distinction between the interface partial pressure and the drying air medium is deployed by Nuthong et al.[14] to state the mass transfer. Ignoring the convective heat transfer among the basic surfaces throughout far-infrared drying, the radiation temperature that achieves the basic surface is equal to the summation of the major radiation temperature from the source and the radiation temperature that is mirrored from other adjacent basic surfaces.[10] During the last few decades, and especially the last two, many articles have shown transfer models.[3,7,10,63,66] The approximate differential equations for mass and heat transfer have substantial resemblances. Due to the linearity approximations of Fourier's law for heat and Fick's law for mass to transport conserved quantities in a flow field, they are certainly extremely comparable.[64]

Drying can be defined as a mass transfer operation having a solid–gas interface. The largely general mass transfer operations containing two phases (distillation, gas absorption, and humidification) specify conditions having interfaces such as variables in space and time.[67–71] García and Ragazzo[72] developed a model of drying comparable to most regular mass transfer operations. They proposed a model that did not need to create suppositions about the transfer mechanism and interfacial conditions. However, the proposed model was restricted to stable conditions and investigational validation.

Water flux is one of the main input parameters that affects the performance of the infrared drying system dramatically. It has been applied in different forms by different researchers.[66,73–77] Some of these forms are dependent on temperature, moisture content, and moisture diffusivity. Ratti and Mujumdar[73] developed another form and stated that this equation is valid only for specific products. Another form of water flux is a partial differential equation that is not easily substituted in the main model; this form was presented by Crapiste et al.[66]

In the infrared drying of food, the effective moisture diffusion coefficient amplifies with temperature. Diffusion is a feature performance of sluggish dry materials in which water vapor drying transfer rates within the materials are guided toward the external surface and with the aim of diffusion. Next, the vapor concentration of the water on the external material's surface reaches equilibrium or extremely near to equilibrium values. The increase in the drying rate is a consequence of the water equilibrium concentration vapor on the material's surface at high heat.[78,79] Ragab et al.[80] determined the moisture diffusion coefficient of rough rice under an infrared heating system followed by cooling. They investigated the effects of initial moisture content, rice drying bed thickness, temperature, and cooling methods on the moisture diffusion coefficient and the moisture diffusivity. To describe the moisture diffusivity, the unsteady diffusion equation based on Fick's law and slope methods were used. The results indicated that rough rice moisture diffusivities under infrared heating and cooling were dramatically influenced by rice temperature and tempering treatment, respectively. The moisture diffusion coefficients during the heating and cooling of infrared dried rice with tempering were much higher than those of convective drying.

Quality of Food Products After IR Heating

For commercial success, it is critical to study the quality and sensory changes occurring during IR heating. Regarding this fact, several research studies have been performed on the quality and sensory changes of foodstuff during infrared heating.

Satisfying the market and industrial demand creates a need to design and use dryers with a high drying rate and good quality of dried products. IR drying is known as a means of dehydration that allows a high rate of water evaporation without quality losses, like changes in color, shrinkage, surface hardening, sample deformation, loss of aroma, the gap between the surface and bottom moisture content, and loss of ascorbic acid.

Food materials have low thermal conductivity in the drying period; therefore, there is a heat transfer limitation during conventional heating[50]; in addition, the convective drying of biological materials causes transfer of the inside elements with the moisture from the depth of the material to the surface, and the infrared radiation is able to penetrate deep within moist materials and heat up trapped water.[33] From another viewpoint, convection drying, whereby hot air flows over a wet material surface, is sometimes not able to supply enough heat to remove the moisture from the solid.[33] As mentioned earlier, the power density of IR drying can be 6–10 times higher than that of convection drying; therefore, decreasing the drying time leads to better quality.[80] On the other hand, the temperature is distributed uniformly in the IR drying system, which can significantly maintain the quality of the final dried product.[43]

In a study performed by Mongpraneet et al.[21] on the drying of Welsh onion with far-infrared radiation under vacuum conditions, the high temperature in the long drying period reduces the rehydration rate. Alternatively, Nathakaranakule et al.[81] combined far-infrared, hot air, and a heat pump to dry fresh longan fruit and stated that increasing the drying rate and creating a more porous structure led to less shrinkage and less hardness for the dried longan. The influence of different intermittencies of infrared radiation on the color change of the material was investigated by Chua et al.[44] They observed that by increasing the drying time, the color of the material became darker. An appropriate temperature setting to control the on–off timing of the IR lamps decreases the degradation of the material color. Different powers of infrared radiation were used at the drying stage of noodle production by Basman and Yalcin.[82] They indicated that using infrared for drying noodles can decrease the cooking loss and total organic matter values as well as improve the quality. Xu et al.[126] used infrared radiation to produce dried kelp and studied the temperature and quality characteristics during drying. They measured the rehydration ratio, color, and texture before and after rehydration to evaluate the quality of dried kelp products. Dielectric properties were also studied to observe the characteristics of rehydrated dried products. The results indicated that the total drying time required for infrared drying products was approximately 120 min, reduced by 56% compared to air drying (275 min).

The application of IR radiation in a stepwise mode by slow power increase and short cooling among power levels leads to less degradation of color than with alternate infrared heating.[44] A decrease in the overall color changes of 37.6 and 18.1% was gained for potato and carrot, respectively. Gabel et al.[83] stated that the color of onion may darken under long infrared heating treatments. Using infrared, the heated onion pungency decreases with a reduction in moisture. Increasing the infrared power causes the amount of chlorophyll in dried onions to increase as well.[84] The IR drying of carrots caused less damage to the tissue than blanching. In addition, the infrared heating of carrots resulted in high tissue strength because it efficiently inactivates the enzymes on the surface of the carrot.[83] The

IR-assisted freeze drying of yam resulted in less color change as well as faster drying compared to regular freeze drying. Furthermore, a shorter drying time decreases material shrinkage.[85]

