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Microwave Processing of Food and Biological Materials: Principles and Various Processing Applications

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ABSTRACT

Microwave processing is one of the novel food processing technologies that use electromagnetic radiation in the wavelength and frequency between 1 mm to 1 m and 300 MHz to 300 GHz, respectively. In this review, principles and various applications of microwave technology for food processing are addressed. A systematic literature search was conducted by using, Google Scholar and, Web of Science, Open access theses and dissertations on the principles and application of microwave processing of food were summarized. Additionally, references of each selected publication were examined to get more relevant articles. In microwave processing, the food material absorbs microwave energy directly, and internally, and converts it to heat. The technology is applicable for different unit operations in food industries such as cooking, heating, drying, pasteurization, sterilization, thawing, tempering, baking, blanching, and the extraction of important food biomaterials. Microwave processing is highly advantageous over conventional food processing techniques, in terms of retaining the nutritional content of the food and reducing processing time. Consequently, the breakthrough of the technology in food processing industry has been predicted before. However, the potential of microwave technology is not widely exhausted in Africa. It is associated with a lack of awareness, a priority setting on the application of emerging technologies for safe and high quality value added products; moreover, its high initial investment and operational power cost may become a bottleneck for food processing companies in Africa. Therefore, food innovation centres in Africa should drive high performance standards from technology adoption to improve the application of microwave technology in food industries.

Introduction

Microwaves are a form of electromagnetic radiation. It is non-ionizing radiation that causes molecular motion by the migration of ions and the rotation of dipoles, but does not cause change in the molecular structure. Microwave energy occupies a part of the electromagnetic spectrum, and it is situated in the wavelength interval between 1 mm and 1 m, and the frequency interval between 300 MHz and 300 GHz (Singh and Heldman, 2001), as indicated below in Figure 1. This electromagnetic radiation is used for the industrial processing of foods, it operates between 915 and 2450 MHz, and due to possible interference of TV and radio waves and for domestic use, at 2450 MHz (Datta and Anantheswaran, 2000), which is allocated by the International Telecommunications Union. The unique characteristic of microwaves is that as they

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travel through a glossy medium, an increase in temperature throughout the medium can be observed. This has led to many applications in the food and agricultural industries and our daily life.

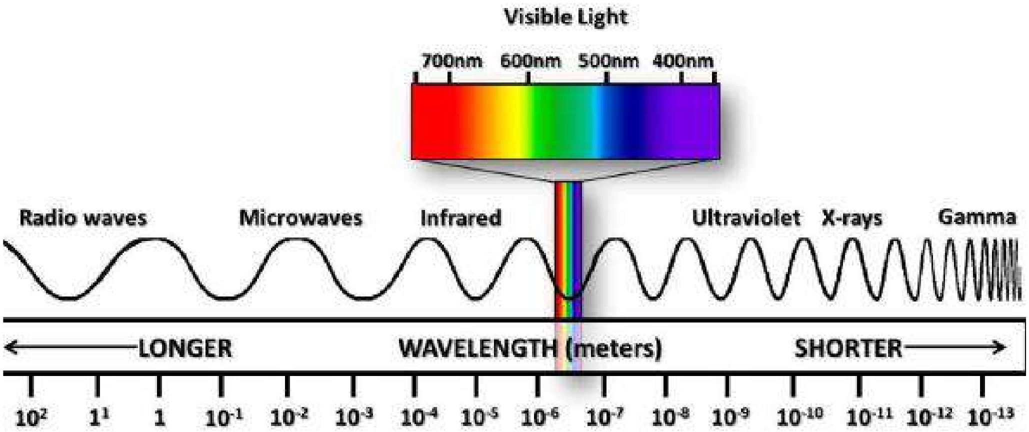

Fig. 1. Electromagneticspectrum (Hauff, 2005)

Microwave heat generation is caused by the interaction between the microwave and the medium by which a part of the electromagnetic energy is dissipated volumetrically in the form of heat (Tang et al., 2002). This technology obtained high acceptability in the food industry due to its high heating rates, short cooking time, uniform heating, simplicity of operation, safe handling, and low maintenance cost (Salazar-Gonzalez et al., 2012). In addition, it changes the sensory and nutritional quality of processed food to a lesser extent when compared to conventional processing methods (Vadivambal and Jayas, 2010).

Generally, microwave processing has various implications in the food processing industry, such as drying, pasteurization, sterilization, thawing, tempering, and baking of food materials (Metaxas and Meredith, 1983; Gupta and Wong, 2007). However, the technology has limitations regarding heating uniformity. Mainly, type of food, packaging material of the food, and the efficiency of the microwave itself are implicated in the non-uniform heating property of the technology. For appropriate application of microwave technology in food processing, the thermal property of the food, shape and size, orientation of the food in microwave oven, physical state of water in the food, and moisture content of the food should be considered (Krishnakumar, 2019).

Materials and methods

A systematic literature search was conducted by using, Google Scholar, Web of Science, and Open access theses and dissertations on the principles, and application of microwave processing of food and the adoption of microwave technology in Africa were summarized. Additionally, different books on novel food processing technologies were reviewed to get further information on microwave technology. Moreover, references of each selected publications were examined to get more relevant articles.

