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Boiling vs. Microwave Heating—The Impact on Physicochemical Characteristics of Bell Pepper (*Capsicum annuum* L.) at Different Ripening Stages

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Abstract: Background: The present study addresses this research gap by evaluating the impact of boiling in water and microwaving on the bioactivity characteristics of bell peppers at different ripening stages. Methods: The total polyphenols, DPPH, ABTS and FRAP were used for the evaluation of the antioxidant potential qualitatively and quantitatively, and the simple reductive sugar texture and color changes were measured. Results: Microwave heating appears to be a favorable treatment in the case of preservation of most of the antioxidant potential. Green and red bell peppers were more resistant to the treatments, while the yellow stage was the one in which the changes were observed the most. Conclusions: However, the results indicate that from a consumer standpoint, microwave heating treatment is more beneficial for red peppers. In contrast, hot water cooking is more beneficial for green and yellow peppers.

Keywords: boiling; microwaves; bell pepper

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1. Introduction

Vegetables play a crucial role in a healthy and balanced diet, providing essential nutrients, vitamins, minerals, and dietary fiber [1]. Among the widely consumed vegetables, bell peppers (*Capsicum annuum*) are highly regarded for their vibrant colors, distinct flavors, and nutritional benefits. Bell peppers are known for their high content of vitamins A, C and E, as well as various phytochemicals with antioxidant properties [2].

Raw bell peppers possess several pro-healthy ingredients that contribute to their nutritional value. Bell peppers play a vital role, e.g., in collagen synthesis, immune function, and antioxidant defense. Additionally, they contain carotenoids such as β-carotene, lutein, and zeaxanthin, which have been associated with reducing the risk of chronic diseases, including cardiovascular disease and certain types of cancer. The presence of phenolic compounds, such as flavonoids and phenolic acids, further enhances the antioxidant capacity of bell peppers [2].

However, the nutritional quality and bioactivity characteristics of bell peppers can be influenced by cooking methods [3,4]. Cooking methods greatly affect the sensory attributes, texture, and nutritional composition of vegetables. The most typical cooking methods for preparing vegetables, including bell peppers, are boiling, steaming, frying, baking, and microwaving. Each method has a unique impact on the final product, altering the taste, texture, color, and nutritional properties. Understanding the effects of these cooking methods on the nutritional quality of vegetables is essential for promoting optimal dietary choices and preserving the bioactive compounds present in raw bell peppers.

While traditional cooking methods like boiling have been widely used to prepare vegetables, microwaving has gained both popularity and controversy in recent years.

Microwaving offers a convenient and time-saving approach to cooking, but its impact on the nutritional composition of bell peppers is often questioned. Despite being demonized by some due to misconceptions, microwaving can be a healthy alternative to traditional cooking methods as it requires minimal water and shorter cooking times, thereby reducing nutrient loss (e.g., the decrease in ascorbic acid content by boiling in hot water was observed up to 34% from the original content) [5–7].

However, the existing literature lacks a comprehensive and merit-based comparison of the real impact of microwaving on the nutrient composition of bell peppers, especially at different ripening stages [8,9]. Many studies have focused on other cooking methods or have provided conflicting results, making it challenging to draw conclusive evidence regarding the effects of microwaving on the nutritional quality and bioactivity characteristics of bell peppers. Therefore, there is a need for further research to investigate the specific changes that occur in the nutrient composition and bioactive compounds of bell peppers when subjected to microwave cooking.

The present study aims to address this research gap by evaluating the impact of boiling in water and microwaving on the bioactivity characteristics of bell peppers at different ripening stages. To the best of our knowledge, this is the first study comparing the effects of cooking and heating in a microwave oven on various physicochemical parameters of bell pepper fruits representing different stages of ripening.

2. Materials and Methods

2.1. Analytical Reagents and Standards Used

The following standards were used for the analyses performed: glucose, Trolox (6-hydroxyl-2,5,7,8–tetramethylchromo-2-carboxylic acid, 2,2–diphenyl–1-picrylhydrazyl (DPPH), 2,2–azino–bis (3-ethyl benzothiazoline-6-sulphonic acid) (ABTS), TPTZ (2,3,5-triphenyltetrazolium chloride), gallic acid and iron (III) sulphate hydrate (Pol-Aura, Zabrze, Poland). Ultra-pure water for the study was obtained using a distillation system to purify water of dissolved mineral salts and gases.

2.2. Experimental Materials Collection

The research material consisted of the fruits of the annual pepper, also known as sweet pepper, which was cultivated in the southern regions of Mazovia in Poland. The tested pepper fruits (variety Ożarowska) represented three main stages of ripening (green, yellow and red).

2.3. Heat Treatments

The tested raw materials were pre-washed in running water. Then, the raw material was cut into fragments 7–8 cm long and about 4–5 cm wide, from which the seeds were removed. Then, the tested raw materials were subjected to two thermal treatments: boiling in water and microwave heating. The process of cooking raw materials in boiling water was carried out at the recommended ratio of raw material to water, which is 3:1 (v/v) for peppers. The time of treatment was started from the moment of boiling the water. The heat treatment was carried out for the recommended cooking time of the peppers of 10 min. A commercial microwave oven (GE83X, Samsung Electronics Poland Ltd, Warsaw, Poland) with a power of between 180 and 800 W was used for microwave heat treatment. The raw material was heated in the microwave at the maximum power for 2 min and 30 s.

