Effects of Microwave Utilization on the Color Properties of Food: A Review

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Abstract

This review discusses the importance of food coloring in determining consumer food preferences and the factors that can affect the color of food. It emphasizes the significance of preventing the degradation of pigments during food preparation and highlights the role of microwave ovens in preserving these pigments by reducing processing time and improving color quality. The review delves into the scientific principles underlying microwave heating and its effects on Maillard browning, caramelization, and other chemical reactions responsible for color changes in food. The potential benefits of microwave cooking (MWC) in preserving the natural color of certain foods are highlighted, along with challenges and considerations in maintaining color stability. The review synthesizes findings from diverse studies, providing a comprehensive overview of the current state of knowledge on the effects of microwave utilization on food color. Insights from this review contribute to a better understanding of the intricate relationship between microwave technology and the visual appeal of food, paving the way for informed culinary practices and the development of innovative MWC strategies.

Keywords: Color, Deterioration, Microwave, Pigments

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1 Introduction

The use of microwaves in the food industry has become increasingly popular in recent years due to its many advantages [1]. By preserving the nutritional value and flavor of food, microwave processing provides a fast and efficient method of cooking, defrosting, and pasteurizing food [2]. In addition, microwave processing in the food industry can reduce energy consumption, production time, and waste [3]. The ability of microwave processing to heat food rapidly and uniformly reduces processing time and improves product quality [4]. In addition, microwaved foods are less likely to be overcooked or undercooked, which can destroy flavor and nutritional content [5]. In addition, the use of microwaves in food processing has been shown to have excellent microbial reduction effects, reducing the likelihood of foodborne illness. For pathogens such as *E. coli*, *Salmonella*, and *Listeria*, microwave processing can provide a 4–6 log reduction. Guo et al. [6] found that the use of microwaves in the food industry has several advantages, which can increase productivity, improve product quality, and reduce waste [6]. As microwave technology continues to develop, it is likely that microwave processing will become much more widely used in the food industry in the future. Consumer acceptance of a food product is greatly influenced by its color. It's a characteristic that has the power to

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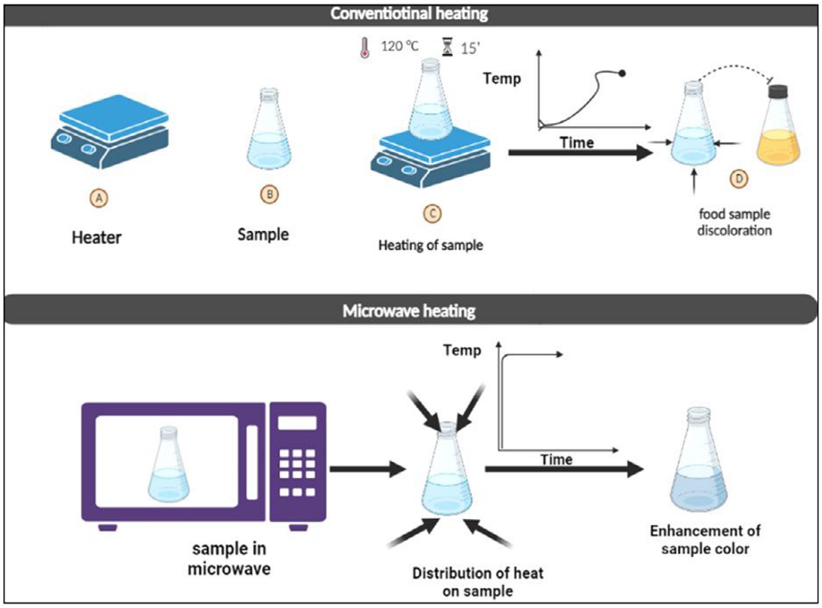


Figure 1. Effect of conventional heating compared by microwave on sample color.

either increase or decrease someone's demand for the product and is often the first part of the product to attract criticism [7].

Food colors are made up of organic pigments such as anthocyanins, reds, flavonoids, carotenoids, chlorophylls, hemoglobin, and myoglobin [8]. Pigments not only add color, but also provide bioactive compounds that have nutritional benefits, such as antioxidant properties that can support good health. Various foods may contain these pigments [9]. Other sensory attributes of food, such as texture and flavor perception, can also be affected by color. For example, the texture of cheese and the apparent sweetness and sourness of beverages can both be affected by color. By exploiting its adjuvant properties, microwave energy increases drying efficiency when used in conjunction with various drying techniques. The advantages of the technique also offset some of its disadvantages, such as uneven drying and high electrical charge rates. Hybrid drying technology, which combines different microwave drying techniques, is a creative way to maintain product quality, as microwave freeze drying (FD) helps to preserve the bioactive chemicals and nutritional status of products, and hot air drying (HAD) accelerates the release of moisture from the core of the product to the surface and then to the environment. The aim of this review is to investigate how microwave heating affects the color characteristics of different food categories [10]. Fig. 1 shows the effect of conventional and microwave heating on the color of samples.

