Impact of Different Microwave Treatments on Food Texture

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Abstract

Electromagnetic waves are frequently used for food processing with commercial or domestic type microwave ovens at present. Microwaves cause molecular movement by the migration of ionic particles or rotation of dipolar particles. Considering the potential applications of microwave technique in food industry, it is seen that microwaves have many advantages such as saving time, better final product quality (more taste, color and nutritional value) and rapid heat generation. Although microwave treatment used for food processing with developing technologies have a positive effect in terms of time, energy, or nutrient value, it is also very important to what extent they affect the textural properties of the food that they apply to. For this purpose, in this study, it has been investigated that the effects of commonly used microwave treatments such as drying, heating, baking, cooking, thawing, toasting, blanching, frying, and sterilization on the textural properties of food. In addition, this study has also covered the challenges of microwave treatments and future work. In conclusion, microwave treatments cause energy saving due to a short processing time. Therefore, it can be said that it affects the textural properties positively. However, it is important that the microwave processing conditions used are chosen appropriately for each food material.

Keywords: drying; texture, microwave treatment, hardness; baking; food processing.

1. INTRODUCTION

Electromagnetic waves are frequently used for food processing (drying, cooking, baking, thawing, heating, toasting, sterilization, frying, etc.) with commercial or domestic type microwave ovens at present. A microwave is a shape of electromagnetic waves and the range of frequencies is changing from 300 MHz (wavelength: 100 cm) and 300 GHz (wavelength: 0.1 cm) (Venkatesh & Raghavan, 2004). The 2 most frequently used frequencies are; 915 MHz of frequency for the commercial microwave oven and 2450 MHz of frequency for the domestic type microwave oven (Venkatesh & Raghavan, 2004; Chandrasekaran et al., 2013; Pandiselvam et al., 2020).

Microwaves cause molecular movement by the migration of ionic particles or rotation of dipolar particles. Ionic conduction refers to the migration of solute or vibrating ions in the electromagnetic field, while dipole rotation refers to the alignment of polarized molecules. The most important polar molecule in foods is water. Water molecules change direction with the effect of microwaves. Other charged particles in the food create a force that causes oscillation at the frequency speed of the microwave and begin to rotate with this force. Moving particles collide with others and heat is produced (Vadivambal & Jayas, 2010). In other words, this kind of kinetic energy formed is converted into heat. In conventional heating, heterogeneous heating is provided by heat transfer from the external medium to the inside of the food material, while in microwave heating the heat is distributed homogeneously (volumetrically) (Chemat & Cravotto, 2013).

One of the electrical properties which are efficient in understanding their behavior in microwaves is the dielectric constant and dielectric loss factor of the food material. The capacity of the material to absorb microwave energy depends on the dielectric constant (ε') and dielectric loss factor (ε''). The dielectric constant (ε') shows how much of the generated energy can be stored, while the dielectric loss factor (ε'') shows how much of the generated energy can be absorbed by the material and converted into heat (Nelson, 2015). The ratio of these two factors is called loss tangent ($\tan \delta$) and it expresses the measure of the transformation of electromagnetic energy into heat energy due to dielectric losses (Ellison et al., 2017).

Considering the potential applications of microwave technique in food industry, it is seen that microwaves have many advantages. For instance, it is known that microwave applications have enabled saving time and better final product quality (more taste, color and nutritional value) thanks to rapid heat generation (Dahmoune et al., 2015). Moreover, it has also been reported to reduce processing time and so, increase energy efficiency (Švarc-Gajić et al., 2013). Since evaporation develops faster in microwave processes, it contributes to energy saving, as well as reduces processing time and stabilizes nutrients or organoleptic properties (Łechtańska, Szadzińska & Kowalski, 2015). Although microwaves are more advantageous compared to conventional methods, they have also a few disadvantages. One of them is the high initial investment cost for commercial microwave (Ciriminna et al., 2016). In addition, in commercial applications, non-homogeneous heating or burns due to overheating at certain points can be seen depending on the high penetration power and the shape of the food. As a solution to this challenge, it can be suggested to use optimization methods to obtain the best processing parameters (Chandrasekaran et al., 2013; Chizoba Ekezie et al., 2017). In addition, the food materials to be placed in the microwave must be placed in microwave-compatible vessels (for example microwave-safe plastics) (Attrey, 2017). The Food and Drug Administration (FDA) has stated that the microwave is completely safe if used under the stated instructions (FDA, 2021).

In addition to its nutritional value, human want to enjoy it while eating. There are three sensory factors for a meal to be enjoyable: appearance, flavor/aroma and texture (Bourne, 2002; Pandiselvam et al., 2017). The texture is one of the most important characteristics used in the food industry to determine the acceptability of the product. Texture also plays an effective role in consumer preference of the processed product. All processes applied beginning from the harvest of the food affect its texture properties. The textural features can be determined by sensory analysis or instrumental equipment such as three-point bending test, compression and puncture test (best-known; Texture Profile Analysis), single-edge notched bend (SENB) test, Warner–Bratzler shear force (WBSF) test, stress relaxation test, etc. (Konopacka & Plocharski, 2004; Chen & Opara, 2013). It is known that mostly researched textural properties such as hardness, firmness, sliminess, resiliency, cohesiveness, fracturability, adhesiveness, wateriness, chewiness, springiness and gumminess can be determined by Texture Profile Analysis (TPA). Researchers think that performing instrumental and sensory analysis together, rather than being analyzed separately, can improve the accuracy and efficiency of food texture measurement (Guiné & Barroca, 2012; Chen & Opara, 2013). Many studies have been performed on the changes in textural properties of the different food materials of processing which is by using microwave energy, recently (Huang et al., 2012; Jaiswal & Abu-Ghannam, 2013; Wen et al., 2015; Phinney et al., 2017; Süfer et al., 2018; Thuengtung & Ogawa, 2020; Devraj et al., 2020;Pure et al., 2021).

Although novel methods used for food processing with developing technologies have a positive effect in terms of time, energy, or nutrient value, it is also very important to what extent they affect the textural properties of the food that they apply to. Because textural properties of the food materials (processed or non-processed) are one of the most important factors both in the acceptability for selling and its preference by the consumer. For this purpose, in this review, it has been investigated that the effects of commonly used microwave treatments such as drying, heating, baking, cooking, thawing, toasting, blanching, frying, and sterilization on the textural properties of food by using recent studies. In addition, this study has also covered the challenges of microwave treatments and future work.

2. IMPACT OF MICROWAVE TREATMENT TECHNOLOGY ON FOOD TEXTURE

2.1 Microwave heating

Conventional heating is based on heat transfer mechanisms which are conduction and convection. However, the heat transfer mechanisms during microwave heating are convection and radiation, and thus volumetric heating is observed (Kappe, 2013). The heat transfer mechanisms of conventional and microwave heating are given in Figure 1. The diffuse of electromagnetic waves into foods is defined as penetration. These waves first spread on the surface and then penetrate the food. In other words, the penetration depth is defined as the distance at the point where the electric field intensity decreases by 37% (1/e) (Vadivambal & Jayas, 2010; Guo et al., 2017). As the frequency of the microwave used increases, the depth of penetration into the food decreases (Tang, 2015). One of the reasons commercial microwaves have a lower frequency is that they can be suitable for processing more products with their high penetration ability. The penetration depth is a function of the dielectric properties of the food, and if the dielectric loss factor is too low, the penetration depth is too large (Mehrdad, 2009). In microwaves, dipole polarization is significant at frequencies above 1 GHz, while ionic losses predominate at frequencies below 1 GHz. The dielectric loss factor increases with increasing frequency for moist foods. Dielectric properties of food materials basically determine their chemical composition or physical structure. The food materials comprise a mixture of organic matter, water, and salt, and the dielectric loss factor increases with the addition of salt at a certain frequency (Chandrasekaran et al., 2013). Short processing time is one of the most important advantages of microwave heating. At the same time, it has been reported in many studies that the nutrient content is better preserved due to the short processing time (Oliveira & Franca, 2002; Lenaerts et al., 2018). In another respect, due to the propagation of waves to different areas, hot or cold spots can be observed in the microwave heating process (Kumar et al., 2016). This situation can be considered as a disadvantage of the method. There are many studies about microwave heating for different food materials such as for paprika powder (Eliasson et al., 2015), for orange juice (Demirdoven & Baysal, 2016), for cornelian cherry concentrate (Naderi et al., 2016), for corn and rice flour (Uthumporn et al., 2016), for porcine muscle (Agyapong et al., 2018), for beef (Liu et al., 2018), for extra virgin olive oil (Kishimoto, 2019), for milk (Han et al., 2020), for coconut inflorescence sap (Pandiselvam et al., 2020), for flax seeds (Hou et al., 2021), etc.

Texture properties are very important in foods of harvesting, processing, packaging, storage, and presentation to the customer. For example, hardness, which is one of the texture properties, is one of the most substantial parameters generally used to determine the freshness of fruits and vegetables (Konopacka & Plocharski, 2004). Crispness is significant in crunchy foods while cohesiveness, springiness, gumminess, and adhesiveness are of prime importance for meat and meat products or gel products (Stejskal et al., 2011; Akwetey & Knipe, 2012; Taniwaki & Kohyama, 2012; Chen & Opara, 2013). These properties can be easily determined with instrumental devices.

The effects of microwave heating on textural properties have been investigated by many researchers and are presented in Table 1. Thermal treatment applications for vegetables and fruits cause irreversible degradation of pectic polysaccharides, resulting in decreased adhesion between cells and finally increased softening of that product (Sila et al., 2006). In meat and meat products, thermal treatment applications give rise to protein denaturation (Dong et al., 2018). Moreover, meat tenderness can be defined as the ease of chewing and mostly used preferred method of objective measurement is shear force (Kong et al., 2008). And the tenderness of meat and meat products can be affected by thermal treatment applications (Andrés-Bello et al., 2013). All these reactions could change the textural properties of foods.

Banerji et al. (2019) treated the flour with microwave heating after that, the dough they made from this flour was stored at -18 °C for 30 days and then their textural properties were examined. The stickiness of dough made from microwave-treated flour was statistically higher than dough made from untreated flour. When the hardness values were examined, this value was found to be lower in the dough obtained from microwave-treated flour. In conclusion especially for cereals products, it is predicted that when similar temperature gradients in conventional methods are applied to the microwave heating treatment, it will provide an effective solution to crust formation (Mizrahi, 2012).

Ruiz-Ojeda and Peñas (2013) applied different microwave powers (650, 750 and 900 W) and different processing times (50, 100, 150, 200, 250, and 300 s) during microwave heating for green bean pods. After processing, he examined the texture property (firmness) of the samples and compared them with the results obtained by the conventional method (at 65 °C for 100 s and 92 °C for 200 s). Optimal conditions for microwave processing of green beans have been determined for different microwave powers: 125 s, 150 s, and 170 s for 900, 750, and 650 W, respectively. It was observed that these processing times were 2 times less than the time applied in the conventional method. As a result, it has been stated that there was no significant difference in product texture quality between the conventional method and microwave treatment under optimum conditions. In addition, it has been reported that microwave treatment is a great alternative to conventional methods since a shorter processing time is obtained.

