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A Review on the Impact of Microwave Processing on Physicochemical Properties of Different Cereal Grains and Flours

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Abstract: Microwave heating has emerged as a new processing treatment for a variety of materials in recent years, especially for food materials. This article provides insight on the effect of microwave heating on quality characteristics of various cereal grains and flours and emphasizes the impact on nutritional composition such as carbohydrates, proteins, lipids, color, vitamins, minerals and anti-nutritional components. Microwaves have the potential to be used for various operations like blanching, sterilization, pasteurization etc. Microwave processing power and time has a significant effect on various nutritional and anti-nutritional components; hence, processing treatment needs to be carefully studied for effective applications on cereal grains.

Keywords: Microwave heating, cereal grains, starch, protein and lipids.

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1. Introduction

Whole grains have seen increasing attention and use in many countries because their consumption is negatively correlated with risk for a variety of diseases and can prevent many common diseases caused by oxidative stress (Hong *et al.* 2023). The regular consumption of whole grain is positively associated with the decreased risk of several chronic diseases such as Type 2 diabetes, obesity, cancer, and heart diseases (Li *et al.* 2021). Grains such as wheat, rice, and maize are the most popular staple crops worldwide and they play an integral part in global agriculture and diet, bringing high energy content, with valuable protein, fat, and minerals. Therefore, in order to preserve cereals in large quantities for human usage, quality deterioration should be minimized not only at procurement level but also during processing. Food grains (cereals and legumes) act as primary sources of energy and dietary protein for the majority of population in the world due to their wider availability and low cost. Food grains are a good source of different bioactive components like fibers, lipids, essential vitamins and minerals (Suhag *et al.* 2021). But presence of different anti-nutritional components like phytic acid, tannins, trypsin inhibitor, saponins, and oxalate in these edible grains restrict their consumption and usage in food processing industry because these anti-nutritional components are known to have harmful effects on human body (Rahate *et al.* 2020). These days various processing treatments can be effectively utilized to decrease the content of antinutritional compounds and improve other quality characteristics and shelf life of cereal products. As a novel alternate thermal processing technology, microwave technology is a promising technology not only because it is easier to operate but also safe, green, environment friendly and sustainable. Utilization of microwave heating has been practiced world-wide and is increasing day by day (Gupta and Wong, 2007). Good penetration power of microwaves leads to generation of heat throughout the volume of the material resulting in volumetric heating. Hence, it is possible to achieve rapid and uniform heating of thick materials (Das *et al.* 2009). Unlike conventional heating which relies on heat conduction and convection, microwave heating utilizes microwave-convective heating and combination of microwave, convection, and radiant heating, which heats the foods instantaneously. Microwaves cause dipole rotation in food molecules causing friction which leads to heating (Guo *et al.* 2017). The primary advantage of microwave heating, compared to conventional electric oven heating, is a large savings in time. Aside from household use, industry has found some applications for the unique heating properties of microwaves, such as tempering, drying pasta and cooking bacon. The future holds promise for microwave processing to be adapted for vacuum and freeze drying, pasteurizing, sterilizing, baking, roasting and blanching (Hong and Wang, 2015).

Microwaves can be used in cereal grains for drying as well as disinfestations purposes. Microwave sterilization not only takes care of health concerning microorganisms but also inactivates enzymes to maintain nutritional quality of food (Marszałek *et al.* 2015). Effectiveness of microwave increases with increase in microwave power and time (Valero *et al.* 2014). Meanwhile, application of microwaves as heat providing media seems to be reasonable from both cost and functionality effectiveness perspectives (Xu *et al.* 2013). The industrial applications using microwaves have seen an expansion in recent years and industrial scale microwave processing units have been developed for drying, pre-cooking of meat, pasteurization of ready meals, and tempering of meat and fish. Modern food consumers are demanding high quality, minimally processed products (Hong and Wang, 2015), which has led to the development of novel microwave processing technologies for thawing, blanching, baking, and microwave-assisted extraction of bioactive compounds (Wang *et al.* 2010). In the light of the above discussion, the aim of this review was to discuss the interaction of microwaves on various properties of different cereal grains and their flours.

2. Basic theory and Principle of Microwave Heating

Microwaves are electromagnetic waves with the frequency varies from 300 MHz to 300 GHz (Chandrasekaran *et al.* 2013). The frequency of the microwave oven is defined to avoid interference with communications. The lower the microwave frequency, the better the penetration. Microwave frequency used in home microwaves is 2.45 GHz while at industrial level 915 Mhz or 2.45 GHz. Alternating magnetic field changes the orientation of polar molecules according to the electric field direction, produces thermal energy and heat the food (2.45 billion times per second) (Guo *et al.* 2017). All electromagnetic waves are characterized by their wavelength (frequency). Typically, the electromagnetic wavelength ranging from 10 to 10^{-3} m can be considered as the dielectric range (Datta and Anantheswaran, 2001). These electromagnetic waves can cause the dipolar rotation of agricultural products. Heat energy is created by two mechanisms under the influence of electromagnetic fields in microwaves: (a) Dipolar polarization, (b) Ionic conduction (Fig. 1). Many molecules such as water, can be dipolar polarized in electromagnetic field. Other molecules may become —induced dipoles because of the stresses from the electric field. Dipolar polarization could be further of two types: Orientation polarization (Inherent to polar molecules) and Distortion polarization (Induceable). When an external electric field is applied on dipolar molecules, the distance between charges within each permanent dipole, which is related to chemical bonding, remains constant in orientation polarization; in a word, the direction of polarization itself rotates, but the electric field attempts to pull them into alignment. However, as the field applied relaxes, dipoles come back to their random orientation only to be pulled toward alignment again as the electric field builds up to its opposite polarity. This causes an energy conversion from the electrical field as shown in (Fig. 2). Energy caused by friction is stored as potential energy and then converted into random kinetic or thermal energy in the material (Mujumdar, 2007).

In ionic conduction, the polarization of molecules occurs as a result of relative displacements between positive and negative ion molecules. Various polar molecules present in salt solution are sodium, chloride, hydronium, and hydroxyl ions, all of which are moved in the direction opposite to their own polarity by the electric field. As a result, they collide with unionized water molecules, when the polarity changes the ions ‘acceleration in the opposite fashion. This happens millions of times depending on the frequency and may cause large numbers of collisions and transfers of friction energy to occur (Robert, 2007). In agricultural products, dipolar polarization is the most essential mechanism to heat the samples in the microwave range, while ionic conductivity plays a major role during low-frequency treatment (Wang *et al.* 2003). Using low-frequency dielectric techniques (such as RF, or 915 MHz MW) can improve not only the operability, but also the penetration and uniformity. Frequency is the factor to decide the penetration depth. However, the depth of wave penetration may not properly characterize the decay of power in a material of finite dimensions (Datta and Anantheswaran, 2001).

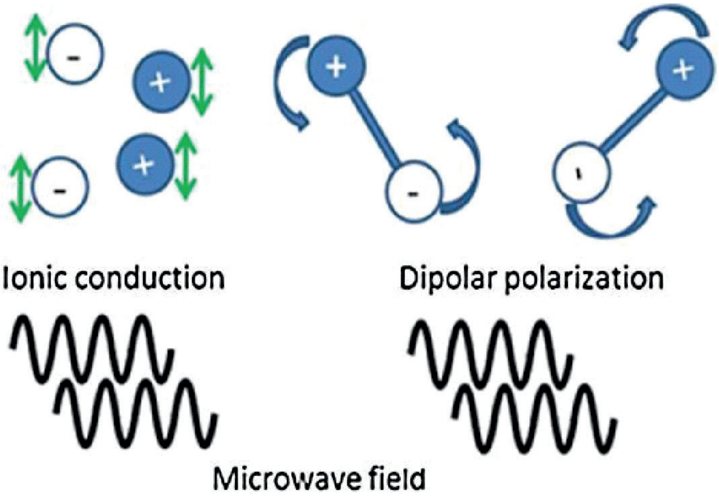


Figure 1: Ionic conduction and dipolar polarization with microwave conditions

Source: Gude ***et al.*** 2013

When the electrical conductivity of surrounding water increases, water should absorb more energy and food must be absorbing less energy; in such a system, heating conductivity took the leading role during sample heating. The temperature profile and heating rate developed during exposure to electromagnetic radiation depends on the distribution and nature of susceptors, the relationships between the dielectric properties with moisture and temperature and frequency, as well as on the thermo-physical properties (thermal conductivity, thermal diffusivity, specific heat, etc.) of the other constituents. A detailed description of the temperature profile of a complex agri-food material is therefore extremely difficult to obtain. It is important to recognize that the dielectric properties are not unique for a given material. They are specific only for a given frequency and state of the material. The dielectric properties of most materials vary with several different factors. In hygroscopic materials such as agri-foods, the dominant factor is the amount of water in the material. Various factors which affect the dielectric properties depend on the frequency of the applied alternating electric field, the temperature of the material, and on the density, composition, and structure of the material. In granular or particulate materials, the bulk density of the air–particle mixture is another factor that influences the dielectric properties. Of course, the dielectric properties of materials are dependent on their chemical composition and especially on the permanent dipole moments associated with water and any other molecules making up the material of interest. With the exception of some extremely low-loss materials, i.e., material that absorb essentially no energy from radio frequency and microwave fields, the dielectric properties of most materials vary considerably with the frequency of the applied electric fields. An important phenomenon contributing to the frequency dependence of the dielectric properties is the polarization arising from the orientation with the imposed electric field of molecules, which have permanent dipole moments (Figure 2).