2 Microwave Technology in Food Processing

The electromagnetic radiation known as microwaves has a wavelength between that of radio waves and that of infrared radiation [11]. When microwaves are used to cook food, they cause water molecules to vibrate rapidly, generating heat. A magnetron, a part that emits microwaves, is used in microwave ovens [12]. The magnetron converts electricity into microwaves and directs them into the microwave oven's cooking chamber. After the food absorbs the microwaves, the water molecules in the food start to heat up [13]. Because microwaves absorb water molecules more strongly than other molecules, they cause the water molecules in the food to heat up faster than other parts of the food [14]. To distribute the microwaves more accurately and prevent uneven cooking, microwave ovens have different rotating turntables. The power settings on microwave ovens allow you to control how much power the oven produces. Higher power settings produce more microwaves and heat than lower power settings. This allows you to control the cooking process and prevent your food from burning or overcooking [15].

3 Heat Characteristics of Microwaves

Microwaves can operate between 300 MHz and 300 GHz. Domestic microwaves operate at a frequency of 2450 MHz, while commercial microwaves operate at a frequency of 900 MHz. The water in the food chamber absorbs microwave energy as part of the heating mechanism, causing the temperature to rise and the water to escape. In dielectric heating systems such as microwave heating, molecules with positive and negative charges, such as those found in sugar, fat, and water, align themselves with the alternating electric field to which the microwaves subject them. This process generates heat as the spinning molecules interact with and move nearby molecules, creating a vapor pressure difference between the inner and outer layers of the food. Unlike HAD, microwave drying is fast, uniform, and efficient because the moisture in the food evaporates quickly. The electromagnetic energy is converted to heat energy to raise the temperature. Fig. 2 shows an illustration of a microwave oven.

The benefits of microwave ovens are 1) faster, more efficient cooking, and processing of different foods [16]; 2) it speeds up processing times and improves production [17]; 3) its versatility makes it a useful appliance for many different types of food processing tasks, such as defrosting and even certain types of dry foods [3, 18]; and 4) it provides more flexibility in terms of cooking. Food can be cooked more evenly and without overcooking or burning because microwaves enter the food from all sides [19]. The disadvantages of microwave ovens are as follows. 1) The chemical composition of food may be altered by microwaves, reducing the overall nutritional value or flavor quality [20]. 2) In addition, some foods may not be suitable for microwave processing due to their unique properties or composition [20]. 3) High installation or equipment costs is another disadvantage. They are heavy and take up extra space. There may be electromagnetic interference [21].

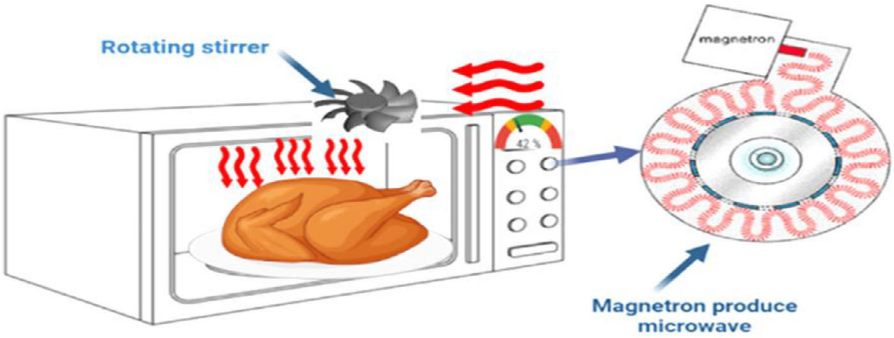


Figure 2. Microwave oven illustration.

4 Food Color Properties

Color is an important element of food quality and influences customer acceptance and desire [22]. It affects not only how the food looks, but also how it tastes, smells, and feels. In the food industry, the color of food greatly influences its marketability and consumer appeal [23]. For example, consumers are often attracted to colorful fruits and vegetables because they are perceived as healthy and fresh. Meat color is also an important indicator of freshness, tenderness, and safety [24]. Tab. 1 shows the factors that influence the color characteristics of foods. Tab. 2 shows a review of studies on microwave use and food color properties.

5 Millard Reaction Mechanisms Causing a Color Change in Microwaved Food

Food can undergo a variety of color, texture, and flavor changes when heated in a microwave oven [33]. Many factors,

Table 1. Factors affecting color properties of food.

