Article

The Effect of Edible Coatings on Selected Physicochemical Properties of Cassava Chips

Diofanor Acevedo-Correa 1,* , José Jaimes-Morales 2 and Piedad M. Montero-Castillo 1

1 Grupo de Investigación en Innovación y Desarrollo Agropecuario y Agroindustrial (IDAA), Universidad de Cartagena, Campus Piedra de Bolívar, Av. Consulado, # 48-152, P.O. Box 130015 Cartagena de Indias, Colombia; pmonteroc@unicartagena.edu.co
2 Grupo de Investigación en Medio Ambiente, Alimentos y Salud (MAAS), Universidad de Cartagena, Campus de Zaragocilla, Cra. 50 #24120, P.O. Box 130015 Cartagena de Indias, Colombia; jjaimesm@unicartagena.edu.co
* Correspondence: dacevedoc1@unicartagena.edu.co

Abstract: The objective of this research was to study the effect of edible coatings on the physicochemical properties of cassava chips. The oil and moisture absorption in fried cassava chips that were not coated and in chips that were coated with pectin and whey protein films were determined using a completely randomized experiment design with a 33 factorial arrangement. The multifactorial ANOVA analysis of variance showed that all factors had significant statistical differences for moisture loss and oil absorption (p < 0.05). The coating type, the control, and the whey protein-coated chips presented a 321% greater oil content on average at 180 °C and 180 s than the pectin-coated chips. The density, heat capacity, and thermal diffusivity had statistical differences at all temperatures (p < 0.05). The sensory analysis showed that the coating type affected all sensory parameters, except crispness, as indicated by significant statistical differences (p < 0.05). The temperature only influenced the color of the control chips, with statistical differences (p < 0.05) at all temperatures.

Keywords: edible coating; cassava chips; physicochemical properties

1. Introduction

The nutritional composition of cassava is important because it is the main component of the root, which is consumed in less-developed countries. Factors associated with geographic location and environmental conditions influence the nutritional value [1]. The root contains significant amounts of carbohydrates and fiber. In addition, it has significant percentages of minerals such as calcium, iron, and phosphorus; and vitamins such as thiamine, riboflavin, niacin, and vitamin C (ascorbic acid). It also contains large amounts of amino acids such as arginine, glutamic acid, and aspartic acid [2,3]. Current cassava processing methods include peeling, smoking, drying, slicing, grating, fermenting, pressing, soaking, grinding, roasting, and frying, which are carried out to remove/reduce toxic substances, impart flavor, and increase shelf-life [4–6]. The frying method stands out. Deep-fat frying is one of the conventional and most common operations in the preparation of a variety of fried foods, which is used worldwide to create desirable flavors and textures in foods [7,8]. The advantageous sensory characteristics of most deep-fried foods derive from the formation of a composite structure that provides a crispy, porous, oily outer layer and a moist, cooked interior [9–12]. Frying is commonly used in the food industry to produce a range of food products with high consumer acceptance although high-fat contents contribute to obesity and cardiovascular disease. When food absorbs fat, it can change the composition, texture, size, and shape of the food, resulting in a loss of nutrients, specifically vitamins [13]. There is growing interest in methods that could minimize oil uptake and reduce the fat content of fried foods. Hydrocolloids have been applied indiscriminately as a food coating or incorporated into chip formulation and have shown...
promising fat reductions and moisture retention during frying [14]. Hydrocolloids are natural compounds, such as polysaccharides and proteins, which have some hydrophilic groups. They have been used as food coatings, film-forming materials, and emulsifiers. Before frying potatoes, the application of a hydrocolloid layer on the surface has been considered an effective method to prevent oil absorption and acrylamide formation [15,16].

Edible coatings are currently used as viable alternatives for frying since these substances adhere to the product and form an external barrier that prevents the absorption of fat during immersion frying processes [17]; however, these thermal processes are currently not fully controlled for temperature and processing time, which usually results in a product with inadequate sensory characteristics and a high oil content. In general, they are artisanal and inefficient, so it is not possible to have an exact control of the process variables [18]. Research by Ajo [19] reported that the application of an edible coating with xanthan gum reduced oil absorption by up to 57% and improved the overall quality of the product, including taste, flavor, and crunchiness. One of the alternatives for processing cassava is cooking it with boiling water and then frying it by immersion in oil and coating it with edible films [20] based on proteins, such as whey, isolated soybean, some carbohydrates, pectins, and hydrocolloids that have oil barrier properties [21].

This results in excessive energy and economic expense on an industrial scale and affects the low acceptability of food by consumers since the final presentation is not traditional [22]. Therefore, it is important to investigate the effects of edible coatings in reducing the absorption of oil by products during frying in order to present consumers with a quality product with adequate processing conditions that reduce fat consumption and develop more acceptable, safe, and healthy cassava products [23]. These coatings were tested on cassava chips because they have been applied on the surface of fresh, frozen, and manufactured foods to improve food quality and increase shelf-life; in addition, they present mechanical properties and a barrier to water vapor and gases [24–26]. Furthermore, coatings were applied to decrease moisture loss values during frying since properties such as crispiness are affected, which is a fundamental parameter for consumers [27,28]. Currently, research is needed to transform this product into alternatives and new presentations that allow and expand its consumption. Therefore, this study aimed to characterize the coatings and determine the effect of coatings based on pectin and whey protein on reductions in oil absorption in fried cassava chips.

