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Radio Frequencey Heating: A Review With Food Applications.

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ABSTRACT

With an advancement in the food, processing techniques consumer trend is now shifting towards minimally processed food products, and Radio Frequency (RF) is one of those techniques. Many publications previously have evolved on this technology but most of them were touching just some parts of it. In this review, the focus was on touching the every important aspect of radio frequency with the main emphasis towards its benefits, applications and dielectric properties of food materials, which are very crucial to understand for developing a good effective RF system. In the end, authors have identified some of the areas in which still research is required to further improve and strengthen the activity for this non-thermal heat processing technique.
Keywords: Radio frequency, Non-thermal heating,Dielectric properties, Applications

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INTRODUCTION

Traditionally the methods used for heating of food materials were hot water, air, steam or a combination of any of these. These are primitive and slow methods because of the heat transfer from the upper part to the inside and it takes a lot of time in this process. The bigger the sample size, longer would be the time taken by the heat to transfer[1]. This slow transfer of heat in food materials results in many quality related issues such as loss of flavor, color, and valuable nutrients. This pressed the need for a technology more efficient in heating with minimum or no side effects on the product quality hence the use of non-thermal heating methods such as Radio Frequency (RF) and Microwave (MW) heating grabbed the attention of food processors.

Because of the fact that many of foods materials are dielectric in nature hence an alternative dielectric heating method was in the mid of 20th century was introduced because it possess many advantages over conventional heating methods such as; heating in a more uniform pattern, rapid heating, as a result, reducing the processing time and above all improved product quality. In recent time, this technology is widely used and is included in one of the efficient and quick methods for heating of food materials[2, 3]. Both Radio Frequency (RF) and microwave heating are included in dielectric heatingZhao, Flugstad [4].

The efficiency of dielectric heating relies on the two aspects first the mechanism of action and second the dielectric properties of the material on which RF waves are applied. Therefore, the focus of this review in on the mechanism of action of these waves and knowledge about the dielectric properties of food materials what are they, their importance and methods how they are determined.

History of Radio Frequency:

Michael Faraday in 1882 guessed the presence of electromagnetic fields. Later after four decades, James Clerk Maxwell statistically forecasted the reality and performance of radio waves. Heinrich Hertz comes then who experimentally confirmed Maxwell's concept in 1885. Jacques dÁrsonval then used Hertz's primary high-frequency oscillator to perform trials on its effects of high frequency (500–1500 kHz), little voltage Ac (Alternating Current) on wildlife. Jacques originates the main consequences of RF on animals was the heat production finally this finding led to the primary high-frequency heat therapy piece in the Hotel-Dieu Hospital in Paris in 1895 after Jacques consent. Afterwards World War II the use of this technology was documented widely.Sherman in 1946 was the first person who explained the production of electric heat and all its possible uses in different kind of food processing techniques.Further, he suggested the possible use of RF technology for vegetables, meat processing, the production of heat, and suggested possible applications for the processing of food but unfortunately, he was not able to make it marketable as the cost of this sophisticated technology was a bit on the higher side at that time

The working of RF heating was studied in 1940's. These studies were focused more on the cooking of food products rather than just heating such as vegetables, meat, and bread[5, 6]. However, it was not a very big success because of the high processing cost in that era. In 1960's there was a shift in the application of RF energy and now it was being used more for the thawing of frozen food products it proves to be a good success at industrial scale and helped a lot in the establishment of many commercial lines[7, 8]. In late 1980's and early 1990's this Radio Frequency also got popular for the drying of bakery products after baking because of less energy consumption and more improved product quality as compared to the traditional baking methods[9-12]. It was applied with success on snack food and cookies for post-baking drying. When regulations about food safety started getting strict in 1990's than this technology was also started to be used in the meat products for sterilization and pasteurization. [13-16]

Working of Radio Frequency:

As part of the electromagnetic spectrum (EM), the RF waves works in the frequency range of (0.003-300MHz). The working principle of these waves is that they basically generate heat in the materials via ionic polarization or the rotation due to dipole moment e.g. in foods it works on this same principle.[17]. The EM spectrum of radio frequency shows that they reside in between the range of 1-300 MHz but at a mass scale they are normally used in an array between 10-50 MHz [18]**.** In other words, the working mechanism for easy understanding is elaborated as that the object to be treated is placed between the high voltage electrodes. In which alternating current passes. These electrodes are located at corresponding to each other. As the Ac current passes through the object, it forces the polar molecules to line up in a conflicting in order to nullify the effect of applied Ac field or match with it, which results in an increase of temperature, because of the polar charges, interrelating with the adjacent polar molecules. This interrelation results in a loss of friction and matrix in molecules. The frequency of AC field is directly proportional to the vigor imparted on the object in the medium until the occurrence gets so high that polar molecules fail to keep up with the pace of applied AC field due to certain matrix limits. This point at which the matrix limit is reached known as ''Debye resonance". At this point of an electric filed extreme energy could be imparted in the medium at which the object is placed.[19]**.** For use in commercial, scientific and therapeutic purposes the limits of RF frequencies are set as 13.56 ± 0.00678, 27.12 ± 0.16272 and 40.68 ± 0.02034 MHz [18]**.** For beneficial execution of RF technology on products it is important to have knowledge of the ''Dielectric constant'' or ''Loss Factor'' of that material. It helps in heating the object remotely using RF waves and eventually not going to result in an increase of temperature of environment surrounding the object. Which is the ensuing goal for using this technology that surroundings of the sample remain undisturbed. This loss factor of each object is depending basically on the frequency being used hence for best results the determination of dielectric constant is very important to find out the finest frequency limit for working on that specific object[20]

RF heating takes place when food materials come in interaction with the electromagnetic waves. Food materials comprise of free ions, which are displaced when they are placed in an alternating electromagnetic field. These free ions respond to the changes, which are taking place in the outside field. The energy which they absorb during their response to the external field is released in the form of heat [21]

One theory is that when the alternating field is applied to the food the ions starts moving towards opposite ends that are positive towards negative and negative towards positive. This movement is termed as ionic depolarization due to resistant heating takes place. The polarity keeps on changing at high frequencies due to this non-static nature it results in the production of heat. The continuously to and fro oscillating ions inside the product are responsible for the production of heat due to friction[22]. As the dissipated heat is in volumetric form this is the reason this type of heating is rapid when it comes in a comparison between the other heating methods which are used conventionally[21]

Conventional and other Electromagnetic heating vs. RF:

Conventional heating most of the time takes place in batch or continues type-processing operations in which the product may or may not be packed. But if we just keep these aspects aside and keep in mind that once the outer surface of product comes in contact with heat it is transferred to the inside of product either by conduction or convection. Both these methods could rule each other at any stage depending upon the heating process. Convection is considered as a faster medium of heat transfer than conduction. In solid food materials, the transfer of heat takes place by conduction and to ensure that the inner part of food is also heated we have to heat it for a longerperiod. Here stand up a chance for the outer surface of the product to beoverheated especially in solid food materials. While in the RF, heating the heat is generated because of the rays passing through the food material and interacting with it. It rules out the chances of the outer surface to get overheated because the heat produced is volumetric [23]

Electromagnetic heating's (EM) are of different types and their mechanism of application is what defines them. In Microwaves heating the waves, strike the product from different directions while in Ohmic heating the product has to come in direct contact with the electrodes pair through which an alternating current of low frequency 50-60 Hz passes into it. The reason for using low frequencies is that because it helps in the cyclic changes to avoid electrolysis althoughSamaranayake, Sastry [24]showed that high frequencies reduce further chemical reactions. In addition, electrodes are used in the RF heating but the electric field applied is higher to generate heat. But in RF no physical contact of the product is required with the electrodes the waves have the capacity the go deep into the normal packagings such as plastic or cardboard. However, in Ohmic heating the product has to be naked and should meet the electrodes or packed in such a material, which has some conductive regions through which the electrical current should pass into it.