The appraisal of soybean flour treated with infrared heating showed the same freshness as fresh flour after one year.[86] Although there was no visible indication in lentils treated by IR heating, lentils dried by IR radiation were darker than raw lentils. In addition, the lentil's cell walls were less sensitive to breakage after infrared heating.[87] A significant improvement in the head rice yield and whiteness of rough rice was achieved using infrared radiation heating.[88] The protein solubility and bitterness of peas were decreased by drying with infrared radiation. The dehulling capacity of canola seeds was also revealed to be higher after IR heat treatment.[89] Treatment of peas under infrared heating at 50 to 60°C for 2 h resulted in deterioration of the quality of peas, which led to an unacceptable product.[90] The jet impingement and infrared heating of bread demonstrated quick drying and improved the color development compared to conventional heating.[91]

The flavor, texture, juiciness, and overall acceptability of ground beef patties were evaluated using infrared heat treatment and gas broiling. The results showed no significant difference between the two methods.[92] Nevertheless, the appearance of the patties treated by gas broiling was rated higher than those treated by infrared heating. The production of beef under infrared drying and conventional heating gave similar quality as indicated by the taste tests and surface appearance.[93] The roasted appearance and brown color, in addition to the efficient pasteurization of the surface of deli turkey, was provided using infrared heat treatment.[94] The interior temperature of strawberries was heated up by infrared radiation, whereas the temperature of the surface was sufficient to inactivate microorganisms. Consequently, infrared radiation heating can be employed to pasteurize pathogens on the surface without deteriorating the foodstuff's quality.[95] Lin-lin et al.[127] compared the drying characteristics and quality of dried shiitake mushroom (*Lentinus edodes*) cubes obtained by hot air drying, intermediate-infrared drying, and vacuum–microwave spouted bed drying (VMSD). Several quality parameters of the products including color, texture, and rehydration capacity were investigated. With similar rehydration capacity, the color of the VMSD product was closest to the original material. In terms of texture, total sugar content, and sensory evaluation, the VMSD product has the best quality.

Hebbar and Ramesh[96] investigated the effect of thermal processing on the compressive strength and kinetics of color changes of cashew kernels during infrared drying within 15 to 55 min over a range of temperatures (55–95°C). Response surface methodology and the peelability factor were used to optimize the drying condition, which showed that 55°C for 55 min is the best for the drying of cashew kernels. A sequential infrared radiation and freeze-drying process was used by Pan et al.[97] to study the drying and quality characteristics of banana slices. They treated the banana slices with a dipping solution containing 10 g/L citric acid and 10 g/L ascorbic acid before IR drying in order to improve the quality of banana chips. Their experiment demonstrates that compared to non-dipped samples, acid dipping improved the color of the banana chips and decreased the freeze-drying time.

In order to control the quality of traditional Slovenian dry-cured ham, Prevolnik et al.[98] examined the capability of near-infrared spectroscopy. In another study, the color, total phenols content, and global chemical composition of four fresh varieties of olive leaves (Chemlali, Chemchali, Zarrazi, and Chetoui) were determined using IR radiation.[99] Shi et al.[100] evaluated the infrared drying characteristics and final product quality of fresh and sugar-infused blueberries dried with a catalytic infrared dryer. Wanyo et al.[101] combined far-infrared radiation with hot air convection drying in order to improve the antioxidant and color properties of mulberry leaf tea. Using the infrared dry-blanching process, Zhu et al.[102] investigated the effect of dipping treatments on the texture and color stabilization of apple cubes. The effect of processing parameters on the drying characteristics of apple slices under simultaneous infrared dry-blanching and dehydration with intermittent heating were investigated.[103] In another published paper, they investigated the same parameters exposed to simultaneous infrared dry-blanching and dehydration with continuous heating.[104] Nowak and Lewicki[105] compared the quality of apple slices dried by convection and NIR heating. Investigation of the drying characteristics, effectiveness of disinfestations, and the milling quality of rough rice have been investigated under the conditions of infrared radiation heating.[106] High moisture diffusivity, drying rate, good milling quality, and effective disinfestations could be achieved by heating rough rice to 60°C using infrared radiation heating followed by tempering and natural cooling. Dondee et al.[107] attempted to reduce the breakage and cracking of soybean grains using NIR radiation combined with fluidized bed drying. These researchers, in addition to Sharma et al.,[24] claimed that the drying time, the temperature inside the dryer, and the control of the on–off timing of IR lamps affected the product quality.

The infrared radiation wavelength and the radiation intensity of the material and heat source are two factors that need to be considered in future experiments due to their significant effects on the quality of the dried product.

COMBINATION OF INFRARED RADIATION HEATING WITH OTHER DRYING METHODS

Although infrared heating is known to be a promising new method, it is not applicable and fit for all drying systems and there is a limitation in its penetrating power.[17,108] As a result, the combination of electromagnetic radiation and other dying methods, depending on the specific process, can be more efficient and useful as this provides synergistic results.

Hot Air

Hebbar et al.[109] combined hot air and infrared heating to dry potato and carrot. The sample was dried in three modes: hot air, infrared, and a combination of the two. They stated that compared to the hot air mode, the drying time was reduced in infrared and its combination with hot air, where the drying time was reduced by approximately 48% . In addition, the energy consumed for water evaporation was lower in these two modes (about 63%). There heat utilization efficiency for potato and carrot was 38.5 and 38.9%, respectively. The authors combined hot air and infrared energy and conducted their experiment again,[52] but in the new work, the local (Bellary) variety of onion was tested by drying temperatures of 60, 70, and 80°C, inlet air temperatures of 30, 40, and 50°C, and air velocities of 0.8, 1.4, and 2.0 m/s. There were higher coefficient of regression values (R^2) in the Page and modified Page models in comparison to the Fick's and exponential models, which were 0.990–0.995 and 0.767–0.933, respectively. They also indicated that the air temperature should be optimized because the temperature of the surface will reduce with the cold air and a higher temperature may cause the surface to harden.