2. Materials and Methods

2.1. Obtaining the Raw Material

Cassava roots (*Manihot esculenta* Crantz), variety MCol 2215, were used, which were obtained from the supply center in the city of Cartagena. Local, refined, 100% vegetable palm oil was also used.

2.2. Elaboration of the Edible Films

Pectin and Whey Protein Films

The films were prepared by slowly dispersing 4, 8, and 12 g of pectin in 400 mL of distilled water. The solution was heated to 90 °C for 10 min with constant agitation at 120 rpm. Forty milliliter aliquots were distributed in 11.8 cm diameter plates, and the films were dried at 28 °C for 48 h [22]. The whey protein films were prepared by slowly dissolving 18, 22, and 26 g of whey protein along with 6.0, 6.6, and 7.8 g of glycerol (respectively) in 140 mL of distilled water. The solutions were heated in a water bath at 90 °C for 5 min with slow agitation at 120 rpm. 20 mL aliquots were distributed in 11.8 cm diameter plates, and the films were left to dry at 28 °C for 24 h.
2.3. Characterization of Edible Coatings

2.3.1. Permeability to Water Vapor and Thickness

The water vapor permeability (WVP) was determined according to ASTM E-96 standard method 1995. The thickness of each film was evaluated using a digital micrometer, using the arithmetic mean of 10 measurements taken at random over the entire film surface.

2.3.2. Solubility in Water

The water solubility of the films was determined using the gravimetric method of Gontard et al. [29]. The films were cut in 2 cm diameter disks. The initial weight of the samples was obtained after drying for a period of 24 h at a temperature of 105 °C. After the first weighing, the samples were immersed in a container containing 50 mL of distilled water and kept at 120 rpm for 24 h. After this period, the samples were removed and dried at a temperature of 105 °C for another 24 h to obtain the final dry weight. The tests were carried out in triplicate. The water solubility (WS) was expressed with the ratio:

\[ WS = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100. \]

2.4. Experiment and Statistical Design

For the frying process, a completely randomized experiment design (DCA) was used with 3³ factorial arrangements, where the factors with their respective levels were: Temperature (140, 160, and 180 °C), time (60, 120, and 180 s), and% of coating (0%, 1% pectin, and 9% whey protein). Each run was done in triplicate, and the results were expressed as the mean and the respective standard deviation. Statistically significant differences were determined in each parameter with a completely randomized analysis of variance (ANOVA) and multiple comparisons using Tukey’s HSD test with a significance level of 5% (\( p \leq 0.05 \)). Table 1 shows the experiment treatments.

| Factor               | Level     |
|----------------------|-----------|
|                      | Low       | Central | High    |
| Type of coating (%)  | 0         | 1       | 9       |
| Time (s)             | 60        | 120     | 180     |
| Temperature (°C)     | 140       | 160     | 180     |

The responses of the experiment design were the physical-chemical parameters of moisture loss and oil absorption (Table 1).

The mathematical model of the complete experiment design with three factors (\( \alpha, \beta, \gamma \)) and the interaction is schematized in Equation (1):

\[ Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_r + (\alpha\beta)_{ij} + (\alpha\gamma)_{ir} + (\beta\gamma)_{jr} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijk} \] (1)

2.5. Frying by Immersion Process

The cassava samples were cut in cylindrical shapes (6 cm length × 3 cm diameter) and cooked for 15 min using a Laboratory Water Bath (Memmert, Germany), controlling the temperature at 100 °C ± 2 °C. For each 100 g of cassava sample, 600 mL of potable water was used. The edible coatings (1% pectin and 9% whey protein) were applied to the cassava samples with immersion. There was a control without coatings. After the coating, the samples were dried at 25 °C, weighed, and fried by immersion. For the frying process, 10 pre-cooked cassava pieces, 4 × 2 × 2 cm, were used. An electric MKE fryer (Indianapolis, Georgetown Rd, USA) with a capacity of 5 L was used, equipped with a thermostat (scale 0–300 °C) with an accuracy of ±0.1 °C. The process conditions included frying temperatures of 140, 160, and 180 °C, with times of 60, 120, and 180 s. The chips were fried in palm oil and placed in a stainless-steel basket. They were then placed in desiccators.
2.6. Thermophysical Properties

The specific heat \((C_p)\), density \((\rho)\), conductivity \((k)\), and thermal diffusivity \((\alpha)\) of the samples were determined using the methodology by Choi and Okos [30]. Systematized in a computer software called DEPROTER (Determination of Thermophysical Properties) [31].

2.7. Physicochemical Parameters

The moisture \((g\text{ water } g^{-1}\text{ dry solids})\) was determined according to official method 925.09b AOAC. 3–5 g of each sample were dried in a LT04/5 convection oven at 105 °C to constant weight. Then, to determine the fat content, the dried samples were weighed, and placed in a Soxhlet extraction equipment with petroleum ether for 8 h at 50 ± 2 °C; after the extraction, a rotary evaporator was used to evaporate the solvent from the oil. Then, the fat was obtained with gravimetry and expressed in g/100 g of dry solid according to conventional method 920.39 AOAC [32].

2.8. Sensory Evaluation

For the sensory evaluation, an untrained panel of 40 panelists was used, with an age range of 20–28 years, who were habitual consumers of cassava. They were given the fried cassava chips on a plate, in an appropriate, ventilated room with controlled temperature conditions. A five-point hedonic scale was used in which the panelists indicated their degree of acceptance for the parameters of color, odor, flavor, crispness, fat and, hardness. The scale categories ranged from 1 = I dislike it very much to 5 = I like it very much. Subsequently, the data were entered into a spreadsheet and transformed into numerical scores for analysis. Uncoated cassava chips (control) and chips coated with pectin and whey protein were tested at 140, 160, and 180 °C for 180 s, for a total of nine experiments.

