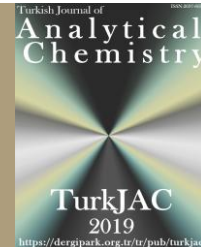




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Physicochemical alterations of carrot properties through the application of edible film coating prior to heat treatment

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Abstract

The objective of this study was to examine the alterations in carrot properties resulting from the application of edible coatings before subjecting them to heat treatment. Three different heat treatments (frying, baking, boiling) and three types of coating solutions [chitosan, zein, hydroxypropyl methyl cellulose (HPMC)] were utilized in the research. The carrots underwent analysis for pH, titratable acidity (TA), texture, water activity (aw), water-soluble dry matter (WSDM), color (L^* , a^* , b^* , C^* , ΔE , hue), total phenolic content (TPC), and antioxidant capacity (DPPH). The results indicated that coated samples generally preserved their physicochemical and nutritional properties better than the uncoated sample. After boiling, the coated samples had WSDM values ranging from 0.951 to 1.270, whereas the uncoated sample measured 0.683. Zein-coated samples exhibited higher WSDM values than the uncoated sample across all cooking methods (21.30, 17.40, and 9.30 for frying, baking, and boiling, respectively). Notably, the HPMC-coated sample exhibited the most significant color difference. In the boiling process, the HPMC-coated sample showed approximately 65% and 112% increases in TPC and DPPH values, respectively, compared to the uncoated sample. In baking, the highest TPC and DPPH values were observed in the chitosan-coated sample, showing approximately 55% and 269% increases relative to the uncoated sample. In contrast, during frying, the coatings were unable to preserve either parameter, and decreases were observed in both. Overall, these findings highlight the potential of edible coatings to enhance the retention of bioactive compounds and antioxidant activity in carrots during thermal processing, contributing to improved food quality and consumer health.

Keywords: Carrot, chitosan, heat treatment, hydroxypropyl methyl cellulose, zein

1. Introduction

Edible coatings represent a packaging method that involves the application of a thin layer to the food surface. These coatings have the potential to preserve the quality and nutritional value of products. In addition, they have been shown to retard the rate of food spoilage and mitigate nutrient wastage by impeding moisture loss and oxygen transmission [1]. Consequently, the freshness of products is maintained for a longer duration, and more durable foods can be offered to consumers. Furthermore, certain edible coatings have been shown to mitigate undesirable effects, such as deformation and softening, that can occur during food preparation by preserving the structural integrity of fruits and vegetables [1,2].

However, not every type of coating is suitable for every food product. Choosing the wrong coating or incorrect application can lead to unexpected results. For

example, some coatings may cause undesirable flavor changes in the product when exposed to excessive heat during cooking or may lead to coating degradation. It can also lead to insufficient ventilation of the product and moisture accumulation, increasing the risk of microbial spoilage [3,4]. Therefore, the product and process conditions to which each coating is applied should be carefully evaluated, and potential impacts should be considered.

Nowadays, in line with modern consumer trends, the demand for easy-to-prepare and practical products has increased, which has increased the popularity of chopped fruits and vegetables. Therefore, many studies have been conducted on the use of edible coatings to extend the shelf life of chopped fruits and vegetables [5–7]. However, it is not known exactly how edible coatings to be applied before cooking will affect the

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nutritional value and structural properties of these products. In the existing literature, there is no comprehensive study evaluating the changes in the nutritional value and physical structure of vegetables coated with different edible coatings after cooking. In this study, we aim to fill this gap and reveal how coatings affect nutrient losses and structural changes of vegetables during cooking.

Carrot (*Daucus carota* L.) is an important product that attracts the attention of consumers as a vegetable with high nutritional value as well as being delicious. It provides important health benefits with its antioxidant, anticancer, healing, and soothing properties. Moreover, it is considered a suitable model food due to its firm texture, high carotenoid content, and sensitivity of its nutrients to thermal processing. It can be consumed both raw and cooked, but due to its short shelf life, it is usually subjected to processes such as freezing, cooking, or drying [8]. Since cooking is a common choice, the effect of cooking methods on the nutritional value of carrots has been the focus of scientific research [8–12].

During the cooking process, various changes occur in the chemical composition and physical structure of

generally lead to losses in nutritional value and deterioration in sensory and structural properties [13]. While there are several studies on how these losses can be reduced by different cooking techniques (boiling, pressure cooking, microwaving, baking, oven cooking, grilling, frying, and steaming), there is limited research on the effects of applying edible coatings as a pre-treatment in this process [14].

The cooking process can increase the release of phytochemicals, leading to the formation of new bioactive compounds as a result of the Maillard reaction. However, water-soluble vitamins and phenolics may be lost or oxidized during cooking [15]. It is suggested that edible coatings can prevent these losses by forming a moisture and gas barrier. In particular, chitosan coatings create a barrier on the surface by reducing moisture and water loss in fruits and vegetables, while zein coatings have high thermal stability and hydrophobicity. HPMC coatings provide a good oxygen barrier and show oil resistance [2,3,16].