Discussion

Principles of microwave drying in food processing

The dielectric property of foods is important in understanding the microwave heating characteristics of foods. The dielectric property is the ability of a food material to convert microwave radiation into heat. The most well-known characteristic of microwave heating is volumetric heating. In volumetric heating, the food materials can absorb microwave energy directly and internally, and convert it to heat (Scott, 2012). This characteristic makes using of microwaves more advantageous than other methods of processing food. Microwave ovens employ electromagnetic waves called microwaves, that are generated by a part of the instrument called a magnetron, to heat food. This electromagnetic radiation propagates at a very high speed, around 2450 times per second. As a food item is exposed to this propagating wave, the ingredients of the food behave differently. From various ingredients of food, water molecules act in a different way and facilitate heating of the food by the activity of microwave energy. The water content of the food and the heating rate of the food have a direct relation, i.e., a higher water content means rate of heating is (Datta and Anantheswaran, 2000).

During microwaving of food, water molecules in the food item act as a magnet, since water is a polar molecule, one end with hydrogen is positively charged and the other end with oxygen is negatively charged. Like a bar magnet held on another bar magnet, when one of the magnets rotates, the other does as well. Correspondingly, due to the polar property of the water molecule and, the oscillation of microwaves during microwave processing of food, water molecules rotate like that of a bar magnet. As depicted below on Figure 2, water molecules orient themselves as per the polarity of electromagnetic radiation. This molecular rotation creates friction with the bounded medium and this leads to heat generation (Salazar-González et al., 2012).

The speed of rotation of microwaves is very high; it is around 2450 times per second. Likewise, the water molecule also rotates, 2450 times. Such rotation of water molecules in accordance with microwaves creates friction between molecules of water. This friction of water molecules becomes a source of heat for microwave processing and it warms the food by transferring the heat via convection, conduction, or radiation through food.

Main components of a microwave

The microwave system consists of a magnetron, a waveguide, a stirrer and a cooking chamber. Figure 3 depicts the schematic diagram of different components of a microwave oven.

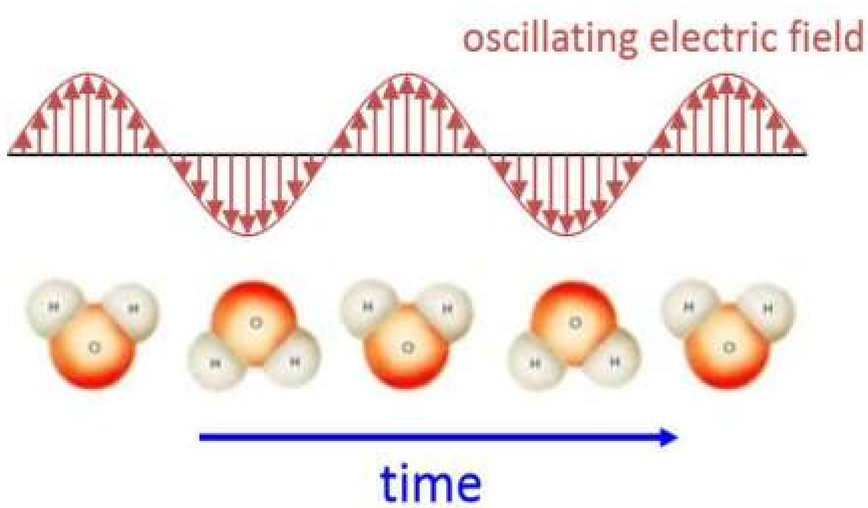

Fig. 2. Dipolar rotation of water molecules (Stein et al., 1997)

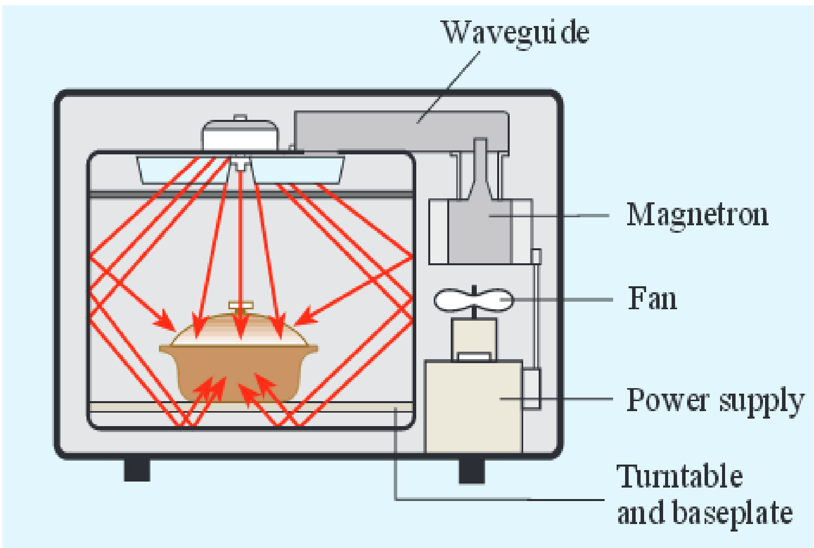

Fig. 3. Schematic diagram of a microwave oven (Hutcheon et al., 1992)

Magnetron (microwave source)

The magnetron is a tube commonly used as a source of microwaves in domestic and industrial applications (Schubert and Regier, 2005). A magnetron consists of a vacuum tube with a central electron-emitting cathode with a highly negative potential. This cathode is surrounded by a structured anode that forms cavities, which are coupled by the fringing fields and have the intended microwave resonant frequency. The interaction between a stream of electrons and the magnetic field while passing in an open cavity, which is a high powered vacuum tube, convert the electrical energy into microwaves (Schubert and Regier, 2006).