3. Results

3.1. Water Vapor Permeability, Solubility and Thickness of Edible Coatings

The pectin films showed higher solubility and lower water vapor permeability and thickness than the whey protein films. Analyzing the 2 and 3% pectin films showed that they were 45.6% more permeable to water vapor than films produced with 1% pectin. Additionally, the pectin films were 68.9% less permeable to water vapor than the whey protein films. The 1% pectin films had the lowest water vapor permeability and thickness, as compared to the 2% and 3% films. In addition, the 9% whey protein films had the lowest permeation and thickness, as compared to the 11 and 13% films. The pectin coatings were totally soluble in water since, after 24 h of immersion, the films were completely solubilized (Table 2). Similar results were reported by Freitas et al. [22], who also demonstrated that pectin films were completely solubilized in water. Pectin is a highly hydrophilic polysaccharide, which rapidly disintegrates in water. Batista et al. [33] similarly stated that all coatings from fatty acids and pectin were completely soluble.

Table 2. Water permeability, solubility, and thickness of edible coatings obtained from pectin and whey protein.

| Coating     | (%) | Water Vapor Permeability (g mm/m² day kPa) | Water Solubility (%) | Thickness (mm) |
|-------------|-----|-------------------------------------------|----------------------|----------------|
| Pectin      | 1   | 1.95 ± 0.03 c                             | 100 a                | 0.025 ± 0.001 c|
|             | 2   | 2.74 ± 0.06 d                             | 100 a                | 0.052 ± 0.003 d|
|             | 3   | 2.94 ± 0.04 d                             | 100 a                | 0.068 ± 0.008 c|
|             | 9   | 6.98 ± 0.12 c                             | 30.66 ± 2.65 c       | 0.103 ± 0.001 b|
| Whey protein| 11  | 7.67 ± 0.27 b                             | 32.54 ± 2.93 c       | 0.118 ± 0.002 a|
|             | 13  | 9.88 ± 0.24 a                             | 36.32 ± 3.14 b       | 0.113 ± 0.001 a|

Different letters in the same column indicate significant statistical differences \((p < 0.05)\).

The solubility of polysaccharide coatings in water is advantageous in situations where the film is consumed with the product, causing low alterations in the sensory properties.
of the food. The coatings obtained from pectin showed less permeation than with whey, which was not very resistant to water vapor, mainly because of the material’s porosity, that is, coatings obtained from whey protein were more porous than those from pectin; this difference was statistically significant and could be related to the thickness of the coatings.

The lower water vapor permeability of the pectin-based coatings could be explained by the lower thickness of the coatings, as compared to the whey protein coatings [34]. Matching results were obtained by Freitas et al. [22], who used pectin and whey protein coatings. A possible explanation for the increased permeability of edible coatings made from whey in this study could be the denaturation of the proteins under the temperature conditions used for their processing, i.e., when the protein was disrupted, it was denatured; the polar amino acids were possibly exposed, which increased the absorption of water.

3.2. Moisture Loss and Fat Absorption

Table 3 shows the multifactorial ANOVA analysis of variance for cassava chips processed with different coatings, frying times, and temperatures. In general, all factors had significant statistical differences for moisture loss \( (p < 0.05) \). Analyzing the coating type showed a statistically significant effect \( (p < 0.05) \) on the cassava chips; that is, the coating type had an influence on this parameter. The same phenomenon was observed at different temperatures \( (p < 0.05) \). Time, on the other hand, did not present statistical differences at 120 and 180 s; that is, the additional time did not affect the increase in the loss of this parameter. Significant statistical differences \( (p < 0.05) \) were only observed with the shortest process time (60 s), rather than the other two times (120 and 180 s).

### Table 3. Influence of coating type, time, and temperature on moisture loss of cassava chips.

| Factor         | \( p \)-Value | Contrast   | +/- Limits | Difference |
|----------------|--------------|------------|------------|------------|
| Type of coating| Control \( ^b \) | C–P 2.05573 | –18.2856 \* |            |
|                | Pectin \( ^a \) | C–WP 2.05573 | 4.40333 \* |            |
|                | Whey protein \( ^c \) | P–WP 2.05573 | 22.6889 \* |            |
|                | 60 \( ^a \) | 60–120 2.18411 | 6.06 \* |            |
|                | 120 \( ^b \) | 120–180 2.18411 | 7.93444 \* |            |
|                | 180 \( ^b \) | 140–160 2.86906 | 9.78889 \* |            |
|                | 140 \( ^a \) | 140–180 2.86906 | 14.1189 \* |            |
| Temperature (\( ^\circ \)C) | 160 \( ^b \) | 160–180 2.86906 | 4.33 \* |            |

\* Different letters for the same factor in the same column indicate statistical differences.

During the chip frying, statistical differences were observed at 60 s for the control sample at all temperatures and at 180 s for the control and whey protein-coated chips \( (p < 0.05) \). In the first 60 s of processing time, no statistical differences were observed at temperatures of 160 °C 180 °C. The same was observed at 120 s in the pectin-coated chips and the control chips; on the other hand, at 180 s, statistical differences were observed in the control sample and the whey protein-coated chips \( (p < 0.05) \). When comparing the uncoated fried samples, the pectin coating treatment decreased the moisture loss of the fried chips by 44.55% at 180 °C and 60 s (Figure 1). The differences in fat and moisture content between the uncoated (control) and coated fried samples were possibly due to the replacement of water by oil after the evaporation process during frying [35]. Evaporation of water by heat transfer during a frying process creates empty spaces in the food that are filled with oil, increasing the oil content of the fried food [36].
Moisture loss during frying of cassava chips at different temperatures and times: The first column indicates the control sample (C), the second column indicates that pectin (P) was used, and the third column indicates that whey protein (WP) was used. Different letters indicate statistical differences (p < 0.05) for the same frying time at different temperatures.