2.4. Extract Preparation

After thermal treatment, the tested raw materials were homogenized using a knife homogenizer. The resulting 5 g of homogenate was extracted with 10 mL of methanol and water (80/20 v/v %) mixture for one hour on a radial stirrer (MX-RD PRO, ChemLand, Stargard, Poland) (at 60 rotations per minute) and then centrifuged (MPW-350, MPW MED. INSTRUMENTS, Warsaw, Poland) for 15 min at 5031$\times$ g. The supernatant obtained after

centrifugation was subjected to the analysis of the total antioxidant and redox potential as well as the content of bioactive substances.

2.5. Determination of Total Phenolic Compounds

The total phenolic compound (TPC) content was determined using the Folin–Ciocalteu reagent according to the method of Yen et al. [10] to which minor modifications were made. Measures of 0.1 mL of Folin–Ciocalteu reagent and 1.58 mL of H_2O were added to the obtained extracts (0.02 mL). After 5 min of incubation, 0.3 mL of saturated sodium carbonate solution (Na_2CO_3) was added. The total phenolic compounds were determined after 20 min of incubation at 38 °C in the dark. The absorbance of the resulting solution was measured at 765 nm. A standard curve was prepared for gallic acid. The TPC results were presented in milligrams of gallic acid equivalent (GAE) per 1 g of raw material used. All the samples were analyzed in duplicate.

2.6. Determination of Antioxidant and Oxidoreductive Activities

2.6.1. DPPH Test

The antioxidant capacity (against the 2,2-diphenyl-1-picrylhydrazyl radical) of the tested extracts was measured according to the Klymenko method [11] with minor modifications. A measure of 0.035 mL of the test solution was measured and added to 1 mL of (0.1 mM) methanolic DPPH solution. The mixture was shaken and left at room temperature for 20 min, after which the absorbance was measured at 517 nm. The anti-radical activity was calculated from the calibration curve and expressed as the mg Trolox equivalent (TE) for 1 g of raw material used. All the samples were analyzed in duplicate.

2.6.2. ABTS Test

The antiradical capacity against the cation radical of 2,2-azo-bis (3-ethyl benzothiazoline-6-sulfonic acid (ABTS•+) for the tested extracts was measured based on the Sridhar method [12], with minor modifications. ABTS•+ solution was prepared by mixing 7 mM ABTS stock solution with 2.45 mM potassium persulfate solution and incubating at room temperature (23 °C) in the dark for 16–24 h. The ABTS•+ solution was diluted with phosphate buffer (0.1 M) to give an absorbance of 0.700 ± 0.05 at 734 nm. A measure of 0.02 mL of the extract to be tested was added to 1.0 mL of the diluted ABTS•+ solution. The absorbance at 734 nm was read exactly 10 s after mixing the test extract with the ABTS•+ solution. The antiradical activity was calculated from the calibration curve and expressed as the mg Trolox equivalent (TE) for 1 g of raw material used. All the samples were analyzed in duplicate.

2.6.3. FRAP Test

The reducing power (ability to reduce ferric ions FRAP) was measured according to the Re [13] method, with minor modifications. The test extract was added to 1 mL of FRAP solution (acetate buffer (300 µM, pH 3.6), a solution of 10 µM TPTZ in 40 µM HCl and 20 µM $FeCl_3$ in a 10:1:1 ratio (v/v)). The mixture was shaken and left at room temperature for 20 min, after which the absorbance was measured at 593 nm. The reducing activity was calculated from the calibration curve and expressed as mg iron(II) sulfate equivalent $FeSO_4$•$7H_2O$ for 1 g of raw material used. All the samples were analyzed in duplicate.

2.7. Measurement of Reducing Sugar Content

The sugar content of extracts was measured using a modified method according to Miller [14], taking advantage of the reducing properties of sugars towards 3,5-dinitrosalicylic acid (DNS). A measure of 1 mL of DNS reagent was added to 1 mL of the test sample and mixed thoroughly. The resulting mixture was then heated in boiling water for 5 min. After the mixture cooled to room temperature, its absorbance at 535 nm was measured. The content of monosaccharides was expressed in g of glucose or fructose equivalent per 1 L of extract tested. All the samples were analyzed in duplicate.

2.8. Color Measurement

The color of bell pepper was assessed using a Konica Minolta CR-310 chroma meter (Ramsey, NJ, USA). Color parameters (L^*, a^*, b^*, chroma (C), and hue (h°)) were taken in triplicate and expressed as mean ± standard deviation [15].

2.9. Texture Measurements

The texture of bell pepper was evaluated through TPA (Texture Profile Analysis) test using an AXIS texture analyzer FC200STAV500 (AXIS, Gdansk, Poland) provided with the software "AXIS FM" as previously reported by Cardinali et al. [16].

In order to determine the textural properties of bell pepper, an analysis of the texture profile was carried out on cylindrical samples with a diameter of 15 mm taken with the skin from the middle fragments of the fruit. Measurements to the fresh pepper were performed from the external side. Hardness (N) was the force at the maximum deformation, whereas cohesiveness, springiness, chewiness, and resilience were calculated from the peaks. Analysis was carried out in quadruplicate at 25 °C on bell pepper cylinders (5 mm height and 20 mm diameter) cut from different pieces of each bell pepper fruit [17]. The results were reported as mean ± standard deviation.

2.10. Statistical Analysis

Data were subjected to one-way and two-way analysis of variance and mean values were compared by Tukey's test ($p < 0.05$). Statistical analysis was performed using Statgraphics Centurion 19 (Statgraphics Technologies, Inc., The Plains, VA, USA) statistical software.

3. Results and Discussion

Antioxidative characteristics of bell peppers after heat treatment are presented in Table 1.