In another study, Lee et al. (2021) applied the heating of white shrimp for 60, 70, 80, 90 and 100 s based on 130 and 90 °C temperatures in a 1300 W microwave power. The texture characteristics of shrimp, hardness, cohesiveness, and chewiness tended to increment with increasing heating time and independent of the treatment temperatures. This finding was explained by the denaturation of the muscle protein in material during the aforementioned process, and thus the contraction and hardening of the tissue structure (Erdogdu et al., 2004). In conclusion, the authors recommended heating this food material in the microwave heating system at 90 °C for a minimum of 100 s or at 130 °C for a minimum of 80 s to obtain the best texture quality. In addition to these studies, there is a study in which the microwave treatment has a negative effect. Chang et al. (2011b) investigated the effect of different temperatures and times applied with microwave and water bath on the texture of the beef product in the study they conducted with beef. As a result, it was observed that especially the hardness value was very high in microwave-heated samples. It was stated that the reason for this is that the microwave treatment negatively affected the solubilization and gelation of the collagen of the beef. In conclusion, it was underlined that a water bath was better for the thermal treatment of beef. In different study, Dong et al. (2018) investigated that effect of applied microwave reheating (Input power: 2780 W, Output power: 1700 W and 80 s of heating time) after conventional heating (at different temperature and time) for abalone (*Haliotis discus hanai*). It was observed that after microwave reheating the samples, which were subjected to a preheating applied for 10 minutes at 60 °C (optimum conditions), had minimum shear force and hardness. In conclusion, it was reported that the textural properties of materials considered after 80 seconds of reheating by microwave were of excellent quality.

To summarize, microwave heating is not preferred in cases where hardness is important in meat and meat products because it can increase this value, it has been recommended to use the method at low-power short-time applications to solve this problem. Moreover, microwave heating has been found to have a very good effect on texture in final products of fruits/vegetables or cereals in recent studies.

2.2 Microwave drying

Drying is one of the oldest known food preservation methods, and water activity reduces with drying. Thanks to the low water content, microorganism/enzyme activity decreases, and the product becomes easy to transport as its weight will decrease (Sunjka et al., 2004). It has encouraged researchers to research alternative drying technologies into conventional (traditional) drying methods (such as solar drying or hot-air drying etc.) in order to increase product quality, reduce production costs and energy consumption. Conventional methods mostly have a long drying time, thus the nutrient value of foods (such as vitamins, minerals, or some bioactive compounds) can be decreased because of a long time (Zhang et al., 2006). Microwave drying is one of the most innovative and fourth-generation methods used to dry food materials (Vega-Mercado et al., 2001). Microwave drying can be used combine with different methods such as with infrared for eggplant (Aydogdu et al., 2015), with osmotic for cranberries (Wray & Ramaswamy, 2015), with freezing for mushroom (Duan et al., 2016), with fluidized bed for ginger (Lv et al., 2016), button mushroom (Gaurh et al., 2017) and nutmeg mace (Srinivas et al., 2020), with hot-air for zucchini (Kutlu & Isci, 2017), with vacuum for green soybean (Cao et al., 2017), with ultrasound for apple (Lv et al., 2019) and convective dried apples (Marzec et al., 2010), while it can be applied as a stand-alone drying method (Wang et al., 2017; Anuar et al., 2018; Lee et al., 2019; Cao et al., 2020).

Microwave drying is an energy-saving method and can enhance product quality with optimum working conditions. One of the significant factors in microwave drying is microwave power. The process temperature can alter according to applied power. Therefore, the applied microwave power can easily affect the drying time and drying rate of that product. In the literature, different conditions are applied for each different sample and the most suitable working conditions are determined for the relevant food product (Li et al., 2010; Kubra et al., 2016). The mechanism of microwave drying is depicted in Figure 2. In microwave drying, the product is heated in volumetrically. This is a sign that the moisture in the product will travel evenly towards the surface. In addition, the most important factor during heat and mass transfer is the effective diffusion coefficient (D_{eff}) in microwave drying (Kumar & Karim, 2019). This coefficient is higher in microwave drying compared with conventional methods and increases with the increasing microwave power (Darici et al., 2021).On the other hand, if the content of water, electromagnetic field, drying time are too high or the shape of the food product is irregular, burns may occur in the product because of flashes. This is the most important disadvantage of microwave drying (Zhang et al., 2006).

The most important factor affecting the texture of the foods during drying is moisture content. Concerning the effect of microwave drying on the texture was examined, it can be seen generally damage the texture of the foods due to the rapid heat and mass transfer. This may cause changes in some textural properties. For example, texture properties such as hardness, stickiness, or chewiness can increase (Fazaeli et al., 2012; Süfer et al., 2018). Because of this situation, microwave drying applied in combination with different drying methods (such as microwave-freeze, microwave-hot air, microwave-vacuum, etc.) is more commonly used than sole microwave drying (Sumnu et al., 2005). For example, during microwave-vacuum drying, the microwaves energy ensures that the water in the foods is transferred to the medium very fast. Herewith, structural collapse and shrinkage can be prevented and can be protected texture properties of foods (Lin et al., 1998; Figiel, 2010).

Shen et al. (2019) dried germinated brown rice using microwave (time of 36, 12, 8, 6, 5 min at microwave intensity of 1, 2, 3, 4 and 5 W/g, respectively) and were reduced the moisture content from 35.94% (initially value) to an average of 13.5%. The applied microwave drying to fresh germinated brown rice not only resulted in high yield but also pores that increased flavor and texture quality. In the study, 3-4 W/g has been suggested as the optimum microwave intensity. In another study, Duan et al. (2020) applied the microwave-freeze drying (0.125 W/g, 0.225 W/g, and 0.37 W/g microwave intensity; a range of 10 to 30 kPa pressure) method for the production of Chinese yam chips. The textural properties of the obtained chips were examined. It has been observed that microwave-freeze dried Chinese yam chips have a significant effect on the improvement of the pore structure. It has also been reported that higher microwave intensity leads to a higher porosity. In one of the newest studies about microwave drying of cereals, Huang et al. (2021) boiled partly (100°C, 15 min)brown rice, and then the samples were dried both with hot air (70°C) and microwave (100 kW, 8 rpm and 91°C). In the microwave dried samples, it was found that the hardness value which is the texture properties was lower and the stickiness value was higher. In conclusion, it was stated that the dried samples obtained by microwave were of satisfactory texture.

Soysal et al. (2019) applied 3 different drying methods (intermittent microwave-conventional, continuous microwave-conventional, and conventional drying) to dry red pepper. The hardness values of the textural properties of the dried peppers obtained were investigated in the study. Consequently, it was indicated that, generally, intermittent microwave-conventional drying had better texture properties than continuous microwave-conventional, and conventional. In particular, it was reported that the interaction of drying time×microwave power is one of the factors affecting the texture. In a study using microwave energy stand-alone, Sarimeseli (2011) dried coriander leaves (*Coriandrum sativum* L.) using by microwave and observed that the rehydration capacity reduced as the microwave power increment from 180 W to 900 W. The author explained this finding with the cellular disintegration of the leaves during the drying process. In another study, in which microwave energy was used in combination with hot air, Zielinska and Michalska (2016) investigated the drying characteristics of blueberry (*Vaccinium corymbosum* L.) by treating them with hot-air convective drying (HACD - 60 and 90 °C), microwave-vacuum drying (MWVD - 1.3 W/g microwave power and 4–6 kPa pressure), and their combination (HACD + MWVD). When the texture properties were examined, it was found that the samples that were obtained with HACD had several times higher hardness, chewiness, and stickiness than samples that were obtained with MWVD or HACD + MWVD. Finally, it was seen that the products with the best final quality were obtained with the HACD (90 °C) + MWVD.

Wang et al. (2013) dried the silver carp (*Hypophthalmichthys molitrix*) with 4 different methods (air, freeze, vacuum and microwave-vacuum drying) and compared its physical and chemical characteristics. When the results obtained on the texture were examined, it was reported that the products obtained by microwave-assisted vacuum drying showed acceptable crispness and appropriate odor. The hardness value was found to be lower than the other methods. This finding has led to the conclusion that dry products at low hardness may be suitable as high crunch snacks. Pankyamma et al. (2019) tried to dry the squid shreds using by hot air, sun, and microwave-assisted vacuum drying and examined the texture changes of the dry samples they obtained. The hardness values of microwave-assisted dried samples were found to be lower than other methods. This finding indicates that less force is needed to chew microwave-assisted dried products. In conclusion, the results showed that squid shreds can be prepared in a shorter time and higher quality texture by microwave-assisted vacuum drying compared to sun and hot air-drying methods.

Wei et al. (2020) applied different process conditions to conventional (HAD), microwave (MD), and conventional+microwave combined drying (HAMCD) methods of tilapia fillets. The process conditions of HAD, MD, HAMCD were determined as 50, 60, 70, and 80 °C temperatures and 0.5 m/s air velocity; at 150, 250, 500, 700, and 900 W powers; and at 50, 60, 70, and 80 °C temperatures and a power of 250 W, respectively. The hardness, cohesiveness, gumminess, and chewing properties of the samples obtained using MD were found to be the highest. Compared to MD, HAD was found to have significantly lower hardness, gumminess, and chewiness, and this finding was based on the different drying times between the two methods. With the combined use of the two methods (HAMCD), the best texture properties were obtained and the use of this method was suggested.

In brief, microwave drying has been used by many researchers in all kinds of foods (cereals, fruits/vegetables, or meats) until now. The best texture data were generally obtained using by the combined methods of the microwave. Moreover, if the microwave will be used stand-alone, it has been recommended that the texture integrity of the foods can be preserved more by using low microwave power instead of high microwave power during microwave drying.

2.3 Microwave cooking

Microwave ovens are now used more often than ever to cook raw foods although they are widely used to reheat ready-to-eat foods. It is important to know the factors (cooking properties) that affect the quality and safety of microwaved food and to improve homogeneity during microwave cooking (Das & Rajkumar, 2013, Guo et al., 2017). When validating a microwave oven's cooking guidelines, it is necessary to standardize its equipment and setup to ensure objective, repeatable use for the consumer. Verification is mandatory to ensure food safety and desired food quality (Vlock, 2020; Alakavuk et al., 2021). Microwave cooking is a recent development that is rapidly gaining popularity in homes and industrial-scale food treatment applications. This alternative method is preferred because of its simplicity, rapid processing, high energy efficiency and ease of use. Therefore, microwave cooking has been proposed in several cooking applications and the quality and textural properties of microwave-cooked food products such as pasta, noodles, meat products, and seasonings have been evaluated (Behera et al., 2004; Cocci et al., 2008; Xue et al., 2008; Cho et al., 2010).

Microwave cooking results from the ability of ingredients to absorb microwave energy and convert into heat, which is related to its dielectric properties (Curet et al., 2014; Franco et al., 2015). When microwave energy is absorbed, polar molecules and ions in the food will rotate or collide according to the changing electromagnetic field, and then heat will be produced for cooking (Musto et al., 2014). Similarly, Mello et al. (2014) stated that in which dipolar polarization is the main heating effect, heating will occur mainly due to frictional losses when molecules attempt to realign with the field. Therefore, both the amount of water and dissolved ions (mainly salts) are the main determinants affecting the microwave cooking rate (Ohlsson & Bengtsson, 2001). Because water is the main absorber of microwave energy in food, and as a result, the higher the moisture content of the food, the faster the heating.