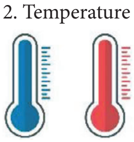
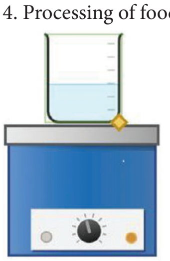
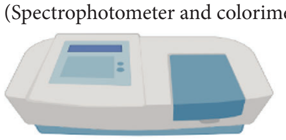
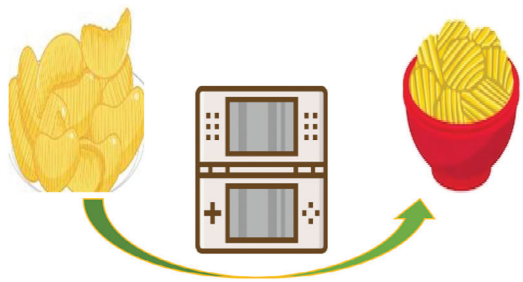
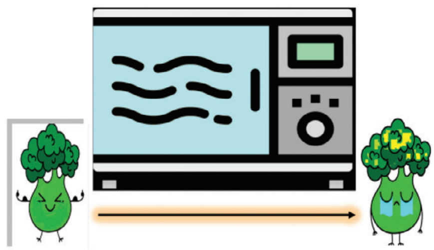
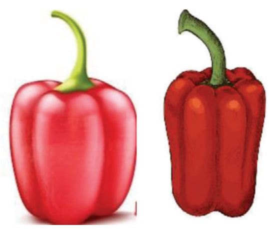
Factors	Examples	References
1. pH 	Food's acidity or alkalinity can affect its color, as seen in red cabbage's pigments, which turn blue when the food's pH shifts from acidic to alkaline.	[25]
2. Temperature 	Food's color can be influenced by heat through degrading pigments or modifying their composition. This describes why cooking improves the color of some foods, such as tomatoes and carrots.	[26]
3. Light 	Specific pigments can fade or change its color when sunlight strikes them. Green veggies can turn yellow or brown when exposed to sunlight because chlorophyll in them can deteriorate.	[27]
4. Processing of food 	Certain vegetables may lose color when they are blanched, whereas some fruits may darken when they are canned.	[28]
5. Instrumental measurement (Spectrophotometer and colorimeter) 	This entails detecting the amount and wavelength of light reflected or transmitted by the food using a colorimeter or spectrophotometer. Another chemical analysis may be conducted using chromatography to extract pigments. Then, it is measured by a colorimeter.	[29]

Table 2. A review of studies on microwave utilization and food color properties.

Influence of microwave treatment on food color	Schematic drawing	References
1. In comparison to traditional frying, the research showed that microwave treatment greatly alters the color of potato chips, providing them a deeper color. This is linked to the Maillard reaction, which takes place at high temperatures and causes food to turn brown.		[30]
2. The scientists found that MWC drastically lowered the broccoli's green color. They hypothesized that pheophytin was produced as a result of the breakdown of chlorophyll.		[31]
3. It has been determined that microwave treatment caused a darker color and less brightness in red pepper. They explained this as the result of capsaicin's breakdown and carotenoids' oxidation.		[32]

including thermal and nonthermal effects, are responsible for these changes. Microwaved foods involve multiple, combinatorial color change mechanisms. They are susceptible to influences from elements such as temperature, pigment level, and food matrix composition. Although MWC can cause severe color changes in foods, these changes do not always mean that the food is unsafe to eat. However, when using a microwave oven, it's important to use the correct cooking times and temperatures and follow safe food handling practices [3, 34]. The principles of color change in microwaved foods will be the focus of this response. Maillard reaction is a major cause of color change in microwaved foods [35]. When food is heated above 140 °C, an interaction occurs between amino acids and reducing sugars, resulting in the development of flavor and color components in the form of brown pigments. As a result of the elevated temperatures induced by microwaves, the Maillard reaction in food can change rapidly. The effect of microwave heating on the Maillard reaction in food has been the subject of several studies. For example, one study found that the degree of browning was significantly higher when chicken breasts were cooked in a microwave compared to other cooking methods. The researchers attributed this to the faster and more extensive Maillard reactions caused by the higher temperatures of microwaves [36]. On the other hand, MWC is said to have little or no effect on the color of chicken breast meat. It was observed that MWC produced a lighter color than traditional cooking. It was suggested that this was due to the lower temperatures and shorter cooking times used in MWC [37]. Finally, Fig. 3 shows the effect of low microwave temperature and time on chicken breast, while Fig. 4 shows the Millard reaction of microwaved chicken breast.