The study aimed to evaluate the changes in physical and chemical quality characteristics of *Daucus carota* carrot cubes coated with zein, chitosan, and HPMC after

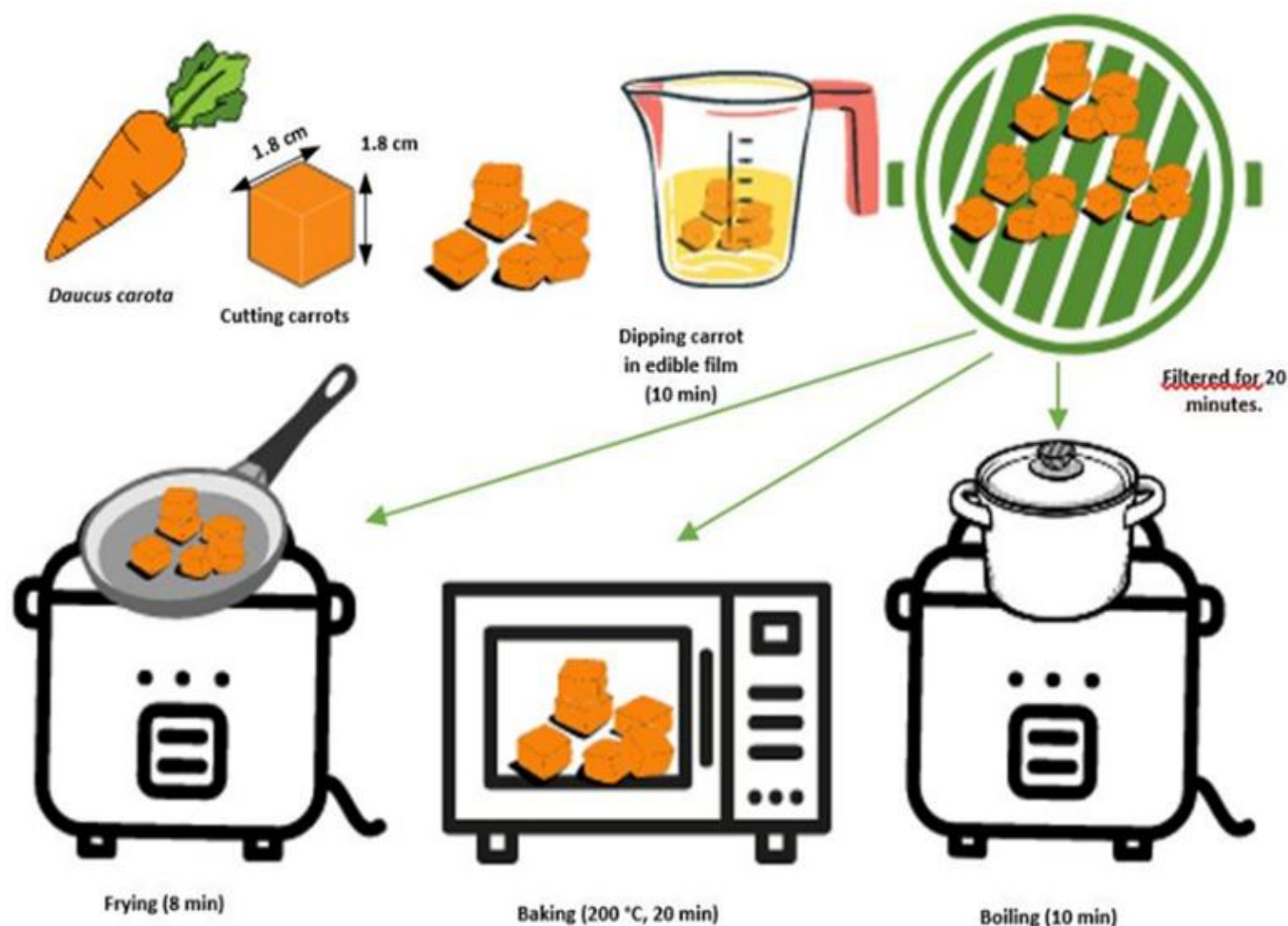


Figure 1. Processes applied to carrots

foods, such as carrots, depending on the method, temperature, pressure, and time used. These changes

different cooking methods (boiling, frying, and baking). The study intends to provide novel insights into the

potential of edible coatings to preserve nutritional value and to fill a gap in the literature. To date, no study has systematically compared the effects of these coatings on both physicochemical and nutritional changes, underscoring the innovative aspect of this research.

2. Material and methods

2.1. Production of edible coatings

Edible coatings were applied as a pretreatment to evaluate their effects on the physical and chemical properties of carrot samples during frying, baking, and boiling processes. Within the scope of this study, the formulations of zein, chitosan, and HPMC coating solutions and the cooking durations were optimized based on initial experiments.

Production of zein-based edible coating: To create a zein-based edible coating, a mixture of 2.5% zein, 20% glycerol (Sigma-Aldrich, Germany), 10% water, and 95% (v/v) ethanol was utilized. The resulting solution was thoroughly blended using a heated magnetic stirrer at 80 °C for a duration of 30 minutes [17].

Production of chitosan-based edible coating: For the production of chitosan-based edible coatings, a solution was prepared using 1.5% chitosan (Sigma, >400 mPa.s, dissolved in 1% acetic acid), 2% glycerol, 1% acetic acid (Isolab 901.013), and water as the solvent. This solution was homogenized using a heated magnetic stirrer at 40 °C for 20 minutes. The concentrations of chitosan, glycerol, and acetic acid were selected based on previous studies in the literature [18].

Production of HPMC-based edible coating: In the case of the edible coating based on HPMC, a solution was created using 2.5% HPMC (Sigma 423203), 2% glycerol, and water as the solvent. The solution was homogenized using a heated magnetic stirrer at 80 °C for 30 minutes [19].

Dicing and coating of carrots: Carrots were diced with a laboratory knife measuring 1.8×1.8×1.8 cm³. They were then immersed in the coating solutions for 10 minutes, and after the carrots had been removed, they were drained in a strainer tray for 20 minutes (Fig. 1).

2.2. Thermal treatment methods

Frying process: In a frying pan, 500 mL of sunflower oil (Sırma, 91%, Türkiye) was added and heated for 5 minutes, both for the uncoated (Control) and coated samples. Subsequently, the samples were placed in the pan and fried over medium heat for 8 minutes. Fresh oil was used for each replicate, and the frying time was determined based on preliminary trials.