The fresh longan fruit of the variety E-dor was dried by Nuthong et al.[14] using a combination of hot air and infrared drying. Infrared powers of 300, 500, and 700 W, air velocities of 0.5, 1.0, and 1.5 m/s, and air temperatures of 40, 60, and 80°C were used. They observed an increase in the radiation heating air temperature and infrared power with a decrease in air velocity, which led to an increase in the drying rate. By increasing the air velocity, the cooling effect was accelerated and this caused a reduction in the temperature of the material.[109] In another study, the relation of the heat and mass transfer coefficient for the drying process of longan fruit leather under a combination of convective and far-infrared drying was studied by Jaturonglumlert and Kiatsiriroat.[110] They tested the ratio of the heat and mass transfer coefficient on two modes of drying: the hot air method and a combination of hot air and infrared. In the first mode, they observed an increase in the ratio of the heat and mass transfer coefficient with an increase in the hot air temperature, and this decreased slightly with an increase in inlet air velocity. In the second mode with a constant rate period, this ratio was lower than that gained from hot air drying; this means that the combined technique has higher heat and mass transfer rates.

The effect of drying process conditions on onion slices was explored under the combination of infrared and hot air drying by Kumar et al.[111] Greater flavor and color were retained for onion slices of 2 mm at a low temperature of 60°C with a moderate air velocity of 2 m/s and air temperature of 40°C. To correlate the drying process variables and the onion slice moisture with drying time, an empirical equation was developed that provided a good fit of R^2=0.92). To correlate the drying process variables and drying time with the pyruvic acid content, similar equations were used that provided an excellent fit (R^2=0.96), and for the total change in the color of the onion slices, the equation fits were satisfactory (R^2=0.86).

Afzal and Hikida[112] showed that in the combination of convective and IR drying of barley, the total energy needed was shortened by about 156, 238, and 245% compared to convection drying alone at 40, 55, or 70°C, respectively. On the other hand, Bekki[113] used FIR heating immediately after hot air drying (at approximately 40°C) for the drying of paddy. The results showed a better quality for the final dried product compared to convective or FIR methods in separate conditions. Gabel et al.[83] also evaluated the quality and drying characteristics of onions dehydrated with forced air convection heating and catalytic infrared heating. The catalytic infrared method (both with and without recirculation of air) required a shorter drying time and showed greater drying performance than the forced air convection method at a moisture content of more than 50% (db). Effects of infrared drying and/or convective drying on the drying kinetics of wine grape pomace were examined by Yinqiang et al.[128] Infrared drying had the highest drying rate, which reduced the drying time by more than 47.3% compared with other methods. Sequential infrared and convective drying had a faster drying rate than convective drying.

Microwave

The combination of infrared radiation, hot air, and microwave was developed by Ragab et al.[80] in order to examine the drying time and quality of beetroot. The parameter settings for all modes were 1.2 and 0.1 m/s for the air flow velocity, 55°C for the temperature of the drying chamber, and 100 and 250 W for microwave-emitted and infrared-emitted power, respectively. They claimed that the application of microwave power should be in the first stage of drying, when the sample has substantial moisture content, because it has the ability to heat the whole sample volume, because the IR warms the surface and accelerates the evaporation of the moisture on the surface. The application of combined microwave, infrared, and hot air heating for foodstuffs was also discussed by Datta and Ni.[115]

The combination of microwave and infrared heating was studied by Wang and Sheng[116] to dry slices of peach. They stated their observations in four results: (1) the energy consumption decreased and the dehydration rate increased with an increase in microwave and infrared power; (2) for both infrared and microwave drying, there were two falling rates; (3) the interaction effects of infrared power and exchanging moisture content affected both the energy consumption and the sensory quality; and (4) the sensory quality and energy consumption decreased linearly with an increase in the exchange of moisture content and microwave power, respectively. Other researchers also used infrared-assisted microwave drying to determine the drying conditions in a halogen lamp–microwave combined with an oven for the production of bread crumbs.[117] They used conventional, microwave, infrared, and infrared-assisted microwave drying separately and in combination to dry the breadcrumb dough from about 40.9 to 8% moisture content. The total color difference and the effect of power on the color changes were studied in all conditions; the values of the total color differences were higher in infrared drying and lower in microwave drying, though there was no observed effect of power on color changes.

Roknul et al.[129] presented experimental results and analysis of four drying methods, viz. hot air drying, hot air–assisted radio frequency drying (ARFD), infrared drying, and microwave-assisted hot air drying on the color, microstructure, density, rehydration capacity, and texture after rehydration of stem lettuce slices (*Lactuca sativa* L.). The results showed that the drying time required for stem lettuce slices using ARFD was the shortest (120 min), followed by microwave-assisted hot air drying (140 min) and infrared drying (180 min); hot air drying required the longest time (360 min). Notably, ARFD yielded uniform drying and the quality of the dried samples using ARFD was also the best among these four drying methods.

Freeze Drying

A comparison of the drying times of sweet potato under three drying methods—that is, air drying, freeze drying, and freeze drying with far-infrared radiation—has been carried out.[118] This study indicated that freeze drying with far-infrared radiation was able to decrease the drying time. In order to describe the drying characteristics of sweet potato during this method, four mathematic models were employed (Page, approximate diffusion, exponential, and diffusion models) in which the lowest residual as well as the RMSE were identified for the Page model.

Chakraborty et al.[119] estimated the quality attributes of the infrared-assisted freeze drying of prawns in terms of the rehydration ratio, final product temperature, and final moisture content. In terms of developing multivariate regression models to evaluate the influence of process parameters on the quality of the freeze-dried prawn, they employed a response surface methodology using a three-parameter and three-level face-centered central composite design. An IR temperature of 65°C, sample thickness of 10 mm with 60 mm distance from the IR heater, and freeze drying time of 6.37 h have been reported as the optimal drying condition. In another work, Burgheimer and Nelson[93] investigated the effect of NIR radiation on lowering the freeze-drying time of beef. Infrared heating decreased the drying time from 11 to 7 h.