6 Factors Affecting Color Change in Microwaved Food

Food type, composition, packaging, and cooking conditions are just some of the factors that can affect how food changes color in the microwave. We will look at these factors in more detail and examine some of the studies that have looked at their effect on this reaction. The composition of food, particularly the amount of pigments present, can affect how food changes color in the microwave. For example, foods with high concentrations of carotenoid pigments, such as tomatoes and carrots, are more likely to change color when exposed to high temperatures. One study looked at how MWC affected the color and pigmentation of tomatoes. The researchers found that the lycopene content

Figure 3. Effect of low temperature and time of microwave on chicken breast.

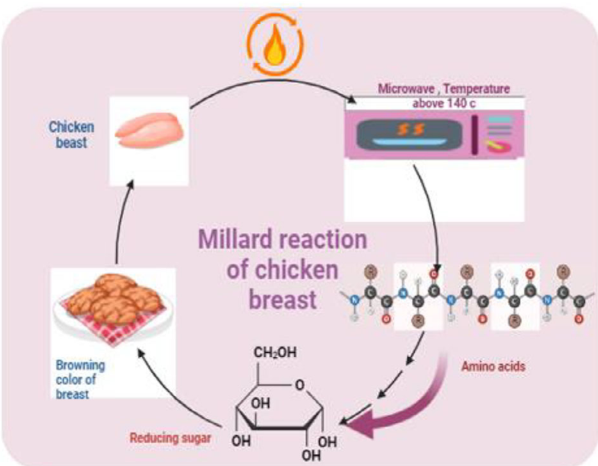


Figure 4. Millard reaction of microwaved breast chicken.

of tomatoes decreased significantly after MWC, causing the tomatoes to lose their red color. However, they also found that the total carotenoid content of tomatoes generally remained constant during MWC [38]. Depending on the type of food, different foods can change their color to different extents when cooked in the microwave. For example, the effects of heating on pigments and other ingredients in the food are more likely to cause color changes in foods with high water content, such as vegetables and fruit. One researcher looked at how MWC affected the color of different vegetables. Green beans, broccoli, and carrots all showed a significant reduction in color after MWC, proving that these vegetables had significant color changes. In contrast, onions, which have a reduced water content, largely retained their color after MWC [39]. The color of foods cooked in the microwave can change depending on the cooking specifications, such as cooking time and power level. Longer cooking times and higher power levels may result in more significant color changes. One study investigated the effect of MWC conditions on the color and texture of carrots. The researchers found that longer cooking times and higher power levels produced darker and softer carrots, indicating more significant color and shape changes [40].

Different types of packaging, such as plastic containers, can absorb microwave radiation and cause uneven heating, resulting in some portions being overcooked and changing color. Different types of packaging affect the color of frozen broccoli when microwaved. The researchers found that when plastic containers were used, the color changes were more pronounced than when glass containers were used. This is probably because plastic retains microwave energy [41]. Finally, Tab. 3 compares the use of microwaves with other food processing methods in terms of color changes.

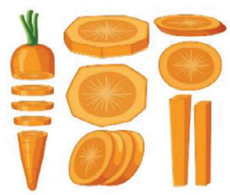
7 Effect of Microwave Processing on the Major Pigment in the Food

A variety of pigments determine food color. Each type of dietary pigments produces different colors. Food pigments add color and health benefits. Antioxidants like carotenoids and flavonoids protect cells from free radical damage. Food color can be changed by pH, temperature, and cooking methods. Green color comes from chlorophyll, a common dietary pigment. It is typically found in leafy greens like broccoli, peas, and green beans. Orange, yellow, and red hues come from carotenoids, which are present in carrots (beta-carotene), tomatoes (lycopene), sweet potatoes, oranges (beta-cryptoxanthin), and spinach. In various plant sources, flavonoids cause blue, purple, red, and yellow colors. Flavonoids include anthocyanins, flavones, flavonols, and catechins in berries, citrus, onions, and tea. Anthocyanins give plants their red, purple, and blue colors. These chemicals are found in blueberries, strawberries, grapes, and red cabbage. Betalains give beets their red-violet color. In turmeric, curcumin and other natural color pigments are yellow. Anatto pigment gives annatto seeds an orange-yellow color. This natural coloration is popular in cooking. Colas, baked goods, and sauces turn caramel brown when sugar is heated. Finally, Tab. 4 shows how microwave processing affects dietary pigments like anthocyanin, carotenoids, chlorophyll, and betalains.