These results can be attributed to the fact that pectins in the outer layer of the samples possibly acted as a protective barrier that closed the pores of the product and prevented water from escaping as steam during the heat treatment, thus preventing the absorption of oil. These results are very important since they can help keep products in good condition in terms of moisture and oil. It is interesting to note that the samples coated with whey protein had a 452% higher oil content than the samples coated with pectin and fried at 160 °C for 60 s (Figure 2), which indicates that this coating was not effective in preventing the product from absorbing oil during and after the immersion frying process.

Figure 1. Moisture loss during frying of cassava chips at different temperatures and times: The first column indicates the control sample (C), the second column indicates that pectin (P) was used, and the third column indicates that whey protein (WP) was used. Different letters indicate statistical differences (p < 0.05) for the same frying time at different temperatures.

Figure 2. Fat absorption during cassava chip frying at different temperatures and times: The first column indicates the control sample (C), the second column indicates that pectin (P) was used, and the third column indicates that whey protein (WP) was used. Different letters indicate statistical differences (p < 0.05) for the same frying time at different temperatures.
In general, the analyses indicated that the cassava chip samples that were treated for a longer time in both the control and the whey protein coatings obtained higher percentages of oil and lower moisture contents (Figures 1 and 2). These results were similar to those reported by Tirado et al. [37] in the immersion frying of tilapia slices and by Alvis et al. [34] during the atmospheric frying of sweet potato slices coated with carboxymethyl cellulose (CMC), where longer processing times meant heat-treated matrices absorbed more oil.

The edible coating containing 1% pectin retained the most moisture in the fried samples. In other words, the use of an edible coating retains moisture in fried foods. The coating can form barriers that prevent moisture loss and reduce fat absorption [38].

The net formed by the pectin edible coating prevented moisture from escaping, thus retaining a higher moisture content in coated samples than in uncoated ones (control) [39].

Table 4 shows the influence of the coating type and frying time and temperature on the oil absorption of the cassava chips. All factors had an influence on the oil absorption of the chips, which was corroborated by the multifactorial ANOVA analysis of variance. For the coating type, significant statistical differences ($p < 0.05$) were observed for oil absorption. The same behavior occurred for frying time and temperature, observing differences between chips coated with pectin and whey protein and the control.

Table 4. Influence of coating type, time, and temperature on oil absorption in cassava chips.

| Factor               | p-Value | Contrast | +/- Limits | Difference |
|----------------------|---------|----------|------------|------------|
| Type of coating      |         |          |            |            |
| Control             | $^a$    | C–P      | 0.334673   | 2.8263 *   |
| Pectin              | $^c$    | C–WP     | 0.334673   | 0.413333   |
| Whey protein        | $^b$    | P–WP     | 0.334673   | −2.41296 * |
| 60 $^c$             |         | 60–120   | 1.6305     | −0.335556 *|
| 120 $^b$            | 0.0000  | 120–180  | 1.6305     | −1.00815 * |
| 180 $^a$            |         | 180–120  | 1.6305     | −0.672593 *|
| Temperature (°C)    |         |          |            |            |
| 140 $^c$            | 0.0000  | 140–160  | 0.820096   | −0.818889  |
| 160 $^b$            |         | 160–180  | 0.820096   | −1.60074 * |
| 180 $^a$            |         | 180–120  | 0.820096   | −0.782222 *|

* Different letters for the same factor in the same column indicate statistical differences.

When analyzing the oil absorption at 60 s, no statistical differences were observed in the whey protein coated chips, but differences were observed in the pectin-coated chips at 180 °C and in the control at 140 °C ($p < 0.05$) (Table 3). At 120 s, the most representative differences were evidenced in the control at all process temperatures; this was also observed at 180 s in the pectin-coated chips, the control, and the whey protein-coated chips at different temperatures. When analyzing coating type, the control and whey protein-coated chips presented 321% more oil content on average at 180 °C and 180 s than the pectin-coated chips (Figure 2).

On the other hand, Freitas et al. [22] investigated the influence of the use of edible coatings from three different hydrocolloids (pectin, whey protein, and soy protein isolate) during the frying of a pre-fried and frozen cassava product. They demonstrated that whey protein showed the best results with respect to fat absorption, with a 27% reduction for the mashed cassava product. The uncoated cassava chips contained the highest oil content, 52.36%. Like the coated cassava chips with a 1% pectin concentration, the oil content of the cassava chips was reduced to 22.31%. The cassava chips treated with a 3% pectin concentration solution had the best or lowest lipid content, 11.75%, where the reduction was up to 40% for the lipid content. This possibly occurred because, during water evaporation, the vapor pressure of water increases the moisture transfer, increasing the porosity of the coating and oil ingress. In addition, high temperatures modify the structure of the material, causing damage to the coating during frying.