Vibration

The effective moisture diffusivity of paddy during drying under the combination of infrared heating and vibration has been evaluated[120]; there were five levels of radiation intensity (1,509, 2,529, 3,510, 4,520, and 5,514 W/m^2) and four levels of grain bed depths (single kernel thickness of 3, 6, 12, and 25 mm). The range of 20–22 Hz and 8–9 mm were identified as the optimum frequency and amplitude of the vibration, respectively, for all grain bed depths; in addition, the values of the average effective moisture diffusivity ranged between 0.778×10^{-10} and $3.884 \times 10^{-10}\,m^2/s$. They indicated that the value of diffusivity (D_{eff}) increases with a decrease in moisture content, an increase in radiation intensity, and a reduction in bed depth. They also stated that compared to other models, the Page model reflected lower RMSE values, which made it the best fit to the experimental drying data. In a previous work, Das and Bal[55] studied the drying characteristics of three varieties of high-moisture paddy (slenderness, Shankar, and basmati) using a batch-type, vibration-aided infrared dryer with radiation intensities of 3,100 and 4,290 W/m^2 and grain bed depths of 12 and 16 mm. They discovered that the drying rate was dependent on the levels of radiation intensity and the drying occurred in the falling rate period.

Nimmol et al.[121] combined FIR radiation with the concept of low-pressure superheated steam drying (LPSSD) for banana and compared its behavior combination to the far-infrared radiation and vacuum drying method (vacuum–FIR) using LPSSD. The results reflected that the drying time was shorter in LPSSD-FIR and vacuum–FIR compared to LPSSD. On the other hand, the energy consumptions of LPSSD-FIR and vacuum–FIR were lower than that of LPSSD for all drying conditions. In another experiment, Nimmol et al.[122] found that LPSSD-FIR has a longer drying time than vacuum–FIR under almost all drying conditions except the highest drying temperature of 90°C, which causes a change in the lightness and redness (darker color) of banana. The drying of Welsh onion was also studied by Mongpreneet and Tsurusaki[123] using the combination of high vacuum and ceramic-coated radiators.

CONCLUSIONS

The idea of this article was first to study the drying of food using infrared radiation and then to review several aspects and features related to this drying method. Indeed, even if the use of other drying means—like hot air and direct sun—are still popular in some countries, infrared drying has several advantages over these older dehydration methods. The motivation for using infrared radiation as a new drying technology becomes more obvious when we compare it with other drying techniques. It is clear that time is one of the most significant factors in all industrial applications; in industrial food drying especially, the drying time has been one of the main factors to improve the system, and this can be decreased by using infrared radiation instead of hot air. The quality of the final dried product and the energy used in the process are also vital factors that should be considered by the dryer designers. Several researchers stated that using infrared radiation in the drying of food results in a better quality of the final dried material and more energy savings. By understanding the advantages of infrared technology in drying processes, it is likely that an advanced jump in the foodstuff-processing sector will be taken by using infrared heating.

Because the penetration of the infrared radiation power to the depth of the material is limited, it is essential to combine infrared heating with hot air, microwave, vacuum, and other common convective and conductive modes of heating in order to obtain optimum energy efficiency. The ability of combining infrared radiation with other drying techniques is considered one of its advantages.

To dry food, one needs an appropriate model that is different for each specific material depending on its specification. Here we have reviewed some examples of modeling for infrared radiation in food drying, including moisture ratio, statistical analysis, general mathematic modeling forms, diffusion equation, mass transfer, heat transfer, etc.

REFERENCES

1. Jayaraman, D.K. Drying of fruits and vegetables. In *Handbook of Industrial Drying*, Vol. 1; Mujumdar, A.S., Ed.; Marchel Dekker: New York, 1995; 643–690.
2. Goula, A.M.; Adamopoulos, K.G. Retention of ascorbic acid during drying of tomato halves and tomato pulp. *Drying Technology* **2006**, *24*(1), 57–64.