8 Conclusions

It has been found that the color characteristics of foods are significantly affected by the use of microwaves in food processing. According to the research reviewed in this paper, MWC can affect the brightness, hue, and chroma of foods, among other color characteristics. However, the extent of these changes varies depending on the type of food, the processing conditions, and the microwave technology used. The main conclusions of this study are that the use of microwaves can alter the color characteristics of a food, which may affect its overall appearance, sensory quality, and consumer acceptability. A variety of causes, such as thermal effects, nonthermal effects, and interactions

Table 3. A comparison of microwave utilization with other food processing methods in terms of color change.

Examined microwave method	Main results and effects	Dried food samples	References
Microwave with HAD	Kaveh et al. [42] found that the values of $a*$ and $b*$ initially increased and then decreased as the microwave predrying time increased. This study showed that HAD massively increased the browning of seafood samples of the marine worm species *Sipunculus nudus.* The results were attributed to the Millard reaction and nonenzymatic browning processes. Meanwhile, Kaveh et al. [42] used an ultrasonic (US) predrying treatment for dried hawthorn fruit. The sample treated with US and dried at a temperature of 55 °C with a MW power of 360 W had the greatest color. It can be observed that the total color changes decreased as the air temperature increased from 40 to 55 °C and the MW power increased from 180 to 360 W.	*Sipunculus nudus*  Hawthorn fruit 	[42]
Microwave with FD	According to Chen et al. [43], freeze-dried samples of oyster mushrooms showed the highest degree of brightness and color and the lowest degree of yellowing and saturation. In addition to Liu et al. [45], microwave FD of foamed products with wave-absorbing material support could significantly reduce drying times and increase process efficiency. In contrast to the conventional FD times of the nonfoamed and foamed samples, the microwave FD time of the foamed blue berry puree sample was reduced by 50.0 % and 17.9 %, respectively. When the power was increased to 0.5 W g^{-1}, the drying time was reduced by 56.5 % and 28.6 % respectively. There was no significant change in the color of either the microwaved or the traditionally freeze-dried items. It is also clear that, according to Chen et al. [43], the dried sample in the microwave FD phase had a color more similar to fresh pineapple. This is due to the fact that the sample still contained a significant amount of ice crystals.	Blue berry  Pineapple  Mushroom 	[43]
Microwave with fluidized bed drying (MWFDB)	According to the study of Jiang et al. [49], carrot slices pretreated with water blanching (WB), 20 % sugar solution (SS), and 1 % citric acid solution were dried in the MWFDB system under ideal drying conditions. An initial microwave power density of 0.44 W g^{-1} and an inlet air temperature of 55 °C increased the brightness, redness, and yellowness of dried carrot slices in the MWFDB system. Chupawa et al. [44] showed that the total color difference (E) of dried red peppers ranged from 10.27 to 33.29 % depending on the drying conditions. The maximum color change occurred at 540 W, 70 C and 15 m s^{-1} and the minimum at 360 W, 40 C and 17.50 m s^{-1}. This may be because high temperatures promote the breakdown of carotenoids, particularly capsanthin, which gives peppers their bright red color. In addition, the high sugar and free amino acid content of peppers led to the development of brown pigments, which reduced the color of peppers. In addition, Chupawa et al. [44] found that FDBMW drying with a step-down mode from 300 to 150 W and bed stability control was the optimum condition for producing brown rice of good color and quality immediately.	 Carrot slices  Brown rice 	[44]

(*Continued*)

Table 3. Continued

Examined microwave method	Main results and effects	Dried food samples	References
Microwave with vacuum drying (MVD)	Song et al. [52] reported the mean color values of fresh and rehydrated stem lettuce slices dried using different vacuum drying methods. As expected, products dried by pulsed spouted MVD had the lowest values for brightness, *L*; redness, a; yellowness, b; and color difference, DE, followed by MVD, and vacuum drying had the highest values. This could be due to the fact that the samples dried by the pulsed spouted method retained more chlorophyll due to the shorter drying time and lower drying temperature. Therefore, after rehydration, the pulsed spouted products exhibited less color variation than the rotating turntable products. Liu et al., [45] demonstrated that the best MVD parameters for garlic slices were 260 W microwave power, 81 kPa pressure, and 49.5 °C temperature. The color $L*$, thiosulfinate content, rehydration ratio, and total score of garlic slices under these conditions were 82.26, 3.0378 mg/100 g, 2.796, and 0.9265, respectively. The composition of dried and fresh garlic slices was identical. The volatile components of dried garlic slices did not change significantly under different drying conditions.	 Lettuce slices  Dried garlic	[45]

Table 4. Effect of microwave on anthocyanin, carotenoids, chlorophyll, and betalains in the food.