Baking process: The uncoated (Control) and coated samples were placed on a greased tray and baked in the

oven at 200 °C for a duration of 20 minutes. The baking time was selected based on preliminary trials.

Boiling process: The water was brought to a boil, and 500 mL of the boiling water was transferred to a pot. Then, the uncoated (Control) and coated samples were placed in the boiling water and boiled for 10 minutes. The boiling time was determined based on preliminary trials.

2.3. Physical and chemical analyses

2.3.1. pH analysis

To measure the pH, a sample of homogenized coated carrots, after heat treatment, was prepared by mixing 5 grams with 25 mL of distilled water. The mixture was stirred and immediately filtered using coarse filter paper. The pH of the filtrate was measured using a pH meter (Ohaus, Starter 3000).

2.3.2. Total acidity analysis

To determine titratable acidity, 15 mL of the filtrate was taken and titrated with 0.1 N NaOH until a pH of 8.1 was reached. The titratable acidity value was expressed as anhydrous citric acid (g/L) [20].

2.3.3. Color analysis

The color of the carrots was assessed using a color measuring device (CEMINOLTA, CR-300, Japan) from three different surfaces of the carrot. The color measurements included L^* (0=black, 100=white darkness/lightness), a^* (a ; +a red, -a green), and b^* (+b yellow, -b blue) values. Additionally, chroma (C), hue angle (h°), which indicates color perception, and ΔE value, which indicates the overall color change trend of the carrots, were calculated based on the L^* , a^* , and b^* values using Eqs. 1, 2, and 3 [21].

$$E = \sqrt{(L^*)^2 + (a^*)^2 + (b^*)^2} \quad (1)$$

$$C = \sqrt{(a^*)^2 + (b^*)^2} \quad (2)$$

$$h^\circ = \tan^{-1}(b/a) \quad (\text{if } a^* > 0 \text{ and } b^* \geq 0) \quad (3)$$

2.3.4. Texture analysis

The force required to puncture the heat-treated carrots at a point 10 mm from the vertical dimension was measured in Newtons. To conduct the measurement, a Zwick Z 0.5 tester (USA) equipped with a stainless-steel head of 10 mm diameter was utilized [22].

2.3.5. Water activity analysis

The water activity of carrots in each group was determined using a water activity device (AquaLab Model Series 3TE) at a temperature of 25 °C. After

placing the samples in the measuring chamber of the device, the moisture content value at which equilibrium was reached was recorded as the equilibrium moisture value [23].

2.3.6. Water soluble dry matter (WSDM, °brix) analysis

The WSDM was measured using an Abbe refractometer (Optic Ivymen system, WYA-S). For each trial, 5 g of homogenized carrots were taken, diluted with 25 mL of water, homogenized, and then passed through coarse filter paper [23].

2.3.7. Phenolic content analysis (TPC)

For analysis, cooked carrots (1:1) were diluted, diced, and extracted with a Methanol-HCl (99:1) solution. The phenolic content of carrots was measured using the Folin-Ciocalteu method and a Hitachi U-2900 spectrophotometer [24,25]. A 0.1 mL sample stock solution prepared for analysis was taken and diluted to 4.6 mL with distilled water. Then, 0.3 mL of 2% sodium carbonate (Na_2CO_3) solution and 0.1 mL of Folin-Ciocalteu reagent (Merck, Darmstadt, Germany) were added and mixed. After 2 hours at room temperature, the absorbance was measured at 760 nm, and the reading was calculated as gallic acid equivalent (GAE) (Merck, Darmstadt, Germany).

2.3.8. Antioxidant capacity analysis (TAC)

Stock solutions of the samples ranging from 10 to 200 $\mu\text{g/mL}$ were prepared, and 1 mL of 0.26 mM TAC solution (Sigma-Aldrich GmbH, Steinheim, Germany) prepared in ethanol was added. Ethanol was added to bring the solution volume in the tube to 4 mL. The solution was thoroughly mixed and incubated for 15 minutes, and then the absorbance was measured at 517 nm. The results were calculated as IC_{50} [25,26].

2.3.9. Statistical analysis

The data obtained in the study were subjected to variance analysis using the SAS statistical program. Based on the results of the variance analysis, the average values of statistically significant factors were compared using the Duncan test.

3. Results and discussion

3.1. Quality attributes of carrot after frying process

The effect of coating types on the pH and total acidity (TA) values of carrot samples after frying was significant ($p < 0.05$). Following frying, the pH value of the uncoated sample was measured as 5.91, while the highest pH value was observed in the HPMC-coated sample (6.19), and the lowest in the chitosan-coated sample (5.59) ($p < 0.05$). Regarding total acidity, the highest TA value was

recorded in the zein-coated sample (0.288), whereas the lowest value was detected in the HPMC-coated sample (0.146) ($p < 0.05$). The TA value of the uncoated sample was 0.173, and no statistically significant difference was found between this and the HPMC-coated sample (Table 1).