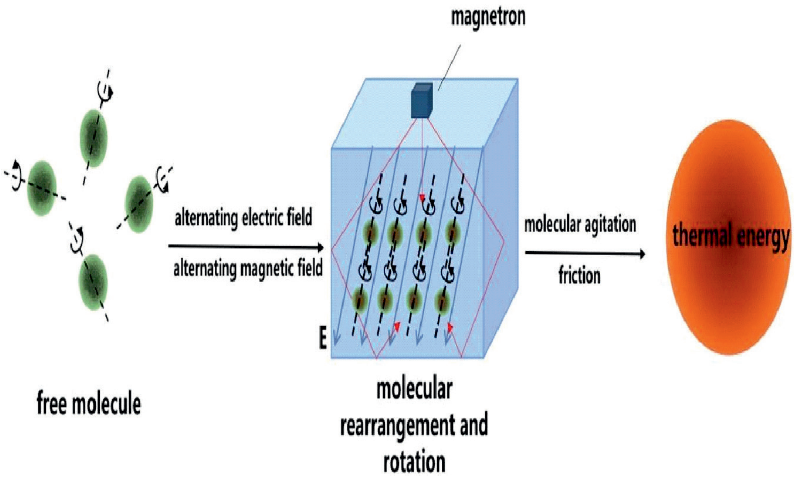
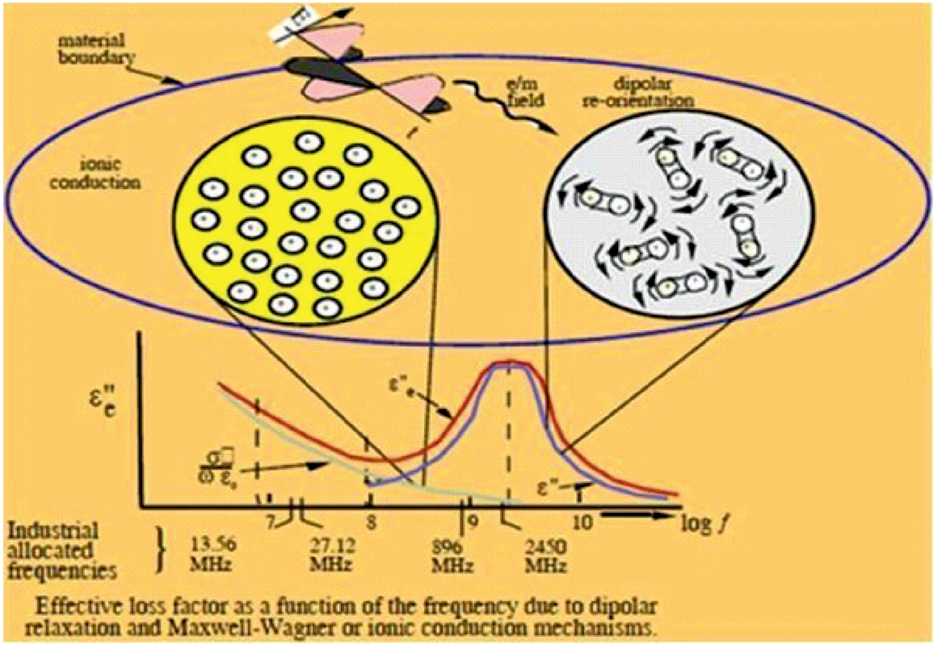


Figure 2: Principle of microwave technology (Hu *et al.* 2021)

The temperature dependence of the dielectric constant is quite complex, and it may increase or decrease with temperature depending on the material. Water is the main absorbent of microwave energy in the foods and consequently, the higher the moisture content, the better the heating. In its pure form, water is a classic example of a polar dielectric (Nelson and Krzyzewski, 1990). The dielectric properties of materials are quite dependent on temperature, and the nature of that dependence is a function of the dielectric relaxation processes operating under the particular conditions existing and the frequency being used. As temperature increases, the relaxation time decreases, and the loss factor peak will shift to higher frequencies. Thus, in a region of dispersion, the dielectric constant will increase with increasing temperature, whereas the loss factor may either increase or decrease, depending on whether the operating frequency is higher or lower than the relaxation frequency. Below and above the region of dispersion, the dielectric constant decreases with increasing temperature. Distribution functions can be useful in expressing the temperature dependence of dielectric properties but the frequency and temperature dependent behavior of the dielectric properties of most materials is complicated and can perhaps best be determined by measurement at the frequencies and under the conditions of interest. It is important to note that food electrical and



Effective loss factor as a function of the frequency due to dipolar relaxation and Maxwell-Wagner or ionic conduction mechanisms.

Figure 3: Ionic conduction and dipole re-orientation variation with microwave frequency (Gude *et al.* 2013)

physical properties, which affect microwave heating, change dramatically at temperatures below freezing point. Dielectric properties increased sharply with temperature during the transition from -10 to 0° C (thawing) (Ohlsson *et al.* 1974).

The dielectric properties of food products are also determined by their chemical composition, with the various dielectric frequencies, the dielectric properties of food would be varied. The influence of water and salt (or ash) content depends largely on the way they are bound or restricted in their movement by the other food components. This complicates the prediction, based on data for single ingredients, of the dielectric properties of a mixture. The organic constituents of food are dielectrically inert and, compared to aqueous ionic fluids or water, may be considered transparent to energy (Mudgett, 1985). Only at very low moisture levels, when the remaining traces of water are bound and unaffected by the rapidly changing microwave field, the components of low specific heat become the major factors in heating. Since the influence of a dielectric material depends on the amount of mass interacting with the electromagnetic fields, the mass per unit volume, or density, will influence the dielectric properties (Nelson, 1992). To understand the nature of the density dependence of the dielectric properties of particulate materials, relationships between the dielectric properties of solid materials and those of air–particle mixtures, such as granular or pulverized samples of such solids, are useful. In some instances, the dielectric properties of a solid may be needed when particulate samples are the only available form of the material. This was true for cereal grains, where kernels were too small for the dielectric sample holders used for measurements (Nelson and You, 1989) and in the case of pure minerals that had to be pulverized for purification. Measurement of dielectric properties of any material with exact dimensions is rather difficult as compared to a pulverized sample.

3. Effect of Microwave Heating on Different Components of Food

3.1. *Carbohydrates*

The most common carbohydrates existing in the plant tissues are starch and saccharides, which include fructo-pyranose, saccharose, amylaceum, etc. Carbohydrates, especially starch, is produced by most plants as energy storage and is also a part of human diet sources including potatoes, wheat, maize, rice and cassava. The starch consists of two units i.e., amylose and amylopectin. Amylose is a linear molecule of (1, 4) linked α-D-glucopyranosyl units, while amylopectin is a highly branched component of starch that is formed through chains of α-D-glucopyranosyl residues linked together mainly by (1, 4) linkages but with 5–6% of (1, 6) bonds at the branch points (Luengwilai and Beckles, 2009). Microwave treatment significantly changes the structure and crystallinity of starch (because of molecular vibration), and therefore the characteristics of starch, such as polarity, free energy, viscosity, gelatinization, molecular weight, particle size etc. (Szepes *et al.* 2005). The crystal structure of potato starch changed from type B to type A after being processed by microwave radiation (Lewandowicz *et al.* 1997). In addition to this, microwave treatment also affects the viscosity properties of both waxy and non-waxy starches. It has been observed that after microwave heat treatment, higher reaggregation of waxy starch granules was observed in comparison to non-waxy starch molecules (Anderson and Guraya, 2006). Synthesis is an important function of microwave treatment applied on carbohydrates. The microwave treatment can accelerate the synthesis/hydrolysis rate of starch significantly, and meanwhile some reactions can be catalyzed by microwave treatment. The synthesis of polyacrylamide-grafted dextrin by microwave assisted heating as the novel polymeric flocculant (Pal *et al.* 2010). It was evident that a novel polymeric flocculant had been developed by grafting polyacrylamide onto the dextrin backbone using microwave heating. The hydrolysis ratio of glucose hydrogel was found to increase from 0.42% to 44.6% at 160°C for 10 min microwave heating (Sun *et al.* 2015). This method was effective to obtain glucose from α-cellulose, microcrystalline cellulose, filter paper, ramie fiber, and absorbent cotton. The rates of microwave heating were five to seven times faster than conventional heating (Adnadjevic and Jovanovic, 2012). It has been observed that increase in microwave treatment time resulted in increased starch digestibility in sorghum starch. The hydrolysis curves of native and microwave-treated sorghum are shown in (Fig. 4) which showed that the total extent of hydrolysis of all the samples increased with digestion time, and native sorghums had higher degrees of hydrolysis than those of the microwave treatments of sorghum, especially in the first 120 min (Li *et al.* 2021).