Examined microwave method	Main results and effects	References
Anthocyanin	To explain the relationship of anthocyanin degradation on microwave heating nonuniformity in blueberry puree, temperature and moisture content distribution were examined. The Weibull model can predict blueberry puree anthocyanin distribution under microwave heating based on temperature and moisture. Hot zone distribution (HTD), highest temperature (MAX), and temperature dispersion value (VT) nonuniformity in blueberry puree under MWC are crucial to anthocyanin degradation. These findings may help microwave-processed berry product quality control.	[46]
	This study treated jujube fruit using standard heating (80 and 95 °C), microwave (600 W for 1 min), chilling (1 and 2 months), and freezing (−18 °C for 1 year). The microwave approach resulted in a 5.7 % and 3.1 % decrease in total monomeric anthocyanin and total phenolic content ($P < 0.05$) compared to conventional heating. The primary anthocyanin in jujube fruit is cyanidin-3,5-diglucoside, which degraded more in normal heating at 80 °C (24.2 %) than in microwave (2.7 %), was chilled for 2 months (20.1 %), and frozen (8.4 %).	[47]
	The utilization of a flow microwave technology can effectively reduce the degradation of valuable bioactive components present in the strawberry puree. The technique effectively reduces the losses of anthocyanins and vitamin C (KA + KDA) by 33 % and 57 %, respectively, compared to standard pasteurization in a pack. The color of strawberry puree stabilized using microwave technology undergoes less significant alterations compared to the product pasteurized within its packaging.	[48]
	Initial anthocyanin as cyaniding-3-glucoside was 89.61 mg/100 mL. In all approaches, black mulberry anthocyanin degradation increased with storage time and temperature. Thermal sterilized juices lost more anthocyanin than microwave and US sterilized juices during all storage temperatures. Thermally treated juice held at 5, 15, and 25 °C for 8 days decreased anthocyanin concentration by 36 %, 37 %, and 45 %. Over the same storage period, microwave and US sterilized juices lost 28–38 % and 24–34 % of their anthocyanin content.	[49]
	HAD, FD, MVD, and microwave freeze vacuum drying (MFD) were used to study the effects of drying on blueberry pomace quality, antioxidant activity, and anthocyanin The quality, antioxidant activity, and anthocyanin composition of blueberry pomace were compared to the nondried control. Blueberry pomace had the highest total phenols, anthocyanins, sugars, and color values from MVD and the lowest from HAD. MVD considerably increased blueberry pomace's ABTS + and DPPH radical scavenging. HPLC linked to the mass spectrometer showed that FD, MVD, and MFD retained more anthocyanin species than HAD. The best method for preserving antioxidant capacity and color was MVD. Thus, MVD of blueberry pomace can boost blueberry fruit processing efficiency and reduce environmental impact.	[50]

(*Continued*)

Table 4. (Continued)