Table 1. Total polyphenol contents and antioxidant activity of bell peppers of different ripening stages after boiling and microwaving.

R-Stage	Processing	TPC GAE μM/g d.b.	DPPH TXE μM/g d.b.	ABTS TXE μM/g d.b.
G	C	2.75 ± 0.42 a	47.02 ± 1.49 b	2.69 ± 0.66 a
	B	9.76 ± 0.11 c	74.91 ± 2.33 c	5.24 ± 1.06 b
	M	7.40 ± 0.33 b	34.81 ± 2.63 a	0.89 ± 0.27 a
Y	C	17.00 ± 0.68 b	57.10 ± 2.04 b	20.08 ± 0.45 a
	B	10.03 ± 0.78 a	82.96 ± 4.88 c	9.40 ± 0.81 c
	M	10.14 ± 0.52 a	25.03 ± 2.13 a	17.09 ± 0.45 b
R	C	17.26 ± 0.64 c	79.91 ± 2.02 b	21.09 ± 0.39 b
	B	1.86 ± 0.11 a	16.08 ± 0.57 a	2.62 ± 0.24 a
	M	15.37 ± 0.69 b	95.88 ± 6.04 c	29.53 ± 0.96 c
R-stage		***	***	***
Processing		***	***	***
R-stage × processing		***	***	***

R-stage—ripening stage; G—green pepper; Y—yellow pepper; R—red pepper; C—control; B—boiling; M—microwaving; GAE—gallic acid equivalent; TXE—Trolox equivalent. Lowercase letters mean statistically significant difference between samples for same R-stage ($p = 0.05$); ***—$p < 0.001$.

3.1. The Polyphenolic Content Changes

There was a significant increase in total polyphenol content (TPC) in green peppers as a result of cooking (9.76 GAE μM/g d.b) (in boiling water), and there was a significant increase in TPC in green peppers as a result of microwaving (7.40 GAE μM/g d.b) relative to the control (2.75 GAE μM/g d.b). However, a significant reduction in TPC was observed

in yellow peppers (17.00 GAE μM/g d.b) due to both cooking (10.03 GAE μM/g d.b) and microwaving (10.14 GAE μM/g d.b).

The commercially available microwave oven used in our research generated non-ionizing microwave radiation (at a frequency of 2.45 GHz and a wavelength of about 120 mm), which causes intense dielectric heating [18]. Kaur et al. observed that the total content of polyphenols in yellow sweet pepper var. Bachata (*Capsicum annuum* L.) subjected to hot air convection drying (at three different temperatures of 40, 50 and 60 °C) decreased from 784.01 mg GAE/100 g to 630.76 mg GAE/100 g [19].

Meanwhile, other results (Table 2) confirmed previous findings that yellow bell peppers contain the most water compared to the green and red peppers [20].

Table 2. Reducing capacity and dry mass content of bell peppers of different ripening stages after boiling and microwaving.

R-Stage	Processing	FRAP $FeSO_4$ μM/g d.b.	Reducing Sugars GE mg/g d.b.	DB in Fresh Mass (%)
G	C	10.5 ± 0.4 a	4.2 ± 0.2 a	8.0 ± 0.4 b
	B	27.4 ± 0.7 c	4.7 ± 0.1 b	6.5 ± 0.3 a
	M	17.0 ± 0.1 b	4.1 ± 0.2 a	12.7 ± 0.1 c
Y	C	19.93 ± 1.64 a	5.6 ± 0.1 b	7.80 ± 0.14 a
	B	20.11 ± 0.04 a	5.5 ± 0.1 b	6.90 ± 0.42 a
	M	22.91 ± 0.89 a	3.5 ± 0.1 a	15.10 ± 0.42 b
R	C	39.79 ± 1.05 b	4.4 ± 0.1 c	10.1 ± 0.0 a
	B	3.66 ± 0.23 a	1.1 ± 0.0 a	10.1 ± 0.1a
	M	40.00 ± 1.32 b	3.2 ± 0.1 b	13.5 ± 0.5 b
R-stage		***	***	***
Processing		***	***	***
R-stage × processing		***	***	***

R-stage—ripening stage; G—green pepper; Y—yellow pepper; R—red pepper; C—control; B—boiling; M—microwaving; GE—glucose equivalent; DB—dry basis. Lowercase letters mean statistically significant difference between samples for same R-stage ($p = 0.05$); ***—$p < 0.001$.

Therefore, the heat generated inside the yellow pepper during processing causes intense heating of the tissues, which in turn is the cause of thermal degradation of a large amount of polyphenolic compounds (Table 1).

The significant reduction in TPC was observed in our research as a result of cooking (in boiling water) red peppers (1.86 GAE μM/g d.b) compared to the control (17.26 GAE μM/g d.b). Rybak et al. also showed a 13.7% reduction in TPC in red peppers that had undergone a similar heat treatment, which was traditional blanching in water [21].

Our study confirmed the highest TPC in red peppers relative to annual peppers from other stages of maturity. According to the observations of Deng et al., a high processing temperature significantly reduces the content of polyphenolic compounds in the tissues of many types of plants [22]. Perhaps the reduction in TPC content due to cooking in red peppers observed in our study was due to the high proportion of heat-sensitive polyphenolic compounds compared to polyphenolic compounds contained in yellow and green peppers.

A large amount of polyphenolic compounds (mainly phenolic acids) is associated with protein and carbohydrate molecules present in the cell walls of plant tissues. It has been confirmed that polyphenol–polysaccharide conjugates can take, among others, the form of neutral arabinogalactans, which are cross-linked with monomeric and dimeric hydroxycinnamate residues with molecular weights of 108 and 157 kDa [23].