There exists a lot of difference between RF and Microwaves because the wavelength and frequency are not directly proportional to each other as the wavelength of RF waves are longer than Microwaves. As the waves penetrate deep into the product they get weaken resulting in a very rapid decrease of their energy. Normally the penetration depth (d_p) is defined as the depth at which the surface energy of the waves is decreased by 1/e (1/2.72). It depends directly on the wavelength. Therefore, it is evident that radio frequency can go deep into the product without the chances of overheating the outer surface and chances are of developing cold/hot spots are also on the lower side, which are very common in Microwave heating. The biggest advantage of RF over MW heating is that it offers to heat in a more uniform pattern because of more penetration power and have a simple and uniform field pattern than MW heating [23].

Applications of RF in food processing:

Application of Radio Frequency heating are comparatively less common in food processing than Microwave heating. But [25, 26] published a lot of data about the applications of RF in food processing and below are listed some of them.

Meat processing:

Meat and its related products are at top of the list about which most of the data has been published so far.Laycock, Piyasena [27] compared the heat treatment of three different meat products cooked by RF heating and in a water bath and found that RF heating reduced the cooking time to 25 times lesser than the traditional method of water bath cooking. Further, they found that the RF cooked meat surface heated more rapidly than the center, which authors believe that may be due to the non-uniform distribution of salt. The RF cooked meat samples were also acceptable in terms of color and juice loss as it was on the very much lower side in comparison with the water bath treated samples.

Orsat, Bai [28] used RF for the pasteurization of ham slices packaged in a vacuum and concluded that with a suitable packaging the RF could help to increase the shelf life of ham slices, by cutting down the loss of moisture and lowering the bacterial load. Overall, the product was good in quality and sensory parameters.

Disinfection and Post-harvest treatment of fruits:

As the environmental concerns about the fumigants used for the disinfection are raising for example methyl bromine which is about to be banned because it is considered as a culprit for ozone depletion moreover also not safe and healthy. So in such situations, RF is being counted as an alternative for the disinfection and treatment of fruits [23]

Tang, Ikediala [29] developed a kinetic study model in which the author presented a study for mortality of pest's insects and stated the potential for developing HTST (High-TemperatureShort-Time) treatment to overcome the issue of codling moth in many fruits. Wang, Tang [30] successfully disinfected walnuts by heating them at 55^{o}C using RF and concluded that all the 5th instar navel orange worm were found dead with the RF application of 27MHz-12Kw. These worms are notorious because of their resistance to heat.

Application in liquid foods:

Due to rapid heating and deep penetration power RF is a striking alternative technology for the processing of liquid foods. Awuah, Ramaswamy [31] used RF (2Kw, 27.12MHz) to figure out most suitable conditions for the inactivation of E. coli and Listeria substitute in milk under a non-turbulent continuous flow. [32-34] accessed the application of RF in juice and apple ciders for the inactivation of microorganisms they concluded that this technology has the capacity to inactivate the E. coli up to a maximum 4.8 log cycle in apple cider, 3 logs in apple juice and 3.3 in orange juices respectively. They also found that apart from inactivating the microorganism's radio frequency waves also have no effect on the loss of ascorbic acid or browning due to enzymes in the orange juice.

Application in enzymes inactivation:

Lyman, Burda [35]studied the application of RF waves on cotton seeds and found that those cotton seeds which were heated using radio frequency show less formation of FFA (free fatty acids) due to which a smell is produced which is not enjoyed a lot. [36]stated that in soybeans those enzymes responsible for the inhibition of growth were inactivated using RF waves. As compared to the control samples the RF, treated soybean seeds were also upright in quality. Oberndorfer and Lücke [37] found that RF heating increases the yield of oil in rapeseeds if they are preheated at different temperatures using RF before pressing. FurtherIrfan and Pawelzik [38]added to this research that the quality of oil also remains the same in rapeseeds who were preheated using RF and no measurable adverse effects were noted. Cserhalmi, Márkus [39] stated that the pungent smell of yellow mustard seeds could be reduced by heating them with RF because it deactivated the myrosinase enzyme responsible for the pungency in seeds. These results were more testified byIldikó, Klára [40]when the author inactivated the same enzyme in mustard seeds also and they also stated that the RF treated seeds have the same colloid-chemical and chemical composition as that of untreated samples. Hence, it is evident that using RF for enzymes inactivation possess no considerable threat to other properties of products.