Table 1. Average data for the analysis of fried carrots ($n=3$)

	Control	Chitosan	Zein	HPMC
pH	5.91 $\pm$ 0.14 ^c	5.59 $\pm$ 0.14 ^a	5.74 $\pm$ 0.14 ^b	6.19 $\pm$ 0.14 ^d
TA	0.173 $\pm$ 0.016 ^{ab}	0.234 $\pm$ 0.049 ^{bc}	0.288 $\pm$ 0.005 ^c	0.146 $\pm$ 0.010 ^a
aw	0.977 $\pm$ 0.002 ^b	0.981 $\pm$ 0.001 ^b	0.968 $\pm$ 0.004 ^a	0.988 $\pm$ 0.001 ^c
WSDM	15.60 $\pm$ 0.85 ^b	13.65 $\pm$ 0.21 ^a	21.30 $\pm$ 0.42 ^c	16.50 $\pm$ 0.42 ^b
Texture	0.383 $\pm$ 0.114 ^a	0.421 $\pm$ 0.138 ^a	0.437 $\pm$ 0.190 ^a	0.511 $\pm$ 0.190 ^a
L^*	53.73 $\pm$ 4.17 ^a	54.27 $\pm$ 1.49 ^a	55.38 $\pm$ 4.35 ^a	55.17 $\pm$ 2.12 ^a
a^*	18.12 $\pm$ 4.56 ^b	18.41 $\pm$ 3.06 ^b	14.11 $\pm$ 1.36 ^a	14.54 $\pm$ 2.19 ^{ab}
b^*	50.29 $\pm$ 6.47 ^a	53.17 $\pm$ 0.72 ^a	54.05 $\pm$ 3.45 ^a	48.68 $\pm$ 5.24 ^a
C^*	53.50 $\pm$ 7.53 ^a	56.31 $\pm$ 1.21 ^a	55.89 $\pm$ 3.22 ^a	50.84 $\pm$ 5.22 ^a
ΔE	00.00 $\pm$ 0.00 ^a	4.08 $\pm$ 1.43 ^b	7.17 $\pm$ 3.25 ^c	6.77 $\pm$ 1.68 ^{bc}
h^*	70.40 $\pm$ 2.65 ^a	70.94 $\pm$ 2.93 ^a	75.31 $\pm$ 1.84 ^b	73.30 $\pm$ 2.59 ^{ab}

* $n=3$, $\pm$ standard deviation, ^{a, b, c} ≤ 0.05 represents the differences in the same line

Coating types also had a significant effect on water activity (aw) during frying ($p < 0.05$). The water activity of HPMC-coated samples was the highest (0.988), while zein-coated samples was the lowest (0.968) ($p < 0.05$). The water retention effect of HPMC requires careful consideration regarding the desired crispness and flavor characteristics of fried products. A certain degree of moisture loss at the surface is necessary to achieve a crispy texture; however, HPMC's limitation of this moisture loss may negatively impact texture, potentially reducing crispness and consumer acceptance. Mallikarjunan et al. [27] reported that HPMC forms a gel-like layer on the product surface at high temperatures, which inhibited moisture migration into the frying oil. On the other hand, zein coatings did not form such a barrier, resulting in higher moisture loss; however, their sensory properties (Fig. 2) should be evaluated in future studies.

Water activity values of chitosan-coated samples were measured as 0.981, with no significant difference compared to the control ($p > 0.05$), while zein-coated samples were significantly lower than the control and other coated samples ($p < 0.05$).

Regarding soluble solids content, the highest value (21.30%) was recorded in zein-coated samples, while the lowest (13.65%) was observed in chitosan-coated samples ($p < 0.05$). No significant difference in WSDM was found between the control group and HPMC-coated samples.

Kurek et al. [28] reported moisture contents in fried samples as 56.55% in the control group (uncoated samples dipped only in water), 49.93% in carboxymethyl cellulose/lyophilized olive oil extract-coated samples, and 39.72% in Arabic gum/lyophilized olive oil extract-

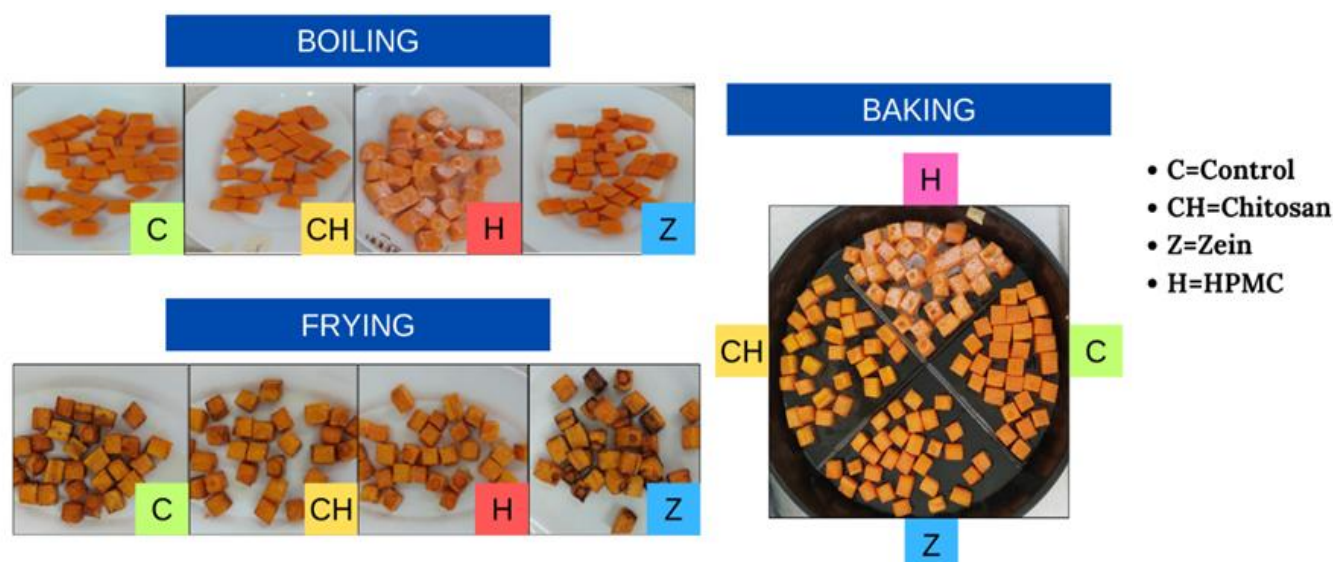


Figure 2. Images after thermal processing

coated samples, indicating a moisture reduction in coated samples compared to control. Additionally, sodium ascorbate-containing coatings showed slightly higher moisture content than other lyophilized olive oil extract coatings, though this difference was not statistically significant. Al-Asmar et al. [29] found that pectin-based coatings did not significantly alter water content in fried potatoes. Mallikarjunan et al. [27] observed reductions in moisture loss of 14.9%, 21.9%, and 31.1% in potato balls coated with corn zein, HPMC, and methylcellulose films, respectively, compared to uncoated samples. In the same study, fat uptake was reduced by 59.0%, 61.4%, and 83.6% in these coated samples, respectively.