It can be concluded that heat treatment breaks, for example, ester bonds between polyphenolic compounds and carbohydrates in cell walls [24]. As a result, polyphenolic compounds released from the cell wall dissolve into the water during cooking, which is the reason for the low content of polyphenolic compounds in red pepper after the cooking process.

On the other hand, polyphenolic compounds (mainly phenolic acids) may be so strongly bound to protein and carbohydrate molecules present in the cell walls of green pepper tissues that the heat treatment process does not break the ester bonds between polyphenolic compounds and carbohydrates but only weakens them and causes subsequent breaking in the homogenization and extraction step (assisted by the movement of the extraction liquid).

The structure of unripe fruits (high content of protopectin, which is responsible for the hardness of the internal structure in unripe fruits) impacts the leaching process of the intracellular content in the case of green peppers, resulting in smaller loss comparing yellow and red peppers [25]. Probably for the same reason, the oxidation process (by polyphenol oxidase) of released polyphenols after cooking green peppers is probably much weaker [26].

In our study, we observed a reduction in the total content of polyphenolic compounds in red peppers due to microwaving (15.37 GAE μM/g d.b) relative to the control (17.26 GAE μM/g d.b). In a study by Rybak et al., it was shown that the microwave drying process of fresh red peppers causes a significant reduction in the content of polyphenolic compounds (from an amount of about 2650 mg/100 g d.b. to 1400 mg/100 g d.b.) [27].

On the other hand, in the research carried out on field tomato (*Solanum lycopersicum* L.), it was shown that the microwave treatment process conducted for 5 min caused a 3,6-fold increase in the total amount of polyphenolic compounds compared to the unprocessed raw material (from 1.92 to 6.955 mg GAE g^{-1} f.b.) [28]. Ling et al. also found a reduction in total polyphenolic compounds in seaweed (*Kappaphycus alvarezii*) that was subjected to a sun-drying process where electromagnetic radiation (in the form of UVA and UVB radiation) is the heat generator [29].

It should be remembered that the thermal treatment processes we use (cooking and microwaving) may cause chemical modifications of the -OH groups and aromatic rings of polyphenols, which determines the durability and stability of these compounds. In addition, the stability of polyphenols is also affected by the content of ascorbic acid or the presence of oxygen [22].

Red peppers are widely recognized as a rich source of ascorbic acid [20]. Research shows that ascorbic acid is thermally unstable and degrades quickly at the boiling point [30]. Therefore, the decreasing amount of ascorbic acid in red (ripe) pepper during thermal processing may not provide adequate antioxidant protection for polyphenolic compounds during cooking of this raw material (Table 1).

3.2. The Antioxidant Activity Changes

3.2.1. DPPH

The total antioxidant activity (TAA) of green pepper was significantly increased by cooking (74.91 TXE μM/g d.b.) and significantly decreased by microwaving (34.81 TXE μM/g d.b.) relative to control (47.02 TXE μM/g d.b.). Ai Mey Chuah et al. also observed an increase in total antifree-radical activity (against the DPPH radical) in green bell pepper tissues, following a cooking process for 30 min compared to green peppers cooked for 5 min. This phenomenon was not observed in red peppers [4].

The increase in antioxidant activity observed in our study after the cooking process in green (unripe) pepper may have been due to the higher resistance of lutein to thermal degradation (and lower levels of its leaching from tissues into water) and the release of hydrophilic antioxidant substances, which were tissue in a highly bound form before the processing. It is possible that non-enzymatic conversion of lycopene and α-carotene to lutein, whose increased content resulted in an increase in antioxidant activity after the cooking process in green and yellow peppers, also occurred due to high temperature [31].

It is likely that the violaxanthin present in yellow peppers and the lutein abundant in green (unripe) peppers enter the water to a lower extent as a result of cooking. Perhaps the thermal inactivation of certain antioxidant oxidation enzymes, such as pheophorbide

oxidase a, which catalyzes the breakdown and oxidation of chlorophyll to phyllobilins, contributes to the increase in TAA after cooking [32,33].

In addition, the increase in TAA in green peppers may contribute to the violation of the structure of cell walls and subcellular compartments in the tissues during cooking, resulting in the release of large amounts of potent non-polyphenolic antioxidants (e.g., glutathione and beta-carotene) that capture free radicals [34]. Similarly, a significant increase in TAA was observed due to cooking (82.96 TXE μM/g d.b.) and significant lowering (significant reduction) due to microwaving (25.03 TXE μM/g d.b.) in yellow peppers relative to controls (57.10 TXE μM/g d.b.).

The research conducted by Kaur also confirmed that the antioxidant activity of yellow sweet pepper as a result of the process of drying in a hot air convection dryer was significantly reduced (from 269.33 nM TXE to 105.93 nM TXE) [19].

The study by Chuah et al. also observed a significant reduction in antifree-radical activity (against the DPPH radical) in green and yellow peppers due to microwave treatment. At the same time, the study by Chuah et al. showed no significant reduction in antifree-radical activity after microwave treatment of red peppers [4].

There was a significant decrease in TAA following cooking of red peppers (79.91 TXE μM/g d.b.) (16.08 TXE μM/g d.b.). Rybak et al. observed that the TAA of red peppers (the antioxidant activity of the extracts expressed by the IC50 parameter) that were subjected to a similar treatment—blanching with hot water—is significantly reduced compared to control (untreated) samples [21].