Microwave cooking is a sustainable and environmentally friendly technology that reduces the negative environmental impact and power consumption (Komarov, 2021). Short heating and exposure times are less detrimental to food compared to conventional heating. Efficiency, compatibility with other equipment and increasing product quality are the advantages of microwave cooking over conventional heating methods. Providing high temperature in a very short time provides nutritional and sensory advantages over traditional cooking techniques (Aymerich et al., 2008; Orsat et al., 2017).

Different thermal and dielectric properties of food ingredients affect microwave energy distribution, resulting in uneven temperature distribution and cooking properties in food (Das & Rajkumar, 2013). This non-uniform temperature distribution also causes the formation of hot and cold spots in the food. It is difficult to detect these points and evaluate the temperature distribution within the food (Das & Banik, 2021). This can be risky for the consumer because they often decide to eat any food based on its appearance. In addition, strategies (turntables, mod stirrers, or moving the product) to minimize problems in ensuring heating are not always sufficient (Fryer & Robbins, 2005; Ulusoy et al., 2019). Excessive heating speed, overheating of the edge, wet texture and lack of browning are other microwave issues.

Microwave cooking leads to cooking defects and some adverse effects on the structural properties by changing the quality parameters of the product (Barbosa-Cánovas et al., 2014; Taskiran et al., 2019). In addition, undesirable texture damage may occur as a result of heterogeneous heat treatment (Datta et al., 2005). The texture of many vegetables is considered a critical attribute and influences their acceptance by customers. Therefore, different cooking methods are applied to save energy, reduce the treatment time and optimize the overall acceptability of the final products (Kamali & Farahnaky, 2015).

Many investigations have been conducted on textural properties of food products with microwave cooking. Although microwave cooking is widely used in meat products, it is also applied in vegetables, fruits, cereals, and legumes. The summary of remarkable results on microwave cooking is presented in Table 2. Jouquand et al. (2015) found that beef burgundy cooked by microwave had a harder texture than by convection oven. However, Choi et al. (2016) observed that the toughness of chicken steaks cooked by a microwave oven was lower than that boiled and grilled chicken. In addition, Muñoz et al. (2017) indicated a significant decrease in the shear force in potato tubers after microwave cooking, as this treatment weakened the cohesive forces between cells. There is a contradictory between these results, and the reason for this may be different food types and different conditions of the heat treatment (Guo et al., 2017). In addition, the changes in sensory properties during microwave cooking may reflect in the textural and color properties of food products (Ling et al., 2014).

Previous studies reported foal meat cooked by microwave had higher shear force and hardness values compared to different cooking methods (roasting, grilling, and frying) (Lorenzo et al., 2015). Researchers suggested that this is caused by less dissolution of collagen in microwave (Półtorak et al., 2015). During cooking, denaturation of myofibrillar proteins causes meat to be tough, while heat leads to dissolve the connective tissue causing the meat to become tender (Nikmaram et al., 2011).

In a study conducted by Özcan and Bozkurt (2015), the effects of different cooking methods on the physical and chemical properties of Kavurma were investigated. In microwave cooking, lower moisture content of meat may be the reason why it is tough. In atmospheric and microwave cooking, the protein releases most of its water, and as a result the meat begins to dry and become tough. In contrast, in pressure cooking, there is steam created by the boiling the liquid in the meat, and there is no way to lose of water. By the end of the research, it was stated that the important quality parameters were in advisable range at atmospheric and pressure cooking method. Rababah et al. (2006) studied on chicken breast meats and found similar results.

Considering the studies, it can be said that microwave application generally increases the hardness values in meat and chicken products except for some contrary cases. However, in the application on fish, the opposite situation was observed in general. For example, Gaurat et al. (2020) indicated that microwave-cooked mackerels were softer than fried. Because rapid increase of heat during microwave process gave rise to less structural changes of myofibrillar protein. These results agree with the findings of the study conducted by Wang et al. (2019).

When the effect of microwave cooking on cereals was examined, it was determined that this method was widely used on rice and increased the hardness compared to other methods. Daomukda et al. (2011) demonstrated that the microwave-cooked and steam-cooked rice were harder than the conventional cooked, but there were no differences in springiness, chewiness, and cohesiveness values of samples. These results are in agreement with those obtained by Lee et al. (2005). The change of textural properties of microwave-cooked rice may be related to a decrease in the degree of starch gelatinization. However, Li et al. (2019) stated that rice cooked by microwave had the lowest stickiness value. A different result was obtained by Chin et al. (2020). The researchers determined that microwave-cooked rice had higher adhesiveness and chewiness than conventional cooking. These results obtained are compatible with found by Thuengtung and Ogawa (2020) in terms of adhesiveness. It is believed that leached amylopectin during cooking accumulates as a sticky coated layer on the outer surface of the cooked rice, causing increased adhesiveness (Thuengtung & Ogawa, 2020). The different results may be due to the different experimental procedures of the TPA test between their studies.

In another study, it was stated that the cooking method and process time affected the cooking quality of instant deep-fried noodles. Accordingly, microwave cooking reduced the hardness and tensile strength of the instant noodles. This is because the instant noodles absorb water during the cooking process, resulting in a cooked noodle with an optimized tastiness (Cho et al., 2010).

A considerable amount of literature has been published on microwave cooking. These also include many articles on the cooking of vegetables and fruits. Potato, white radish, sweet corn (Wang et al., 2014), broccoli, and Brazilian zucchini (de Castro et al., 2020), cabbage, radish, turnip (Kamali & Farahnaky, 2015; Farahnaky et al., 2018), courgette (Douiri-Bedoui et al., 2011), watermelon rind (Athmaselvi et al., 2012), and Jerusalem artichoke (Baltacıoğlu & Esin, 2012) were among the materials used in the studies to examine the effects of microwave cooking on the product. Looking at these studies, the hardness values of the microwave-cooked samples were lower than that of cooked by other methods.

Relating to the cooking methods, water is the most significant factor for foods to be cooked by microwave. Therefore, dry heat cooking and lower power is not appropriate for cooking vegetables (Chandrasekaran et al., 2013). However, this method may be used with higher powers and less time where the sensory properties can be better preserved.

2.4 Microwave thawing

One of the common methods for the preservation of fresh foods with high water content is freezing (Zhu et al., 2019). To preserve the quality characteristics of fresh and processed foods for a long time, many techniques are used, in which many low temperatures are used. The efficiency of the freezing process is determined by the crystallization, which is thought to be affected by the mass and heat transfer process during the process. Large crystals formed under uncontrolled conditions as the water in the food reaches low temperatures can damage the structure of the food (Kiani& Sun, 2011). This damage can cause chemical, physical and microbiological changes, especially water loss by dissolution with increasing pressure after the damage to the cell membrane by the large crystals formed during freezing (Fadiji et al., 2021).

Freezing is a very effective method in food preservation and thawing these foods is also important (Cai et al., 2020b). Thawing is a process involving phase change and significant for the post quality of frozen foods (Bedane et al., 2018). The multi-component content of the food affects the temperature range needed for thawing. Due to the heterogeneous structure that occurs in the food during thawing, this process must be carried out carefully in order to preserve the properties of the food. Industrially, many traditional methods such as thawing at room temperature, thawing in refrigerator conditions, vacuum thawing and thawing in water are used. In addition, these methods, the ultrasound-assisted thawing, high-voltage electrostatic field (HVEF) thawing, ohmic thawing, high pressure thawing and microwave thawing were novel methods (Cai et al., 2019).

The penetration of microwave into the food and the heat increase it provides is one of the important factors in preferring it in the thawing process. Microwave thawing can provide many advantages such as shorter processing time, microbial safety, and prevention of chemical degradations (Li & Sun, 2002). However, it is a problem for microwave thawing that the energy provided by the vibration of water molecules in the electric field causes the heating to be localized (Watanabe & Ando, 2021). In order to eliminate overheat that may be encountered in microwave thawing, there are many studies supported by vacuum (Cai et al., 2018; Cai et al., 2020b; Watanabe & Ando, 2021) and refrigerated air (Campañone & Zaritzky, 2010). The boiling point of water can be reduced to low temperatures under low pressure conditions by vacuum treatment (Cai et al., 2018) while controlled surface temperature can be achieved with the convection of refrigerated air (Campañone & Zaritzky, 2010), which is another application.

After the physical changes that occur during freezing, the effectiveness of thawing is supported by its short duration and low temperature. By microwave thawing generally the level of drip loss, which may also be caused by cell deformations that may occur during freezing decreased (Wen, 2015). It is possible to weaken the covalent bonds as a result of the disintegration of the cells during freezing-thawing and to affect the textural properties with the effect of the released enzymes (Phothiset & Charoenrein, 2014). Preserving the biochemical properties of the food and providing the desired textural properties for the consumer make the thawing process important. Wen et al. (2015) reported that microwave application with higher energy (700 W) than different thawing methods applied to frozen hami melon causes lower drip loss and textural damage due to the rapid thawing provided, as well as less color loss.

Microwave thawing process can be affected by factors such as shape and aspect ratio, and the fact that the dissolution occurs on the surface limits the penetration of the microwave into the food, which can prolong the thawing time (Chamchong & Datta, 1999). Campañone and Zaritzky (2010), with their mathematical modeling, they stated that although the volume of the food grows, faster thawing is achieved compared to conventional applications, while a non-uniform temperature profile with high temperature increases at the extreme points to ensure thawing at all points. Microwave thawing has beneficial effect on nutritional properties of food compared to other methods (Guzik et al., 2021). Wen et al. (2015) reported that half of the ascorbic acid was preserved with the 500W microwave treatment in the thawing of the hami melon. Holzwarth et al. (2012), stated that microwave treatment in the thawing of strawberries was very effective in preserving the ascorbic acid content and the amount of phenolic component. The most important effect of ice crystals formed by freezing-thawing processes is on structural properties affects the textural properties (Phinney et al., 2017). It is seen that microwave thawing process does not cause remarkable differences on textural properties in products with high water content such as fruits and vegetables. The effects of microwave thawing on textural properties have been investigated by many researchers are presented in Table 3.

In a study, which examined the textural properties of mushroom samples by freezing and thawing treatments, a loss of hardness was detected with thawing, regardless of the method (Li et al., 2018). Similarly, it has been reported that the method has no significant effect on hami melon (Wen et al., 2015), apple (Watanabe & Ando, 2021) and potato (Phinney et al., 2017). It was stated that with the use of microwave application in the dissolution of Red seabream (*Pagrus major*), the hardness value increased compared to the fresh sample, while the Springiness value decreased, other parameters were not affected. Similar effects were also achieved with far-infrared thawing application (Cai et al., 2020). In another study, it was stated that microwave thawing process applied to swimming crab (*Portunustri tuberculatus*) affected the hardness, springiness and chewiness values, it was not differed from water immersing thawing and lotic water thawing processes (Yanget al., 2021). Oliveira et al.(2015)

found a higher shear force with the use of microwave in the thawing of chicken breast meat compared to the fresh sample and other methods. They explained this effect with increased drip loss and protein denaturation with microwave treatment. Similarly, it has been reported that the gel properties of myofibrillar proteins obtained from the porcine longissimus dorsi muscle are weakened by microwave thawing (Wang et al., 2020). It has been interpreted with weak H bonds depending on the overheat phenomenon (Cai et al., 2020).