Texture is a critical quality attribute influencing vegetable flavor and consumer acceptance. Therefore, the effects of different coating types on the texture of fried carrots were evaluated. Post-frying images of coated and uncoated carrot samples are presented in Fig. 2. Although no statistically significant differences were found between the samples in terms of texture values, coated samples exhibited higher average texture values than controls. This finding aligns with previous studies indicating the protective effect of coatings on texture [7].

Furthermore, the formation of a crispy crust on the surface during frying is one of the most desired characteristics in fried foods [30].

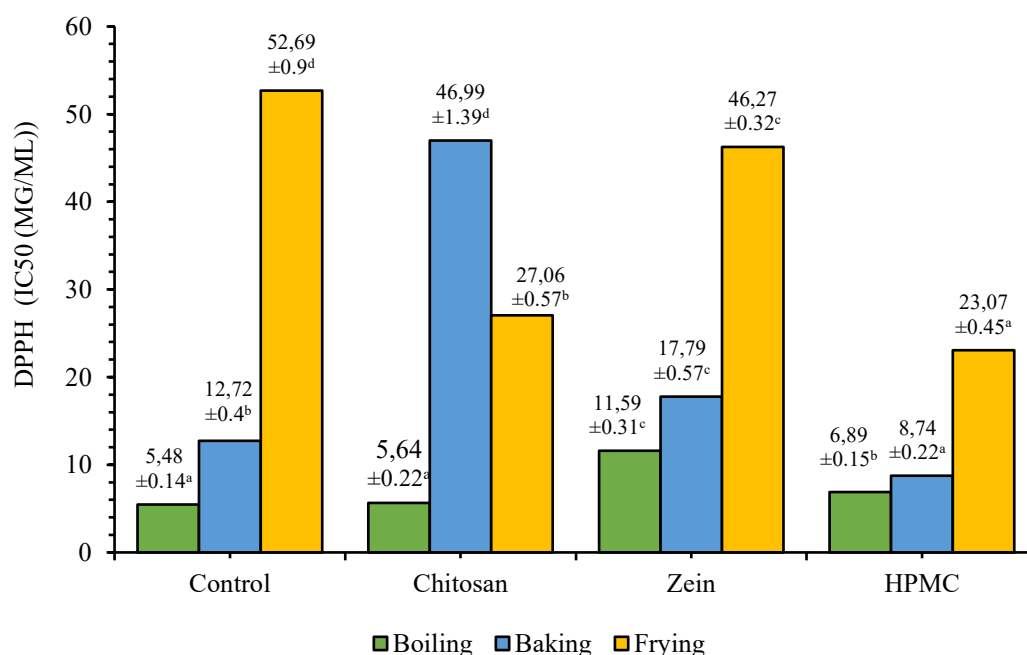


Figure 3. Total antioxidant capacity of coated (Chitosan, HPMC, Zein) and uncoated (Control) samples after frying, baking and boiling processes (*n=3, ± standard deviation, ^{a, b, ...} ≤ 0.05 shows the differences between groups in the same heat treatments.)

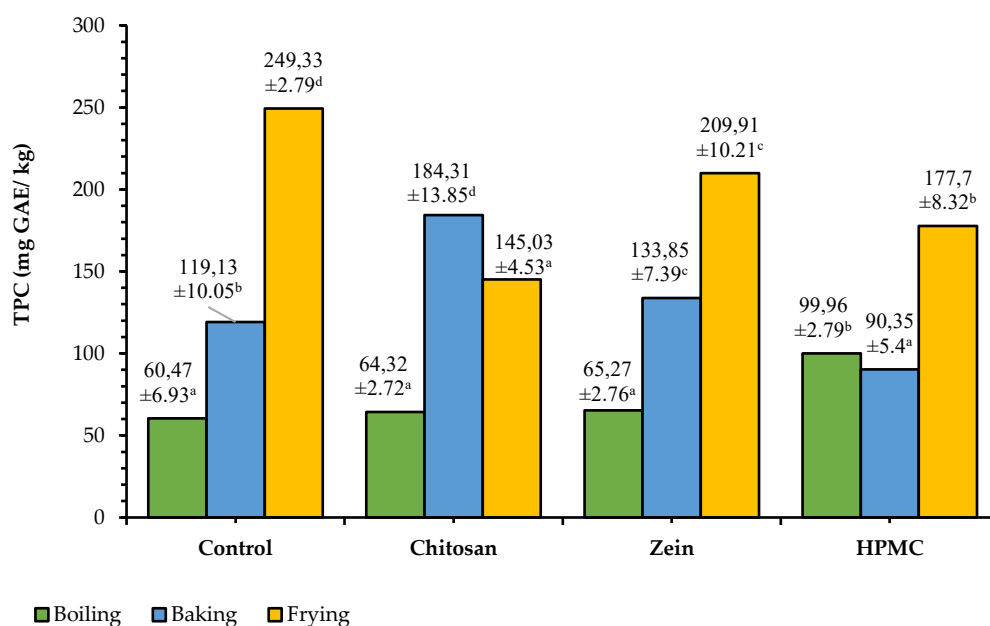


Figure 4. Total phenolic matter contents of coated (Chitosan, HPMC, Zein) and uncoated (Control) samples after frying, baking and boiling processes (* $n=3$, $\pm$ standard deviation, ^{a, b, ...} ≤ 0.05 shows the differences between groups in the same heat treatments.)