In addition to polyphenols, red peppers also contain high amounts of carotenoids and vitamin C, which are responsible for the high TAA of the unprocessed raw material [35]. Thermal processing of food raw materials, such as pasteurization, boiling (as low as 70 °C) and blanching in a stream of hot water, cause almost complete loss of vitamin C [36]. Perhaps this was the reason that TAA due to cooking was significantly reduced only in red peppers.

A significant increase in TAA due to microwave treatment (95.88 TXE μM/g d.b.) was observed in red peppers (79.91 TXE μM/g d.b.). Different results were obtained by Rybak et al. according to whom the TAA (measured by the DPPH method) of raw red peppers (which, expressed by the IC50 parameter, was 0.24 mg d.b./mL of extract) significantly decreases (to 0.9 mg d.b./mL of extract) after the microwave drying process [27].

In a study conducted by Arslan and Özcan, it was also shown that microwave treatment (at a device power of 210 W) increased the antioxidant activity (measured as a percent of the total DPPH free-radical scavenging capacity) of raw red peppers from 48.00% to 68.97% (DPPH Scavenging %). In the same experiment, when a higher microwave treatment power (700 W) was applied, an even greater increase in antioxidant activity was observed (an increase from 48.00% to 74.03% of DPPH radical scavenging (DPPH Scavenging %) was recorded [37].

Also, in the research carried out on field tomato (*Solanum lycopersicum* L.), it was shown that the microwave treatment process conducted for 5 min increased the TAA by more than 21% compared to unprocessed raw material [28].

It should be borne in mind that the antioxidant activity of microwave-processed pepper fruits is not only due to the phenolic compounds themselves. Other compounds such as carotenoids, ascorbic acid, and non-enzymatic browning products (e.g., melanoidins) also contribute to the total antioxidant activity [38].

3.2.2. ABTS

No significant differences in green bell pepper TAA were observed between microwaved peppers (0.89 TXE μM/g d.b.) and control peppers (2.69 TXE μM/g d.b.). However, a significant increase in antioxidant activity was observed with cooked green peppers (5.24 TXE μM/g d.b.).

A significant reduction in TAA was observed for cooked yellow peppers (9.40 TXE μM/g d.b.) and a significant reduction in TAA of microwaved yellow pep-

pers (17.09 TXE μM/g d.b.) relative to the control (20.08 TXE μM/g d.b.). A significant reduction in TAA was observed due to the cooking of red peppers (2.62 TXE μM/g d.b.) and an increase in TAA of microwaved red peppers was observed (29.53 TXE μM/g d.b.) relative to the control (21.09 TXE μM/g d.b.).

Similar results in terms of lower TAA of red peppers after hot water blanching were obtained by Rybak et al. In this study, similarly lower values were also obtained for TAA measured by the ABTS method relative to the DPPH method (for untreated and heat-treated raw material) [21].

Obtaining lower TAA values for the ABTS method in relation to the TAA values for the DPPH method confirmed that the DPPH method may be more suitable (than the ABTS test) for evaluating the TAA of color-rich plant raw materials, such as peppers, which contain both hydrophobic (carotenoids) and hydrophilic (polyphenols) antioxidants [39].

However, a significant increase in the TAA of red peppers (measured by ABTS) was observed as a result of microwaving (29.53 TXE μM/g d.b.) relative to the control (21.09 TXE μM/g d.b.). Different results were obtained by Rybak et al., who found that the TAA (measured by the ABTS method) of raw red peppers (which, expressed by the IC50 parameter, was 0.15 mg d.b./mL of extract) is significantly reduced (to 0.36 mg d.b./mL of extract) after the microwave drying process [27].

The reductive characteristics and dry weight of bell peppers after heat treatment are presented in Table 2.

3.2.3. FRAP

A significant increase in the oxidoreducing potential of green peppers (10.5 $FeSO_4$ μM/g d.b.) was observed as a result of cooking (27.4 $FeSO_4$ μM/g d.b.) as well as a significant increase (in the oxidoreducing potential of green peppers) as a result of microwaving (17.0 $FeSO_4$ μM/g d.b.). In contrast, no significant differences were observed in the oxidoreductive activity of yellow peppers (19.93 $FeSO_4$ μM/g d.b.) as a result of the heat treatment methods used.

No significant differences in oxidoreductive activity were observed for red peppers (39.79 $FeSO_4$ μM/g d.b.) that were microwaved (40.0 $FeSO_4$ μM/g d.b.). In contrast, a significant reduction in the oxidoreductive activity of red peppers was observed as a result of cooking (3.66 $FeSO_4$ μM/g d.b.).

A study in Ornelas-Paz Braulio also showed that the cooking process causes an almost 20% reduction in the reducing power of red chili peppers of the Jalapeño variety (*Capsicum annuum*), relative to the raw material that was not thermally processed. Perhaps the reduction in the reducing power of the raw material studied due to cooking is a consequence of the leaching of some hydrophilic antioxidants, mainly ascorbic acid, into the hot water [40].

Kaur et al. reported a significant reduction in the reducing activity of fresh yellow sweet pepper (from 453.21 mg Trolox/100 g d.b. to 345.81, 364.61 and 399.72 mg Trolox/100 g d.b.) as a result of drying the tested raw material at temperatures of 40, 50 and 60 °C, respectively [19].

Perhaps the reduction (by more than 90.61%) of the reducing activity of red pepper due to cooking that we observed was due to the loss of carotenoids due to high temperature—Table 2.