In cereals, amylose tends to form complexes with lipids, resulting in reduced digestibility. Generally, cereals with higher amylose content have lower digestibility. In the present study, the amylose content of LML1 sorghum was much lower than that of the other two sorghum species. The digestibility of the three sorghum species may have been significantly different before microwave treatment, which might be related to the ratio of amylose to amylopectin in sorghum**.** The digestibility of the three sorghum varieties was significantly

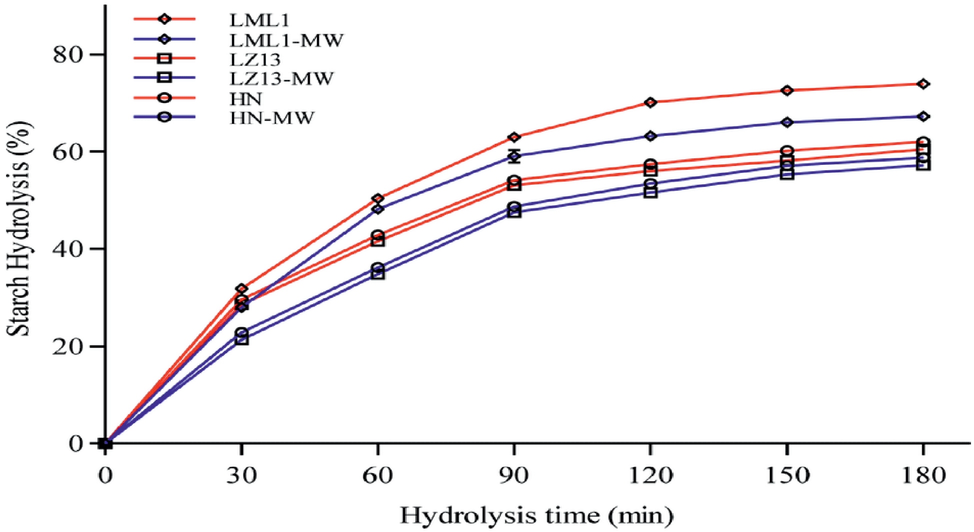


Figure 4: Trend between starch digestibility and microwave treatment of three sorghum varieties (Li *et al.* 2021)

decreased, while the dietary fiber content was significantly increased after microwave treatment (Li *et al.* 2021). The change in carbohydrate structure is always accomplished with the changes of physicochemical properties. After microwave treatment the gelatinization range of starches shifted to higher temperatures, and the crystal structure changed from type B to type A (Lewandowicz *et al.* 2000). The molecular weight of these wet starches also reduced considerably after microwave processing (Staroszczyk *et al.* 2013). Moreover, the viscosity of the starch solution also showed a downward trend. Microwave treatment of the starches affected their crystalline structure and morphology (Szepes *et al.* 2005). It has been shown in various studies that the dietary fiber content in cereals has a negative effect on their digestibility. This might be attributed to the fact that dietary fiber can reduce the release rate of glucose by inhibiting the action of amylase, thereby reducing the digestibility of starch (Lim *et al.* 2001).

The general effect of microwaving is to increase starch gelatinization and, consequently, digestibility (Khatoon and Prakash, 2005; Anderson and Guraya, 2006). The glycemic index of microwaved cereal products can be higher than the non-heated grains, but the effects of microwaving might not be dramatic (Braşoveanu and Nemţanu, 2014). Anderson and Guraya (2006) measured marginal increases in starch digestibility of rice starches with microwave power, but microwave time substantially reduced the pasting viscosity.

Microwave heating significantly enhanced the activity of isomerase and the effects of acceleration might be a non-thermal microwave effect (Yu *et al.* 2011). Microwave heating also causes significant changes in reducing sugars content of microwave various grain samples. However, the application of the lowest heating times (15, 45 and 60 sec) caused a significant increase in reducing sugars content. While, at the higher heating times (90, 120 and 180 sec) a gradual decrease in reducing sugars content was observed (Warchalewski *et al.* 2011).

3.2. Proteins

Proteins play a critical role in nearly all biological processes, including catalyzing metabolic reactions and DNA replication, responding to stimuli, and transporting molecules from one location to another. Most proteins fold into unique three-dimensional structures. Biochemists often refer to four distinct aspects of a protein's structure (Burgess and Deutscher, 2009). It can be easily found that proteins and peptides have higher dielectric constant by consulting the dielectric constant reference guide issued by Institute of Electrical and Electronics Engineers (IEEE). As a result, microwave irradiation may have a significant impact on their activity and structure (Plagemann *et al.* 2014). Microwave treatment has a significant effect on protein degradation and accelerating reaction. These effects may be accomplished with the structure changes. Microwave heating for a short period (five minutes) with a lower energy input can improve the nutritive value and utilization of crude protein in barley grains (Yan *et al.* 2014). The water absorption was slightly impaired owing to some possible configurational changes during microwave treatment (Khan *et al.* 2011). The microwave-heated solutions exhibited more extensive protein aggregation than conventionally heated ones (Gomaa *et al.* 2013). Furthermore, the trypsin activity was found to be dramatically increased when the reaction mixture was irradiated by microwave energy at a constant temperature (Mazinani, DeLong and Yan, 2015). Microwave treatment can also accelerate the degradation of kinetics to a certain extent during the stability of protein-based flavoring heated with microwave energy (Lotfy *et al.* 2015). Microwave treatment (3 mins) with increase in power resulted in significant reduction in solubility of gluten protein (Fig. 5). Solubility properties of gluten proteins were negatively influenced with the microwave treatment. Both the microwave treatment time and power level were found to be significantly effective on solubility values. It has been observed that application of different power levels with increased treatment time resulted in gradual decrease in solubility of microwave-heated gluten proteins. The samples heated at 50%

power level had significantly higher solubility values than those heated at 80 and 100% power levels since at 50% power level, less microwave energy was generated within the sample, which resulted in slower heating as compared to 80 and 100% power levels (Yalcin, 2008).

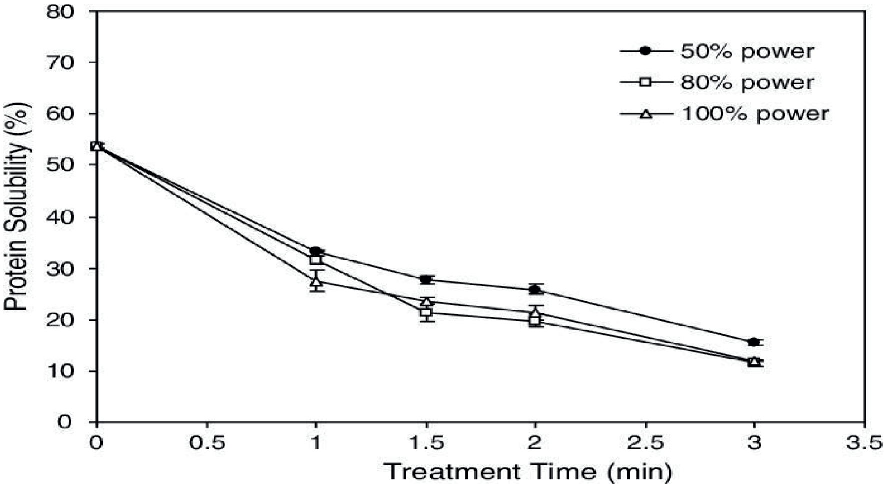


Figure 5: Effects of microwave heating power and treatment time on protein solubility (%) of gluten proteins dissolved in distilled water at 1% (w/v) concentration (pH=3). (Yalcin, 2008)

The effects of microwave treatment on the protein solubility, foaming capacity and foaming stability is described in (Table 1). Protein solubility of sorghum grains significantly reduced ($P < 0.05$) from 12.5% to 11.9 and 7.6%, respectively with the application of microwave treatment at 350 and 500W for 15 sec. This decrease in protein solubility of sorghum grain during microwave treatment might be due to the denaturation of the protein, caused by exposure of hydrophobic groups and aggregation of unfolded protein molecules (Afify *et al.* 2011). In a study carried out by Yalcin et al (2008), also confirmed that the solubility of wheat gluten proteins diminishes with microwave treatment. However, other properties like crude protein and *in vitro* protein digestibility does not significantly affected with the microwave treatment. Before microwave treatment, the foaming capacity was found to be 12.2%. However, after microwave treatment at 350 and 500W for 45 sec, foaming capacity significantly ($P < 0.05$) reduced to 3.29 and0.98%, respectively. Application of microwave heating at 500 W caused extreme reduction in the foaming capacity of sorghum grain. This was reduced to > 1% when the treatment lasted 45 s

(Table 1). The results obtained on the foaming capacity of microwaved and control grains showed similarity (Sharanagat *et al* (2019), who also found that high microwave power significantly reduced the foaming capacity of the grain. Foaming stability gradually increased with the application time and power levels. The decrease in the foaming capacity of sorghum grain after exposure to microwave energy might be because of changes in the solubility and nature of protein that occurred during treatment.