Thus, coating with film solutions may positively influence textural quality, which is advantageous for product quality. Color is an important quality parameter directly affecting product visual quality and consumer preferences. In carrots, color can deteriorate during cooking due to the oxidation of polyunsaturated compounds [31]. Cooking time, temperature, method, and pretreatments such as coating also influence color. This study investigated color changes in coated and uncoated carrot samples subjected to different cooking methods and assessed the effects of coating types.

Results showed that coating materials and cooking methods significantly affected color parameters including L^* (lightness), a^* (redness), b^* (yellowness), C^* (chroma), ΔE (total color difference), and h° (hue angle) (Table 2). L^* values range from 0 (black) to 100 (white). After frying, no significant differences were found among groups for L^* , b^* , and C^* values ($p > 0.05$). However, a^* values were lower in zein- and HPMC-coated samples, with the difference being statistically significant only in zein-coated samples ($p < 0.05$). Additionally, the highest ΔE and hue angle (h°) values were observed in the zein coating group. Kurek et al. [28] reported that coated potato samples had higher a^* values compared to controls, while b^* and ΔE values did not significantly differ.

Thermal processing can cause either decreases or increases in phenolic compound content, as reported by several researchers [32,33,34]. This may result from the degradation of phenolic compounds during heat treatment or from increased release of free flavanols [35]. This study evaluated the protective effects of coating types on phenolic compounds and antioxidants during

frying. As shown in Fig. 3, the total phenolic content (TPC) of the uncoated fried sample was 249.33 mg GAE/kg. Coated samples exhibited significantly lower TPC levels compared to the uncoated sample ($p < 0.05$). Among coatings, zein was more effective in preserving phenolic content during frying. The lowest TPC (145.03 mg GAE/kg) was measured in chitosan-coated fried samples, with the difference being statistically significant ($p < 0.05$).

A similar result was obtained for the total antioxidant content. The highest value was observed in the control sample with 52.69 $\mu\text{g/mL}$ (IC_{50}). Compared to other film coatings, zein was more effective in preserving the antioxidant capacity of carrots. However, as can be seen, the coating process was not effective in preserving the phenolic content and total antioxidant capacity during frying. Overall, all three coatings contributed to greater nutritional losses during frying, highlighting a significant drawback of the coating process.

3.2. Quality characteristics of carrots after baking

The average values of the analyses performed on baked carrot samples are presented in Table 2. As observed in the data, similar to the frying process, statistically significant differences were found among the pH values of all carrot samples after baking ($p < 0.05$). The pH values of coated samples were higher than that of the uncoated sample (4.46). Notably, the zein-coated sample exhibited the highest pH value of 5.66 after baking ($p < 0.05$).

Following the baking process, the total acidity (TA) value was found to be highest in the control sample, with a value of 0.545. Although statistically significant

Table 2. Average data of the analyzes performed on baked carrots ($n=3$)

	Control	Chitosan	Zein	HPMC
pH	4.46 ± 0.00 ^a	5.20 ± 0.00 ^b	5.66 ± 0.01 ^d	5.61 ± 0.01 ^c
TA	0.545 ± 0.010 ^d	0.273 ± 0.016 ^c	0.204 ± 0.005 ^b	0.142 ± 0.016 ^a
aw	0.987 ± 0.003 ^a	0.988 ± 0.001 ^a	0.989 ± 0.011 ^a	0.991 ± 0.002 ^a
WSDM	10.20 ± 0.85 ^a	11.40 ± 0.85 ^a	17.40 ± 0.85 ^b	10.50 ± 0.42 ^a
Texture	0.396 ± 0.122 ^a	0.511 ± 0.202 ^a	0.476 ± 0.145 ^a	0.422 ± 0.142 ^a
L^*	52.74 ± 1.99 ^a	55.57 ± 2.77 ^b	53.18 ± 1.31 ^{ab}	54.05 ± 2.03 ^{ab}
a^*	17.06 ± 2.96 ^a	17.80 ± 2.53 ^{ab}	18.34 ± 1.14 ^{ab}	20.33 ± 2.87 ^b
b^*	44.77 ± 2.00 ^a	45.20 ± 2.24 ^a	45.25 ± 2.15 ^a	50.00 ± 2.17 ^b
C^*	47.97 ± 2.41 ^a	48.60 ± 2.50 ^a	48.84 ± 1.93 ^a	53.99 ± 2.98 ^b
ΔE	0.00 ± 0.00 ^a	4.58 ± 1.74 ^b	2.85 ± 0.62 ^b	6.67 ± 3.32 ^{bc}
h^*	69.21 ± 3.14 ^a	68.53 ± 2.34 ^a	67.91 ± 1.72 ^a	67.96 ± 2.14 ^a

* $n=3$, $\pm$ standard deviation, ^{a, b, ...} ≤ 0.05 represents the differences in the same line.

differences were observed among the coated samples, the lowest TA value was measured in the HPMC-coated sample (0.142) ($p < 0.05$).