Role of Dielectric properties for application of RF:

DP or dielectric properties are the main the factors which give us the knowledge about a particular material is going to act when EM (electromagnetic) energy is provided to it during the process of dielectric heating. These parameters are of special importance especially for those food products, which are processed using the novel heating methods such as radio frequency (RF) or microwaves (MW). It is very important to understand fully the knowledge of DP of a certain foodstuff to figure out the changes, which may take place when it would be subjected at different frequencies and temperatures using RF[41].

Among all dielectric properties, two are most important energy loss and storage for the electric permittivity. As these aspects are due to the frequency, temperature and composition parameters of the object under study. Permittivity (ε) and permeability are two significant parts in which we the food materials dielectric properties are divided. Permeability is normally same as that of free space and hence is not believed to have any role in the heating of food stuff[42]. However, permittivity is what determines loss factor (ε″) and dielectric constant (ε′) both have a solid role to play in the heating of food materials. Both ε′ and ε″ are parts of ε and they are stated as:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

ε′ = capacity of the object material to transmit, reflect and absorb energy from electric part of the electrical field[43]. It remains unchanged under constant conditions at a specified frequency. It also gives an idea about the medium that how much it is polarized when an electric field is applied to it.

ε″= estimates the energy loss from electrical field, which is proportional to the energy absorbed and converted into heat when the waves pass through that material.

$$j=\sqrt{-1}$$

So low ε″ means that lesser absorbance of energy and ultimately less heat production because this type of material is very transparent for the electromagnetic energy. However, it is important to mention that apartfrom just dielectric properties of food materials other parameters like specific heat they also have some of the impacts in helping the rise of temperature in product.

Methods used for determining the dielectric properties:

Içier and Baysal [44] mentioned various methods for determining the dielectric properties of materials. Overall, the choice of a measuring instrument depends on the frequency range, accuracy, and material. The cost and accessibility of equipment are also the determining factors [45].

Most popular methods used for the measurement of dielectric properties are three. Which are as follows:

Open-ended coaxial probe:

This method relies on a line, which is coaxial, and it ends tersely at the angle where the material is present, for testing (

Figure *1*)the advantage of using this method is that if offers measurements in a broad range and also minimizes the chances of disturbance in a sample. It is also very easy to use because it does not require any special container or a definite sample shape [46-49]

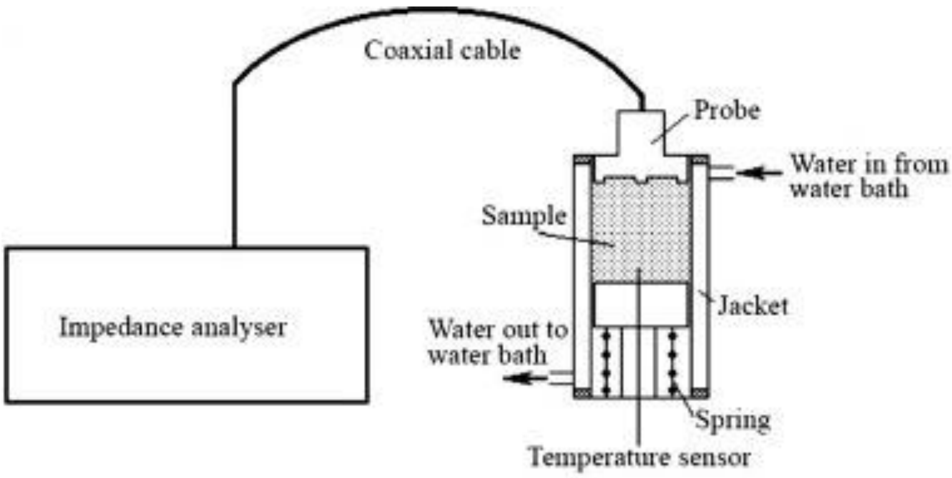

Figure 1: Open-ended coaxial probe diagram. [1]

The transmission line method:

In this method, the sample is placed inside a closed transmission line as the (
Figure *2*) schematic diagram shows. It is important that inside of the transmission line should be filled precisely with the sample. In comparison with the first method, this method is considered as the more sensitive and accurate in measurement. However, the drawback is that it consumes a lot of time and not easy to implement.