Moreover, the lower foaming capacity of the treated sorghum may be attributed to a reduction in some polar amino acids, change in their polarity or denaturation, and dissociation of the constituent protein (Obasi *et al*. 2014). Almaiman *et al.* (2021) also reported significant reduction in emulsion capacity and emulsion stability of sorghum grains, particularly at high microwave power due to changes in the protein aggregation as well as surface hydrophobicity and charge characteristics of proteins (Cheftel *et al.* 1985). Further, the nutritional quality of protein not only depends on the amino acid composition but also on the availability of these amino acids. In this context, Hassan *et al.* (2021) reported no change in the free amino acids of corn grains when they were exposed to MW power of 300W until temperature reaches to 60°C.

Table 1: Effects of microwave treatment on protein solubility, foaming capacity and foaming stability of sorghum grains. (Almaiman *et al.* 2021)

Microwave power (W)	*Time (s)*	*Protein solubility (%)*	*Foaming capacity (%)*	*Foaming stability (%)*
Control	Control	12.5	12.2	80.3
350	15	12.4	9.80	86.8
	30	12.3	7.62	86.8
	45	11.9	3.29	89.3
500	15	12.4	8.31	92.1
	30	8.2	6.47	93.4
	45	7.6	0.98	93.8

3.3. *Lipids*

Lipids are a group of compounds that are generally soluble in organic solvents and largely insoluble in water. Lipids may be broadly defined as hydrophobic or amphiphilic small molecules. Except for energy storage, lipids also serve both structural and metabolic functions. The amphiphilic nature of some lipids allows them to form structures, such as vesicles, multilamellar/ unilamellar liposomes, or membranes in an aqueous environment (Akoh, 2017). Considering lipid is a too large category, oil and fat are sometimes used to refer to the lipids in the food industry. It is a strong polarity molecule for analyzing the structure of lipids. For this characteristic, lipids always showed high dielectric constant and loss factor at a certain frequency (Zhang *et al.*2007). Oil had low dielectric constant and loss factor at the frequency, meanwhile the dielectric properties were affected by their fatty acid composition significantly (Lizhi *et al.* 2008). Fat extraction was also an important application of microwave treatment. It can be considered as a new and general alternative for the lipids extraction by using microwave energy because of the high efficiency. The microwave extraction was identified as the most simple, easy, and effective method for lipid extraction from microalgae (Lee *et al.* 2010). It has been observed that forty-two minutes of microwave extraction can be equivalent to eight hours of conventional heating extraction method by accounting the amount of total fat extracted from foodstuffs (Virot *et al.* 2008). Microwave heating significantly increased the oil content of sorghum grains from 6.55 to 7.99% and improved the fatty acid composition by increasing the saturated and unsaturated fatty acid content from 14.93% and 82.83% to 15.02 and 83.12%, respectively (Hassan *et al.* 2017). Microwave heating cause phytosterol oxidation which might be attributed to the presence of double bonds, which can easily undergo free radical attack followed by hydrogen abstraction on the carbon atoms in α-positions to the double bonds (Leal-Castaneda *et al.* 2015). The stability of phytosterol depended on both the heating time and the surrounding medium (Leal-Castaneda *et al.* 2015). The fatty acids inside rice bran showed no significant difference between raw and microwave-heated rice bran during 16 weeks storage except for the oleic and palmitic acid content (Ramezanzadeh *et al.* 2000). Microwave heating also played an important role in enzyme inactivation in various cereal grains. In a study carried out by Keying *et al.* (2009), authors reported inactivation of lipases in naked oat kernels using microwaves. Further, Qu *et al* (2017) also reported inactivation of lipases and lipoxygenases in wheat kernels with the microwave heating at 700W for 60s. Abdul-Hamid *et al* (2007) performed rice bran stabilization by microwave heating at 2450 MHz for 2 min. Due to this stabilization process, certain enzymes including peroxidases and lipases get inactivated and results in extended shelf life of rice bran.

In a study carried out by Liu *et al* (2021) on wheat bran, authors reported significant reduction in lipase activity of wheat bran with the application of MW treatment. Further, authors also reported significant reduction in free fatty acid content of wheat bran with the application of MW treatment. Further, a decrease in FFA content of rice and corn grains was reported with an increase in MW power, respectively (Zhao *et al* (2007) and Hassan *et al* (2021)). Similarly, Adebowale *et al.* (2020) reported that the FFA content of MW-treated whole grain sorghum flour was approximately 50% lower than that of an untreated sample. This degradation of FFA content at higher MW power could be due to the unstable nature of peroxides which degrade into volatile compounds, (Malheiro *et al.* 2011; Doblado-Maldonado, 2012). Fatty acid composition is also one of the important oil quality parameters. Microwave heating of corn grains at 300W was done until the temperature reaches to 60°C reported to affect the saturated fatty acids insignificantly while significantly affecting the unsaturated fatty acids of corn grains (Hassan *et al.* 2021).

3.4. Color/flavor Components

Color is an important sensory parameter which highly influences the consumer acceptability of food products and may be used as a criterion of food quality. However, heat treatment can enhance reactions that could affect the overall quality of food. In general, thermal processing can change the color parameters of food products by the loss or degradation of pigments and generation of some colored compounds due to certain chemical reactions including Maillard reaction and caramelization (Bisharat *et al.* 2014). Liu *et al.* (2021) carried out a study to determine the influence of MW heating on color characteristics of wheat bran and reported that MW heating significantly affected the color values. From their studies, authors reported that control wheat bran had L^*, a^* and b^* values of 80.73, 4.80 and 18.90, respectively. As the MW treatment time increased, the L^* value decreased while a^* and b^* values increased. This variation in color values could be attributed to the non-enzymatic browning and caramelization reactions takes place during browning reactions. However, another study carried out by Hassan *et al.* (2021) reported no change in color values of corn grains when they were exposed at MW power of 300W until temperature reaches to 60°C. Le *et al.* (2014) carried out a study to determine the effect of different microwave powers (1000 and 2000W) for exposure times (3, 26, 31, 41, 66, and 159 sec) on paddy and white rice characteristics. From their study, authors reported that at higher microwave power and longer exposure time, there occurs an increase in whiteness index and decrease in color intensity of white rice. While, for paddy, the whiteness index changed variously after microwave treatment depending on exposure time and the color intensity increased remarkably. This could be attributed to the higher moisture gradients corresponding with high temperature generated inside the rice kernel which facilitates the movement of pigments from bran layer to endosperm.

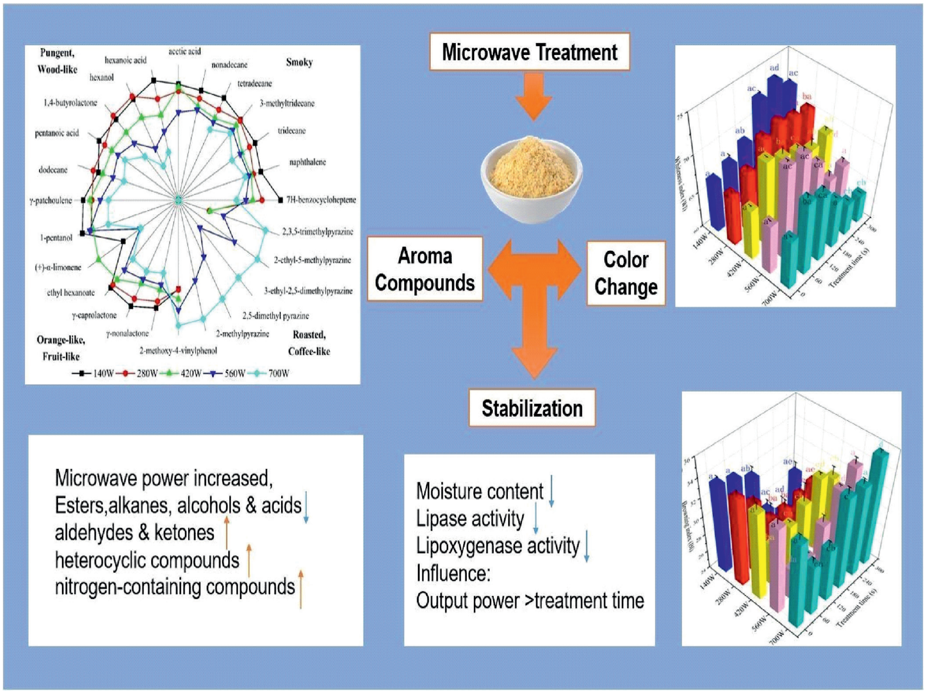


Figure 6: Characterization and comparison of predominant aroma compounds in microwave-treated wheat germ and evaluation of microwave radiation on stability. (Zhang *et al.* 2020)