Wave guide and stirrer

The microwaves generated from the magnetron pass through a rectangular metal tube which directs the microwaves to the cooking cavity. It also prevents direct exposure between spattered food and the magnetron. The waveguides are elements that are used to guide the electromagnetic wave, consisting of hollow conductors, normally with constant cross section, rectangular, and circular forms being of most practical use. Within the waveguide, the wave may spread out in so-called modes, which define the electromagnetic field distribution within the waveguide. The stirrer distributes the microwaves from the waveguide to the food material for uniform heating (Schubert and Regier, 2005).

Cooking chamber (applicator)

The oven door is a glass panel with microwave proof mesh with holes to prevent the microwave radiation from passing through. A turn table is attached in the cooking chamber, which rotates the food products for even exposure of microwaves. Common applicators can be classified by the type of field configuration into three types: (i) near-field, (ii) single-mode, and (iii) multi-mode applicators. Multi-mode applicators play by far the most important role in industrial and domestic uses because of the typical dimensions of microwave ovens (Schubert and Regier, 2005).

Fundamentals and applications of microwaves in the food industry

Microwave energy has been used in the area of food processing for various commercial purposes. Baking, drying, frying, cooking, thawing and tempering, pasteurization and sterilization, roasting, blanching, and extraction, microwave vacuum-drying, and microwave freeze-drying are some of the commercially proven applications of this technology (Vadivambal and Jayas, 2010; Salazar-González et al., 2012). Table 1, summarizes some applications of microwaves in biomaterials processing.

Microwave drying

Microwave drying has the advantage of achieving fast drying rates and improving the quality of some food products. The energy absorption level is controlled by wet products which can be used for selective heating of the interior parts of the sample containing moisture and without affecting the exterior parts. During microwave drying, volumetric heating generates vapours inside and develops an internal pressure gradient, which forces the water outside. This prevents the shrinkage of food materials in microwave drying. Microwave drying is suitable for products with a high moisture content, like carrots, mushrooms, and cabbage, because of the high dielectric properties of water, which can quickly absorb the microwave energy (Prakash et al., 2003). The internal heat generated during microwave heating provides vapour pressure within the product, and this pumps the moisture to the surface (Turner and Jolly, 1991). But the use of microwave drying at the industry level is lower because of the non uniform heating associated with the change in the dielectric property of food materials as moisture content decreases, and it may end up with undesirable textural damage related with excessive rapid mass transport (Mullin, 1995; Zhang et al., 1998). Microwave energy combined with other drying methods can improve the drying efficiency as well as the quality of food products, which is far better than that achievable by microwave drying only or by other conventional methods only (Zhang et al., 1998).

Microwave baking

Baking is one of the dry heat cooking processes that cause several physicochemical changes in the food. Even though, some quality problems such as firmness, tough texture, lack of crust, rapid stalling, and lack of surface browning are evident on microwave baked food items (Sumnu, 2001), several literature sources indicate that baking by using a microwave is a successful application area in the food industry. Microwave-induced gluten changes, insufficient starch gelatinization, and leaching of amylose are justified as the main reasons behind firm and tough texture of microwave-baked foods. The long exposure in the conventional oven ensures the completion of the Maillard reactions responsible for browning. Since, in the case of microwave ovens heating, time is too short for the completion of the browning reaction. Consequently, in most applications, combined microwave and hot air baking reduced oven time for baking by up to 66% (Richardson 1992). Decareau (1985), reported that microwave baking resulted in a good retention of the yeasty flavour and attributed this to the lower ambient temperature conditions.

Microwave Thawing and Tempering

Thawing is conversion of frozen food into unfrozen state. It is a reverse of freezing (Archer et al., 2008). During processing of frozen food materials, they require thawing before the main cooking process, otherwise it remains uncooked in the centre or overcooked or burnt on the surface. Microwave thawing requires a shorter processing time but has a drawback of uneven or runaway heating. During runaway heating, some parts of the food item may cook and the other parts will remain frozen. This non-uniformity is associated with uneven power distribution and greater power absorption in liquid regions.

Tempering is bringing the temperature of food up to a few degrees below the freezing point (-5 to -2 °C) to retain a firm texture for subsequent processing (Archer et al., 2008). The process can be used as an alternative to thawing because complete thawing sometimes results in unnecessary energy expenditure, quality deterioration, and increased process time. Microwave tempering is preferable to the thawing process, due to its ability to handle a large amount of frozen food products at a minimum cost and, increased yield, and it can be achieved in a small space without any microbial growth (Metaxas, 1996).

Microwave pasteurization and sterilization

Pasteurization is a means of killing main pathogens and inactivating vegetative microbes, as well as their enzymes, to make the food palatable (Ahmed and Ramaswamy, 2007). Sterilization is a more severe thermal treatment of foods. Heat generated by microwaves can significantly reduce the time required for commercial pasteurization and sterilization. As a result, the use of microwave heating for food pasteurization or sterilization provides better product quality. Microwave aided pasteurization and sterilization are more effective in processing foods which contain water and salt (Shaheen et al., 2012).