Finally, it can be said microwave thawing is preferred method for retained nutritional compounds, decreased drip loss and short thawing time contrary to texture properties of not affected assertively according to other thawing methods. For this reason, it is necessary beware to the power and time of process according to the structure of the food to be used and the water content.

2.5 Microwave baking

In recent years, there has been an increasing interest in the microwave oven due to the demand for ready-to-eat foods and the changing lifestyle. Nowadays, it is one of the indispensable household appliances (Chhanwal et al., 2019). Over the past few decades, there have been several investigations into the effects and comparisons of microwave and conventional ovens on bakery products. More recent attention was focused on the provision of using microwaves in baking process and improving the quality of microwaved products (De Pilli & Alessandrino, 2020).

In the microwave oven, heat is produced by the interaction of the radiations with the charged particles and polar molecules in the food (De Pilli & Alessandrino, 2020). It is more efficient to convert energy into heat throughout the product since microwaves penetrate into the food and do not move only at the surface level (Contreras et al., 2017). In addition, microwaves themselves do not directly play a role in heating. Instead, polar molecules and ions (such as water and salts) convert electromagnetic energy into heat with frictional energy. There is no need to heat another source (air, water, etc.) for heating of foods so energy conversion is more efficient (Soleimanifard et al., 2018).

The advantages and disadvantages of microwave baking are presented in Figure 3. The penetration depth of the radiation causes the rapid heating of microwaves and short application time. In addition, this process contributes to the reduction temperature difference between the surface and interior of the food (De Pilli & Alessandrino, 2020). In microwave baking, the rapid heat transfer occurs from the inside of the food to the surface. However, the ambient temperature is not high, so water condensation may happen on the surface of the food. As a result, the Maillard browning reaction cannot be completed, and the crust formation slows down, resulting in undesirable textural properties (Chhanwal et al., 2019; De Pilli & Alessandrino, 2020). In microwave baking, the ambient temperature is lower than conventional baking, so the surface temperature of the product cannot reach higher levels. Therefore, the conditions for Maillard browning reaction or caramelization cannot be provided and as a result, the desired brown color and flavor components cannot develop in the product (Chavan & Chavan, 2010; Yolacaner et al., 2017).

The rapid staling of the baked products is another challenge of microwave baking. However, the reasons underlying this problem are still poorly understood, and it is required that the effect of microwaves on each physicochemical reaction should be deeply understood (Bou-Orm et al., 2021). In addition, it is stated that foods baked by microwave has tough and firm texture because of changes in the gluten structure, inadequate gelatinization, and excessive amylose leaching. These disadvantages cause the weak quality of the products baked by microwaves, and improving the quality of microwaved products is still a challenge for researchers today (Bou-Orm et al., 2021).

Texture, which is one of the most important quality parameters of cereal foods, is significant to obtain high quality standard (Chavan & Chavan, 2010). For this reason, for example, in baking process, the conditions should be appropriately designed so that the dough transforms into bread, taking into account the stages of starch gelatinization, protein denaturation, volume expansion, water evaporation and crust formation (Therdthai& Zhou, 2014). Moreover, a number of authors have considered the functions of individual recipe ingredients in order to develop formulations suitable for use in microwave baking (Al-Muhtaseb et al., 2013; Tanvarakom & Therdthai, 2015; Bou-Orm et al. 2021).

Microwave baking is commonly used in bakery products such as cakes, cookies, and bread because of the short process time. There are a large number of studies on the effect of microwave baking on the textural properties, sensory characteristics, and nutritional quality of the products. Therdthai et al. (2016) concluded that microwave baking increased the volume of the bread, while decreased the baking time. However, they also stated that the crust of the bread baked by microwave was pale. In another study, it was determined that microwave-baked Madeira cake at 250 W had optimal textural properties in terms of springiness and cohesiveness. On the other hand, cake microwaved at 900 W showed the most unfavorable hardness, gumminess, and chewiness properties (Al-Muhtaseb et al., 2013). Soleimanifard et al. (2018) indicated that microwave power affected the microwave baking time to obtain covetable textural properties. In their study, they investigated the effects of different microwave powers (150, 300, 450, and 600 W) and process time (3.5, 5, 8, and 16 min), and it was reported that the microwave-baked cake at 600 W had the lowest hardness, gumminess, chewiness values, and the shortest process time, but the highest cohesiveness and resilience values. In addition, the crispness decreased as the microwave exposure time decreased with the increase in microwave power. A study similar to this one was carried out, and Konak et al. (2017) found that the microwaved cakes had the hardest texture. They also used the combination of conventional and microwave method, and determined that the reducing microwave baking time in the combined methods caused a decrease in the hardness values of the cakes. Moreover, the cakes baked with microwave had the lowest cohesiveness and resilience values.

Previous research established that microwave-baked products were found firm, tasteless and non-crisp by consumers, and the crust was not smooth, and did not have the desired color properties (Chavan & Chavan, 2010). In addition, in microwave baking, flavor compounds might not be produced due to the short process time in baking. In the research, it was determined that the expansion rate values of microwave-baked cookies were lower than the control samples, and the microwave method caused the shrinkage effect on the products. In another study on cookies, microwave-baked cookies had significantly higher values of the breaking stress and the fracturability than conventional-baked ones (Waleed et al., 2019).

With the growing interest in gluten free breads, it is increasingly important to improve textural and sensory properties of these products. For this purpose, Therdthai et al. (2016) used three methods: hot air baking, microwave baking and microwave-assisted hot air baking. The crust gradually formed with the microwave baking due to condensation on the surface and the low surface temperature. The slow crust formation caused the volume expansion for a longer time. Moreover, the chewiness and hardness values were higher in microwave and microwave- assisted hot air method, but the cohesiveness were lower in microwaved bread than the others. Likewise, Tanvarakom and Therdthai (2015) developed gluten free bread using rice flour. The results in the study indicated that the highest values of the hardness, gumminess, and chewiness was in the breads baked by microwave, but the springiness ad cohesiveness values were lower than the breads baked by hot air. By the end of the study, it was stated that microwave baking caused a pale crust, and the brown crust was developed when the microwave method was applied together with the hot air baking. In another major study, Dogan et al. (2010) indicated that specific volumes of breads baked by microwave were lower. It can be said that the reason for this is the shorter baking time in the microwave method.

In their research, Bou-Orm et al. (2021) presented many studies that indicate microwave application hardened the bread texture. The researchers observed that the hardness of bread was related to the amylopectin retrogradation and the speed of heating during baking. In addition, they stated that the staling rate was faster and the crumb texture was firmer when the heating rate increased. Therefore, it was shown that microwave baking could cause several textural defects. Similarly, Chandrasekaran et al. (2013) found that microwave baking reduced the moisture content, and so increased the hardness of breads. They also claimed that this method had adverse effects on the staling of the bread, and was not a good choice for bread baking. Consequently, more research is required to make it an ideal option.

Numerous studies have compared microwave baking and conventional baking and found that the microwave method makes the texture of bakery products firmer. Alifakı and Şakıyan (2017) determined that the microwaved cakes containing chickpea flour had the harder texture than conventionally baked cakes. Moreover, they reported that the increase in baking time significantly increased the hardness values, and this might be related to humidity loss in the product. Similar results were obtained by Boukid et al. (2018). They also revealed that the hardness of the cakes increased depending on the increasing microwave power. Therefore, low microwave power may be a good alternative to obtain cake with tender texture.

The steamed-cake is a traditional food in China, and has good elasticity and chewiness. Zhou et al. (2021) made steamed-cake with traditional method and microwave method, and investigated the textural properties of cakes baked by both methods. The study demonstrated that the microwaved steamed-cake had higher hardness, chewiness, resilience, and specific volume values than prepared cakes by the traditional steaming method. A study by Netshishivhe et al. (2019) reached different conclusions. Accordingly, the maximum force required to fracture the microwave-baked snacks was higher than the oven-baked snacks, whereas the maximum force required to compress was the same for both. Therefore, it can be said that there are no differences between baking methods in terms of hardness.

In conclusion, elimination of preheating, rapid heating, ease of process control, and energy efficiency are the advantages of this method, while there are also disadvantages such as a decrease in product volume, heterogeneous heating, excessive moisture loss, and loss of color. It is very important to use suitable process conditions by carrying out product-based studies.

2.6 Microwave sterilization

One of the most effective food preservation methods preferred in food production is sterilization. Sterilization in foods, expressed as commercial sterilization, is a method that targets the inhibition of all living cells and spores (Heldman & Hartel, 1999). Although conventional applications are widely used for sterilization in the food industry, non-conventional applications are also included (Li & Farid, 2016). One of these is microwave radiation, which can be applied based on the dielectric properties of foods. The use of microwave radiation in food pasteurization and sterilization processes dates back to the 1970s (Stanley & Petersen, 2017). Lethal effect of microwave radiation on microorganisms can be explained oxidative-stress mediated DNA damage (deactivation of oxidation-regulating genes) (Shaw et al., 2021), by affecting (reducing or increasing) enzyme activity (Dreyfuss & Chipley, 1980), membrane damage (Wang et al., 2020).

There are different opinions about the inhibitory effect of microwave on microorganisms. These are non-thermal (chemical structures that change depending on the presence of components in the environment that can be released during microwave irradiation (Olsenet al., 1966), high peak powers with short pulse modulation (Shin & Pyun, 1997) and thermal effect (Vela & Wu, 1979). The thermal effect is provided by the increase in temperature in the structure. Heat increase occurs in intracellular and extracellular structures with the vibration energy generated by electromagnetic waves, which occur in microwave radiation dipole structures. The thermal change in the structure can also be achieved by conventional methods. As a result of dipole polarization, the electromagnetic field and the bipolar positioning of the molecules occur and this effect cannot be achieved with conventional methods (Zelentsova et al., 2006). Barnabas et al. (2010), in which the non-thermal effect was discussed, reported that pathogen microorganisms were inhibited when they were exposed to 2.45 GHz microwave radiation at different intensities by applying them on a glass slide with low dipole properties and drying them in still air. Shaw et al. (2021), provided 6 log reductions in *E. coli* and 4 log reductions in *S. aureus* in the non-thermal application they provided by using pulse microwave radiation (3.5 GHz). With the study, surface deformations were detected in the cells, and while serious cell damage was not detected in certain discharge applications, it was stated that the inhibition was detected and the inactivation was caused by radiation. There is no microbial inhibition by thermal effect, but cell inhibition may not occur only by lysis (Woo et al., 2000). Thermal and non-thermal effects are both responsible for the inactivation of microorganism by microwave radiation.

The use of microwave radiation can positively affect product quality with a shorter processing time compared to conventional methods (Zhang et al., 2014). Non-uniform heat distribution is the problem of microwave treatment (Vadivambal & Jayas, 2010). Therefore, the short processing time limits the efficiency of the process unless hot and cold spots are taken into account (Ma et al., 1995).