Also, Dragich and Krochta [40] stated that chicken strips coated with 10% denatured whey protein isolate (DWPI) resulted in a surprising 30.68% reduction in fat absorption, as compared to a non-whey protein coating. The DWPI solution possibly dehydrated during the frying process to form a film on the outer surface of the coated chicken strips.
Mechanisms that are independent of or in addition to the formation of the barrier film or a possible increase in interfacial tension between chicken with a DWPI solution surface coating and the frying oil may have been responsible for the reduction in fat absorption. Different results were obtained by Aminlari et al. [41] with the application of whey protein on potato slices, resulting in a 5% reduction in fat absorption. The rate of oil absorption can be affected by changes in interfacial tension through the accumulation of surfactants in the frying oil. The formulation may alter the water holding capacity and consequently affect oil absorption. As a result of the strong hydrogen bonding between water molecules with hydrophilic materials, the displacement of water by oil/fat during the frying process is restricted.

3.3. Thermophysical Properties of the Cassava Chip Control

In general, both the thermal conductivity and diffusivity increased with processing temperature (Table 5), which was due to the fact that the food material conducted heat better, possibly because a temperature increase resulted in dehydration of the product and therefore faster heating. The density, heat capacity, and thermal diffusivity showed statistical differences at all temperatures ($p < 0.05$), indicating that this variable had an effect on these thermal properties. The conductivity increased with increasing temperatures, but no significant statistical differences were observed, which is why temperature had no effect on this parameter [42]. This property is related to the decrease in moisture loss. Sahin et al. [43] stated that the thermal conductivity of food materials depends on porosity, structure, and chemical constituents.

| Property          | Units   | 25 °C   | 140 °C  | 160 °C  | 180 °C  |
|-------------------|---------|---------|---------|---------|---------|
| Conductivity      | W/m °C  | 0.47 ± 0.07 $^a$ | 0.48 ± 0.06 $^a$ | 0.49 ± 0.27 $^a$ | 0.53 ± 0.19 $^a$ |
| Density           | Kg/m³   | 1043.11 ± 0.52 $^d$ | 1120.38 ± 0.33 $^c$ | 1124.73 ± 0.9 $^b$ | 1138.44 ± 0.16 $^a$ |
| Heat capacity     | J/Kg °C | 3111.84 ± 0.41 $^d$ | 3118.66 ± 0.98 $^c$ | 3155.75 ± 0.76 $^b$ | 3176.86 ± 0.24 $^a$ |
| Thermal Diffusivity | m²/s   | 1.09 × 10⁻⁷ ± 0.30 $^d$ | 1.38 × 10⁻⁷ ± 0.10 $^c$ | 1.58 × 10⁻⁷ ± 0.67 $^b$ | 1.69 × 10⁻⁷ ± 0.66 $^a$ |

Letters in the same row at different temperatures for each property indicate significant statistical differences ($p < 0.05$).

Several researchers have confirmed that thermophysical properties are important parameters in the description of heat transfer during the heating of solid foods, providing great advantages for information gathering, especially for energy costs and quality assurance in different products [31,44]. It was observed that temperature significantly ($p < 0.05$) affected density, a result that may be related to moisture loss and oil absorption. It was also observed that temperature had a significant influence ($p < 0.05$) on heat capacity and thermal diffusivity. These two thermal properties increased with increasing temperatures. The results of this study were different from those reported by Sosa-Morales et al. [45] during the frying of pork meat, who stated that heat capacity and thermal diffusivity decreased with increasing frying time because of moisture loss.

3.4. Sensory Analysis

Table 6 shows that the coating type affected all sensory parameters, except crispness, which was corroborated by the significant statistical differences ($p < 0.05$). It was also evidenced that temperature only had an influence on the color of the control chips, with statistical differences ($p < 0.05$) at all temperatures.

When analyzing the color of the cassava chips, the highest scores for this parameter were observed at intermediate temperatures (160 °C) with pectin coatings; statistical differences were also observed ($p < 0.05$), this same result was evidenced in the odor (Table 7), which is a parameter that produces a sensation because of volatile substances. At a temperature of 140 °C, no statistical differences were observed in the odor of the cassava chips, and the lowest scores were obtained with the whey protein coated chips. No statistical differences in chip flavor were observed at temperatures of 140 °C and 180 °C;
however, higher scores were observed at 160 °C with the uncoated chips. The greasiness did not show significant differences between the three temperature groups. The crispness of the cassava chips showed significant statistical differences $(p < 0.05)$ at 180 °C between the control and the pectin-coated chips, and both coatings had differences $(p < 0.05)$. The hardness had statistical differences $(p < 0.05)$ at 140 °C between the pectin-coated chips and the other treatments. No statistical differences were observed between the control and the whey protein coated chips. The same results were observed at 180 °C. At 160 °C, no significant statistical differences were observed (Table 7).

**Table 6.** Influence of coating type and temperature on sensory parameters of cassava chips.

| Type of coating | p-Value | Color | p-Value | Odor | p-Value | Flavor | p-Value | Greasiness | p-Value | Crispness | p-Value | Hardness |
|-----------------|---------|-------|---------|------|---------|--------|---------|------------|---------|-----------|---------|----------|
| Control         | 0.0000  | C a   | 0.0012  | P a  | 0.0003  | P b    | 0.0268  | C b        | 0.3574  | C a       | 0.0001  | C b      |
| Whey protein    |         |       |         |      |         | WP a   |         |            |         |           | WP b    | WP b     |
| Pectin          |         |       |         |      |         | WP b   |         |            |         |           | WP b    | WP b     |

Different letters in the same column for each factor indicate significant statistical differences. Control chips (C), pectin-coated chips (P), and whey protein chips (WP).