Microwave blanching

Blanching is a technique of inactivating enzymatic activity in vegetables and some fruits for further processing. Blanching is not exclusively used as a means of preservation but, as a result of raw materials and for later operations like heat sterilization, for dehydration and freezing (Fellows, 2000). Furthermore, blanching provides colour retention, cleansing the product, initial microbial load reduction, gas exhaustion from plant tissue, and preheating the product before processing (Shaheen et al., 2012).

In conventional blanching techniques, foods are immersed in hot water, steam, or boiling solutions containing acids or salts (Chandrasekaran et al., 2013). These techniques have some disadvantages, such as leaching of vitamins and soluble nutrients, tissue softening, and waste water generation (Goncalves et al., 2007; Shaheen et al., 2012). But, microwave blanching overcomes those drawbacks of conventional methods by reducing processing time, avoiding extra water requirement, and it provides products better quality and nutritional value (Shaheen et al., 2012). During microwave blanching, little or no water is used for the effective heat transfer in the food, which retains the nutrients by preventing the leaching of nutrients, and it is preferable to hot water immersion (Puligundla et al., 2013).

Microwave Roasting

Microwave heating is used to roast coffee beans (Nebesny and Budryn, 2006), cocoa beans (Krysiak, 2011), black cumin seeds (*Nigella sativa L.*) (Kiralan, 2012), sunflower seeds (Anjum *et al.,* 2006), pumpkin seeds (*Cucurbita spp.*) (Yoshida et al., 2006), cumin seeds (*Cuminum cyminum L.*) (Behera et al., 2004), and rice bran (Garcia et al., 2012). The study findings indicate that microwave roasting is preferable to convective roasting. It can reduce the final temperature of roasted coffee beans; consecutively, it results in the retention of volatile aroma compounds and a more acceptable taste and flavours of brews. Moreover, brews obtained from humidified (to 10% moisture prior to roasting) and microwave roasted (at 700 W for 12.4 min) coffee beans had the best sensory properties (Nebesny and Budryn, 2006).

Microwave extraction

Microwave heating is also used to extract different compounds from different sources. Due to its rapid heating of the solvent and the sample, microwave extraction is known to reduce the amount of solvent used for extraction and the process time required. Moreover, it has a higher extraction rate (Huie, 2002). In addition, the microwave extraction technique is less dependent on high solvent affinity, meaning that a wider range of solvents can be used (Eskilsson and Bjorklund, 2000).

Table 1. Summary of microwave heating and its applications

Application		Product	Processing conditions	Quality parameters	Significant findings	References
Baking		Madeira cake	MV, 2450 MHz, power, 100-900 W	Baking time, textural properties like firmness, springiness and moisture content	93% reduction in baking time at high power, a cake baked at 250 W has improved textural properties (springiness, firmness, and moisture content).	Megahey et al. (2005)
Drying	Hot air assisted	*Moringa olifera*	MV, 2450 MHz, power, 750 W, temp', 50-70 ºC	Drying kinetics, colour, rehydration, and volatiles	80% reduction in drying time, no constant drying rate, greater change in colour, good rehydration characteristics, retention of 23% of volatile compounds.	Dev et al. (2011)
	Vacuum Assisted	Green bell pepper	MV, 2450 MHz, power, 300 W, vacuum, 200 mm Hg	Drying time, diffusivity value, drying rate, quality of drying, and activation energy	83% reduction in drying time, high diffusivity value, no constant drying rate, better quality of pepper, and lower activation energy.	Kumar and Shrivastava (2017)
	Freeze dying assisted	Instant vegetable soup	MV, 2450 MHz, power, 900 W, pressure, 100 pa, vacuum pump temp' (-40 ºC to -45 ºC)	Drying characteristics and sensory properties	Highest drying rate, short drying time, and poor product quality.	Wang et al. (2009)
Thawing		Chicken breast	MV at 2450 MHz, power at 250 W temp' -4 ºC	pH, lightness, yellowness, proximate composition	No significant difference in pH, lightness, yellowness, and proximate composition, except moisture.	Kim et al. (2011)
Tempering		Potato puree	MV at 2450 MHz, power at 705 W	The effect of the different power level on tempering time	Increment of microwave power decreased tempering time	Seyhun et al. (2009)
Pasteurization		Citrus juice	MV 2450, power-600 W, temp'-70 ºC holding time 15 s	Destruction of *Lactobacillus plantarum*	Reduction of *L. Plantarum* from 10^8 CFU/mL to a level of below the limit of detection.	Nikdel et al. (1993)
Sterilization		Macaroni and cheese	MV at 915 MHz, power- 500 W	Texture, flavour, and consumer acceptability	No significant change in texture and flavour. The products are acceptable by the consumer panel.	Guan et al. (2002)
Blanching		Green bean	MV at 2450 MHz, power, 650 W, time 60 s	Weight loss, effect on ascorbic acid and chlorophyll content, colour	High weight loss, ascorbic acid and chlorophyll contents are less affected and the colour of the bean is lighter.	Muftugil, (1986)
Roasting		Sunflower seed	MV, 2450 MHz, power. 500 W, time, for 5, 10 and 15 min	Physico-chemical composition and oxidative stability of sunflower seed oil	Oil content decreased significantly (P<0.05), no change in fibere, ash, and protein. Significant increase in free fatty acids, saponification, conjugated diene and triene, density, and colour value. But iodine value and tochopherol decreased. Oleic acid increased 16-42%, linoleic acid decreased 17-19%, palmetic and stearic acids not affected.	Fozia et al. (2006)
Extraction		Oregano	MV, 2450 MHz, power, 622 W	Processing time, essential oil yield, physical properties, and composition of essential oils	Processing time reduced by 80%, higher essential oil yield. No significant difference in the physical properties and composition with essential oils extracted by hydro distillation.	Bayramoglu et al. (2008)