Examined microwave method	Main results and effects	References
Carotenoids	Fast, nondestructive Raman spectroscopy can identify heat-induced degradation of extra virgin olive oil carotenoids during microwave versus traditional cooking. Carotenoids degraded gradually at 180 and 140 °C in microwave and traditional heating techniques, respectively, followed by fast degradation at 180 °C only with conventional heating. The primary difference was that conventional heating eliminated carotenoids' Raman bands at 203 °C, but microwave heating preserved them up to 225 °C. Both heating procedures also lost cis double bonds and minimally changed free fatty acid. Partial least squares regression was utilized to create an accurate calibration model for detecting carotenoids degradation during heating. Model accuracy was measured using root mean square errors and correlation coefficient.	[51]
	Compared to HAD, MVD reduced color alterations and considerably ($p < 0.05$) increased total carotenoid retention (89.1 %) in pumpkin slices. Microwave power affected total and all-trans carotenoids during MVD. Higher microwave power led to a substantial decrease in total carotenoid concentration ($p < 0.05$), and particular carotenoids, such as all-trans-α-carotene, β-carotene, and lutein, were also reduced. The levels of 13-cis-β-carotene, 15-cis-β-carotene, 9-cis-β-carotene, and 9-cis-α-carotene showed an overall rising trend. With specific vacuum levels, trans carotenoid quality of finished items improves. In addition to microwave energy, isomerization was thought to degrade all-trans carotenoids. These results suggested that improper pumpkin drying may cause substantial all-trans carotenoids losses.	[52]
	Orange juice carotenoids were degraded during microwave (MW) heating at different times/temperatures. Carotenoids were discovered and measured using HPLC. At 60 and 70 °C for 10 min, viola-xanthin and antheraxanthin degraded fastest, while lutein and provitamin A carotenoids were more stable. After 1 min of MW heating at 85 °C, practically all carotenoids decreased 50 %. Total carotenoids had a temperature sensitivity (*z* value) of 14.2 °C, while specific components ranged from 10.9 °C for b-carotene to 16.7 °C for antheraxanthin. These results suggest that orange juice MW treatment can manage carotenoids and nutritional values at an appropriate temperature.	[53]
	This study examined the effects of MWC on phenolic, carotenoids, pigment profiles, and antioxidant activity of fresh water-grown chicory (*Cichorium intybus L.*) leaves. The quantification included six carotenoids and ten pigments. Major carotenoids included all-E-lutein, all-E-β-carotene, all-E-neoxanthin, and all-E-violaxanthin. During MWC, carotenoids increased significantly. 13 hydroxy-chlorophyll b, chlorophyll a, and chlorophyll b were abundant pigments. With MWC, pigments fell. Lipid peroxidation, total polyphenol content (TPC), and total flavonoid content (TFC) increased considerably with MWC. Radical scavenging activity (RSA) rose or held steady. Finally, frying or microwave-preparing chicory leaves in food sectors increased bioactive compounds for consumer health.	[54]
	This study examined whether microwave heating in persimmon juice pretreatment can produce functional juice and added-value solid residue from the Diospyros Kaki "Jiro" cultivar. Results show that the solid juice residue contains provitamin A carotenoids (~278 g retinol activity equivalents).	[55]
	The study examined the impact of pasteurization (P) treatment (90 $\pm$ 2 C for 35 s) using continuous semi-industrial microwave (MW) under various conditions (high power/short time, low power/long time) or conventional pasteurization on orange-colored smoothies' storage at 5 C for 45 days. Vitamin C and antioxidant capacity (FRAP) in CP were significantly lower than in unheated and MWP smoothies. However, all heating treatments enhanced total phenolic chemicals and carotenoids.	[56]
Chlorophylls	The quality of spring and autumn tea gathered and stored was affected by microwave and oven enzyme inactivation. The chlorophyll concentration of spring and autumn tea after microwave heating was higher and more stable than after oven heating and storage, suggesting that microwave heating could reduce chlorophyll breakdown.	[57]
	Overall chlorophyll, ascorbic acid (ASA), and overall color difference were measured in blanched green bell peppers dried in hot air and microwave. The dehydration dynamics of blanched and unblanched green bell peppers were examined at 60 °C. To quantify total chlorophyll, AsA, and TCD, HAD was done at 40–70 °C and microwave drying at 500–800 W. First-order reaction kinetics decomposed total chlorophyll, AsA, and TCD. Arrhenius-type temperature dependence was seen for each rate constant. Hot air-drying activation energies (*E*) for total chlorophyll, AsA, and TCD were calculated.	[58]
	This study compared the effects of 915 MHz microwave-assisted thermal pasteurization and conventional hot water pasteurization (F10 90 = 10 min) on chlorophylls in green beans stored at 10, 7, and 2 °C for 100 days. Vacuum-sealed N2-flushed containers processed frozen-cut green beans. The beans lost 28.3 % and 33.9 % chlorophyll a following microwave and hot water processing. Samples handled with microwave-assisted thermal pasteurization showed reduced deterioration (21 days at 10 °C, 42 days at 7 °C, and 100 days at 2 °C) and better chlorophyll preservation (47–50 %) during storage.	[59]

(*Continued*)

Table 4. (Continued)