In order for microwave sterilization to be successful, the dielectric properties of the food must be known. Dielectric properties can be affected by temperature as well as being dependent on the components of the food (Resurreccion Jr et al., 2013). As foods are heterogeneous structures, the selection of a microwave radiation applicable to foods also poses a challenge. Therefore, mathematical models can be preferred to overcome this disadvantage (Barbosa-Cánovaset al., 2014). In addition, another way of sterilization by using microwave energy, which is easily suitable for foods, is microwave assisted thermal sterilization (MATS). With this application, the sterilization of the food in contact with the water heated by the microwave can be achieved. Thus, it is possible to obtain high quality products (Barbosa-Cánovas et al., 2014). With this application, by using various markers, hot and cold spots are determined on the food packaging, increasing the efficiency of the thermal process applied, and sterilization can be achieved in a shorter time compared to the conventional method (Wenjia Zhang et al., 2015)

Compared to conventional methods, the biochemical properties of foods are less affected by microwave sterilization (Al-Hilphy & Ali, 2013), the processing time is shortened (Peng et al., 2017) and the varying textural effects in different foods (Joyner et al., 2016; Xue et al., 2021; Ying-ping et al., 2016). The effects of microwave sterilization on textural properties have been investigated by many researchers are presented in Table 4. In microwave sterilization, non-thermal and thermal effects are seen at the same time. The thermal effect is effective with changes in the texture of foods such as protein denaturation, starch gelatinization, turgor change, pectin solubility (Kadam et al., 2015). With the thermal treatment, shrinkage occurs between myofibrillar proteins at 40-60 ºC, a gap occurs between actin myosin, gelation of sarcoplasmic proteins occurs at the same time and denaturation continues up to 80ºC in meat (Bořilová et al.). Similarly, protein denaturation in fish and fish products affects the texture (Coppes et al., 2002).

Tsai et al. (2021) investigated the effects of microwave sterilization at 1300 W power applied for 80 s and 100 s, induction heating applied for 100 s and 80 s at 90ºC and 130 ºC, and microwave assisted induction heating (MAIH) applied for 100 s and 80 s at temperatures of 90ºC and 130 ºC, where microwave and induction heating, on white shrimp. Higher microbial inhibition was achieved with the microwave process compared to the induction heating method. Maximum inhibition was obtained with the MAIH method. Hardness, cohesiveness, and chewiness values were determined higher in microwave application than induction heating method. The highest values were determined with MAIH method. The changes in the textural properties were explained by the protein denaturation that occurs upon reaching high temperatures during thermal processes.

The enzymatically and chemically change of pectin in fruits and vegetables refers to the textural changes (Van Buggenhout et al., 2009) and turgor loss (Anthon et al., 2005). Peng et al. (2017), in their study, cold spots were determined in carrots in prepackaged modified atmosphere packages, using gellan gel as a model, and heating patterns were detected. The dielectric loss factor decreased from 72 to 58 with an increase in temperature from 20 ºC to 100 ºC in the treated samples. Firmness of carrots decreased with the conventional and microwave treatment. It was explained with the transformation of the pectin polymers in the cell membrane structure (Anthon et al., 2005). With $CaCl_2$ addition, pectin-Ca interaction in cell membrane and lamellas, increased firmness of structure. In another study, Ying-ping et al. (2016), obtained higher hardness and elasticity values with the 120 s microwave sterilization process (for the inhibition of *Lactobacillus plantarum*) at 600 W power applied to the pickled lettuce compared to the pasteurization process.

As a result, microwave sterilization has found use in ensuring the safety of foods. It is thought that with the determination of the optimum application conditions during the sterilization process, both a short process time and superior product quality can be can be widely used in a wide variety of foods.

2.7 Microwave frying

The utilization of microwave energy in comparison to conventional heating for the frying process can yield number of benefits in terms of techno-economic feasibility of the process by improving the speed of manufacturing and product quality; and simultaneously cutting down on the manpower, floor space and capital investment (Schiffmann, 2017). The summary of remarkable results on microwave frying is presented in Table 5.

Microwave frying can be particularly advantages for the frying of the materials that exhibit poor penetration of the heat up to the interior of the food matrix and exhibits better product quality in terms of reduced oil uptake, better color and texture, low acrylamide formation and enhanced sensorial characteristics can be obtained by employing microwave frying (Schiffmann, 2017; Su et al., 2016; Quan et al., 2016; Quan et al., 2014; Sansano et al., 2018; Jumras et al., 2020). The major reason for the reduced oil uptake during microwave frying is the severe gelatinization of starch and its consequent complex formation with oil to form type V starch lipid complex (Yang et al., 2020). Oztop et al. (2007) optimized the microwave frying of potato slices by Taguchi Technique and reported optimal conditions of frying to obtain reduced oil uptake, optimum texture and color by employing 550 W power, frying time of 2.5 minutes and utilization of sunflower oil for frying. The coupling of microwave vacuum frying of potato chips allowed reduced oil uptake in the product as a result of accelerated removal of moisture by application of microwave resulting in the lesser disruption of cellular structure for the oil uptake (Su et al., 2017). The pre-treatment of osmotic dehydration and coating has shown drastic reduction in the oil uptake (15.2-53.5%) during the microwave vacuum frying of potato chips.

Pre-treatment of osmotic dehydration with sodium chloride and coating with 1% CMC-Na also resulted in improving the textural properties of the microwave vacuum fried potato chips (Su et al., 2021). The synergistic utilization of ultrasound and microwave for the vacuum frying of potato chips has shown quality superior characteristic and efficient energy utilization. The potato chips fried by this hybridized technique exhibited reduction in the oil uptake (27.4%-32.3%). The combined treatment of microwave and ultrasound rendered the microstructure of potato chips more porous that resulted in reducing the volume shrinkage of the fried chips. The application of microwave in vacuum frying resulted in accelerated removal of moisture with consequent modification of the texture and resulted in crispier chips (Su et al., 2018). Similar hybridized frying technique has also been employed for the frying of apple slices and similar manifestation of reduced oil uptake, improved color and crispiness were observed in the final product. The formation of Maillard reaction product was also lower by this frying technique (Faruq et al., 2019). Devi et al. (2018), Qiu et al. (2018) and Chitrakar et al. (2019) also reported quicker frying, better color and texture and reduced oil uptake by application of ultrasound in microwave vacuum frying of mushroom, sweet potato and Chinese yam chips respectively. In addition to improving the aforesaid attributes, ultrasound microwave vacuum frying also allowed better retention of total anthocyanins in purple fleshed sweet potato chips (Su et al., 2018a). Islam et al. (2019) also reported improved texture and color, reduced oil uptake and better retention of chlorophyll and vitamin C by ultrasound microwave vacuum fried edamame. However, in the case of ultrasound microwave vacuum fried pumpkin slices color was not much affected by ultrasound treatment whereas improvement in the texture and reduction in the oil content was observed by ultrasound treatment (Huang et al., 2018; Chitrakar et al., 2019).

The reduction in the frying time by microwave frying has also been manifested with the lower acrylamide formation in the batter formulations in comparison to conventional frying that resulted in acrylamide formation and consequently darker product. Particularly rice flour based batter formulation exhibit superior product quality and reduction in the acrylamide content of the fried products (Barutcu et al., 2009b). Microwave vacuum drying also exhibited good color retention in the durian chips with textural properties (hardness) as on par with the conventionally fried chips. However, utilization of microwaves resulted in drastic reduction of 90% of oil uptake in durian chips in contrast to conventionally fried chips (Bai-Ngew et al., 2011).

Microwave frying of the batter formulations for the coating of the chicken also exhibited simulate textural characteristic in comparison to conventional frying. However, in comparison to rice or soy flour, utilization of wheat flour and chickpea flour yields better microstructure due to formation of bigger gas cells on the outer surface of the fried batter (Barutcu et al., 2009a). Microwave drying of the fish nuggets using wheat and corn based batter formulations exhibited similar crust quality and texture in comparison to conventionally fried nuggets. However, the inclusion of 1% CMC/HPMC resulted in reduction in the oil uptake and color changes in the fried nuggets (Chen et al., 2009). In comparison to meat based batter formulations, the direct frying of beef patty by microwave frying had shown harder texture of the patty as compared to control sample. However, the cooking loss was markedly lower in microwave fried patty in comparison to conventionally fried patty (Noor Hidayati et al., 2021). However, microwave assisted vacuum frying was found to be effective for frying of fish fillets and was manifested with reduced hardness, better color, appearance and sensory acceptability in comparison to conventional and vacuum fried fillets (Shi et al., 2019).

Briefly, the reduction in frying time with microwave frying causes acrylamide formation and therefore darker product formation. In addition, with this method, less oil intake has been observed, and this is of great importance for the frying treatment.

2.8 Microwave roasting (tempering)

Microwave roasting is gaining much attention for the roasting of cereals, nuts and oilseeds in comparison to conventional roasting due to better process control, quicker processing time and modelling of the process. The effects of microwave roasting on textural properties have been investigated by many researchers are presented in Table 6. Microwave roasting has demonstrated improvement in the bioactive constituents, antioxidant activity, oil yield, oxidative stability, sensory appeal of oil seeds, nuts, legumes and cereals and techno-functionality of resultant flours (Juhaimi et al., 2018; Ghafoor et al., 2019; Sharanagat et al., 2019; Baba et al., 2018; et al., 2016; Mulla et al., 2018; Mazaheri et al., 2019; Suri et al., 2020; Jogihalli et al., 2017). In addition to enhancing the techno-functional and bio-functional properties of cereal, nuts, legumes and oilseeds, it also exerts profound on its textural characteristics. Microwave roasting of almonds resulted in better textural properties and were crispier in comparison to conventional hot air roasted almonds. Furthermore, the higher degree of roasted was manifested with improved crispiness (Milczarek et al., 2015). Similar trend was also observed for wild almonds where increase in the microwave roasting time improved the crunchiness of the almonds along with improving oil yield and total volatile compounds (Hojjati et al., 2016). Peanuts roasted by microwave roasting in comparison to conventional drum roasted peanuts were less hard and showed better quality attributes in terms of low browning index and peroxide value and higher overall acceptability (Raigar et al., 2016). Pistachios roasted by conventional air roasting were crunchier as compared to microwave roasted pistachios. However, increasing the microwave power and roasting time demonstrated reduction in the hardness and increase in the phenolics in roasted pistachios (Hojjati et al., 2015). The utilization of combination of microwave and infrared roasting has been recommended for hazel nut and other nuts based on the improved quality attributes of microwave-infrared roasted hazel nuts in terms of color, texture and fatty acid composition as compared to conventionally roasted counterparts (Uysal et al., 2009).