Integration of microwave drying with other novel technologies

Microwaves combined with other novel technologies provide a synergistic effect on food processing. Combining microwave technology with other emerging technologies can save energy, reduce process time and operational cost, and it helps to improve the quality of processed foods (Stefanoiu et al., 2016; deBruijn et al., 2016). Some of the novel technologies that have effectively integrated with microwave technology are addressed in the following section.

Microwave-assisted infrared heating

Combining microwaves with infrared radiation has various benefits in food processing, like instant heating, compactness of the equipment, rapid regular response, and the product quality is also affected minimally (Krishnamurthy et al., 2008). IR technology is mainly used for surface heating purposes, as a result of its weak penetrating power. Moreover, the exposure of a food item for an extended period of time during IR processing can result in unnecessary swelling, as well as fracturing of the food material. But, combining IR radiation with microwave processing is more advantageous than using both techniques separately. Considering that microwave energy has higher penetrating power than IR radiation and it may also result in minimum temperature difference between the surface and the inner part of the food (Puligundla et al., 2013). As a result, combining microwaves with IR radiation overcomes the limitations of IR heating and it allows the production of products with desirable properties.

In addition, using microwave processing alone for baking creates a problem with crust formation. So, combining both IR radiation and microwaves during food processing provides a synergistic effect. For instance, IR heating has limited application for the production of baked goods and confectioneries because of its poor in-depth heating and non-uniform moisture distribution within the heated food. Nevertheless, combining both technologies reduce process time, and effectively distributes the temperature into the inner part of the food; furthermore, IR heating ensures crust formation (Sumnu et al., 2007). A study by Ozkahraman et al. (2016), stated that legume cakes baked in a microwave-infrared combination (MW-IR) oven have better sensory qualities such as texture and, reduced gelatinization index, moreover, the product becomes more voluminous, with a desirable surface colour, than products baked by using a conventional oven (Ozkahraman et al., 2016).

Microwave-assisted ultrasonication

Currently, ultrasonication technology is widely employed in food industries as a result of the melioration of food preservation, assistance of thermal treatments, and due to its desirable effect on food quality parameters. In addition, ultrasonication doesn't need downstream purification; through this it reduces processing cost. With all these advantages, the technology is employed for various purposes in food industries such as freezing, drying, sterilization, and extraction (Tao and Sun, 2015). Eventhough ultrasonication technology has all the aforementioned benefits in food processing industries, some physicochemical effects of ultrasonication like quality deterioration, that appear as off-flavours, a change in physical parameters, and the degradation of components take place (Chemat et al., 2011). Consequently, to overcome the limitations of each technique, combining microwaves with ultrasonication requires theoretical and experimental knowledge and thus the combined technology has been widely studied for the food industry (Chen et al., 2016).

Microwave-powered cold plasma

Plasma is a non-thermal technology used in food industry for microbial decontamination. It contains a group of active particles, e.g., electrons, ions, radicals, and excited species, which have enough energy to break covalent bonds and induce reactions (Won et al., 2017). Plasma inactivates microbes by using its reactive species that cause damage in genetic materials such as DNA. Consequently, this results in the formation of malondialdehyde in microbial cells and ends up with the formation of DNA adducts and cell damage (Thirumdas et al., 2014). In coupling of microwaves with plasma, microwave energy used to form plasma provides several benefits, including, increasing the efficiency of generating reactive species, increasing the density of electrons, and making the process contamination free. A study by Won et al. (2017), on the efficacy of microwave-powered cold plasma treatment (MCPT) for the inhibition of *Penicillium italicumandim* indicates that nitrogen (N2) cold plasma treatment (CPT) at the microwave power of 900 W for 10 min, showed a 84% reduction in disease incidence (Won et al., 2017).

Another most efficient and effective technology against pathogenic microorganisms and their spores during storage is the high microwave density cold plasma treatment (HMCPT). The good side of this technology is that it doesn't considerably affect the quality parameters of treated products. According to Kim et al. (2017), the main reason associated with the effectiveness of HMCPT against spores is that, the treatment cleaves disulphide bonds in the protein coat of spores, which makes them more prone to the effect of excited moles of cold plasma (Kim et al., 2017).

Microwaves coupled with E-beam irradiation

Electron-beam irradiation is the utilization of high energy electrons to inactivate microorganisms, and the technique is called "electronic pasteurization". This method doesn't leave any chemical residue in treated food, it also reduces the time required to process the food and improves the shelf life of the processed food (Mulmule et al., 2017). Electron-beam irradiation affects the microorganisms by causing lethal damage on the genetic materials (DNA and RNA), which halts their multiplication (Li et al., 2015). So, coupling microwaves with E-beam irradiation makes the final product more consistent and safer, since microwave processing retains the nutritional content of the food and E-beam irradiation detains the growth of spoilage microorganisms in the food.