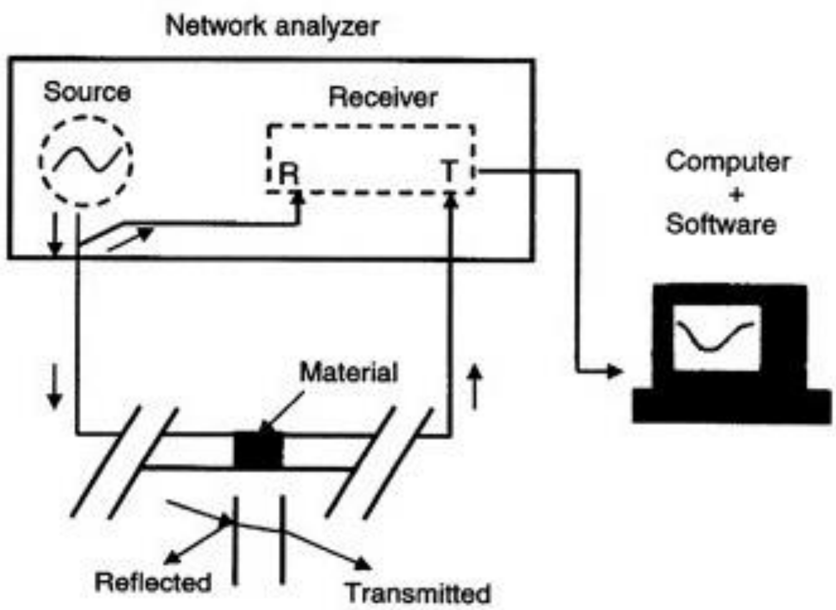

Figure 2: Diagram of transmission line method [2]

Resonant cavity method:

The dielectric property is computed by measuring changes in the cavity power and resonance frequency when a sample whose geometry is known placed inside the cavity (
Figure 3). This method is accurate and more suitable especially for those materials, which has a very low dielectric loss factor. The limitation of using cavity method is that it gives the DP at only fixed frequency [43]

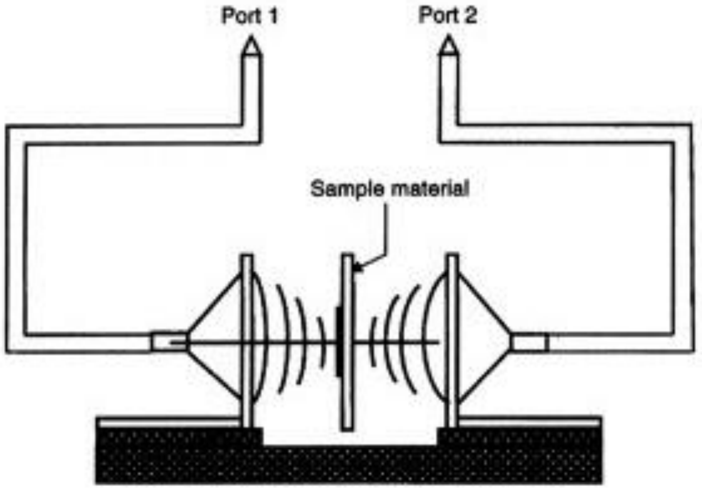

Figure 3: The cavity method [2]

Factors affecting dielectric properties of foods:

The dielectric properties of a material depend upon a number of factors. Some are intrinsic such as the structure and composition of material while other are extrinsic which are depending upon the process parameters such as frequency and temperature. The age factor of food materials also has a role to play to some extent[41]. Some of the major factors on which the dielectric properties of materials depends are:

Composition:

In food materials, normally water is the major component and its influence largely depends on how it behaves with other components such as salts and minerals. Dielectric heating is greatly affected by the presence of water. Water absorbs most of the energy of EM waves and hence those products in which more water content is present gets heated in a good manner. Komarov, Wang [50]stated that high levels of moisture are directly related to the loss factor and dielectric constant of foods. However, high moisture may also put the bounded water in motion resulting in loss of essential moisture content from the product [18]

Density:

Ryynänen [51] was the scientist who found that the physical arrangement of a material also has a role to play in the dielectric properties of a material. Further [52]confirmed this belief by stating that the behavior of electromagnetic waves interaction is affected by the density of a material. This was further proved byBerbert, Queiroz [53]in which the author gave the example of coffee grain. Berbert and his coworkers found that the permittivity was on the lower side when the bulk density of coffee grains was lower and when the bulk was higher the permittivity was on the higher side. From this experiment, they concluded that moisture content and bulk density certainly has affected the dielectric properties of coffee grains. [54]Also, found same results when they conducted experiments on the flour of chickpea. They stated that loss factor and dielectric constant increases as the density and moisture content of chickpea flour increases.

Temperature:

Depending on the ionic conductance, of a material normally if the temperature increases at the lower frequencies the loss factor also increases[55] and when the frequency is higher if temperature is increased the loss factor decreases because the water which is in free form gets dispersed[56]. Hence, it is believed that the role of temperature in affecting the dielectric properties of is very multifaceted it could go on the sides either (decrease or increase) depending upon the type of material. Tang [18]Stated that the temperature alone cannot affect the dielectric properties of a material but it is depending on many another factors also such as the moisture, composition of the food material, contents of salt and the frequencies, which are going to be used for the application.

Frequency:

Apart from those materials, that does not absorb any energy from the applied magnetic field (loss factor at very low side), the dielectric properties are largely depending upon the frequencies, which are used[41]. When an electric field is applied, the molecules gets polarized resulting in the everlasting dipole moment, which makes the frequency an important factor to influence the dielectric properties of a material[57].Liu, Tang [58]used a customized Debye equation to find out the dependence of loss factor on frequency in bread. The ionic conduction between 1-1800 MHz was found to be the biggest contributor, at high frequencies the dipole movement of free water was manipulated accordingly. In (

Figure ***4***)both the effect of frequency and temperature could be observed.

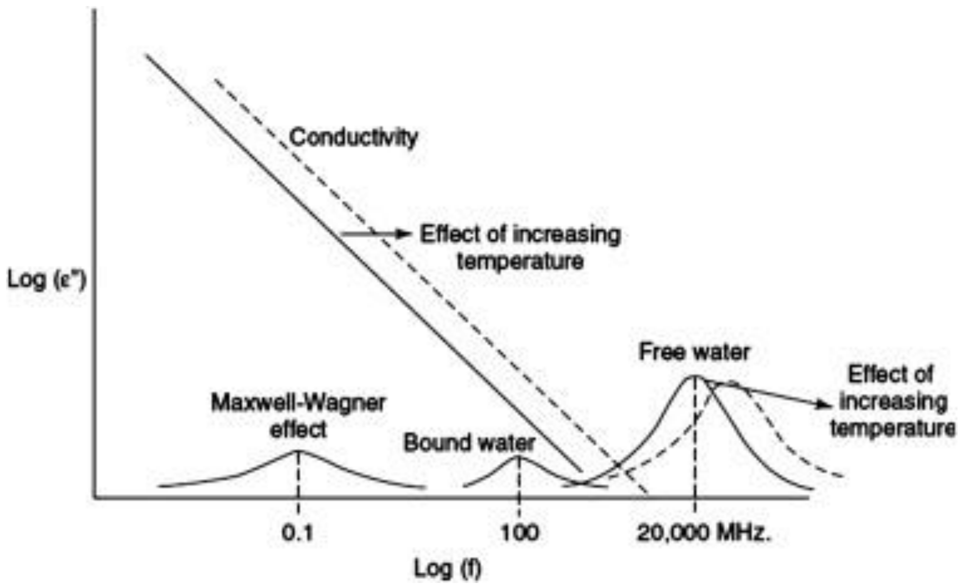

Figure 4: Role of different mechanisms in loss factors of materials with high moisture content as function of temperature and frequency [3]