3.3. The Reducing Sugars Changes

No significant changes were observed in the total content of reducing sugars in green peppers as a result of microwaving (4.1 GE mg/g d.b.) relative to the control (4.2 GE mg/g d.b.). In contrast, a significant increase in the content of reducing sugars in green peppers was observed as a result of cooking (4.7 GE mg/g d.b.). No significant differences were observed in the total content of reducing sugars in yellow peppers (5.6 GE mg/g d.b.) that were subjected to cooking (5.5 GE mg/g d.b.).

However, a significant reduction in the total content of reducing sugars in yellow peppers was observed as a result of microwaving (3.5 GE mg/g d.b.) relative to the control (5.6 GE mg/g d.b.). In contrast, a significant reduction in total reducing sugars was observed in red peppers due to cooking (1.1 GE mg/g d.b.) relative to the control (4.4 GE mg/g d.b.). According to a study by Rybak et al., thermal treatment of red peppers involving a process of blanching in hot water resulted in a reduction in the content of reducing sugars [21].

The total content of reducing sugars in microwaved red peppers (3.2 GE mg/g d.b.) was also significantly reduced relative to the control (4.4 GE mg/g d.b.). According to a study by Rybak et al., the content of reducing sugars, which is about 63.1 g/100 d.b. in fresh red peppers, is significantly reduced by the microwave drying process to 61.1 g/100 g d.b. [21].

Cooking plant raw materials in water causes dynamic heat penetration into the tissues. This results in the degradation of tissue and cellular structures, which involves the process of releasing certain types of substances, such as sugars, which move into hot water due to their high solubility [41].

Perhaps the increase in total reducing sugars in green peppers due to cooking that we observed was due to less tissue damage to the peppers (and thus lower mass transfer), which was not conducive to the free passage of sugars into the boiling water.

The textural characteristics and dry weight of bell peppers after heat treatment are presented in Table 3.

Table 3. Texture parameters of bell peppers of different ripening stages after boiling and microwaving.

R-Stage	Processing	Hardness	Cohesiveness	Springiness	Chewiness	Resilience
G	C	69.7 ± 9.9 b	0.784 ± 0.023 a	0.667 ± 0.000 a	36.32 ± 4.08 b	0.683 ± 0.090 b
	B	18.5 ± 2.6 a	0.583 ± 0.037 a	0.574 ± 0.058 a	6.13 ± 0.15 a	0.660 ± 0.047 ab
	M	4.6 ± 0.1 a	0.734 ± 0.104 a	0.588 ± 0.078 a	2.00 ± 0.51 a	0.493 ± 0.018 ab
Y	C	12.7 ± 7.9 a	0.884 ± 0.036 b	0.657 ± 0.081 a	6.99 ± 3.41 a	0.889 ± 0.148 a
	B	7.5 ± 1.2 a	0.744 ± 0.044 a	1.000 ± 0.000 b	5.62 ± 1.19 a	0.791 ± 0.007 a
	M	9.0 ± 1.1 a	0.765 ± 0.028 a	0.810 ± 0.033 a	5.54 ± 0.67 a	0.699 ± 0.043 a
R	C	48.6 ± 1.1 c	0.720 ± 0.015 a	0.62 ± 0.03 a	21.73 ± 1.10 b	0.729 ± 0.120 a
	B	33.3 ± 2.2 b	0.648 ± 0.057 a	0.70 ± 0.05 a	15.05 ± 0.69 b	0.703 ± 0.035 a
	M	17.0 ± 3.4 a	0.718 ± 0.032 a	0.90 ± 0.14 a	11.21 ± 4.41 a	0.819 ± 0.017 a
R-stage		***	**	*	***	ns
Processing		***	**	**	***	**
R-stage × processing		***	ns	**	***	ns

R-stage—ripening stage; G—green pepper; Y—yellow pepper; R—red pepper; C—control; B—boiling; M—microwaving. Lowercase letters means statistically significant difference between samples for same R-stage ($p = 0.05$); ns—statistically non-significant; *—$p < 0.05$, **—$p < 0.01$, ***—$p < 0.001$.

3.4. The Morpho-Textural Characteristic Changes

There was a significant reduction in the hardness of green peppers, both after cooking and (to a much greater extent) after microwaving. No significant differences were observed in the hardness of yellow peppers after the heat treatment methods used. A significant reduction was observed in the hardness of red peppers due to cooking, as well as (to an even greater extent) a reduction in the hardness of red peppers due to microwaving.

The observed changes in bioactive properties were the result of both the application of the appropriate treatment method (cooking or microwave) and depended on the variety of the tested bell pepper.

According to a study by Du Toit, the process of cooking green peppers for 10 min results in a significant reduction in the hardness of the processed raw material (707.28 g) relative to the raw material (1137.61 g).

A similar study indicated that the process of cooking nopal (*Opuntia ficusindica*) fruit for 10 min also causes a significant reduction in hardness (from 506.89 g to 474.50 g), suggesting that cooking this type of vegetable raw material significantly softens the texture [42].

The changes in the external appearance of bell peppers after heat treatment are shown in Figure 1.