Microwave-assisted ohmic heating

Ohmic heating is one of the most recent food processing methods that require the transfer of electrical current through the food, which generates internal heat due to electrical resistance (Reznick, 1996). It requires the conversion of electrical energy to thermal energy by alternating electric current across a food material (Shim et al., 2010). In addition, this method enhances uniform heating in single phase foods (Nguyen et al., 2013). Nonetheless, attaining uniform ohmic heating of particulate foods is challenging due to electrical conductivity of the food materials (Sarang et al., 2007). During microwave processing of food, the electrical conductivity of the food must be considered, but combining microwaves with the ohmic heating technique gives the opportunity of processing the food without considering its electric conductivity.

The effect of microwave processing on the food structure and the sensory and nutritional quality of foods

Processing of food modifies the taste, aroma, and texture of the food with the objective of improving the shelf life of the food. In general, every food processing method has an effect on different quality parameters of the food. Microwave processing has both positive and negative effects on structure, sensory quality, nutritional quality, vitamins, and antioxidant and phenolic compounds of the food.

The effect of microwave processing on food structure

Microwave processing can denature proteins by modifying their tertiary structure. But, the rate of degradation depends on the heating time and temperature. It has been shown that the nutritive value of proteins in foods treated by conventional and microwave heating are comparable (Hill et al., 1998; Petrucelli and Fisher, 1994). At a given frequency, lipids have a constant loss factor. A study by Hernandez-Carrion et al. (2011) on the microstructure and dielectric properties of different fat-based sauces processed by microwaves found that the processing method didn't affect the size and shape of the fat (Hernandez-Carrion et al., 2011). One of the main storage carbohydrates in plants is starch and different studies have been done on the effect of microwave heating on starch. An early study by Lewandowicz et al. (1997), noticed a change of the crystal structure of potatoes from type B to type A (Lewandowicz et al., 1997). This finding was further supported by Szepes et al. (2005), they found that the microwave treatment brought change in the structure and crystallinity of starch due to molecular vibration. As a result, some properties like polarity, free energy, viscosity, gelatinization, molecular weight, and particle size of the starch were altered (Szepes et al., 2005).

The effect of microwave processing on the sensory quality of foods

Heat processing induces different reactions that modify the overall quality of food. Quality deterioration of a given food involves factors such as taste, colour and flavour. Reducing the processing time is the best method to reduce the effect of processing on such quality parameters. So, microwave processing is preferable for retaining sensory quality. A study by Wang and Xi, (2005) stated that thickness of slice and microwave power affected the beta carotene content of carrots (Wang and Xi, 2005). In addition, microwave drying of ginger and basil resulted in the product with increased amounts of essential oils when compared to oven drying at 50ºC (Orphanides et al., 2016). On the contrary, Benlloch-Tinoco et al. (2015), found that the microwave treatment of kiwifruit puree resulted in the loss of 42-100% of chlorophyll and 62-91% of caretenoids (Benlloch-Tinoco et al., 2015).

The effect of microwave processing on the nutritional quality of foods

i. The effect of microwave processing on carbohydrates

A comparative study by Gonzalez and Perez (2002), on the effect of microwave and extrusion cooking of lentil starch, based on their physical, chemical, rheological, and morphological characteristics shows that, the reducing sugars increased for microwaved starch. The functional properties of lentil starches such as water absorption, solubility, and swelling power were found to decrease more prominently for microwave processing. This decrease in functional properties is mainly associated with intergranular molecular rearrangement that decreased the accessibility of the amorphous area. Amylographic viscosities were also found to be lowered for both microwaved and extruded samples due to a decrease in swelling power and solubility (Gonzalez and Perez, 2002).

ii. The effect of microwave processing on proteins

A study by Quitain et al. (2006), identified that the hydrothermal degradation rate of proteins to amino acids showed a significant increment in amino acid yield in comparison with conventional heating (Quitain et al., 2006). In another study, concerning a microwave irradiation treatment of barely grain, the researchers pointed out the increased degradation of degradable crude protein sub fractions. The researchers compared raw grains treated for five minutes and found a rapid reduction of degradable crude protein sub fraction from 45.22 to 6.36% crude protein and the treatment accelerated the degradation rate. Finally, they generalized that microwave heating for a short period with lower energy picks up the nutritive value and consumption of crude protein of barely grain (Yan et al., 2014).

iii. The effect of microwave processing on lipids

Various studies have been conducted to investigate the stability of lipids on microwave cooking, including studying the hydrolysis of triglycerides in soya, egg yolk, and meats; fatty acid profiles in chicken and beef patties, chicken fat, beef tallow, bacon fat, rainbow trout, and peanut oil; peroxidation of polyunsaturated fatty acids in meat, egg yolk, and chicken. Available evidence suggests that microwave cooking did not result in significant chemical modifications (Hill et al., 1998). Research findings by Zhang et al. (2007), concluded that fat had an effect on the thermal properties of food but when compared to salt, the effect is lower. In another study, investigators found that heating time and the surrounding medium can affect the degree of phytosterol degradation during microwave processing. Those parameters also have an impact on the quality and safety of the food (Leal-Castaneda et al., 2015).