Storage length:

As the moisture content during the storage of a product varies, it influences the dielectric properties of the product also. [59] experimented the change in DP of mangoes during the storage from 0, 4, 8, and 16 days at a constant temperature of 21^oC. The authors found that both the loss factor and dielectric constant was decreased over the period because of the moisture loss and pH increase. A similar type of study was conducted by on shell eggs they used the probe method to figure out the dielectric properties of hen shell in a frequency range of 10 to 1800MHz. measurements were done at selected three points of the eggs on 1, 2, 4, 8, and 15th day of storage at 22^oC. The results showed that dielectric properties and loss factor increased until the last day of storage by 22% at 20MHz[60]. While in the case of apple storage at 4^oC and 24^oC for more than

70 days the loss and dielectric constant surprisingly remained the same in similar frequency range used to determine the dielectric properties of hen shell[61].

Dielectric properties of some vegetables and fruits:

In **Error! Reference source not found.** updated data of commonly used vegetables and fruits at most common frequencies are listed. The frequency range listed in table 1 is the most widely used in the RF heating process.

Table 1: Dielectric properties of some vegetables and fruits

Fruit or Vegetable	Temperature (°C)	Moisture Content % w.b	Frequency Dielectric Constant		Frequency loss factor		Reference
			27.12MHz	915MHz	27.12MHz	915MHz	
Golden Apple	20	–	72.5	74.3	120.4	8.5	[1]
Avocado	20	–	115.7	59.9	699.6	27.4	[2]
	50	–	137.9	57.9	1136.2	39.8	
Banana	23	78	–	64.0	–	19.0	[3]
Carrot	23	87	_	59.0	_	18.0	[3]
Grape	23	82	–	69	–	15	[3]
Lemon	–	91	–	73	–	15	[3]
Lime	–	90	_	72	–	18	[3]
Logan	20	–	75.2	68.2	230.1	13.3	[2]
Mango	_	86	_	64	–	13	[3]
Orange	20	–	84	72.9	223.3	16.5	[1]
Onion	–	92	–	61	–	12	[3]
Peach	–	90	–	70	–	12	[3]
Potato	–	79	–	62	–	22	[3]
Strawberry	–	92	–	73	–	14	[3]
Turnip	–	92	–	63	–	13	[3]
White Sapote	20	–	76	62.6	258.6	24	[2]
	50	–	74.5	60.3	433.1	24.9	

Research areas in RF heating:

In last less than a decade, considerable scientific papers have been published on the applications of Radio Frequency (RF) and it looks like that in future same pace is going to be maintained. However, the fact of matter is that apartofa such number of publications and considerable advantages over other non-thermal heating process this technology was not taken up at larger industrial scale Marra, Zhang [23]pointed out some the main reason behind this slow uptake:

i. So far, most of the focus is on the application in meat industries while the other wide array of foods materials has been neglected until today. In-depth knowledge on all quality aspects of foods is also not been studied so far and a substantial information on this part is lacking.
ii. Radio frequency has the potential to be used as sterilization technique so in this aspect a fair bit of room is present so far to publish data on the microorganism’s inactivation and finally its impact on the product.

iii. Conventional methods are understood more with respect to the distribution of temperature within the products while for RF still a lot more work is required. This is one of the potential reason for the industries in not adopting this technology, as they are more comfortable with the traditional methods because in-depth data of all aspects is available for them.
iv. The economics part of RF also needs a lot of work especially in designing large-scale systems for the industry. It would give a better understanding about the initial cost involved in the installation of this technology.
v. A pool of data on dielectric properties of packing materials along with foodstuffs is also required. This area is very important in understanding the temperature distribution aspect and especially in designing the RF system.

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