**Table 7.** Sensory analysis of control cassava chips coated with pectin and whey protein at different frying temperatures.

| Experiments | Sensory Parameters |
|-------------|--------------------|
| T (°C)      | Coating            | Color | Odor | Flavor | Greasiness | Crispness | Hardness |
| 1 140 180   | Control            | 3.59 ± 0.58 a | 3.86 ± 0.78 a | 3.74 ± 0.38 a | 3.73 ± 0.65 a | 3.67 ± 0.52 a | 3.02 ± 0.34 b |
| 2 140 180   | Pectin             | 4.54 ± 0.23 a | 3.76 ± 0.35 a | 3.61 ± 0.38 a | 4.09 ± 0.84 a | 3.59 ± 0.58 a | 4.34 ± 0.37 b |
| 3 140 180   | Whey protein       | 3.67 ± 0.52 b | 3.62 ± 0.51 a | 3.47 ± 0.45 a | 3.86 ± 0.22 a | 4.14 ± 0.43 a | 3.37 ± 0.28 a |
| 4 160 180   | Control            | 3.65 ± 0.43 b | 4.52 ± 0.37 b | 4.78 ± 0.19 a | 3.62 ± 0.36 a | 3.72 ± 0.88 a | 3.74 ± 0.44 a |
| 5 160 180   | Pectin             | 4.48 ± 0.25 a | 4.08 ± 0.64 a | 4.21 ± 0.53 a | 4.44 ± 0.42 a | 4.34 ± 0.28 a | 4.02 ± 0.34 a |
| 6 160 180   | Whey protein       | 3.25 ± 0.26 b | 3.67 ± 0.56 b | 2.27 ± 0.77 b | 3.83 ± 0.36 a | 3.92 ± 0.44 a | 3.85 ± 0.31 b |
| 7 180 180   | Control            | 3.48 ± 0.57 a | 3.92 ± 0.84 ab | 4.13 ± 0.55 a | 3.83 ± 0.36 a | 3.85 ± 0.11 b | 3.12 ± 0.73 b |
| 8 180 180   | Pectin             | 4.45 ± 0.37 a | 4.43 ± 0.56 a | 4.00 ± 0.34 a | 4.69 ± 0.20 a | 4.27 ± 0.25 a | 4.83 ± 0.11 a |
| 9 180 180   | Whey protein       | 2.13 ± 0.94 b | 3.09 ± 0.47 b | 3.46 ± 0.66 b | 3.93 ± 0.74 b | 3.86 ± 0.26 b | 3.77 ± 0.45 b |

Different letters in the same column indicate statistical differences between the three coatings tested at each temperature.

In the case of color, higher scores (4.54) were observed at intermediate temperatures (160 °C) (Table 7). The coating favored browning and coloring reactions in the cassava chips. Similar results were obtained by Muhamad and Shaharuddin [46], indicating that chips coated with 2% pectin had the highest score for this parameter; the pectin coating did not change the initial color during frying of the cassava chips, and the characteristic golden color of the chips can be attributed to non-enzymatic browning of the starch. On the other hand, the best rating for odor (4.52) was in the control samples, which was possibly due to the fact that, under these conditions, the chemical components responsible for flavor were enhanced, which was also found by Aguirre et al. [47] in chips of different banana varieties.

Regardless of the type of coating used and the temperature applied, higher greasiness acceptance was observed in those samples coated with pectin, with higher scores at 180 °C; i.e., at higher temperatures, the oil absorption in the cassava chips was reduced. Muhamad and Shaharuddin [47] found that pectin-coated cassava chips samples absorbed less oil than uncoated chips. The substantial reduction in oil absorption can be attributed mainly to the barrier properties because coatings make the surface stronger and more brittle, with fewer small pores, which reduces evaporation and leads to less fat absorption. The crispness did not present statistical differences $(p < 0.05)$ in any of the treatments.

**4. Conclusions**

The pectin films showed higher solubility and lower water vapor permeability and thickness than the whey protein films. Moreover, the pectin films were 68.9% less water vapor permeable than the whey protein films. All factors influenced the moisture loss and oil absorption of the cassava chips. When analyzing the coating type, the control and whey
protein-coated chips presented a 321% greater oil content on average at 180 °C and 180 s than the pectin-coated chips. The thermal properties were affected by process temperatures, except for conductivity. The sensory analysis showed that the coating type affected all sensory parameters, except crispness. Temperature only had an effect on the color of the control chips. It would be interesting to conduct future studies using vacuum frying, with different hydrocolloids and oils, to further study the physicochemical properties of cassava chips.

Author Contributions: D.A.-C. methodology, formal analysis, writing—original draft preparation. J.J.-M. validation, formal analysis, writing—original draft preparation. P.M.M.-C. supervision, software, writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support this study are available from the corresponding author.