A study by Nezihe et al. (2011), found that microwave processing increased the unsaturated fatty acid content of castor oil (Nezihe et al., 2011). Furthermore, a study by Zhang et al. (2013), analysed the chicken fat processed by using microwaves and obtained an increased retention rate with lowest peroxide, acid, and thiobarbituric acid values (Zhang et al., 2013). Microwave processing is employed in fat processing for heating and extraction purposes. It is reported that microwave processing makes edible oils degraded by accelerating oxidation, hydrolysis, and polymerization. Moreover, based on the treatment conditions, microwave heating can also result in increased acidity. As compared to traditional heating methods, the rate of reaction is fast (Inchingolo et al., 2013).

iv. The effect of microwave processing on antioxidants and phenolic compounds

The microwave treatment of cabbage reduced the amount of total phenolic and total flavonoid compounds. A study by Jaiswal and Abu-Ghannam, (2013) noticed up to 85-90% total phenolic compound and 60-73% total flavonoid loss from the initial. Moreover, chroma, firmness, and antioxidant capacity all degraded due to microwave treatment (Jaiswal and Abu-Ghannam, 2013). Similarly, a study by Hirun et al. (2014), found a reduction of phenolic and curcuminoid content in turmeric after vacuum microwave drying (Hirun et al., 2014).

v. The effect of microwave processing on vitamins

Many studies have been conducted so far to compare the retention of vitamins in different types of meat and vegetables subjected to conventional and microwave cooking. In general, water-soluble vitamins such as vitamin B and C are more susceptible to heat treatment. The retention of vitamins varies with the size and shape of food, cooking time, and internal temperature. Some literature sources suggest that vitamin retention in microwave-processed foods is equal or better than in conventionally prepared foods because of the shorter heating time of microwave cooking (Decareau, 1992; Hill et al., 1998). Findings from different experiments depict that microwave treatment of food has an impact on the vitamin content of food. The results of a comparative study of drying encapsulated lipid vitamins by conventional and microwave drying, performed by Barba et al. (2015), showed that microwave drying became the main reason of degradation of fat-soluble vitamins. On the contrary, conventional heating degraded 17% of the vitamins during 12 hours of processing to achieve a similar moisture content (Barba et al., 2015). Another study by Karatas and Kamsl (2007), analysed the impact of infrared and microwave heating on vitamin A, C, and E in apricots. They found that the values of vitamin A, C, and E in a product dried by a microwave is higher than in samples dried by using infrared heating. An early study by Yoshida et al. (1992), on the effect of microwave energy on the relative stability of vitamin E, showed a loss of α-techopherol, followed by γ-, β- and δ-techopherol (Yoshida et al*.,* 1992).

Safety of microwave processed foods for consumers

One of the main limitations of microwave processing is its non-uniform heating. Several factors associated with non-uniform heating such as food shape, size, and dielectric properties of the food, moisture content of the food, microwave power, and cycling represent important factors for the efficiency of microwave heating (Chamchong and Datta, 1999; Vilayannur et al., 1998). The problem is more prominent in frozen food microwave processing, because the difference in the dielectric properties of ice and water become a main source of variation, and frozen foods processed by microwaves are not microbiologically safe to use as ready-to-eat. In fact, the final microwave treatment guarantees food safety, but the treatment forms hot and cold spots as a result of a complex interaction of the food with electromagnetic radiation, because the processing time is not sufficient enough for thermal diffusion between hot and cold spots (Ma et al., 1995). Furthermore, some frozen foods cannot be heated sufficiently to reach the appropriate temperature that kills pathogens.

In terms of making the food radioactive, the technology is safe and it cannot make the processed food radioactive, since microwave radiation energy is directly converted into heat, while it is absorbed by the food (O.S.H.A, 2012).

The opportunities of applying microwave processing in Africa in terms of the development of the economy and food safety aspects

Using microwave drying technology in Africa is not extensively practiced, due to its initial investment cost. Different reports depict that 1/3 of the food items produced globally are lost during and after harvesting, and majority of this loss is evident in Africa. The main reasons behind postharvest loss of food products are inappropriate postharvest handling, including improper drying of produce, which may end up with an infestation of various mycotoxins and other storage pests. The prevalence of mycotoxin infestation in food products is very high in Africa. This has the power to affect food security and safety. If the microwave drying technology is adopted in Africa to dry different agricultural products before storage for long periods, it may maintain the safety of food and ensure sustainability. Traditional drying methods such as sun drying of cereals are widely used in African countries and they do not provide a complete removal of moisture or they do not provide uniform drying of the products. To overcome such limitations, microwave drying is preferable.

Microwave food processing technology is versatile when compared to conventional processing methods and it can be used for various unit operations in food industries. Specially, the volumetric heating property of microwaves provides the opportunity for diverse biomaterial processing. Their increased rate of processing and, the ability to maintain the nutritional quality of final products makes them preferable. Furthermore, power consumption of the technology is relatively lower than that of conventional methods. Consequently, unnecessary power cost for food processing industries can be put away and this will have profound effects on the economy.

Late-comers advantage in the adoption of the microwave processing technology in Africa

The problem of malnutrition is widespread in Africa, including Ethiopia, especially undernutrition and micronutrient deficiency, it is highly linked with inappropriate food preparation methods and improper post-harvest handling of agricultural produce. Conventional food processing methods may result in a loss of significant amounts of nutrients and over-processing of food is a common trend in Africa. Microwave cooked products have the advantage of maintaining more sensory and nutritional value as compared to those cooked by other conventional methods. Therefore, the problem of not getting necessary nutrients from food as a result of extensive traditional food processing techniques can be alleviated by adopting microwave food processing technology. In another way, postharvest loss of food products is a recurrent problem of African countries due to the lack of appropriate storage and the limited use of novel processing technologies. As a result, using microwave drying is advantageous over tradition sun drying of agricultural produce for the purpose of long period storage.