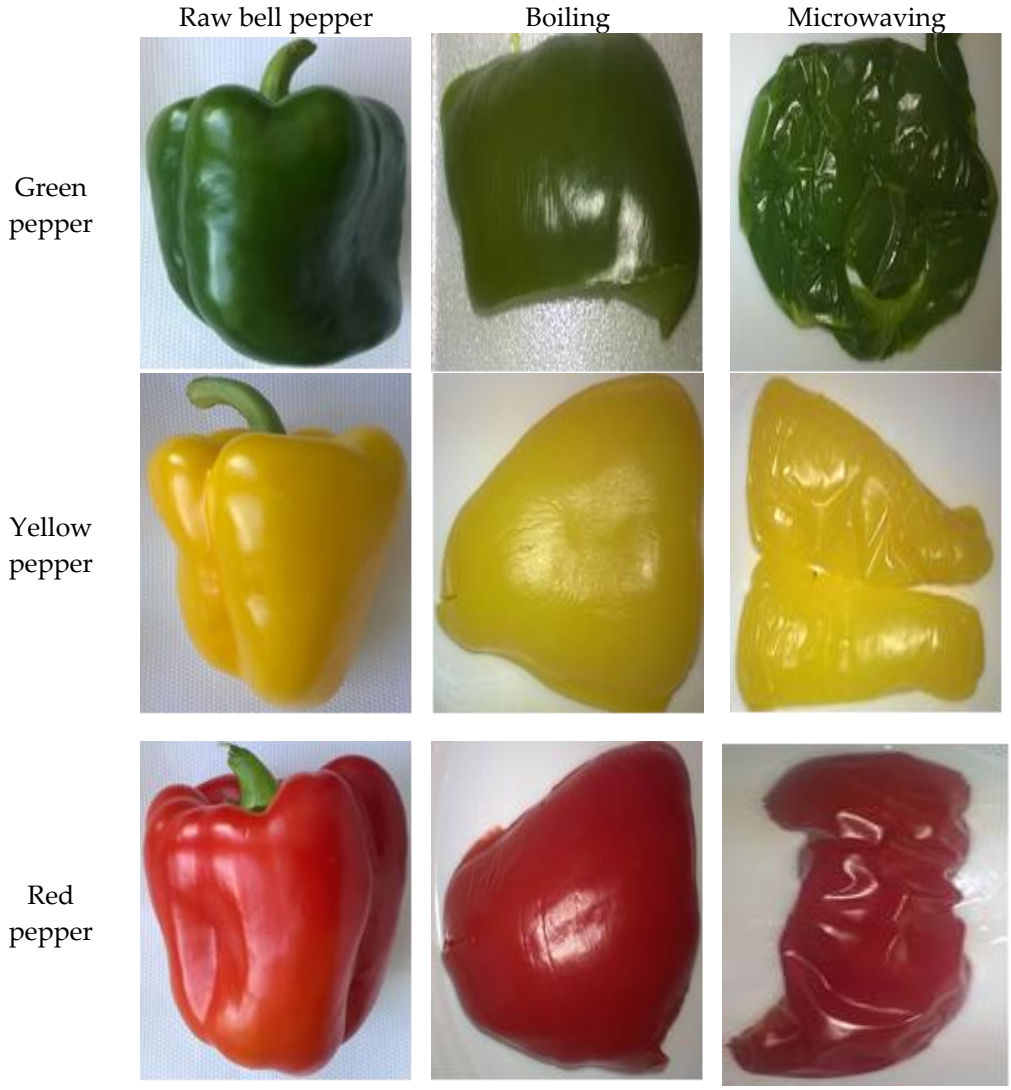

Figure 1. Morphological characteristics of bell pepper after heat treatment.

Results obtained by Du Toit showed that even a 1-minute microwave treatment of raw green peppers significantly reduces the hardness of this raw material (from 1137.61 g to 443.50 g) [42].

It has also been indicated that microwaving nopal (*Opuntia ficusindica*) fruit for 5 min, in turn, significantly increases the hardness (from 506.89 g to 596.17 g) of the processed raw material [42]. It has been indicated that prolonged microwave processing can remove water from the raw material, contributing to its drying and hardening [43].

Only yellow pepper showed a statistically significant reduction in cohesiveness after heat treatments regardless of the method; also, only in this stage of ripening, there was an observed change in springiness, specifically the increase and only after cooking, which was probably strongly connected with excessive water absorption, as the dry basis lowered in that case (Table 2).

Significant reductions of chewiness were only observed for green peppers that were subjected to cooking and green peppers that were microwaved (to an even greater extent).

No significant difference in chewiness was recorded for cooked red peppers, but the microwaved ones showed a reduction in chewiness. As this parameter is also related to the water content, the highest dry matter after microwave treatment in red pepper seems to confirm the observation.

A significant reduction in resilience was observed as a result of microwaving green peppers relative to the control. It was confirmed that the obtained changes in the textural properties of bell peppers depended both on the ripening stage of the tested raw material as well as on the type of thermal treatment used.

Multivariate analysis of variance showed significant changes in hardness as a result of two thermal treatments—microwaving and cooking. The most statistically significant change in hardness was observed for green (unripe) peppers, where both the cooking and microwaving processes reduced the hardness by 73.46% and 96.38%, respectively, in a statistically indistinguishable way.

The opposite phenomenon was observed for yellow peppers (medium ripening stage), where no changes occurred compared to the control sample, regardless of the method of heat treatment. Peppers in the final stage of ripening (red peppers) were more susceptible to water loss, which is visible in the statistically significant difference between the control and microwaved peppers. This difference was not observed between the control (unprocessed) peppers and the cooked peppers.

The color parameters change in bell peppers after heat treatment is presented in Table 4.

Table 4. Color change in bell peppers at different ripening stages after boiling and microwaving.