Examined microwave method	Main results and effects	References
	This study studied basil, lovage, mint, oregano, parsley, and rocket leaf chlorophyll a and b concentration, a∗, b∗, and chroma color after microwave-convective drying. Drying occurred at 40 °C in 0.8 m s^{-1} air perpendicular to the material layer and 300 W microwave power. Degradation of chlorophyll differed by herb species after drying. Lovage, basil, and mint kept chlorophyll a and b. Only lovage left chlorophyll an unaffected by drying. The chlorophyll b of basil, lovage, and mint is statistically consistent. Rocket leaves had the largest chlorophyll a/b loss. Drying lowered a∗, b∗, and chroma in all herbs except rocket leaves. Rocket (Brassicaceae) and Apiaceae (lovage and parsley) altered least. Oregano, mint, and basil were less consistent, color wise. Taxonomic group affected color alterations. Apiaceae herbs turned green and yellow due to chlorophyll changes. Since chlorophyll a and a∗ parameter deterioration was significantly connected in all plants, it was not the main source of color changes.	[60]
	Wild edible *Polygonum cognatum Meissn*. is called madimak in Turkey. Spring-grown shoots are eaten as vegetables. HAD affected sample color more than microwave drying. Microwave-dried plants preserved chlorophyll a, b, and total chlorophylls. Color and chlorophyll characteristics showed that microwave drying is better for madimak plants than hot air or ambient drying. 750 W microwaves produced the lowest color change and greatest chlorophyll. The minimal specific energy requirements for 80 °C HAD and 160 W microwave power level were 44.58 and 107.00 kWh kg^{-1}, respectively. The particular energy required did not differ across HAD temperatures but did between microwave power levels.	[61]
	The study examined the impact of using a continuous microwave treatment pasteurization (MW, 11 kW; 30 s) compared to traditional pasteurization (85 °C; 5 min) on the quality of a new pesto sauce created from fresh faba bean seeds. The evaluation was conducted over a period of 20 days at a temperature of 5 °C. Unheated mixed samples were utilized as the control. The samples treated with MW exhibited superior texture, consistency, and color, while also maintaining their chlorophyll and carotenoid levels.	[62]
Betalains	Betanin decomposes under dielectric heating (microwave irradiation, power: 25–200 W, 3–24 kJ g^{-1}) using first-order kinetics and a rate constant comparable to conventional conduction heating (half-life < 2 min at 100 °C). Betanin bleaches upon thermal treatment, although beetroot juice and spray-dried powder create colored decomposition products. Betanin loses antiradical capacity when heated, yet it still outperforms ASA and trolox. In thermally treated betanin samples, mass spectrometry and second-derivative absorption spectroscopy detected betalamic acid, a high-capacity antiradical.	[63]
	Red beet has high-concentration betalains utilized as food colorants and additives for their health benefits. Processing redbeet before eating changes betalains' stability, which affects its appeal and health benefits. The study examined how microwaving, boiling, roasting, and vacuuming affect red beets. Belatains and antioxidant activity of treated samples assessed processing influence. With spectrophotometric data, betalains content increased up to 20 % with vacuum treatment, 7 % and 19 % with microwave treatment of 900 and 1800 W for 30 s, and decreased with boiling and roasting. High performance liquid chromatography (HPLC) tests show that microwave treatments at 450 and 900 W increase betanin concentration but decrease it at 1800 W. Compared to the control, boiling, roasting, and microwave treatments increased antioxidant activity 2-to-3-fold.	[64]
	This study examined the impact of pulse ratio and microwave power on drying red beetroot at 40 °C using intermittent microwave and hot air. Increasing microwave power from 360 to 900 W and dropping pulse ratio from 6 to 2 significantly reduced drying time. By increasing microwave power and pulse ratio, betacyanins and betaxanthins reached 79.47 and 44.20 %, respectively.	[65]

between microwaves and food components, could be responsible for these changes. The mechanisms behind the effects of microwaves on the color characteristics of foods require further investigation. Investigating how different microwave frequencies, power levels, and exposure times affect color changes in different types of food is one possible aspect of this. In addition, future research should also investigate the possible advantages and disadvantages of using microwaves to process foods from a sensory and nutritional point of view. The results of this study have significant implications for the food sector, particularly for companies producing microwaveable foods. Manufacturers can improve their processing conditions to achieve desired color results and maintain product quality by being aware of how microwaves affect the color properties of food. Furthermore, using this knowledge to guide product development, companies can produce microwaveable foods that meet consumer demands for appearance, flavor, and texture.

9 Future Trends

As microwave technology continues to develop, further understanding and optimization of the effects of microwave processing on food color properties and the preservation of nutritional benefits will be essential. Specifically, future trends involve the exploration of more efficient and sustainable processing methods that minimize color alterations and nutrient loss while maximizing food quality. Additionally, the investigation into the potential use of microwave technology in novel food applications, such as the development of microwave-assisted drying, pasteurization, and preservation techniques, will likely continue to evolve in response to the growing demand for convenient, high-quality food products in the food industry. Moreover, the ongoing study of microwave technology in combination with other food processing methods, such as hybrid drying technology, microwave vacuum drying (MVD), and FD, will further enhance the understanding of how to effectively utilize microwave processing for improved food color preservation and nutritional quality in the future.

Availability of Data and Materials

The data that support the findings of this study are available on request from the corresponding author.

Author's Contribution

All authors have equally contributed in writing the review, drafting the manuscript, revising the manuscript, and approval of the version of the manuscript to be published.

Conflicts of Interest

The authors declare no conflict of interest.

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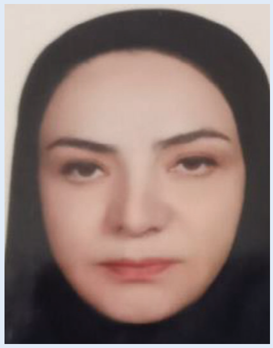

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