Promising future trends in the level of technology, knowledge-sharing, and collaboration

Microwave technology is highly advantageous as compared to the conventional processing methods. The technology consumes less energy, since heat is produced inside the food and most microwaves save about 20% of energy based on the type of food processed (Hill et al., 1998). Even though, there is no well documented data on the market share of microwave-processed foods in Africa and the presence of microwave processing technology in food industries, a lot is expected to be done in the adoption of the technology. One of the main demerits of the use of microwave technology at the food industry level is its non-uniform heating property and the literature suggests that coupling microwaves with other novel technologies like infrared radiation to overcome the problem as a possible solution, but this coupling makes the investment cost a little bit high. In fact, it might be challenging to scale up batch type microwave processing to the commercial scale level because of several factors, including the change in absorption and the limited penetration depth of the radiation into the medium, since the volumetric heating property of microwaves is relatively effective on a small scale (Moseley, 2011). In order to overcome these factors, regional and national level innovative research institutes are very critical to the development and use of microwaves at the industrial level. Thus, for industrial application of the technology with high throughputs, researchers and microwave manufacturers have already developed continuous flow microwave heating. It overcomes the drawbacks of batch microwave processing, including associated costs (De La Hoz et al., 2011).

The other bottleneck for the use of microwave processing for food processing in Africa is its fast and coordinated technology adoption and operational management. As a result, solid support from each African union member and the private sector should be given in order to motivate the today's generation of young people to re-think the application of novel technologies for food and nutrition security, in order to contribute to poverty reduction, transforming sustainable food systems for affordable healthy diets, and reducing food losses along the production and supply chains. Therefore, for the purpose of future application and usage of microwave technology in the food processing industry, further integration and harmonization, as part of technology innovation and adoption, into systems development in Africa should be aimed towards making the technology easy for implementation. Moreover, adopting such technologies requires international collaboration for the purpose of knowledge transfer and putting together both the physical components of the technology and the skill to operate it.

Global market share value of microwavable food products

According to the report by Zion Market Research (2018), microwavable food market was valued around USD $104.67 billion in 2017 globally. The products are grouped as frozen shelf-stable, chilled meals like vegetarian meals, frozen, and chilled pizza. Such food items are preferred due to the increased population number and fast moving life style of individuals. Moreover, the microwave processing method has gained more popularity as a method for saving energy and time. In addition, the WHO recommended that if microwaves are used as per manufacturer's guidelines, they are a safe and convenient cooking method for health. The market share of microwavable food items is also forecasted to grow at CAGR of 5.0%, from 2018-2024; it is approximately USD $142.44 billion. The reason for such a predicted upsurge is the growing demand for easy-to-prepare foods and the rising number of working women resulting in changes in family dynamics that lead to increased dependency on ready-to-cook foods. Furthermore, disposable income and the rapidly raising large retail chains are likely to support the increment of the microwavable food market shares.

Geographically, North America is the fastest growing region in the global microwavable food market, as a result of the traditional culture of snaking quick and easy-to-prepare meals and processed food consumption. In general, the global market share finds its scope in Europe, North America, Latin America, Asia Pacific, Middle East, and Africa (Zion Market Research, 2018).

Conclusions and future prospects

The successful applications of microwave heating technology for processing various foods have been discussed in the present review. Microwaves are in the electromagnetic spectrum that is situated in the wavelength and frequency between 1mm to 1m and 300 MHz to 300 GHz, respectively. This energy is used for industrial and domestic food processing. It works by using dielectric properties of foods through volumetric heating. In volumetric heating, the materials can absorb microwave energy directly and internally, and convert it to heat. Various interacting factors can affect the uniformity of microwave heating and they are related to food, packaging and the microwave oven itself. During microwaving food, thermal property of the food, the size and shape of the food, the orientation of the food in the microwave oven, and the physical state of water and moisture content of the food need to be considered. Microwaves are used in a wide range of areas; mainly in food industries for baking, drying, thawing and tempering, pasteurization and sterilization, blanching, roasting, and extraction. Moreover, the technology is coupled with other novel technologies to get a synergistic processing effect. Microwaves can be combined with infrared radiation, ultrasound, cold plasma, E-beam irradiation, and the ohmic heating technology. Processing food by using microwave technology has an effect on the structure, and the sensory and nutritional quality of the food, but still, it is preferable to conventional processing methods.

In general, microwave-processed products have advantages of retaining sensory and nutritional quality as compared to those processed by other conventional methods. Still, the technology is not well adopted extensively in Africa due to the lack of technology awareness and the priority settings in the application of novel technology for mass production towards high-market oriented value added biological products. The breakthrough of microwave technology in the food processing industry due to its high potential has been predicted many times before. Nonetheless, the potential of microwave technology in the food industry and the combined application with emerging food processing technologies are far from being exhausted, specifically in Africa. Therefore, food innovation centres in Africa should drive high performance standards from technology adoption to improve the application of microwave technology in food industries.

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