Acknowledgments: In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Bayata, A. Review on Nutritional Value of Cassava for Use as a Staple Food. Sci. J. Anal. Chem. 2019, 7, 83–91. [CrossRef]
2. Gil, J.L.; Buitrago, A.J.A. La yuca en la alimentación animal. In La Yuca en el Tercer Milenio: Sistemas Modernos de Producción, Procesamiento, Utilización y Comercialización, 1st ed.; Ospina, B., Ceballos, H., Alvarez, E., Bellotti, A.C., Lee, C., Arias, B., Cadavid, L.F., Pineda, B., Llano, G.A., Eds.; CIAT: Cali, Colombia, 2002; Volume 1, pp. 527–569.
3. Tewe, O.O.; Lutaladio, N. The Global Cassava Development Strategy. Cassava for Livestock Feed in Sub-Saharan Africa, 1st ed.; FAO: Rome, Italy, 2004; pp. 55–57.
4. Nambisan, B.; Sundaresan, S. Effect of processing on the cyanoglucoside content of cassava. J. Sci. Food Agric. 1985, 36, 1197–1203. [CrossRef]
5. Oyewole, O.B. Cassava processing in Africa. In Application of Biotechnology in Traditional Fermented Foods. Report of an Ad-hoc Panel of the Board on Science and Technology for International Development, 1st ed.; Office of International Affairs National Research Council; National Academies Press: Washington, DC, USA, 1992; pp. 89–92.
6. Sukara, E.; Hartati, S.; Ragamustari, S.K. State of the art of Indonesian agriculture and the introduction of innovation for added value of cassava. Plant Biotechnol. Rep. 2020, 14, 207–212. [CrossRef]
7. Bouchon, P.; Aguilera, J.M.; Pyle, D.L. Structure oil absorption relationships during deep-fat frying. J. Food Sci. 2003, 68, 2711–2716. [CrossRef]
8. Zamani-Ghalehshahi, A.; Farzaneh, P. Effect of hydrocolloid coatings (Basil seed gum, xanthan, and methyl cellulose) on the mass transfer kinetics and quality of fried potato strips. J. Food Sci. 2021. [CrossRef]
9. Moreira, R. Deep fat frying. In Heat Transfer in Food Processing: Recent Developments and Applications, 1st ed.; Yanniots, S., Sunden, B., Eds.; WIT Press: Boston, MA, USA, 2007; pp. 209–236.
10. Asokapandian, S.; Swamy, G.J.; Hajjul, H. Deep fat frying of foods: A critical review on process and product parameters. Crit. Rev. Food Sci. Nutr. 2020, 60, 3400–3413. [CrossRef]
11. Liu, Y.; Sun, L.; Bai, H.; Ran, Z. Detection for Frying Times of Various Edible Oils Based on Near-Infrared Spectroscopy. Appl. Sci. 2020, 10, 7789. [CrossRef]
12. Kita, A.; Nowak, J.; Michalska-Ciechanowska, A. The Effect of the Addition of Fruit Powders on the Quality of Snacks with Jerusalem Artichoke during Storage. Appl. Sci. 2020, 10, 5603. [CrossRef]
13. Marciniak-Lukasiak, K.; Zbikowska, A.; Marzec, A.; Kozlowska, M. The Effect of Selected Additives on the Oil Uptake and Quality Parameters of Fried Instant Noodles. Appl. Sci. 2019, 9, 936. [CrossRef]
14. Lumanlan, J.C.; Fernando, W.M.A.D.B.; Jayasena, V. Mechanisms of oil uptake during deep frying and applications of predrying and hydrocolloids in reducing fat content of chips. Int. J. Food Sci. Technol. 2020, 55, 1661–1670. [CrossRef]
15. Clemens, R.A.; Pressman, P. Food gums: An overview. Nutr. Today 2017, 52, 41–43. [CrossRef]
16. Al-Asmar, A.; Naviglio, D.; Giosafatto, C.V.L.; Mariniello, L. Hydrocolloid-based coatings are effective at reducing acrylamide and oil content of French fries. *Coatings* 2018, 8, 147. [CrossRef]

17. Jiang, Y.; Qin, R.; Jia, C.; Rong, J.; Hu, Y.; Liu, R. Hydrocolloid effects on Nε-carboxymethyllysine and acrylamide of deep-fried fish nuggets. *Food Biosci.* 2021, 39, 100799. [CrossRef]

18. Devi, S.; Zhang, M.; Law, C.L. Effect of ultrasound and microwave assisted vacuum frying on mushroom (*Agaricus bisporus*) chips quality. *Food Biosci.* 2018, 25, 111–117. [CrossRef]

19. Ajo, R.Y. Application of hydrocolloids as coating films to reduce oil absorption in fried potato chip-based pellets. *Pak. J. Nutr.* 2017, 16, 805–812. [CrossRef]

20. Kurek, M.; Šeter, M.; Galić, K. Edible coatings minimize fat uptake in deep fat fried products: A review. *Food Hydrocoll.* 2017, 71, 225–235. [CrossRef]

21. Bouchon, P. Understanding oil absorption during deep-fat frying. In *Advances in Food and Nutrition Research*, 1st ed.; Toldra, F., Ed.; Academic Press: Cambridge, UK, 2009; Volume 57, pp. 209–234.

22. Freitas, D.D.G.C.; Berbari, S.A.G.; Prati, P.; Fakhouri, F.M.; Queiroz, F.P.C.; Vicente, E. Reducing fat uptake in cassava products during deep-fat frying. *J. Food Eng.* 2009, 94, 390–394. [CrossRef]

23. Lucas, J.C.; Quintero, V.D.; Leal, J.F.V.; Nuñez, L.C. Evaluación de los parámetros de calidad durante la fritura de rebanadas de papa criolla. *Sci. Technol.* 2011, 2, 299–304. [CrossRef]

24. Varela, P.; Fiszman, S.M. Hydrocolloids in fried foods. A review. *Food Hydrocoll.* 2011, 25, 1801–1812. [CrossRef]

25. Campos, C.A.; Gerschenson, L.N.; Flores, S.K. Development of edible films and coatings with antimicrobial activity. *Food Bioprocess Technol.* 2011, 4, 849–875. [CrossRef]