3. Marfil, P.H.M.; Santos, E.M.; Telis, V.R.N. Ascorbic acid degradation kinetics in tomatoes at different drying conditions. *LWT - Food Science and Technology* **2008**, *41*(9), 1642–1647.
4. Nicoleti, J.F.; Silveira, V.; Telis-Romero, J.; Telis, V.R.N. Influence of drying conditions on ascorbic acid during convective drying of whole persimmons. *Drying Technology* **2007**, *25*(4–6), 891–899.
5. Santos, P.H.S.; Silva, M.A. Retention of vitamin C in drying processes of fruits and vegetables; a review. *Drying Technology* **2008**, *26*(12), 1421–1437.
6. Chua, K.J.; Mujumdar, A.S.; Chou, S.K.; Hawlader, M.N.A.; Ho, J.C. Convective drying of banana, guava and potato pieces: Effect of cyclical variations of air temperature on drying kinetics and color change. *Drying Technology* **2000**, *18*(4–5), 907–936.
7. Krokida, M.K.; Tsami, E.; Maroulis, Z.B. Kinetics on color changes during drying of some fruits and vegetables. *Drying Technology* **1998**, *16*(3–5), 667–685.
8. Lewicki, P.P.; Pawlak, G. Effect of drying on microstructure of plant tissue. *Drying Technology* **2003**, *21*(4), 657–683.
9. Reyes, A.; Vega, R.; Bustos, R.; Araneda, C. Effect of processing conditions on drying kinetics and particle microstructure of carrot. *Drying Technology* **2008**, *26*(10), 1272–1285.
10. Vega-Galvez, A.; Lemus-Mondaca, R.; Bilbao-Sainz, C.; Fito, P.; Andres, A. Effect of air drying temperature on the quality of rehydrated dried red bell pepper (var. Lamuyo). *Journal of Food Engineering* **2008**, *85*(1), 42–50.
11. Sakai, N.; Hanzawa, T. Applications and advances in far-infrared heating in Japan. *Trends in Food Science and Technology* **1994**, *5*(11), 357–362.
12. Ranjan, R.; Irudayaraj, J.; Jun, S. Simulation of infrared drying process. *Drying Technology* **2002**, *20*(2), 363–379.
13. Mongpraneet, S.; Abe, T.; Tsurusaki, T. Kinematic model for a far infrared vacuum dryer. *Drying Technology* **2004**, *22*(7), 1675–1693.
14. Nuthong, P.; Achariyaviriya, A.; Namsanguan, K.; Achariyaviriya, S. Kinetics and modeling of whole longan with combined infrared and hot air. *Journal of Food Engineering* **2011**, *102*(3), 233–239.
15. 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*(3), 217–222.
16. Nowak, D.; Lewicki, P.P. Infrared drying of apple slices. *Innovative Food Science and Emerging Technologies* **2004**, *5*(3), 353–360.
17. Hashimoto, A.; Honda, T.M.; Shimizu, T.; Watanabe, A. Penetration of infrared radiation energy into sweet potato. *Nippon Shokuhin Kogyo Gakkaishi* **1990**, *37*(11), 876–893.
18. Sawai, J.N.T.; Hashimoto, A.; Shimizu, M. A comparison of the hydrolysis of sweet potato starch with b-amylase and infrared radiation allows prediction of reducing sugar production. *International Journal of Food Science Technology* **2004**, *39*(3), 967–974.
19. Masamura, A.S.H.; Nabetani, H.; Nakajima, M. Drying of potato by far-infrared radiation. *Nippon Shokuhin Kogyo Gakkaishi* **1988**, *35*(5), 309–314.
20. Afzal, T.M.; Abe, T. Diffusion in potato during far infrared radiation drying. *Journal of Food Engineering* **1998**, *37*(4), 353–365.
21. Mongpraneet, S.; Abe, T.; Tsurusaki, T. Accelerated drying of Welsh onion by far infrared radiation under vacuum conditions. *Journal of Food Engineering* **2002**, *55*(2), 147–156.
22. Pathare, P.B.; Sharma, G.P. Effective moisture diffusivity of onion slices undergoing infrared convective drying. *Biosystems Engineering* **2006**, *93*(3), 285–291.
23. Sharma, G.P.; Verma, R.C.; Pathare, P. Mathematical modeling of infrared radiation thin layer drying of onion slices. *Journal of Food Engineering* **2005**, *71*(3), 282–286.
24. Sharma, G.P.; Verma, R.C.; Pathare, P.B. Thin-layer infrared radiation drying of onion slices. *Journal of Food Engineering* **2005**, *67*(3), 361–366.
25. Togrul, H. Simple modeling of infrared drying of fresh apple slices. *Journal of Food Engineering* **2005**, *71*(3), 311–323.
26. Fenton, K.M. Rapid dry weight determination of kiwifruit pomace and apple pomace using an infrared drying technique. *New Zealand Journal of Crop Horti Science* **1998**, *26*(2), 35–8.
27. Hashimoto, A.; Kameoka, T. Effect of infrared irradiation on drying characteristics of wet porous materials. *Drying Technology* **1999**, *17*(7–8), 1613–1626.
28. Hashimoto, A.; Igarashi, H.; Shimizu, M. Irradiation power effect on pasteurization below lethal temperature of bacteria. *Journal of Chemical Engineering in Japan* **1993**, *26*(3), 31–33.
29. Ionel, R. *Electromagnetic Radiations in Food Science*; Springer-Verlag: Berlin, 1992.
30. Christina, S. Infrared heating. In *Thermal Technologies in Food Processing*; Richardson, P., Ed.; CRC Press: New York, 2001; 301–389.