Effect of microwave treatment on aroma compounds in microwave-treated wheat germ and evaluation of microwave radiation on stability is shown in (Fig. 6). de Morais Cardoso *et al.* (2014) reported in a study that carotenoids content as well as their retention in sorghum grains significantly decreased after microwave treatment. In a study carried out by Zhang *et al.* (2020) on wheat germ stabilization by microwave treatment, authors stated that with the increase in microwave processing time, the whiteness value increased initially and then decreased. Above shown (Fig. 6) indicated that with the increase in the microwave power, there occurs increase in the aldehydes and ketones, heterocyclic compounds and nitrogen-containing compounds which further increase the color and flavor of microwave treated wheat germ. In addition, gas chromatography-mass spectrometry analysis of volatile compounds showed that several aromas such as esters (fruity), acids (pungent), alcohols (green and aromatic) and alkanes (smoky) decreased or even disappeared as the microwave output power increased, while some other compounds emerged or increased, such as nitrogen containing compounds with roasted and coffee-like aromas, heterocyclic compounds (cooked potato), aldehydes (almond-like) and ketones (coffee-like) (Zhang *et al.* 2020).

3.5. Vitamins

Vitamin can be described as an organic chemical compound (or related set of compounds) of which the organism cannot synthesize in sufficient quantities and must be obtained through the diet. Vitamins have various biochemical functions on human health. Vitamins are sensitive to water, light, oxygen, and temperature. For this reason, the vitamin content would be lost dramatically during heating. Cooking has been shown to increase the level of carotenoids in steamed dent corn, boiled kernels, and coarsely ground maize samples. Finely ground corn porridge, corn flour, corn grits showed maximum losses in vitamin A as compared to popping of corn, frying tortillas, and corn flakes, which showed medium losses. Boiling and steam treatment causes lower reductions in coarsely ground hutu, porridge, baby corn, and sweet corn. The cooking temperature is an important determinant of cooking losses in carotenoids (Pretorius and Schonfeldt, 2012).

Being most sensitive among various vitamins, Vitamin C is often used as target vitamin to evaluate the influences of food processing on vitamin contents. Otemuyiwa, Falade, and Adewusi, (2018) carried out a study to determine the influence of different cooking methods on the vitamin (Vitamin C, pyridoxine, thiamine and folic acid) content of various rice varieties. From their studies, authors stated that microwave cooking caused less than 33% retention of Vitamin C. Other vitamins including pyridoxine, thiamine and folic acid are also degraded and showed retention of 63.2%, 54.4% and 55.2%, respectively by microwave cooking. Vitamin B1 losses following cooking are dependent on the method of cooking with the lowest observed losses during boiling and the highest in the case of pressure cooking (Silveira, 2017). The rate of vitamin B1 loss at 121°C is faster than that at 99°C or below, indicating that temperature is a prominent factor in determining cooking losses. Similarly, vitamin B2 loss is low following boiling and higher after microwave and pressure cooking. In pasta, the losses of vitamin B3 have been reported to be higher than B1 and B2. Vitamin B3 can leach into the cooking water; therefore, pasta products should not be cooked in excess water, and the cooking water should not be discarded. Following the cooking of rice, the vitamin losses (B1, B2, B3, B5, and B6) were lower for the rice fortified by soaking than for the rice fortified using a spraying method.

Similarly, lower reduction in content Vitamin B9 has been observed on boiling and stir frying as compared to microwave and pressure cooking. The vitamin B9 losses in samples cooked using a dry-heat method (wheat flour cake, bread loaf, couscous, and corn cake) were lower than those cooked using a moist-heat method (white cream sauce) due to leaching into the water. The losses of vitamin B12 after boiling are intermediate (Kyritsi *et al.* 2011). Employing microwave techniques as the heating methods, encapsulated liposoluble vitamins are dried by conventional and microwave drying. Microwave treatment at power 690 W promoted the recovery of 100% of the vitamin and reduced drying times to about 30 minutes, while 230 W degraded 40% of the vitamin after longer treatment. In contrast, the conventional heating degraded 17% of the vitamin during 12 hours of processing to achieve the same moisture content (Barba *et al.* 2015). Vitamin E is an important antioxidant that plays an important role in growth and reproduction. In a study carried out by Hong *et al* (2023), the contents of α-, β-, γ-, and δ-tocopherols of processed Qingke (highland hull-less barley) significantly reduced with microwave baking. Further, de Morais Cardoso *et al.* (2014) also reported that there is a significant increase in the total Vitamin E content of sorghum from 2029 to 3112 µg/100 g along with their better retention after microwave treatment.

3.6. Minerals

Unlike vitamins, minerals, are not destroyed by light, heat, pH, or oxidizing agents. Heat processing can affect bioavailability of minerals by changing their solubility and by degrading food components which further increases or decreases the mineral availability. Minerals can be removed from foods during processing such as leaching and physical separation or can be added into processed foods from the instruments (Ummadi *et al.* 1995). In general, minerals are concentrated in bran and germ portion of grains, and their subsequent removal by milling leaves behind a pure endosperm having lower mineral content. Conversion of whole wheat to white flour results in 16-86% loss of iron, magnesium, zinc, copper, and selenium (Reddy and Love, 1999). Lara *et al.* (2021) carried out a study on microwave heating of floury and sweet specialty maize kernels and evaluated them for various characteristics including minerals (calcium, magnesium, zinc, phosphorus, potassium, and iron) composition. They reported from their studies that microwave heating till 390 s showed insignificant effect on mineral content of floury and sweet maize kernels.

3.7. Bioactive Compounds

Polyphenols and flavonoids are important bioactive compounds which possess health-promoting effects for the human body (Dhua *et al.* 2021). The change in polyphenol and flavonoid contents followed by thermal processing mainly depends on the raw materials and the processing method. In a study carried out by Hong *et al.* (2023), authors reported significant reduction in flavonoids and phenolic compounds of Qingke (hull-less barley) due to the thermal degradation which takes place during microwave baking treatment. Further, authors also reported that the amount of free phenolic compounds in Qingke was decreased significantly because high temperature and longer processing time leads to the decomposition of free phenolics more easily. However, microwave baking treatment retained freer phenolics as compared to other thermal processing treatments. Further, Dhua *et al.* (2021) also reported significant reduction in content of phenolics, flavonoids and anthocyanins of wheat samples during microwave roasting (600 W for 5 min) due to thermal degradation during microwave heating.

A study by Kataria, Sharma and Dar (2021) on microwave heating at 900W for 2-5 min also reported significant reduction in TPC and TPC of brown teff grains. Similarly, Arora *et al* (2021) reported significant reduction of 69.3% 81.36% and 85.09%, respectively in anthocyanins content of black rice samples during microwave heating at 300W, 600W and 900W. On the contrary, Mishra et al. (2014) reported significant increase in TPC of red rice samples (from 163 to 246 mg/100g Gallic acid Equivalent) after microwave heating at 900W for 120s. Authors also reported significant reduction in flavonoids content of red rice samples from 0.74 to 0.56 mg QE/g during microwave heating. Further, Sharanagat *et al.* (2019) also reported significant increase in TPC (from 2.64 to 4.67mg GAE/100g) of sorghum samples after microwave heating at 300, 450 and 600W for 5, 10 and 15 min. They concluded that thermal processing caused alterations in the chemical structure of the protein-phenolic components, degraded hydrolysable tannins to smaller phenolic compounds and resulting in an increase in TPC. Authors also reported reduction of 18.77%, 30.33% and 30.07% in TFC content of sorghum samples roasted at 300 W, 450 W and 600 W, respectively.

3.8. Anti-nutritional Components

Anti-nutrients are natural or synthetic compounds that interfere with the release or uptake of nutrients, thereby reducing the bio-accessibility and bioavailability of nutrients in food (Rousseau *et al*, 2020). In plants, antinutritional factors participate in the chemical defence mechanism against fungi, insects, and predators, thereby proving beneficial while in the animal/ human body they reduce the nutrient bioavailability thus reducing the nutritional value of foods

(Sinha and Khare, 2017). Edible crops have various anti-nutritional factors primarily include

Phytic acid, saponins, lectins, enzyme inhibitors like amylase inhibitor and protease inhibitor etc.