26. Porta, R.; Mariniello, L.; Di Pierro, P.; Sorrentino, A.; Giosafatto, C.V.L. Transglutaminase crosslinked pectin and chitosan-based edible films: A review. *Crit. Rev. Food Sci. Nutr.* 2011, 51, 223–238. [CrossRef] [PubMed]

27. Falguera, V.; Quintero, J.P.; Jiménez, A.; Muñoz, J.A.; Ibarz, A. Edible films and coatings: Structures, active functions and trends in their use. *Trends Food Sci. Technol.* 2011, 22, 292–303. [CrossRef]

28. Marquez, G.R.; Di Pierro, P.; Esposito, M.; Mariniello, L.; Porta, R. Application of transglutaminase-crosslinked whey protein/pectin films as water barrier coatings in fried and baked foods. *Food Bioprocess Technol.* 2014, 7, 447–455. [CrossRef]

29. Gontard, N.; Guilbert, S.; CUQ, J.L. Edible wheat gluten films: Influence of the main process variables on film properties using response surface methodology. *J. Food Sci.* 1992, 57, 190–195. [CrossRef]

30. Choi, Y.; Okos, M. Effects of temperature and composition on the thermal properties of foods. *J. Food Process Appl.* 1986, 1, 93–101.

31. Alvis, A.; Caicedo, I.; Peña, P. Determinación de Propiedades Termofísicas de Alimentos en Función de la Concentración y la Temperatura empleando un Programa Computacional. *Inf. Technol.* 2012, 23, 111–116. [CrossRef]

32. Association International of Analytical Chemists. *Official Methods of Analysis*, 18th ed.; Horwitz, W., Ed.; AOAC International: Gaithersburg, MD, USA, 2005.

33. Batista, J.A.; Tanada-Palmu, P.S.; Grosso, C.R.F. Efeito da adição de ácidos graxos em filmes à base de pectina. *Ciênc. Tecnol. Aliment.* 2005, 25, 781–788.

34. Alvis, A.; González, A.; Arrázola, G. Efecto del Recubrimiento Comestible en las Propiedades de Trozos de Batata (Ipomoea Batatas Lam) Fritos por Inmersión, Parte 2: Propiedades Termofísicas y de Transporte. *Inf. Technol.* 2015, 26, 103–116. [CrossRef]

35. Khazaei, N.; Esmaili, M.; Emam-Djomeh, Z. Effect of active edible coatings made by basal seed gum and thymol on oil uptake and oxidation in shrimp during deep-fat frying. *Carbohydr. Polym.* 2016, 137, 249–254. [CrossRef]

36. Kim, D.N.; Lim, J.; Bae, I.Y.; Lee, H.G.; Lee, S. Effect of hydrocolloid coatings on the heat transfer and oil uptake during frying of potato strips. *J. Food Eng.* 2011, 102, 317–320. [CrossRef]

37. Tirado, D.; Acevedo, D.; Montero, P. Transferencia de Calor y Materia durante el Freído de Alimentos: Tilapia (*O. niloticus*) y Fruta de Pan (*Artocarpus communis*). *Inf. Technol.* 2015, 26, 85–94. [CrossRef]

38. Singthong, J.; Thongkaew, C. Using hydrocolloids to decrease oil absorption in banana chips. *LWT Food Sci. Technol.* 2009, 42, 1199–1203. [CrossRef]

39. Ananey-Obiri, D.; Matthews, L.; Tahergorabi, R. Chicken processing by-product: A source of protein for fat uptake reduction in deep-fried chicken. *Food Hydrocoll.* 2020, 101, 105500. [CrossRef]

40. Dragich, A.M.; Krochta, J.M. Whey protein solution coating for fat-uptake reduction in deep-fried chicken breast strips. *J. Food Sci.* 2010, 75, S43–S47. [CrossRef]

41. Aminlari, M.; Ramezani, R.; Khalili, M.H. Production of protein-coated low-fat potato chips. *Food Sci. Technol. Int.* 2005, 11, 177–181. [CrossRef]

42. Ziaiifar, A.M.; Heyd, B.; Courtois, F. Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep-fat frying using a modified Lees method. *J. Food Eng.* 2009, 95, 373–378. [CrossRef]

43. Sahin, S.E.R.P.L.; Sastry, S.K.; Bayindirli, L. Heat transfer during frying of potato slices. *LWT Food Sci. Technol.* 1999, 32, 19–24. [CrossRef]

44. Arrazola, G.; Paez, M.; Alvis, A. Composición, Análisis termofísico y análisis sensorial de frutos colombianos: Parte 1: Almendro (*Terminalia Catappa L.*). *Inf. Technol.* 2014, 25, 17–22. [CrossRef]

45. Sosa-Morales, M.E.; Orzuna-Espiritu, R.; Vélez-Ruiz, J.F. Mass, thermal and quality aspects of deep-fat frying of pork meat. *J. Food Eng.* 2006, 77, 731–738. [CrossRef]
46. Muhamad, I.I.; Shaharuddin, S. Evaluation on Quality Attributes of Pectin Coated-Cassava Chips. *Mater. Today* **2019**, *19*, 1473–1480. [CrossRef]

47. Aguirre, J.C.L.; Castaño, V.D.Q.; Leal, J.F.V.; Artamonov, J.D.M. Evaluación de los parámetros de calidad de chips en relación con diferentes variedades de plátano (*Musa paradisiaca* L.). *Rev. Lasallista* **2012**, *9*, 65–74.