31. Dagerskog, M.Infrared radiation for food processing II. Calculation of heat penetration during infrared frying of meat products. *Lebensmittel Wissenschaft und Technologie* **1979**, *12*(4), 252–257.
32. Krust, P.W.; Mcquistan, R.B. *Elements of Infrared Technology*; John Wiley & Sons: New York, 1962.
33. Abukhalifeh, H.; Dhib, R.; Fayed, M.E. Model predictive control of an infrared-convective dryer. *Drying Technology* **2005**, *23*(3), 497–511.
34. Pawar, S.B.; Thorat, B.N. Infrared drying of alumina-silicate mineral cake. *Drying Technology* **2011**, *29*(7), 819–824.
35. Swasdisevi, T.; Devahastin, S.; Sa-Adchom, P.; Soponronnarit, S. Mathematical modeling of combined far-infrared and vacuum drying banana slice. *Journal of Food Engineering* **2009**, *92*(1), 100–106.
36. Arsoy, S. Temperature-controlled infrared drying characteristics of soils. *Drying Technology* **2008**, *26*(12), 1477–1483.
37. Dostie, M.S.J.; Maure, D.; Tonthat, Q.A.; Chatingy, R. Preliminary measurements on the drying of thick porous materials by combinations of intermittent infrared and continuous convection heating. In *Drying '89*; Mujumdar, A.S.; Roques, M.A., Eds.; Hemisphere Press: New York, 1989; 456–473.
38. Navari, P.; Gevaudan, A. Studies on infrared and convective drying of nonhygroscopic solids. In *Drying 92*; Mujumdar, A.S., Ed.; Elsevier Science: Amsterdam, 1992; 685–694.
39. Mongpraneet, S.A.T.; Tsurusaki, T. Accelerated drying of Welsh onion by far infrared radiation under vacuum conditions. *Journal of Food Engineering* **2002**, *55*(2), 147–156.
40. Nowak, D.; Lewicki, P.P. Infrared drying of apple slices. *Innovative Food Science and Emerging Technologies* **2004**, *5*(3), 353–360.
41. Sandu, C. Infrared radiative drying in food engineering; a process analysis. *Biotechnology Progress* **1986**, *2*(3), 109–119.
42. Bae, S.H.; Nam, J.H.; Song, C.S.; Kim, C.J. A numerical model for freeze drying processes with infrared radiation heating. *Numerical Heat Transfer Part A* **2010**, *58*(5), 333–355.
43. Wang, J.; Sheng, K.C. Modeling of multi-layer far-infrared dryer. *Drying Technology* **2004**, *22*(4), 809–820.
44. Chua, K.J.; Chou, S.K.; Mujumdar, A.S.; Ho, J.C.; Hon, C.K. Radiant–convective drying of osmotic treated agro-products: Effect on drying kinetics and product quality. *Food Control* **2004**, *15*(2), 145–158.
45. Doymaz, İ. Infrared drying of sweet potato (*Ipomoea batatas* L.) slices. *Journal of Food Science and Technology* **2012**, *49*(6), 760–766.
46. Nasiroglu, S.; Kocabiyik, H. Thin-layer infrared radiation drying of red pepper slices. *Journal of Food Process Engineering* **2009**, *32*(1), 1–16.
47. Jezek, D.; Tripalo, B.; Brncic, M.; Karlovic, D.; Brncic, S.R.; Vikic-Topic, D.; Karlovic, S. Dehydration of celery by infrared drying. *Croatica Chemica Acta* **2008**, *81*(2), 325–331.
48. Kocabiyik, H.; Tezer, D. Drying of carrot slices using infrared radiation. *International Journal of Food Science and Technology* **2009**, *44*(5), 953–959.
49. Celma, A.R.; Lopez-Rodriquez, F.; Blazquez, F.C. Experimental modelling of infrared drying of industrial grape by-products. *Food and Bioproducts Processing* **2009**, *87*(C4), 247–253.
50. Celma, A.R.; Rojas, S.; Lopez-Rodriguez, F. Mathematical modelling of thin-layer infrared drying of wet olive husk. *Chemical Engineering and Processing* **2008**, *47*(9–10), 1810–1818.
51. Kamon, P.N.M.; Somchart, S.; Sirithon, S. Modeling of combined far-infrared radiation and air drying of a ring shaped-pineapple with/without shrinkage. *Food and Bioproducts Processing* **2011**, *17*(3), 93–119.
52. Kumar, D.G.P.; Hebbar, H.U.; Ramesh, M.N. Suitability of thin layer models for infrared-hot air-drying of onion slices. *LWT - Food Science and Technology* **2006**, *39*(6), 700–705.
53. Togrul, H. Suitable drying model for infrared drying of carrot. *Journal of Food Engineering* **2006**, *77*(3), 610–619.
54. Abe, T.; Afzal, T.M. Thin-layer infrared radiation drying of rough rice. *Journal of Agricultural Engineering Research* **1997**, *67*(4), 289–297.
55. Das, I.; Bal, S. Drying performance of a batch type vibration aided infrared dryer. *Journal of Food Engineering* **2004**, *64*(1), 129–133.
56. Midilli, A.K.H.; Yapar, Z. A new model for single-layer drying. *Drying Technology* **2002**, *20*(7), 1503–1513.
57. Celma, A.R.; Cuadros, F.; Lopez-Rodriguez, F. Characterisation of industrial tomato by-products from infrared drying process. *Food and Bioproducts Processing* **2009**, *87*(C4), 282–291.
58. Ranjan, R.; Irudayaraj, J.; Jun, S. A three-dimensional control volume approach to modeling heat and mass transfer in food materials. *Transactions of the American Society of Agricultural Engineers* **2001**, *44*(6), 1975–1982.
59. Turner, I.W.; Perre, P. Comparison of the drying simulation codes Transpore and Wood2D which are used for the modeling of two-dimensional drying processes. *Drying Technology* **1995**, *13*(3), 695–735.
60. Tsai, C.; Nixon, G. Transient temperature distribution of amultiplayer composite wall with effects of internal thermal radiation and conduction. *Numerical Heat Transfer* **1986**, *10*, 95–101.
61. Dufour, P.; Blanc, D.; Toure, Y.; Laurent, P. Infrared drying process of an experimental water painting: Model predictive control. *Drying Technology* **2004**, *22*(1–2), 269–284.
62. Fasina, O.O.; Tyler, R.T.; Pickard, M.D. Modelling the infrared radiative heating of agricultural crops. *Drying Technology* **1998**, *16*(9–10), 2065–2082.
63. Boudhrioua, N.; Giampaoli, P.; Bonazzi, C. Changes in aromatic components of banana during ripening and air-drying. *Lebensmittel-Wissenschaft und Technologie* **2003**, *36*(6), 633–642.
64. James, R.; Welty, C.E.W. *Fundamentals of Momentum, Heat, and Mass Transfer*; John Wiley & Sons: Hoboken, NJ, 1976.
65. Theodore, L.B.; Adrienne, S.L.; Frank, P.I.; David, P.D. *Fundamentals of Heat and Mass Transfer*, 4th ed.; Wiley: New York, 2001.
66. Crapiste, G.H.; Whitaker, S.; Rotstein, E. Drying of cellular material. *Chemical Engineering Science* **1988**, *43*(11), 143–159.
67. Holland, C.D. *Fundamentals and Modeling of Separation Processes*; Prentice Hall: Englewood Cliffs, NJ, 1975.
68. Treybal, R.E. *Mass-Transfer Operations*, 3rd ed.; McGraw-Hill: New York, 1987.
69. McCabe, W.L.S.; Harriot, P. *Unit Operations of Chemical Engineering*; McGraw-Hill, International Edition: New York, 1993.
70. Badger, W.L.B. *Introduction to Chemical Engineering*; McGraw-Hill: Tokyo, 1980.
71. Geankoplis, C.J. *Transport Processes and Unit Operations*; Prentice Hall: Englewood Cliffs, NJ, 1993.
72. García, M.A.; Ragazzo, A. Mathematical modeling of continuous dryers using the heat and mass transfer properties and product–air equilibrium relation. *Drying Technology* **2000**, *18*(1–2), 67–80.
73. Ratti, C.; Mujumdar, A.S. Simulation of packed-bed drying of foodstuffs with flow reversal. *Journal of Food Engineering* **1995**, *26*(3), 259–271.
74. Giner, S.A.; Mascheroni, R.H.; Nellist, M.E. Cross-flow drying of wheat. A simulation program with a diffusion-based deep-bed model and a kinetic equation for viability loss estimations. *Drying Technology* **1996**, *14*(7–8), 1625–1671.
75. Spencer, H.B.A. Mathematical simulation of grain drying. *Journal of Agricaltural Engineering Resources* **1969**, *14*(3), 226–235.
76. Kiranoudis, C.T. Design of batch grape dryers. *Drying Technology* **1998**, *16*(1/2), 141–162.
77. Ratti, C.; Crapiste, G.H. A generalized drying curve for hygroscopic shrinking materials. In *Drying 92*, Montreal, Quebec, Canada, August 2–5; Mujumdar, A.S., Ed.; Elsevier: Amsterdam, 1992; 864–874.