To remove the antinutritional factors present in food grains different processing techniques such as thermal (boiling autoclaving, hot air oven), enzymatic, soaking, germination, irradiation, and fermentation are used. These methods improve the nutritional quality of edible food grains by reducing the anti-nutritional factors (Samtiya *et al.* 2020). But each of these methods have one or other disadvantages such as extensive time consumption and loss of water-soluble nutrients during soaking, loss of heat sensitive nutrients during thermal processing, difficulty in controlling the process parameters during enzymatic treatment and fermentation and generation of waste during most of these processes. These limitations lead to the usage of alternative methods such as high-pressure processing, extrusion, and microwave treatment for the reduction of antinutritional factors in food products (Linsberger-Martin *et al.* 2013). During microwave processing of cereals, there are three mechanisms that takes place in the antinutritional factors like thermal denaturation in phytic acid, oxalate, trypsin inhibitor, saponins and tannins, which results in structural changes in oxalate, trypsin inhibitor and saponins as well which leads to formation of insoluble complex in tannins and phytic acid as shown in (Fig. 7). Application of microwave has been found to affect the antinutritional factors as shown in (Table 2). Microwave treatment (900W, 2450 MHz) for 40-100 s results in 11.76% reduction of phytic acid and 74.54% of tannin.

3.8.1. ***Phytic acid***: Phytic acid and its salt known as phytates occurs naturally in grains such as cereals, legumes, nuts, and oilseeds (Bora, 2014). Phytic acid content in the grains increases as they mature and accounts for 60–90% of the total phosphorous present in dormant grain (Kumar *et al.* 2010). Phytic acid is typically negatively charged and commonly binds with positively charged metal ions like iron, zinc, calcium, and magnesium to form a complex, thus reducing the bioavailability of these ions by decreasing the absorption rates (Samtiya *et al.* 2020). It is a good natural chelating agent due to the presence of six reactive phosphate groups. It is known to be the most important anti-nutrient in food that causes deficiencies of mineral ions inhuman and animal nutrition primarily due to these chelating effects (Grases *et al.* 2017). Microwave treatment has been successful in reducing the phytic acid content of several food grains. Reduction of 35.6% and 34.7% (900 W, 2450 MHz, 2–12 min) in phytic acid of white and black colored seed coat accessions, respectively, with an increase in microwave treatment time (Kala and Mohan, 2012). Mishra *et al*. (2014) also reported significant reduction in the amount of phytic acid (168.1 to 83.36 mg/100g) of red rice samples after microwave treatment at 900W for 120s. Similarly, Kataria *et al*. (2021) also reported significant reduction in phytate content of brown teff grains after microwave heating at 900W for 2-5 min. Authors also reported that this degradation might be attributed to various reasons including formation of some insoluble complexes between phytate and other compounds such asphytate-protein, phytate-mineral, and phytate-protein-mineral complexes or cleavage of the phytate ring itself or partial dissociation of phosphorus from the phytic acid structure.

3.8.2. Tannins

Tannins are water-soluble phenolic compounds with molecular weights greater than 500 Da (Nikmaram *et al.* 2017). They are secondary compounds that mainly occur in fruits, barks and leaves of pomegranate, cocoa bean, berry fruits, and beverages (tea, beer, and wine). They are also present in cereals like barley, sorghum and millets (Morzelle *et al.* 2019). Tannins may be classified into two types (i) hydrolysable (e.g., ellagitannins and gallotannins): (ii) condensed (e.g., proanthocyanidins). Condensed tannins can be found in millets and peanuts in plenty (De Camargo and Lima, 2019). Tannins are considered as anti-nutritional compounds because they negatively affect the digestion of various nutrients like proteins by inactivating their respective enzymes through multiple hydrogen bonding between tannin's hydroxyl group and protein's carbonyl group. Microwave processing at 850 W for 30 min reduced the tannin content by 27.5% in buckwheat (Deng *et al.* 2015).

Table 2: Effect of microwave treatment in the reduction of the antinutritional factor of cereal grains

Food grain	*Antinutritional factor*	*Maximum reduction (%)*	*Microwave processing parameters*	*References*
Sorghum	Phytic acid Tannins	11.76 74.54	Microwave treatment (900W, 2450MHz) for 40-100 s	Singh *et al.* (2017)
Wheat	Phytic acid Tannins Saponins	33.43 27.49 20.12	Microwave heating power 850W At frequency 2450MHz for 30 min	Deng *et al.* (2015)

Microwave treatment for 1, 1.5, 2, and 2.5 min of horse chestnut grain decreased tannin content by 54.84%, 64.52%, 66.94%, and 68.15%, respectively

(Rafiq *et al.* 2016). These authors too attribute the heat labile nature of tannin as the main cause of reduction by microwave treatment. Microwave cooking of peanuts at 2450 MHz showed a decrease of 6.7% and 18.0% in tannins content for a cooking time of 6 and 12 min, respectively. The degradation of tannin at higher temperature and their interaction with other components such as protein to form insoluble complexes were suggested as the main cause for their reduction in microwave treatment. All these findings indicate that there is a significant potential for microwave processing to reduce the tannin content of various food grains. Microwave treatment reduces tannins by breaking the tannin-protein complex and the heat labile free tannin degrades due to heat generated by microwaves. In contrast, a study by Kataria, Sharma and Dar (2021) reported that microwave processing (at 900W for 2-5 min) initially decreased the tannins content of brown teff grains followed by an increase in their level upon increasing the duration of the treatment. This could be because of the inhibition of polyphenol oxidase enzyme, during thermal treatment which justifies the increase in tannin after a few minutes of microwave processing.

3.8.3. Saponins

Saponins are known as secondary, non-volatile, active surface metabolites and are mainly found in plants. Saponins contain sugar moiety in their structure and are steroids or triterpenes in nature (Rekiel *et al.* 2020). Microwave heating of cereal bran at 2450 MHz for 1.5, 2.0, and 2.5 min respectively showed 55.04%, 82.01% and complete elimination of saponin (Kaur *et al.* 2012). This indicates the effectiveness of microwave heating in terms of efficiency and reduction levels of saponins in cereal bran. In buckwheat, microwave heating at 850W for 30 min showed a 20.12 % reduction in saponin content (Deng *et al.* 2015). The efficacy of saponins reduction in buckwheat by microwave treatment was greater than high hydrostatic processing but lesser than boiling in distilled water at 100°C for 30 min. Reduction in saponin content during microwave processing could be due to various structural changes (Badifu, 2001). These findings suggest that microwave processing can significantly reduce or eliminate saponins from food grains, thereby improving the nutritional quality and safety of food grains for human consumption. However, a study by Kataria, Sharma and Dar (2021) reported that microwave processing (at 900W for 2-5 min) of teff grains, initially increased the saponin content followed by their reduction at prolonged treatment time. This was attributed to the increase in the permeability of cell membrane which maximizes the extraction of saponins. At a particular time, the saponins remain heat-stable for a certain duration. But severe heat treatment then led to a reduction which may be due to hydrolysis of the glycosidic bond between the sapogenin and glycosidic residue (Nyembwe *et al.* 2015).

3.8.4. Oxalates

Oxalate can reduce the bioavailability of minerals like calcium, iron (II), and magnesium in humans due to its tendency to form bonds with divalent metal cations. High oxalate-rich food intake may contribute to the formation of calcium oxalate crystals, which significantly affect the blocking of renal tubules and the development of urinary calculus and human hypocalcemia (Nikmaram *et al.* 2017). Microwave processing led to reduction in oxalate present in different food grains. 44.21%, 57.29% and 65.00% reduction in oxalate content of cereal brans at microwave processing for 1.5, 2.0 and 2.5 min respectively (Kaur *et al.* 2012). Microwave-heating was found most effective in reducing the oxalate content in rice bran by 34.9% (Irakli *et al.*2020). Microwave treatment can therefore be an easy, quick and efficient treatment method for removing oxalate from grains. The reduction in oxalate with respect to microwave heating could be due to heat stress which destroys the total oxalate (Kala and Mohan, 2012). Mechanism of microwave action on antinutritional factor as shown in (Fig. 7). Interaction of microwaves with food material is dependent on its dielectric properties such as dielectric constant which is the ability of a material to store electrical energy and dielectric loss which indicates the ability of the material to convert electrical energy into heat (Chandrasekaran, Ramanathan, and Basak, 2013). The heat generated inside the food product by microwave processing reduces antinutritional factors due to their heat-labile nature. The mechanism for thermal degradation of antinutritional factors involves the hydrolysis of peptide bonds, deamidation (splitting of covalent bonds), destruction or interchange of disulfide bonds (Rahate, Madhumita, and Prabhakar, 2021).