Roasted chickpeas can be a very palatable and nutritious snack and commonly sand and pan roasting are utilized for the roasting of the chickpeas. Microwave roasting of chickpeas has shown reduction in its hardness with the increase in roasting power and time. Microwave roasting can allow better puffing, improved antioxidant potential and functionality of chickpeas (Sharanagat et al., 2018; Jogihalli et al., 2017). *Pistacia terebinthus* beans can be used healthier alternative to decaffeinated coffee due to higher antioxidant (Orhan et al., 2012). Roasting of *Pistacia terebinthus* beans is crucial process since it results in the flavor development of beans and roasting conditions are predominant determinant of its flavor. Usually, labour intensive conventional and pan roasting are employed for roasting of *Pistacia terebinthus* beans and often lead to unevenly roasted and burned beans that negatively affects its quality (Bolek & Ozdemir, 2017). Process was optimized for the microwave roasting was employed for the roasting *Pistacia terebinthus* beans. The force required to break the beans showed inverse relation with roasting power and time. However, the optimum power and roasting time was 540 W and 14 minutes respectively (Bolek & Ozdemir, 2017). Roasted sunflower seeds are gaining great attention as snack due to its nutraceutical properties owing to unsaturated fatty acids, minerals, vitamins and antioxidants (Franco, 2018; Nandha et al., 2014; Guo et al., 2017). Goszkiewicz et al. (2020) concluded that microwave roasting as superior method for roasting sunflower seeds as compared to convection roasting due to improved texture, lower peroxide value and better shelf life.

As a result, microwave roasting has been preferred more attention, especially for roasting grains, nuts, and oilseeds because of its faster processing time and easier control. This method, especially during the roasting of nuts, shows better texture properties and increases the possibility of its preference by consumers.

2.9 Microwave blanching

Blanching is a pre-treatment process that aims to inactivate enzymes and is used to prevent browning reactions and texture changes that usually occur during product preparation (Dorantes-Alvarez et al., 2011). Other purposes of blanching are to reduce the microbial load of food products, soften tissues for a shorter cooking time, and remove intracellular air to prevent oxidation (Ruiz-Ojeda & Peñas, 2013). In particular, blanching fruits and/or vegetables with water with traditional methods (such as water blanching or steam blanching) causes both excessive mass loss and a decrement in nutritional value. For this reason, microwave blanching, an alternative to traditional methods has become widespread in recent years. Recent studies were shown that blanching fruits and/or vegetables in the microwave cause smaller losses in nutrient value compared to blanching with the traditional method (Bernaś & Jaworska, 2015).

Nguyen et al. (2019) treated green asparagus (*Asparagus officinalis* L.) with four different microwave power (150, 300, 450 and 600 W) and processing time (2, 4, 6 and 8 min) by microwave blanching to overcome the disadvantages of traditional blanching methods. When the samples treated at 300 W microwave power were examined, it was observed that the green color of the asparagus became darker and the texture of the asparagus softened after 8 minutes. The suitability of this method has been emphasized because it will help the other processes (drying, extraction, etc.) to be carried out after both because of the tissue softness and the color is better preserved.

Sezer and Demirdöven (2015) applied the microwave blanching (360, 630 and 900 W; 10, 155 and 300 s) to carrot slices and examined the texture properties of the final products. After optimization, it was found optimum conditions for the blanching of carrots as 360 W, 300 s for microwave power and processing time, respectively. As a result, the authors found that increasing microwave power was associated with a decrease in the hardness properties of the samples. The reason for this is thought to be because of the effect of microwave on the hydrogen bonds of hemicellulose and cellulose, which affects the hardness.

In another study using catfish *(Pangasianodon hypophthalmus)* fillet as material, the product was treated at 2450 MHz for 18 s. The final temperature of the fillets was recorded as 65 degrees after microwave blanching. At the end of the study, it was reported that data obtained from microwave blanching was closer to fresh fish meat and better preserved textural and sensory properties (Binsi et al., 2014).

In conclusion, microwave blanching has directly changed food products' texture, especially hardness properties. Since the texture properties demand in the products may be different, an optimization study is definitely recommended for microwave blanching.

3. Challenges and future trends

Microwave processing is a promising green technology that amalgamates energy efficiency and reduced processing time. The utilization of the microwaves in food processing due to short processing time offers better nutritional characteristics. However, the short processing time may prevent development of desired textural and sensory properties. Therefore, the effectiveness of microwave processing often relies on its amalgamation with other processes techniques. Newer technologies such as radiofrequency, infrared, induction, and jet impingement can improve the quality of microwave processed products (Chhanwal et al., 2019). But there are obvious difficulties in scaling up the non-conventional ovens at industrial level.

There are numerous studies pertaining to the microwave sterilization, however much of the work has not been commercialized owing to difficulty in predicting the real temperature distribution (Tops, 2000). Furthermore, the alteration in the dielectric properties during microwave heating as a result of starch gelatinization or protein denaturation may affect the efficacy of sterilization (Zhang et al., 2001). In addition, these changes may be manifested with detrimental effect on the textural properties of the food such as softening of vegetables and hardening of beef (Raaholt et al., 2017; Chang et al., 2011b). Thus, appropriate modeling of microwave sterilization or cooking should be done keeping in mind the degradation kinetics in order to ensure inactivation of microorganisms/anti-nutrients and preservation of nutritional constituents, sensorial and textural attributes of food (Ahmed & Ramaswamy, 2007). In addition, microwave processing may be manifested with excessive drip loss during thawing process (Oliveira et al., 2015) and requires appropriate mitigation techniques such as utilization of additives. Even though microwave cooking mostly result in improving the textural characteristics, certain rice varieties have shown higher chewiness, stickiness, and hardness values with microwave cooking and still requires careful optimization (Chusak et al., 2019; Chin et al., 2020).

Even though microwave roasting has demonstrated improvement in the techno-functionality and bio-functional attributes (Jogihalli et al., 2017), it is tough to obtain the fine tuned balance of all the functional properties. Sahni and Sharma (2020) and Sahni et al. (2021) reported the improvement in the hydration properties and freeze and refrigeration thaw stability along with improvement in the bioactive potential of alfalfa and dhaincha seeds after microwave processing. However, microwave processed alfalfa and dhaincha exhibited compromise on the foaming properties and thus were not congenial for utilization in the food systems where foaming is essential. Jogihalli et al., (2017) also reported drastic reduction in the foaming capacity of microwave roasted chickpea. Microwave frying has demonstrated superior process performance owing to quicker process, healthier product and better quality attributes. However, there are still few studies on the application of microwave frying in meat and meat based products. Furthermore, possible interventions in the form of utilization of other processing techniques like ultrasound can be employed to overcome detrimental effect of the textural properties of fried meat products (Noor Hidayati et al., 2021). In case of microwave fried batter based applications there is wide scope in the utilization of variable flour combinations, development of gluten free formulations and utilization of hydrocolloids and other additives to improve the frying operation and nutritional, textural and sensorial quality of the final product.

4. CONCLUSION

In this study, the effects of microwave drying, heating, baking, cooking, thawing, blanching, roasting (tempering), frying, and sterilization on the textural properties of foods were investigated in detail. When all processes are examined separately, the importance of the selection of optimum process conditions using optimization methods can be shown as a common conclusion. The fact that the microwave time is too fast can have a negative effect on the structure of the food in some cases. As a solution to this, it is recommended to use microwave-assisted methods, such as microwave-hot air, microwave-vacuum, microwave-freeze, and microwave-radio frequency. When the problems related to the industrial scale-up microwave (initial investment cost, production capacity, etc.) can be resolved and this method will be frequently used in food processing and improving food texture.

AUTHOR CONTRIBUTIONS

Naciye Kutlu: Conceptualization; writing-original draft; writing-review & editing. **R. Pandiselvam**: Conceptualization; resources; writing-original draft; writing-review & editing. **Irem Saka:** Writing-original draft. **Aybike Kamiloglu:** Writing-original draft. **Prashant Sahni:**Writing-original draft. **Anjineyulu Kothakota:** resources; writing-review & editing

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ETHICAL REVIEW

This study does not involve any human or animal testing

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study

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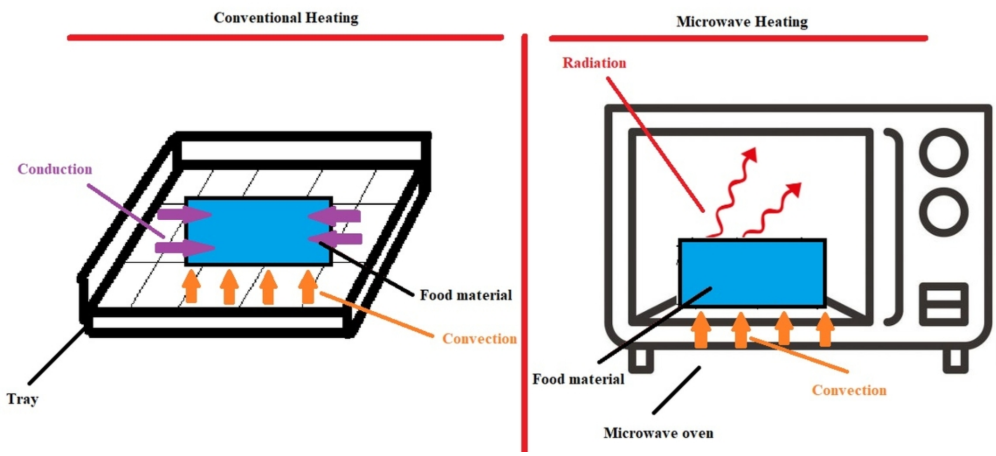
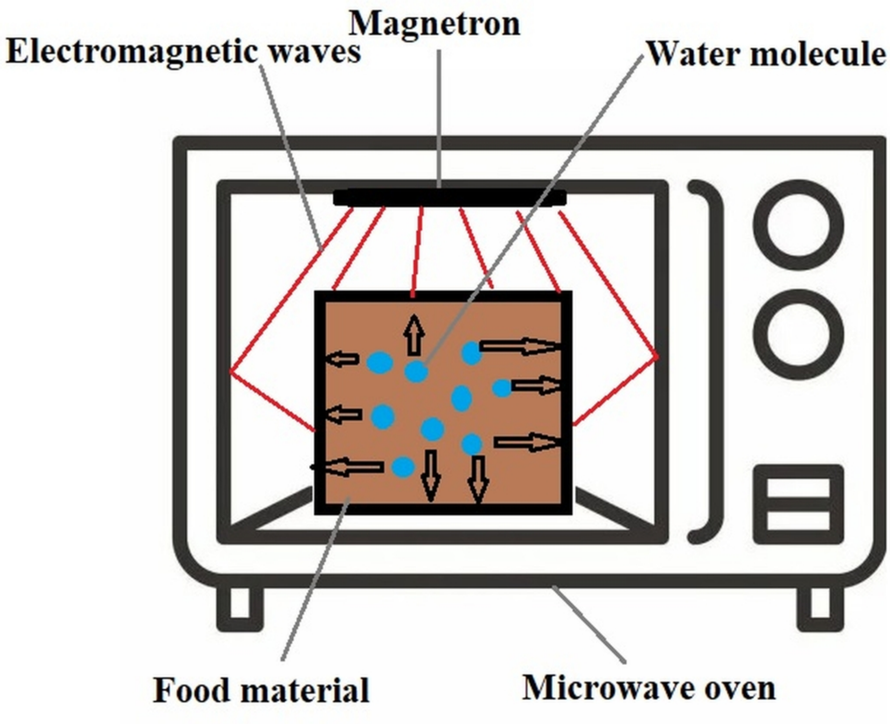
Figure 1. The heat transfer mechanisms of conventional and microwave heating