78. Cemeroğlu, B.; Acar, J. Meyve ve sebze is_leme teknolojisi. Gıda Teknolojisi Derneği, No: 6. Ankara, Turkey, 1986.
79. Toğrul, I.T.; Pehlivan, D. Modelling of thin layer drying kinetics of single apricot. *Journal of Food Engineering* **2003**, *58*, 23–32.
80. Ragab, K.; Zhongli, P.; Adel, S.; Bruce, R.H.; Sherief, M. Moisture diffusivity of rough rice under infrared radiation drying. *Food Science and Technology* **2011**, *44*(81), 1126–1132.
81. Nathakaranakule, A.; Jaiboon, P.; Soponronnarit, S. Far-infrared radiation assisted drying of longan fruit. *Journal of Food Engineering* **2010**, *100*(4), 662–668.
82. Basman, A.; Yalcin, S. Quick-boiling noodle production by using infrared drying. *Journal of Food Engineering* **2011**, *106*(3), 245–252.
83. Gabel, P.Z.; Amaratunga, K.S.P.; Harris, L.J.; Thompson, J.F. Catalytic infrared dehydration of onions. *Journal of Food Science* **2006**, *71*(9), E351–357.
84. Mongpraneet, S.A.T.; Tsurusaki, T. Accelerated drying of Welsh onion by far infrared radiation under vacuum conditions. *Journal of Food Engineering* **2002**, *55*(2), 147–156.
85. Lin, Y.P.; King, V.A.E. Effects of far-infrared radiation on the freeze-drying of sweet potato. *Journal of Food Engineering* **2005**, *68*(2), 249–255.
86. Kouzeh, K.M.; Roozen, J.P.; Pilnik, W.A modified procedure for lowtemperature infrared radiation of soybeans.II. Inactivation of lipoxygenase and keeping quality of full fat flour. *Lebensmittel Wissenschaft und Technology* **1982**, *15*(3), 139–42.
87. Arntfield, S.D.; Malcolmson, L.J.; Watts, B.M.; Cenkowski, S.; Ryland, D.; Savoie, V. Reduction in lentil cooking time using micronization: Comparison of 2 micronization temperatures. *Journal of Food Science* **2001**, *66*(3), 500–505.
88. Meeso, N.A.; Madhiyanon, T.; Soponronnarit, S. Influence of FIR irradiation on paddy moisture reduction and milling quality after fluidized bed drying. *Journal of Food Engineering* **2004**, *65*(2), 293–301.
89. McCurdy, S. Infrared processing of dry peas, canola, and canola screenings. *Journal of Food Science* **1992**, *57*(4), 941–944.
90. Maxcy, R.B. Fate of post-cooking microbial contaminants of some major menu items. *Journal of Food Science* **1976**, *41*, 375–378.
91. Olsson, E.E.M.; Tragardeh, A.C.; Ahrné, L.M. Effect of near-infrared radiation and jet impingement heat transfer on crust formation of bread. *Journal of Food Science* **2005**, *70*(8), E484–491.
92. Khan, M.A. Quality assessment of ground beef patties after infrared heat processing in a conveyorized tube broiler for foodservice use. *Journal of Food Science* **1985**, *50*, 707–709.
93. Burgheimer, F.S.M.; Nelson, A.I. Effect of near infrared energy on rate of freeze drying of beef spectral distribution. *Journal of Food Science* **1971**, *36*(1), 273–276.
94. Muriana, P.G.N.; Robertson, W.; Jordan, B.; Mitra, S. Effect of prepackage and postpackage pasteurization on postprocess elimination of *Listeria monocytogenes* on deli turkey products. *Journal of Food Protein* **2004**, *67*(11), 2472–2479.
95. Tanaka, V.P.; Scheerlinck, N.; Morita, K.; Iwasaki, K.; Nicolaı, B. Investigation of far infrared radiation heating as an alternative technique for surface decontamination of strawberry. *Journal of Food Engineering* **2007**, *79*, 445–452.
96. Hebbar, U.H.; Ramesh, M.N. Optimisation of processing conditions for infrared drying of cashew kernels with testa. *Journal of the Science of Food and Agriculture* **2005**, *85*(5), 865–871.
97. Pan, Z.L.; Shih, C.; McHugh, T.H.; Hirschberg, E. Study of banana dehydration using sequential infrared radiation heating and freeze-drying. *LWT - Food Science and Technology* **2008**, *41*(10), 1944–1951.
98. Prevolnik, M.; Skrlep, M.; Janes, L.; Velikonja-Bolta, S.; Skorjanc, D.; Candek-Potokar, M. Accuracy of near infrared spectroscopy for prediction of chemical composition, salt content and free amino acids in dry-cured ham. *Meat Science* **2011**, *88*(2), 299–304.
99. Boudhrioua, N.; Bahloul, N.; Ben Slimen, I.; Kechaou, N. Comparison on the total phenol contents and the color of fresh and infrared dried olive leaves. *Industrial Crops and Products* **2009**, *29*(2–3), 412–419.
100. Shi, J.L.; Pan, Z.L.; McHugh, T.H.; Wood, D.; Hirschberg, E.; Olson, D. Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating. *LWT - Food Science and Technology* **2008**, *41*(10), 1962–1972.
101. Wanyo, P.; Siriamornpun, S.; Meeso, N. Improvement of quality and antioxidant properties of dried mulberry leaves with combined far-infrared radiation and air convection in Thai tea process. *Food and Bioproducts Processing* **2011**, *89*(C1), 22–30.
102. Zhu, Y.; Pan, Z.L.; McHugh, T.H. Effect of dipping treatments on color stabilization and texture of apple cubes for infrared dry-blanching process. *Journal of Food Processing and Preservation* **2007**, *31*(5), 632–648.
103. Zhu, Y.; Pan, Z.L.; McHugh, T.H.; Barrett, D.M. Processing and quality characteristics of apple slices processed under simultaneous infrared dry-blanching and dehydration with intermittent heating. *Journal of Food Engineering* **2010**, *97*(1), 8–16.
104. Zhu, Y.; Pan, Z.L. Processing and quality characteristics of apple slices under simultaneous infrared dry-blanching and dehydration with continuous heating. *Journal of Food Engineering* **2009**, *90*(4), 441–452.
105. Nowak, D.; Lewicki, P.P. Quality of infrared dried apple slices. *Drying Technology* **2005**, *23*(4), 831–846.
106. Pan, Z.L.; Khir, R.; Godfrey, L.D.; Lewis, R.; Thompson, J.F.; Salim, A. Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality. *Journal of Food Engineering* **2008**, *84*(3), 469–479.
107. Dondee, S.; Meeso, N.; Soponronnarit, S.; Siriamornpun, S. Reducing cracking and breakage of soybean grains under combined near-infrared radiation and fluidized-bed drying. *Journal of Food Engineering* **2011**, *104*(1), 6–13.
108. Sakai, N.F.A.; Hanzawa, T. Heat transfer analysis in a food heated by far infrared radiation. *Nippon Shokuhin Kogyo Gakkaishi* **1993**, *40*(7), 469–477.
109. Hebbar, H.U.; Vishwanathan, K.H.; Ramesh, M.N. Development of combined infrared and hot air dryer for vegetables. *Journal of Food Engineering* **2004**, *65*(4), 557–563.
110. Jaturonglumlert, S.; Kiatsiriroat, T. Heat and mass transfer in combined convective and far-infrared drying of fruit leather. *Journal of Food Engineering* **2010**, *100*(2), 254–260.
111. Kumar, D.G.P.; Hebbar, H.U.; Sukumar, D.; Ramesh, M.N. Infrared and hot-air drying of onions. *Journal of Food Processing and Preservation* **2005**, *29*(2), 132–150.
112. Afzal, T.M.; Hikida, Y. Energy and quality aspects of combined FIR–convection drying of barley. *Journal of Food Engineering* **1999**, *42*, 177–182.
113. Bekki, E. Rough rice drying with a far-infrared panel heater. *Journal of Japan Society Agricalture Machinery* **1991**, *53*(1), 55–63.
114. Institotation of Agricultural Machinery. Recirculating Batch Grain Dryer Using Far-Infrared Radiation. http://www.brain.go.jp/Organ/sei0301e.htm. Accessed July 25, 2004.
115. Datta, A.K.; Ni, H. Infrared and hot-air-assisted microwave heating of foods for control of surface moisture. *Journal of Food Engineering* **2002**, *51*(4), 355–364.
116. Wang, J.; Sheng, K.C. Far-infrared and microwave drying of peach. *LWT - Food Science and Technology* **2006**, *39*(3), 247–255.
117. Tireki, S.; Sumnu, G.; Esin, A. Production of bread crumbs by infrared-assisted microwave drying. *European Food Research and Technology* **2006**, *222*(1–2), 8–14.