4. Cereal Flours

Physical hydrothermal processes allow modifying the functional properties of the flours for being used in food processing. During hydrothermal treatments, the starch is subjected to high moisture and temperature. Microwaves have shown to increase the swelling power of starch granules because of starch gelatinization depending on the intensity of treatment (Atwell, 1988). However, microwave irradiation showed no effect on the optical and thermal properties of rice starch during gelatinization with respect to conventional heating (Fan *et al.* 2012). Nevertheless, flours, as compared to starches, have a higher nutritional value and the extraction process is more economical with a lower

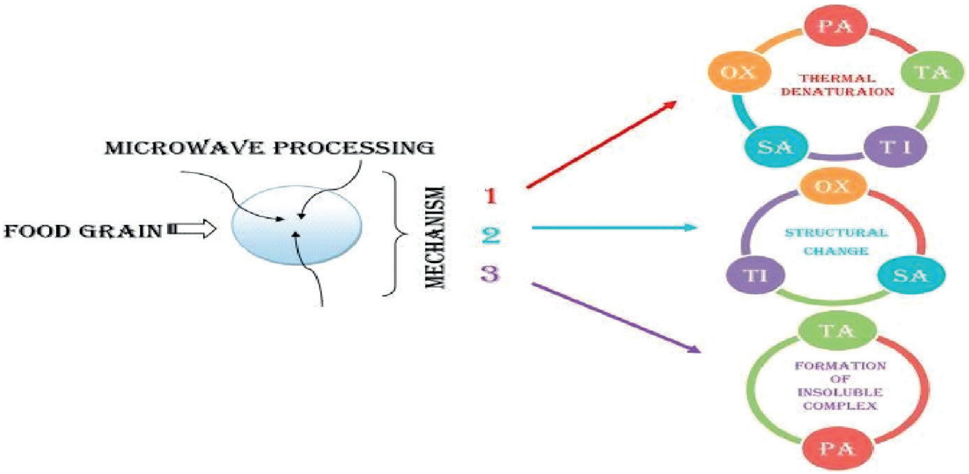


Figure 7: Mechanism of microwave action on antinutritional compounds (Suhag *et al.* 2021), (PA-Phytic acid, OX-Oxalate, SA-Saponins, TI-Trypsin inhibitors, TA-Tannin)

environmental impact (Eckhoff and Watson, 2009). Furthermore, the peak viscosity of rice flour decreased as temperature and microwave power level applied to rice grain increased (Pinkrová *et al.* 2003). Further, the feasibility of microwave energy for the inactivation of α-amylase in wheat and wheat flour has been successfully tested by (Aref *et al.* 1969). They concluded that the levels of enzyme activity decreased without damaging the flour with respect to its capacity to form dough, maintaining its viscoelastic properties. The application of microwave energy to rice flour for β-glucanase inactivation and enhancement of β-glucans bioactivity of fortified rice-based gluten-free breads while bread physical quality was hardly affected by flour microwave pretreatment. The microwave radiation absorption capacity of flour, the moisture changes during the treatment, the particle morphological structure as well as crystallinity/amorphous region ratio and flour thermal properties were studied revealing significant gelatinization temperature rise and the amylopectin retrogradation extent in treated-flours. The treatment resulted in lower viscometric profiles, amylose retrogradation and higher pasting temperatures (Villanueva *et al.* 2018). However, cereals such as sorghum, wheat, corn, oats rice etc., contains a large amount of starch and has a higher digestibility, leading to a rapid rise in blood sugar levels after eating. Therefore, it is important to find an effective processing method to reduce the in vitro digestibility of cereal starch to promote the development of cereal food.

Depending on the intensity of the treatment, starch might be gelatinized, broken the structure of granules, increase the swelling power of the granule and lose the crystallinity (Atwell, 1988). Microwave irradiation had no effect on the optical and thermal properties of rice starch during gelatinization with respect to conventional heating (Fan *et al.* 2012). An increase in gelatinization temperature of cereal starch has been found to reduce the solubility in case of maize and wheat. Increase of gelatinization temperature results in decrease in the paste viscosity of microwaved maize starch (Stevenson *et al.* 2005). Fig. 8 shows more disaggregated structure in microwaved flours (b and c) as compared to native flours. It was also observed that these flours lose gradually the compact matrix where starch granules were integrated into the protein; instead, starch granules showed more naked and slightly swollen structure. This effect increased with the time of treatment.

Microwaves might cause structural reorganization of starch granules i.e., annealing which causes swelling of starch granules owing to the excess of water at temperatures above the glass transition temperature (Biliaderis, 2009). In addition, no breakage of the starch granules was observed, indicating that starch gelatinization was not complete; thus, either the temperature or the time of treatment was not enough to produce starch gelatinization. Therefore, the effect of microwave heating has been focused on starches. Nevertheless, flours, as compared to starches, have a higher nutritional value and the extraction process is more economical with a lower environmental impact (Eckhoff and Watson, 2009). Shear stability of treated flours is improved while setback viscosity is reduced. Therefore, microwave treatment could be used to obtain modified maize flours more suitable for some food applications. Heat treatment of cereal grains caused changes in the protein and starch, so rheological characteristics and pasting properties were also investigated. Studies have shown that subjecting flours to heating resulted in improved water-holding, oil-binding, emulsifying and foaming capacities of the flours (Seema *et al.* 2012). Rheological properties also get affected by heat treatment. Flour that undergone heat treatment showed increased dough elasticity which might be attributed to the higher resistance, rigidity and viscosity of dough during mixing (Marston Khouryieh, and Aramouni, 2016). Rheological changes can be caused by protein aggregation, together with changes in starch-protein and starch–starch interactions (Bucsella *et al.* 2016). The effects of heat treatment on the wheat proteins have been studied by various research groups. Rearrangement of disulphide bonds leads to denaturation and polymerization of proteins. Denaturation of albumins and globulins occurs at 60°C followed by binding to high-molecular-weight proteins. Due to the conformational structure and low thiol availability, gliadins were only partially denatured at 90 °C and aggregated into polymers (Lamacchia *et al.* 2016). The extent of protein extraction lowered due to increased aggregation of glutenin's on heating (Lamacchia *et al.* 2010).

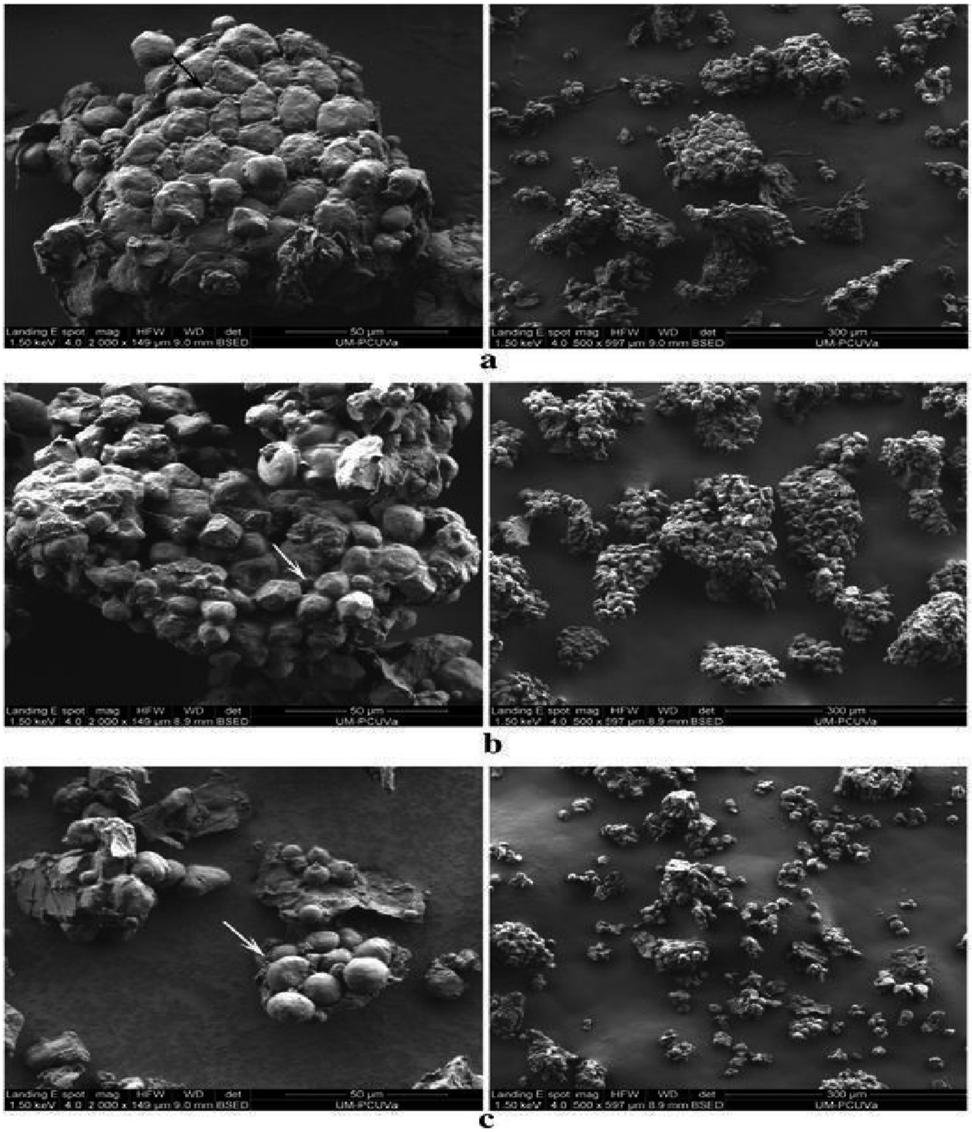


Figure 8: Effect of microwave treatment on Scanning electron microscope of maize flours. a Native. b Treated for 0.5 min. c Treated for 4 min. White and black arrows show disaggregated and aggregated structures, respectively (Biliaderis, 2009).