Regarding water activity (aw), no statistically significant difference was detected between coated and uncoated samples after baking; measured values ranged from 0.987 to 0.991. In terms of soluble solid content, as observed in the frying process, the highest value was recorded in the zein-coated baked sample (17.40) ($p < 0.05$). The WSDM value of the control sample was 10.20, and no significant differences were found when compared with the chitosan- and HPMC-coated samples.

Visual appearances of the coated and uncoated baked carrot samples are shown in Fig. 2. Although there was no statistically significant difference in texture values among the samples, similar to the frying results, the average texture values of the film-coated baked samples were higher than that of the control group.

According to the color analysis, the L^* value of the chitosan-coated sample was significantly higher than that of the control ($p < 0.05$), while no significant differences were observed in L^* values for zein- and HPMC-coated samples. The a^* , b^* , and C^* values were recorded as 17.06, 44.77, and 47.97 for the control, and 20.33, 50.00, and 53.99 for the HPMC-coated sample, respectively. Statistically significant differences were found among the groups for these three parameters ($p < 0.05$). The highest total color difference (ΔE) was observed in the HPMC-coated sample ($p < 0.05$), whereas hue angle (h°) values did not differ significantly among the samples.

Unlike the frying process, the baking process resulted in an increase in total phenolic content (TPC) and total antioxidant capacity for the chitosan- and zein-coated samples ($p < 0.05$) (Fig. 3 and Fig. 4). TPC values were measured as 119.13, 184.31, 133.85, and 90.35 mg GAE/kg for control, chitosan, zein, and HPMC-coated samples, respectively. These results indicate that HPMC coating had a negative effect on the phenolic content ($p < 0.05$).

Antioxidant capacity determined by the DPPH method was 12.72, 46.99, 17.79, and 8.74 $\mu\text{g/mL}$ (IC_{50}) for control, chitosan, zein, and HPMC-coated samples, respectively. These findings demonstrate that the chitosan coating was the most effective in preserving antioxidant capacity during the baking process ($p < 0.05$). On the other hand, the HPMC coating negatively affected antioxidant capacity, leading to a significant decrease compared to the control ($p < 0.05$).

These findings highlight the importance of selecting appropriate edible coatings to preserve nutritional quality during baking and indicate that chitosan and zein coatings, in particular, could be applied in the industry for baked products.

3.3. Quality characteristics of carrots after boiling

Boiling induces various chemical changes in the structure of vegetables and significantly affects key quality parameters, particularly pH and total acidity (TA) [36,37]. Cellular breakdown occurring in vegetable tissues during boiling facilitates the leaching of soluble compounds into the cooking water, which may lead to alterations in pH balance [38]. In this context, the present study evaluated the effects of different edible film coatings on the pH and TA values of boiled carrot samples.

The average results of the analyses for boiled carrots are presented in Table 3. According to the findings, the pH values of the samples coated with zein and HPMC were significantly higher than those of the control and chitosan-coated samples ($p < 0.05$). This suggests that certain coating materials may protect vegetable tissue during boiling and thus limit the loss of soluble substances. Regarding TA values, the highest value was recorded in the control sample, as observed in the baking process; however, no significant difference was found among the coated samples ($p > 0.05$).

The water activity (aw) values of the samples following the boiling process revealed no statistically significant differences between coated and uncoated groups; aw values ranged from 0.991 to 0.992 across all samples. In terms of water-soluble dry matter (WSDM) content, the highest percentage (9.30%) was observed in samples coated with chitosan and zein ($p < 0.05$). No significant difference was found between the control and HPMC-coated samples, with values measured at 7.65% and 7.35%, respectively.

Previous studies [39,40] have reported that boiling increases the loss of soluble substances in vegetables, thereby reducing WSDM content. In contrast, the current study found that chitosan and zein film coatings limited soluble matter loss during boiling, resulting in higher WSDM content compared to the control group.

Table 3. Average data for the analysis of boiled carrots ($n=3$)

	Control	Chitosan	Zein	HPMC
pH	5.75 ± 0.00 ^a	6.13 ± 0.04 ^b	6.43 ± 0.02 ^c	6.42 ± 0.01 ^c
TA	0.184 ± 0.065 ^b	0.069 ± 0.010 ^a	0.080 ± 0.016 ^a	0.076 ± 0.010 ^a
aw	0.992 ± 0.001 ^a	0.992 ± 0.001 ^a	0.991 ± 0.001 ^a	0.991 ± 0.000 ^a
WSDM (%)	7.65 ± 0.21 ^a	9.30 ± 0.42 ^b	9.30 ± 0.42 ^b	7.35 ± 0.21 ^a
Texture	0.683 ± 0.155 ^a	1.270 ± 0.356 ^b	0.951 ± 0.462 ^{ab}	1.035 ± 0.154 ^{ab}
L^*	48.63 ± 2.25 ^a	50.85 ± 1.59 ^{ab}	51.84 ± 1.36 ^{bc}	53.47 ± 2.03 ^c
a^*	18.85 ± 1.42 ^b	17.79 ± 1.50 ^{ab}	15.55 ± 3.45 ^a	19.05 ± 2.85 ^b
b^*	45.36 ± 4.44 ^a	47.16 ± 3.31 ^a	48.55 ± 1.66 ^a	53.65 ± 2.5 ^b
C^*	49.16 ± 4.22 ^a	50.42 ± 3.34 ^a	51.06 ± 2.05 ^a	56.97 ± 3.17 ^b
ΔE	00.00 ± 00.00 ^a	4.44 ± 1.79 ^b	6.25 ± 2.69 ^b	10.18 ± 2.20 ^c
h^*	67.31 ± 2.43 ^a	69.29 ± 1.57 ^{ab}	72.30 ± 3.63 ^b	70.54 ± 2.11 ^b

* $n=3$, $\pm$ standard deviation, ^{a, b, c}... ≤ 0.05 represents the differences in the same line

The barrier effect formed by the coatings restricted mass transfer, thereby mitigating the adverse effects of boiling.