118. Lin, Y.P.; Tsen, J.H.; King, V.A.E. Effects of far-infrared radiation on the freeze-drying of sweet potato. *Journal of Food Engineering* **2005**, *68*(2), 249–255.
119. Chakraborty, R.; Mukhopadhyay, P.; Bera, M.; Suman, S. Infrared-assisted freeze drying of tiger prawn: Parameter optimization and quality assessment. *Drying Technology* **2011**, *29*(5), 508–519.
120. Das, I.; Das, S.K.; Bal, S. Drying kinetics of high moisture paddy undergoing vibration-assisted infrared drying. *Journal of Food Engineering* **2009**, *95*(1), 166–171.
121. Nimmol, C.; Devahastin, S.; Swasdisevi, T.; Soponronnarit, S. Drying and heat transfer behavior of banana undergoing combined low-pressure superheated steam and far-infrared radiation drying. *Applied Thermal Engineering* **2007**, *27*(14–15), 2483–2494.
122. Nimmol, C.; Devahastin, S.; Swasdisevi, T.; Soponronnarit, S. Drying of banana slices using combined low-pressure superheated steam and far-infrared radiation. *Journal of Food Engineering* **2007**, *81*(3), 624–633.
123. Mongpraneet, S.A.T.; Tsurusaki, T. Accelerated drying of Welsh onion by far infrared radiation under vacuum conditions. *Journal of Food Engineering* **2002**, *55*(2), 147–156.
124. Yunhong, L.; Wenxue, Z.; Lei, L.; Xin, L.; Huichun, Y. A Mathematical model for vacuum far-infrared drying of potato slices. *Drying Technology* **2014**, *32*(2), 180–189.
125. Rudobashta, S.; Zueva, G.; Zuev, N. Mathematical modeling and numerical simulation of seeds drying under oscillating infrared irradiation. *Drying Technology* **2014**, *32*(11), 1352–1359.
126. Xu, B.G.; Zhang, M.; Bhandari, B. Temperature and quality characteristics of infrared radiation–dried kelp at different peak wavelengths. *Drying Technology* **2014**, *32*(4), 437–446.
127. Qi, L.-L.; Zhang, M.; Mujumdar, A.S.; Meng, X.-Y.; Chen, H.-Z. Comparison of drying characteristics and quality of shiitake mushroom (*Lentinus edodes*) using different drying methods. *Drying Technology* **2014**, *32*(15), 1751–1761.
128. Yinqiang, S.; Yang, J.; Qiuhong, Y.; Hua, L.; Wang, H. Infrared, convective, and sequential infrared and convective drying of wine grape pomace. *Drying Technology* **2014**, *32*(6), 686–694.
129. Roknul, A.S.M.; Zhang, M.; Mujumdar, A.S.; Wang, Y. A comparative study of four drying methods on drying time and quality characteristics of stem lettuce slices (*Lactuca sativa* L.). *Drying Technology* **2014**, *32*(6), 657–666.
130. Islam, Md.R.; Thaker, K.S.; Mujumdar, A.S. A diffusion model for a drum dryer subjected to conduction, convection, and radiant heat input. *Drying Technology* **2007**, *25*(6), 1033–1043.
131. Islam, Md.R.; Ho, J.C.; Mujumdar, A.S. Simulation of liquid diffusion-controlled drying of shrinking thin slabs subjected to multiple heat sources. *Drying Technology* **2003**, *21*(3), 413–438.
132. Rosenthal, I. *Electromagnetic Radiations in Food Science*; Springer-Verlag: Berlin, 1992.