Figure 2. The mechanism of microwave drying

Figure 3. The advantages and disadvantages of microwave baking (Chhanwal et al., 2019)


Conventional Heating
Conduction
Food material
Convection
Tray
Microwave Heating
Radiation
Food material
Convection
Microwave oven


Magnetron
Electromagnetic waves
Water molecule
Food material
Microwave oven

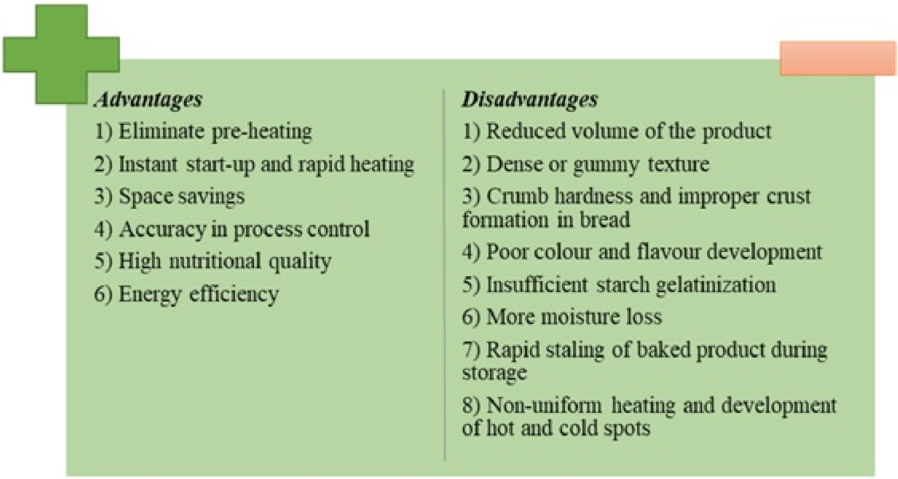

Advantages
1) Eliminate pre-heating
2) Instant start-up and rapid heating
3) Space savings
4) Accuracy in process control
5) High nutritional quality
6) Energy efficiency
Disadvantages
1) Reduced volume of the product
2) Dense or gummy texture
3) Crumb hardness and improper crust formation in bread
4) Poor colour and flavour development
5) Insufficient starch gelatinization
6) More moisture loss
7) Rapid staling of baked product during storage
8) Non-uniform heating and development of hot and cold spots

TABLE 1 Recent selected studies about the effects of microwave heating on food texture

Material	Conditions of Microwave Heating	Results	Reference
High-concentrated particulate phase of 6 mm carrot dices (16.7% w/w)	- Power: 3.9, 4.7, 5.6 and 6.4 kW - Temperature: 100, 110, 120 and 130 °C - Residence time: 7.5, 15, 30, 60 and 120 s	- Softer carrot with increasing temperature and residence time - High match between perceived mouthfeel and texture measurements	Raaholt et al. (2017)
Grape tomato	- Power: medium (50%) and high (100%) - Heating time: 10, 20, 30, 40 and 50 s	- Optimum texture quality at medium power and 40 s	Lu et al. (2011)
Soy protein isolate	- Power: 210 W - Heating time: 30, 40, 80 and 90 s	- Better viscoelastic properties by comparison to the conventional heating	Liu and Kuo (2011)
Intramuscular connective tissue and collagen in beef semitendinosus	- Power: 250 W - Time and temperature: 3, 6, 9, 11, 14 and 19 min for 40, 50, 60, 70, 80 and 90 °C, respectively	- Lower mechanical strength (N) at 60 °C by comparison to the conventional heating	Chang et al. (2011a)
Wheat Starch-Papaya	- Power: 60, 70 and 80 W - Time: 4 min	- Better viscoelasticity and hardness at 80 W	Xu et al. (2020)
Camel *longissimus dorsi* muscle	- Power: 600 W (internal temperature of 75 °C) - Time: 3 min	- High shear value and compression force	Yarmand et al. (2013)
Surimi	- Power: 7 W/g, 5 W/g and 3 W/g - Time: 48 s, 72 s, 96 s and 120 s.	- Superior texture characteristics	Cao et al. (2018)
Wheat kernels	- Power: 700 W - Time: 10, 20, 30, 40, 50 and 60 s	- Softer and better quality at 20 s	Qu et al. (2017)
Brown rice (two varieties)	- Power: 950 and 1400 W - Time: 72 and 91 s	- Both the brown rice varieties showed a better texture with reduced stickiness and increased hardness	Devraj et al. (2020)
Green bean pods	- Power: 650, 750 and 900 W - Time: 50, 100, 150, 200, 250 and 300 s	- Best firmness at 175 s for 650 W, 150 s for 750 W, and 135 s for 900 W	Ruiz-Ojeda &Peñas (2013)
Green asparagus butt segment	- Power: 150, 300, 450 and 600 W - Time: 2, 4, 6 and 8 min	- Longer time or the higher microwave power caused softer texture	Nguyen et al. (2019)

Beef *semitendinosus* muscle	- Power: 600 W - Time and temperature: 3, 6, 8, 9, 10, 11, 12, 14, 16 and 19 min for 40, 50, 55, 60, 65, 70, 75, 80, 85 and 90 °C	- Higher hardness compared to water bath treatment	Chang et al. (2011b)
Water dropwort (*Oenanthe javanica* DC.)	- Power: 450, 600 and 700 W - Time: 1 and 2 min	- Obtained higher overall acceptability in the sensory evaluation at 600 W for 1 min	Tang et al. (2019)
Hongsuchicken dish	- Power: 480 W - Time: 3.21 min (The sample was heated to the center temperature of 72 °C)	- Microwave reheated samples had the best sensory scores, the taste and texture	Wang et al. (2018)

TABLE 2 Recent selected studies about the effects of microwave cooking on food texture

Material	Conditions of Microwave Cooking	Results	Reference
Veal (*Longissimus dorsi*)	-Power: 600 W	-The highest compression force values -A significant difference between microwaved cooked and raw meat in terms of shear force values ($p<0.01$)	Nikmaram et al. (2011)
Beef (*Longissimus dorsi*) (Kavurma)	-Power: 700 W -Time: 10, 20, 30, 40, and 50 min	-Higher hardness and chewiness values	Özcan and Bozkurt (2015)
Chicken thigh and breast meats	-Power: 180 W -Time: 10 min	-Higher shear force value in breast meat compared to the conventional cooking -A significant increase in the hardness values of both chicken thigh and breast meats ($p<0.05$)	Taşkıran et al. (2019)
Chicken meat caruncles	-No information	-Higher crispness, meat flavor intensity and overall acceptability -Higher cooking efficiency and lower calories, acidity and hardness	Singh et al. (2012)
Grass carp meat (*Ctenopharyngodon idellus*)	-Power: 600 W	-Softer texture -Lower shear force value	Wang et al. (2019)
Black and red (nonwaxy) and purple (waxy) pigmented rice	-Power: 600 W -Time: 12 min	-No differences between the firmness values of microwaved and steam- cooked rice, except for purple rice (Steam-cooked purple rice was harder) -An increase in the adhesiveness of cooked rice about 2 to 3 times higher than steam cooking.	Thuengtung and Ogawa (2020)
The flower of Clitoria ternatea and Jasmine white rice	-Power: 800 W -Time: 11 min	-Higher chewiness, stickiness, and hardness values	Chusak et al. (2019)

Two commercial rice varieties (Dongbei Jingmi and Medium grain rice)	-Power: 1000 W -Time: 8 min	-The lowest stickiness value (microwaved) -The highest stickiness value (electronic pressure cooking) -An intermediate one (water-absorption cooked)	Li et al. (2019)
Riceberry rice	-Power: 360 W, 600 W, and 900 W	-Higher adhesiveness and chewiness than conventional cooking -The lowest springiness (conventional-cooked)	Chin et al. (2020)
Deep-fried instant noodles	-Power: 557 W (medium power) and 657 W (full power) -Time: 8.5 and 7.5 min	-High water absorption and poor hardness values (medium power) -Higher hardness, chewiness and tensile strength (full power)	Cho et al. (2010)
Broccoli (*Brassica oleracea, var. Italica*), Carrot (*Daucus Carota*), and Brazilian zucchini (*Cucurbita moschata*)	-Power: 40% of its full power (320W) -Time: 6-16 min	-It has been found that the use of a lower power microwave for dry heat cooking is not suitable for cooking vegetables.	de Castro et al. (2020)
Cabbage, radish, turnip and potato	-Power: 900 W -Time: up to 75 min	-Decrease in the hardness, gumminess, and chewiness values depending on the treatment time -Increase in the springiness depending on the treatment time	Kamali and Farahnaky (2015)
Courgette	-Power: 350, 500, 650, 750, 1000 W -Time: 35, 28, 23, 20 and 16 min	-Decrease in the maximum puncture force (microwave and conventional cooking)	Douiri-Bedoui et al. (2011)
Fresh kohlrabi (German cabbage), radish, turnip, and potato	-Power: 900 W	-Decrease in the hardness values (ohmic, microwave and conventional cooking)	Farahnaky et al. (2018)
Watermelon rind	-Power: 2650 W	- The lower hardness values -No significant differences between the springiness and adhesiveness values	Athmaselvi et al. (2012)
Cheddar and Mozzarella	-Power: 900 W	-Better scores for stretchability	Gulzar et al. (2020)

cheeses	-Time: 2 min	-Worse scores for firmness and stringiness	
Carrot	-Power: 450 W -Time: 10 min	-The hardest texture in microwave-cooked. -Followed by boiled and steamed carrots, respectively	Paciulli et al. (2016)
Jerusalem Artichoke	-Power: 600 W and 900 W -Time: 60, 75, 90, 105, 120, 135 and 150s -600 W for 105 s (for the best results)	-The lowest hardness for 60 s at 600 W -Higher hardness values compared to the fried slices.	Baltacıoğlu and Esin (2012)

TABLE 3 Recent selected studies about the effects of microwave thawing on food texture