Qu *et al*. (2017) reported that microwave heating at 700W for 60s significantly slows down the process of lipid rancidity in wheat flours. Gluten is known to provide a framework for flour-based products in bakery items like bread. Microwave treatment affects the secondary structure of gluten leading to polymer disaggregation. Power and time affected gliadins extractability in both linear and quadratic fashion. With the increase of microwave power and microwave treating time, the water loss rate increased, so did the gluten mass loss; the gluten color also changed obviously, and with the increase of microwave power and heating time, the color evaluation index reduced. The content of hydrophobic amino acid of the gluten protein increased, and the content of amino acids including glutathione, arginine and lysine decreased obviously. The secondary structures in gluten protein changed after microwave treatment. The formation of helix and turn were promoted, and the expansion of the structure and intermolecular fold was significantly reduced. And when the microwave power exposure increases to a certain extent, the mass loss does not change any more. When the microwave power changed from 200 W to 400 W, the mass loss and the color changes were not significantly different. Gluten digestibility and the free amino groups of gluten digests increased with the increase of enzymatic hydrolysis (Warchalewski *et al.* 2011). Table 3 summarizes the effects of microwave treatment on the wet gluten content (WGC), gluten index (GI) and sedimentation value (SV) of gluten in the whole wheat flour. It can be seen from the data in (Table 4) that microwave treatment for 10 s had little impact on wet gluten content compared to the control (0 s), and wet gluten content fell slightly with microwave heating for 20 s. Gluten quality and quantity are of great importance in making wheat flour-based food, and they can be determined by gluten index and sedimentation value tests. Gluten index measures the gluten characteristics and indicates if the gluten is weak, normal or strong. Sedimentation value reflects the differences in both protein quantity and protein quality. Sedimentation value and gluten strength showed positive correlation, which controls loaf volume. The data in (Table 3) showed that the gluten index and sedimentation value were changed very little by 10 s of microwave treatment. The gluten index increased from 63 to 78, and sedimentation value decreased a little from 23.40 to 21.08 after 20 s of microwave treatment. Data indicated that short time treatment impacted gluten quality very less (Diraman, 2010), however, greater than or equal to 30 s time period treatment makes the gluten scattered and unable to be determined. Heat treated gluten broke down into small aggregates of gluten (Neill *et al.* 2012). Raising the temperature of grain above 64°C resulted in significantly affecting the color, endosperm structure, sugar content and endogenous amylolytic activity of wheat (Warchalewski *et al.* 2011). Final viscosity is the measurement of reorganizing of the solubilized amylose molecules during the cooling process (Bucsella *et al.* 2016). Microwave treated starches are observed to have shown higher final viscosity due to increased damaged starch which is further attributed to destruction of intermolecular force between the starch and gluten proteins. This structural change between starch and gluten protein resulted in higher retrogradation indicated by higher setback viscosity.

Table 3: Farinographic properties of gluten and flour made from microwave treated wheat kernels. (Kaur *et al.* 2016)

Microwave Treatment time (s)	*Wet gluten content (%)*	*Gluten Index*	*Sedimentation Value (ml)*	*Development Time (min)*	*Stability (min)*	*Consistency (FU)*	*Water absorption (%)*	*Degree of softening (FU)*
0	37.22	63	23.40	3.40	1.84	489	79.5	114
10	38.61	59	24.35	3.39	2.00	510	73.2	129
30	_	_	_	_	_	_	_	_

The impact of microwave on gelatinization properties were presented in (Table 4). The results showed that the initial pasting temperature increased as the microwave treatment time increased, from 65.2 °C (control, 0 s) to 85.5 °C (60 s, 700 W). This may be because microwave heating influenced the structures and arrangements of starch molecules, which needed higher temperatures to gelatinize. The peak viscosities were between 1549 and 1732 cP, and the changes were irregular. The reduction in breakdown values were described as the resistance of starch granules to higher temperatures (Susanna and Prabhasankar, 2011). Hassan *et al* (2021) evaluated the influence of microwave heating on the pasting properties of the corn flours and reported that microwave heating significantly affects the pasting properties of corn flours. Further, authors also stated that microwave-treated grains had the lower peak and final viscosities due to the destruction of starch granule structure after microwave treatment which decreases its water holding capacity and reduces the ability of starch to swell. Similarly, Dhua *et al* (2021) evaluated the effect of microwave heating (600 W for 5 min) on pasting properties of wheat samples and reported that microwave treatment significantly reduced all pasting properties. However, higher pasting temperature was observed for microwave treated wheat samples in comparison to untreated wheat samples.

Table 4: Pasting properties of flour made from microwave treated wheat kernels. (Susanna and Prabhasankar, 2011)

Microwave treatment time (s)	*Pasting Temp. (°C)*	*Peak viscosity (cp)*	*Final viscosity (cp)*	*Setback Viscosity (cp)*	*Breakdown Viscosity (cp)*
0	65.2	1645	2070	975	550
10	73.4	1732	2161	926	497
30	78.9	1665	2285	1059	439

Further, Le *et al* (2014) studied the effect of microwave heating (at 1000 and 2000W) for different exposure times (3, 26, 31, 41, 66, and 159 sec) on paddy and white rice characteristics. From their studies, authors reported that microwave treated samples showed higher viscosity properties (peak viscosity, final viscosity and setback viscosity) in comparison to control samples. In addition to this, authors also stated that microwave irradiation induces rearrangements of starch molecules, leading to changes in various properties such as swelling power, solubility, rheological behavior, gelatinization temperatures and enthalpy as well as granule morphology and crystallinity.

5. Future Aspects and Challenges

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 impact of microwave processing often relies on its amalgamation with other processes techniques. Newer technologies such as radio frequency, 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 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 effects on the properties of the food such as softening of vegetables and hardening of beef (Raaholt *et al.* 2017). Thus, appropriate modeling of microwave sterilization or cooking should be done keeping in mind the degradation kinetics to ensure inactivation of microorganisms/anti-nutrients and preservation of nutritional constituents, sensorial and textural attributes of food (Ahmed and 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 results 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. The improvement in the hydration properties of freeze and refrigeration thaw stability along with improvement in the bioactive potential of alfalfa and dhaincha seeds after microwave processing (Sahni *et al.* 2021). Microwave frying has demonstrated superior process performance owing to quicker process, healthier product and better-quality attributes (Jogihalli *et al.* 2017). 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 effects 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 sensory quality of the final product.

6. Conclusion

Microwave heating has gained popularity in food processing due to its ability to achieve high heating rates, a significant reduction in cooking time, more uniform heating, safe handling, ease of operation and low maintenance. Microwaves have very extensive applications in food industry like thawing, baking, dehydration, melting, tempering, and pasteurization, sterilization, heating, and re-heating, etc. Microwave processing is heating through the interaction of electromagnetic radiation with the dielectric properties of foods, which creates polarization within a substance when exposed to an external electric field. The main objective of this review is to present an overview of recent development regarding microwave applications in the food industry. Applications of microwave drying include microwave assisted hot air drying, microwave vacuum drying and microwave freeze drying. Microwave drying combined with other conventional methods of drying enhances the drying characteristics of the sole effect of microwave drying. Microwave cooking is affected by the presence of moisture and fat content in food materials. Microwave cooking has the advantages of retaining more taste, color, quality and nutritional value as compared to conventional cooking. Microwave pasteurization is shown to be more effective in the destruction of pathogens or in the inactivation of enzymes, due to significant enhancement or magnification of thermal effects. Although microwave energy has wide application and uses in various food processes, it needs significant research aimed at improvements in certain areas. Specifically, methods to obtain final food products with better sensorial and nutritional qualities need to be explored. Improving the energy efficiency in rice cooking and obtaining good quality products in bread baking are examples of other potentially challenging areas. Microwave processing of food materials needs to be carried out to a greater extent at a pilot scale level than at laboratory conditions so that the results might be useful for industrial applications. Despite the complex nature of microwave–food interactions, more research needs to be carried out for a better understanding of the process. It allows to increase the efficiency of processes while maintaining high quality. It is anticipated that microwaves will become increasingly popular, with the development of new microwave technologies solving many problems in the future.

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