R-Stage	Processing	*L**	*a**	*b**	C	h
G	C	55.6 ± 0.9 a	−14.11 ± 1.04 a	16.0 ± 1.7 a	21.35 ± 1.94 a	131.4 ± 0.9 c
	B	60.5 ± 0.2 b	−6.56 ± 0.37 c	19.1 ± 1.9 b	20.17 ± 1.97 a	109.0 ± 0.7 a
	M	60.1 ± 0.1 b	−10.69 ± 0.42 b	19.7 ± 0.3 b	22.43 ± 0.46 a	118.4 ± 0.6 b
Y	C	60.3 ± 2.4 a	52.53 ± 2.48 b	26.9 ± 0.8 a	59.03 ± 2.08 a	27.1 ± 1.6 a
	B	85.2 ± 1.3 b	−4.65 ± 0.18 a	63.5 ± 2.2 b	63.63 ± 2.14 b	94.2 ± 0.3 b
	M	87.6 ± 0.4 b	−3.62 ± 0.38 a	72.3 ± 0.5 c	72.35 ± 0.55 c	92.8 ± 0.3 b
R	C	97.8 ± 0.1 c	10.75 ± 0.10 a	85.6 ± 1.2 c	86.23 ± 1.16 c	82.90 ± 0.00 b
	B	59.5 ± 0.4 a	43.16 ± 0.33 b	25.9 ± 0.6 a	50.34 ± 0.57 a	30.93 ± 0.37 a
	M	60.7 ± 1.0 b	57.240.78 c	40.6 ± 11.8 b	67.12 ± 1.16 b	31.45 ± 0.44 a
R-stage		***	***	***	***	***
Processing		***	***	***	***	***
R-stage × processing		***	***	***	***	***

R-stage—ripening stage; G—green pepper; Y—yellow pepper; R—red pepper; C—control; B—boiling; M—microwaving. Lowercase letters mean statistically significant difference between samples for same R-stage ($p = 0.05$); ***—$p < 0.001$.

Cooking and microwaving green peppers was shown to significantly increase the value of the *L* parameter. In addition, cooking and microwaving yellow peppers causes a significant increase in the *L* parameter (relative to the control). It was further shown that cooking and microwaving red peppers causes a significant decrease in the values of the *L* parameter, as a result of cooking and microwaving.

In the case of green peppers, it was shown that the cooking and microwaving process caused a significant increase in the value of the parameter *a* (relative to the control). At the same time, it was shown that the cooking and microwaving process of yellow peppers caused a significant decrease in the value of the parameter *a* (relative to untreated yellow peppers). In addition, a significant increase in the value of the parameter *a* for green peppers due to cooking and microwaving was observed compared to the control (green peppers).

A significant increase in the value of the *b* parameter was observed for green peppers as a result of cooking and microwaving (relative to the control). However, no statistically significant differences were observed between cooking and microwaving for green peppers.

In addition, a significant increase in the value of the *b* parameter was observed for yellow peppers as a result of cooking and microwaving (relative to the control). A significant decrease in the value of the *b* parameter was also observed for red peppers as a result of cooking and microwaving (relative to the control).

No statistically significant changes were observed in the value of the C parameter as a result of cooking and microwaving green peppers (relative to the control). However, a statistically significant increase in the value of the C parameter was observed as a result of cooking and microwaving yellow peppers (relative to the control). In addition, a statistically significant decrease in the value of the C parameter was observed as a result of cooking and microwaving red peppers (relative to the control).

In the case of yellow peppers, simultaneous increases in the *L**, *b** and *C** parameters and decreases in the *a* parameter were observed, indicating that the application of both cooking and microwaving does not cause darkening of the surface tissues of this raw material.

In the case of green peppers, an increase in the parameters *L**, *b** and *C** was observed with an increase in the value of the parameter *a*, indicating that the application of either cooking or microwaving does not cause such intense darkening of the surface tissues as in the case of yellow peppers.

In the case of red peppers, a decrease in the parameters *L**, *b** and *C** was observed with an increase in the value of the parameter *a*, indicating that the application of cooking or microwaving can cause the surface tissues of red peppers to lighten.

Statistical analysis confirmed that changes in color parameters depended both on the type of raw material (tested variety of bell pepper) and on the applied thermal processes.

The observation we made may be due to differences in the susceptibility of the tested peppers to the inactivation of the enzyme system, which is responsible for the darkening of plant materials. Perhaps microwave radiation causes stronger (than green and yellow peppers) inactivation of polyphenol oxidase in red peppers. This enzyme catalyzes the conversion (oxidation) of phenolic compounds to quinones, which polymerize to form insoluble dark-colored polymers (melanins) [44]. Perhaps this process is more intense in red peppers and occurs much more intensely as a result of microwaving than the cooking process.

A different observation was made by Rybak et al. where, for microwave-dried red peppers, there was an increase in the *L**, *b** and *C** parameters with a simultaneous decrease in the *a** parameter (compared to the control), indicating the darkening of the raw material under study during heat treatment [27].

4. Conclusions

Based on the obtained results, it can be concluded that the applied thermal treatment techniques have a profound effect on the content of bioactive compounds, antioxidant activity and textural properties of green, yellow and red peppers.

Overall, microwave heating and cooking increased the TPC in green peppers and reduced it in yellow and red peppers, while cooking increased the TAA in green and yellow peppers and reduced it in red peppers.

The reduction in TAA in cooked red peppers was greatest, while the reduction in TAA during microwaving was greatest for yellow peppers. This finding indicates that from a consumer standpoint, microwave heating treatment is more beneficial for red peppers. In contrast, hot water cooking is more beneficial for green and yellow peppers. However, when there is a need to cook red peppers, as little water as possible and a relatively short cooking time should be used for this treatment, so as to avoid a large loss of bioactive compounds (present in red peppers) during processing. It is also important to also consume, or use for culinary purposes, the water obtained from cooking the peppers, as bioactive compounds that have been washed out of the cooked tissues (of red peppers) may be present in large amounts in this water.

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