Material	Conditions of Microwave Thawing	Results	Reference
Potato strips	- Power: 270 W - Time: 3 min	- F max (cutting force) values were not differed between control and microwave pre thawed samples	Tuta, et al.(2010)
Fresh bread	- Power: 70 W - Time:3 min	- Decreased unrelaxed force, porosity and failure force - Caused rubbery character (except xanthan contained samples) - Increased failure deformation	Mandala and Sotirakoglou (2005)
Potato slices	- Power: 125 W - Time: 3 min	- Not gave textural benefits to samples according to room temperature thawing	Phinney et al. (2017)
Largemouth bass (*Micropterus salmoides*)	- Power: 300W - Time : Up to 0 °C	- Higher hardness and chewiness compared to conventional thawing	Cai et al. (2020b)
Potato cubes (*Solanum tuberosum L)*	- Power: 318.14W - Time: Up to 4 °C	- Decreased firmness at non-blanched samples according to conventional thawing	Icier et al. (2017)
Sliced red radish	- Power: 500 W - Time: Up to 4 °C	- Lowest firmness value	Xu et al. (2021)
Korean rice cake	- Power: 200 E - Time: Up to 25 °C	- Provided lower chewiness and hardness values than thawing at incubator (25°C) - Largest thawing lost	Ku et al. (2018)
Chicken breast meat	- Time: 6 min	- Highest shear force and drip loss	Oliveira et al.(2015)
Bread dough	- Power: 100 and 300 W - Time: Up to 20°C	- Both 100 and 300 W microwave thawing provide highest hardness and chewiness values. Cohesiveness value was decreased by 100 W microwave treatment	Yang et al.(2020)
Beef	- Power: 700 W - Time: 0.4h (up to 0 °C)	- Better texture of sensory evaluation between other thawing methods.	Kim et al. (2013)
Raspberry	- At thawing condition of microwave oven	- Least drip lost - Sensory evaluation of microwave thawing gave best results - Hardness (sensorial) of microwavethawed samples closed to fresh	Liu et al. (2020)

		raspberry.	
Largemouth bass (*Micropterus salmoides*)	- Power:300 W/20 g - Time: 2 min	- Obtained lowest elasticity value - Microwave thawed samples had lower G' value (storage modulus) than cold thawing samples	Cai et al.(2020a)
Mashed potatoes	- Power: 600 W/650g - Time: 15 min	- Microwave thawing increased cohesiveness of commercial an natural mashed potatoes	Alvarez et al.(2005)
Hami melon (*Cucumis melo L. var. Saccharinus*)	- Power: 300, 500 and 700 W - Time: Up to 0 °C	- Hardness of samples increased with increasing microwave power.	Wen et al. (2015)
Mashed potatoes (Kennebec)	- Power:600W - Time: 20 min	- Highest consistency, adhesiveness, firmness and gumminess values were obtained with microwave thawing	Alvarez et al. (2007)

TABLE 4 Recent selected studies about the effects of microwave sterilization on food texture

Material	Conditions of Microwave Sterilization	Results	Reference
Brown rice (*Oryza sativa L.*) and barley (*Hordeuvulgare L.*)	- Power: 700 W - Time: 10, 20, 30, 40 and 50 s	- Values for texture (sensorial analysis) were reduced by 40-50s Microwave treatment - *Aspergillus flavus* and *Aspergillus parasiticus* growth was inhibited by 90% by 20s microwave application.	Lee et al.(2017)
Ready to eat meals (pasta with broccoli rabe (PB), meatball with tomato sauce(MT), cad with tomato sauce(CT) and mashed broad bean with chicory(BC)	- Power: 600 W - Time: 200s (PB), 120s (MT), 180s (CT, BC)	- PB and CT samples, cohesiveness values were decreased with microwavetreatment - Firmness values were decreased in MT and CT samples - Partial inactivation of *Listeria monocytogenes* (25%) was achived	Matera et al. (2020)
Caixin (*Brassica chinensis* L)	- Power: 1400 W, 400W - Time: 90s (1400 W), 150s (400 W)	- Microwave treatment decreased shear strength of samples. - 400W 150s treatment was more effective on microorganisms than control and high power microwave treatment	Liu et al.(2014)
Asparagus	- Power: 915 MHz - Time : F0 = 3 min and 121 °C	- Shear stress of asparagus decreased after use of microwave-circulated water treatment. - Textures of asparagus not effected from different thermal processes. - Microwave circulated water treated asparagus showed highest antioxidant activity among conventional methods.	Sun et al.(2007)

Carrot	- Power: 915 MHz - Time: F90 °C = 3 min and 10 min	- Compared to conventional hot water process, microwave treatment reduced process time, cook values and improved quality properties - Texturel properties were not differed with two method	Peng et al. (2017)
White shrimps (*L. vannamei*)	- Power: 1300 W and 2450 MHz - Time: 80 and 100s	- Provided higher hardness, cohesiveness, chewiness values than induction heated samples	Tsai et al. (2021)
Canned flavor crab meat sauce	- Power: 400 W - Time: 4 min	- Microwave treated samples showed similar hardness and viscosity with the control group	Zhu et al. (2021)
Oncorhynchus keta Walbaum fillets	- Power: 896MHz - Time: $F_{90\,°C}$ = 10 min	- Hardness and gumminess of microwave treated samples were lower than conventional process	Xue et al. (2021)
Pasta	- Power: 915 MHz - Time: F_{90} = 11.9 min	- Firmness and extensibility of microwave treated samples decreased	Joyner et al.(2016)
William Bartlett (*Pyrus communis*) pears	- Power: temperature from19.92 ± 1.36 to 101.11 ± 2.50 °C - Time: 4.7 min	- Hardness value of microwaved samples were higher than conventional process	Devi et al. (2021)

TABLE 5 Recent studies about the effects of microwave frying on food texture

Material	Conditions of Microwave Frying	Results	Reference
Potato chips	-Power: 1000 W	- Pre-treatment of osmotic dehydration with sodium chloride and coating with 1 % CMC-Na improved the textural properties of microwave fried chips	Su et al. (2021)
		-Crispier product as compared to conventionally fried chips	Su et al. (2018)
	-Power: 12, 16 and 20 W/g -Frying time: 2, 4, 6, 8, and 10 min	-Reduction in the breaking force -Breaking force was reduced as the frying time increased from 4 to 10 minutes	Su et al. (2016)
	-Power: 600, 800, and 1000 W - Frying time: 120, 240 and360 s	- The crispiness of potato chips decreased linearly with the increase in the microwave power and frying time	Quan et al. (2014)
Beef patty	-Power: 50 and 70 % -Frying time: 2 min	-Texture of microwave fried was harder in comparison to conventionally fried counterpart -Increase the power level resulted in harder texture of beef patty	Noor Hidayati et al. (2021)
Banana chips	-Power: 1000 W -Frying time: 5 and 10 min	-Crispiness of microwave vacuum fried banana chips nut significantly different from commercially available conventionally fried banana chips	Jumras et al. (2020)
Apple slices	-Microwave Power:800 and 1000 W -Ultrasound power: 600 W -Frying time: 6, 8,10, 12,14 and 16 min	-The synergy of ultrasound treatment and microwave resulted in apple slices with enhanced crispiness	Faruq et al. (2019)
Edamame	-Microwave Power: 1000 W -Ultrasound power: 600 W -Frying temperature: 80, 90 and 100 °C -Frying time: 3,6,9,12,15 and 18 min	-The breaking force significantly lowered by the application of ultrasound in microwave vacuum fried edamame	Islam et al. (2019)

Chinese yam (*Dioscorea polystachya*)	-Microwave Power: 1800, 2400 and 3,000 W -Ultrasound power: 300 and 600 W	-Reduction in the hardness of chips with the increase in microwave and ultrasound power	Chitrakar et al. (2019)
Fish fillets (*Aristichthys nobilis*)	-Power:800, 900 and 1000 W	-Microwave assisted vacuum fried fillets were less harder in comparison to vacuum fried fillets -The value of hardness for microwave assisted vacuum fried fillets increased from 5 to 20 min followed by reduction from 25 to 36 min	Shi et al. (2019)
Mushroom chips (*Agaricus bisporus*)	-Power:800, 900 and 1000 W -Frying time: 2, 4, 6, 8, 10, 12 and 14 min	-Breaking force decreased with the increase in microwave power and frying time and resulted in crispier chips -Utilization of ultrasound treatment with microwave frying further enhanced the crispiness of chips	Devi et al. (2018)
Sweet potato chips	-Microwave Power:800 W -Ultrasound power: 150, 300, and 450 W for 20 min and 300 W for 10, 20, and 30 min	-Utilization of ultrasound treatment in microwave vacuum frying of sweet potato yielded crispier product -Crispiness of chips followed linear relation with power of ultrasound and the time of treatment	Qiu et al. (2018)
Purple fleshed sweet potato	-Microwave Power: 0, 600 and 800 W -Ultrasound power: 0, 300 and 600 W	-Reduction in the breaking force with the increase in the microwave and ultrasound power	Su et al. (2018)
Pumpkin slices	-Microwave Power: 600, 800 and 1000 W -Ultrasound power: 0, 300 and 600 W	-Utilization of ultrasound treatment improved the crispiness of microwave vacuum fried pumpkin slices, particularly at 600 and 800 W microwave power	Huang et al. (2018)
French fries	-Power: 315, 430 and 600 W	-Microwave fried French fries were crispier in comparison to conventional deep fried French fries	Sansano et al. (2018)
	-Power: 10, 15, 20 W/g	-Hardness of the French fries reduced with the increase in the microwave power	Quan et al. (2016)
Durian chips	-Power: 582, 824 and 1085 W	-Hardness was similar to conventionally fried durian chips	Bai-Ngew et al. (2011)

Batter coated chicken	-Power: 365W -Frying time: 1.5 minutes	- Hardness of microwave fried chicken was as par and lower in comparison to conventionally fried chicken -Lowest value of hardness was observed with chickpea flour batter followed by soy and rice flour respectively	Barutcu et al. (2009a)
Batter coated fish nuggets	-Power: 2400 and 2500W	-Crust quality and texture was similar to conventionally fried fish nuggets	Chen et al. (2009)

TABLE 6 Recent selected studies about the effects of microwave roasting on food texture

Material	Conditions of Microwave Roasting	Results	Reference
Sunflower seeds	Power: 500, 600 and 800 W Roasting time: 4, 6 and 8 min	-Sunflower seeds roasted by microwave treatment were less harder in comparison to conventionally roasted seeds - Microwave power and roasting time showed no correlation for the textural properties of roasted sunflower seeds	Goszkiewicz et al. (2020)
Chickpea	Power: 450, 600 and 900 W Roasting time: 5, 10 and 15 min	Hardness of the roasted chickpeas decreased with the increase in roasting power and time	Sharanagatet al. (2018)
Pistacia terebinthus beans	Power: 360, 540 and 720 W Roasting time: 5, 11 and 17 min	The force required to break the beans showed inverse relation with roasting power and time	Bolek and Ozdemir (2017)
Peanuts	Power: 180, 540 and 900 W Roasting time: 60, 180 and 300 s	-The hardness of roasted peanuts decreased linearly with the increase in roasting power and time -The hardness of microwave roasted peanuts was less in comparison to conventional drum roasted peanuts	Raigar et al. (2016)
Wild Almonds (*Amygdalus scoparia*)	Power: 480 W Roasting time: 3 and 4 min	The increase in the roasting time decreased the forced required to cut the almonds and improved its crunchiness	Hojjati et al. (2016)
Pistachios	Power:480 and 640 W Roasting time: 2, 3 and 4 min	-Pistachios roasted by conventional air roasting were crunchier as compared to microwave roasted pistachios -Increasing the microwave roasting time resulted in improving crunchiness of pistachios	Hojjati et al. (2015)
Almonds (*Prunus dulcis*)	Power: 0.841, 0.910 and 0.913 W/g Roasting time: 45-180 s	- Microwave roasted almonds were less harder than hot air roasted counterparts -Dark roasted almonds were least hard followed by medium and light roasted respectively	Milczarek et al. (2015)
Hazel nut	Power: 68.2, 204.6, 341, 477.4 and 613.8 W	The force required to break hazel nut was decreased with the increase in microwave power for roasting	Uysal et al. (2009)