Post-boiling images of coated and uncoated carrot samples are presented in Fig. 2. Texture analysis revealed that chitosan-coated samples exhibited significantly higher texture values (1.270) compared to the control group (0.683) ($p < 0.05$). Similar positive effects of film coatings on texture were also observed in the baking and frying processes. Texture is a critical quality attribute influencing flavor perception and consumer acceptance of vegetables. Abreu et al. [8] reported that cooking treatments applied to carrots result in softening and decreased firmness, a phenomenon observed across all cooking methods. Particularly during boiling, the softening of vegetable tissue due to moisture transfer leads to considerable quality loss. Therefore, applying edible film coatings prior to boiling may help preserve cellular structure, reduce textural degradation, and prevent quality deterioration [7]. Thus, coating treatments can be considered an effective pre-treatment strategy for preserving textural integrity during boiling.

The L^* value of the control sample was determined to be 48.63, which was lower than that of the other film-coated samples except for the chitosan coating ($p < 0.05$). The a^* value of zein-coated boiled carrots was significantly lower than those of the control and HPMC-coated samples ($p < 0.05$). The b^* and C^* values were recorded as 45.36 and 49.16 for the control sample and 53.65 and 56.97 for the HPMC-coated sample, respectively, with both parameters showing statistically significant differences ($p < 0.05$). As with the baking process, the greatest color difference following boiling was observed in the HPMC-coated samples. The highest h^* values were recorded in samples coated with zein and HPMC. However, there was no statistically significant difference between them and chitosan, while differences with the control were significant.

Many researchers have reported that, compared to other cooking techniques, boiling leads to greater losses in antioxidant activity, phenolic compound content, and water-soluble vitamins [39,41]. At this point, edible films may serve as a pre-treatment to help prevent the loss of phenolic and antioxidant compounds. In our study, when the total phenolic content (TPC) was evaluated after boiling, no statistically significant difference was observed between the control sample and carrots coated with chitosan or zein (Fig. 3). However, the TPC of the HPMC-coated samples was significantly higher than that of the control ($p < 0.05$). The antioxidant capacity of the zein- and HPMC-coated samples was also found to be higher compared to the control and chitosan-coated samples. The DPPH values (IC_{50}) were determined to be 5.48, 5.64, 11.59, and 6.89 $\mu\text{g/mL}$ for the control, chitosan, zein, and HPMC samples, respectively (Fig. 4).

These results suggest that edible coatings, particularly HPMC and zein, can help reduce the negative impact of boiling on phenolic compounds and antioxidant capacity. This protective effect may be particularly important in thermal processes where nutrient leaching into the cooking medium is pronounced. However, further studies are needed to clarify the underlying mechanisms and to determine whether this effect is consistent across different vegetables and processing conditions.

4. Conclusions

In this study, the effects of different edible film coatings on the physicochemical and bioactive properties of carrots were evaluated following common thermal processes such as boiling, baking, and frying. To the best of our knowledge, this is the first comparative study demonstrating how different edible coatings (chitosan, zein, HPMC) alter the physicochemical and bioactive properties of carrots under three common cooking methods. The results showed that thermal treatments caused significant changes not only in phenolic

compounds and antioxidant capacity but also in key quality parameters such as pH, total acidity (TA), water-soluble dry matter (WSDM), water activity (a_w), texture, and color. These changes highlighted the need to evaluate whether the coatings acted as a protective barrier during cooking. Coatings applied prior to boiling and baking were particularly effective in maintaining textural integrity and limiting the loss of soluble compounds.

Coatings applied prior to boiling and baking were found to be particularly effective in preserving textural integrity. It was observed that edible films generally acted as a protective barrier during cooking, thereby limiting the loss of soluble compounds. During boiling, HPMC coating resulted in a significant increase in total phenolic content (TPC), whereas in baking, chitosan and zein coatings led to significant improvements in both TPC and antioxidant capacity ($p < 0.05$). Conversely, film coatings during frying were associated with a reduction in TPC levels, with this effect being most pronounced in chitosan-coated samples.

The findings from the frying process indicate that the moisture-retention capacity of the coating materials directly influences product texture and crispness. The high-water activity and barrier properties of HPMC may hinder the formation of the desired crispy structure. Zein-coated samples, on the other hand, exhibited the highest WSDM content after frying.

During baking, zein and chitosan coatings showed positive effects on phenolic content and antioxidant capacity, while HPMC-coated samples exhibited the highest ΔE and C^* color values. In terms of texture, all coated samples across the thermal treatments demonstrated higher average texture values compared to the control group.

Overall, edible film coatings stand out as an effective pre-treatment strategy, particularly in relatively controlled thermal processes such as boiling and baking, by preserving the nutritional value and physical quality of vegetables. However, in high-temperature processes like frying, the selection of appropriate coating materials becomes critical, as it directly impacts the final product quality and should therefore be carefully considered before application. In future studies, the effects of coating materials on oil during frying and whether the product absorbs the frying oil should be further evaluated. Moreover, the impact of edible coatings on different vegetables, various thermal processing methods, and alternative coating materials should be explored to expand the applicability of these findings.

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Author contribution

The conception and design of the study, execution of the experimental procedures, interpretation of the results, and writing of the manuscript were performed by the first author. The second author contributed by conducting the experimental analyses.

Declaration of ethical code

The authors declare that this study did not require ethics committee approval and that all ethical guidelines outlined in the "Directive on Scientific Research and Publication Ethics of Higher Education Institutions" were fully adhered to.

Conflicts of interest

The authors declare that there is no conflict of interest.

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