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ORIGINAL PAPER

Assessment of hydrocolloid coating variations on cassava stick characteristics using a two-stage nested design

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Abstract
In Indonesia, cassava roots rank as the third most consumed staple food and are often processed into fried cassava sticks. However, frying increases fat content, posing health concerns. Hydrocolloid coatings, such as hydroxypropyl methylcellulose (HPMC) and xanthan gum, offer a promising strategy to reduce oil absorption during frying. While many studies have examined these coatings individually, limited research has addressed the combined influence of hydrocolloid type and concentration. This study assessed the effects of hydrocolloid concentration nested within hydrocolloid types on cassava stick characteristics. To ensure coating consistency, the effects of immersion time, stick dimension, and frying temperature on moisture content and oil absorption were also analyzed. Immersion time significantly influenced both parameters, with 10-minute immersion yielding optimal moisture retention and reduced oil absorption. In contrast, stick dimension and frying temperature had no significant effect ($P>0.05$). Hydrocolloid type significantly affected most parameters, except pre-fried moisture ($P=0.138$) and colour ($P\geq0.132$), while concentration significantly influenced all parameters except redness in fried samples ($P=0.999$). High statistical power (≥0.800) was observed for fried moisture content, oil absorption, crude fat content, and hardness. Xanthan gum was more effective than HPMC in retaining moisture (37.92% vs. 36.71%), reducing oil absorption (26.92% vs. 28.76%), and producing softer texture (0.99 kg vs. 1.10 kg). Increasing hydrocolloid concentration reduced lightness and yellowness but had minimal impact on redness. These findings support the use of hydrocolloid coatings to develop healthier fried cassava products with optimized texture, reduced fat content, and improved quality through controlled processing variables.

Keywords Cassava stick · Hydroxypropyl Methylcellulose · Xanthan gum · Two-stage nested design

Introduction

Cassava roots (*Manihot esculenta* Crantz) serve as a staple food, providing carbohydrates and energy to over two billion individuals globally, especially in Sub-Saharan Africa and in developing countries in Asia [1, 2]. In Indonesia, cassava roots rank as the third staple food after rice and corn [3]. Cassava roots can be processed in various ways (steamed, boiled, and fried) to produce traditional Indonesian foods such as *tapai*, *gethuk*, *gaplek*, *tiwul*, and *gatot* [4]. Cassava roots can also be processed into cassava sticks with characteristics similar to French fries. Frying plays a crucial role in transforming cassava roots into moist and tender cassava sticks with a porous, crunchy crust. During the frying process, water escapes from the crust and causes the formation of a weakened crust with empty pores that are free to be filled with the fat that migrates from the frying medium [5, 6]. This frying process may result in a significant increase in fat content, occasionally amounting to one-third of the total weight of the product [6, 7]. The increased fat content in fried cassava sticks may lead to adverse health consequences, specifically, an increased risk of obesity, elevated cholesterol levels, and coronary heart disease [8, 9].

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A recent study by Wan et al. (2024) found that consuming fried foods more frequently (≥ 1.5 servings per day) significantly increased the hazard ratio for obesity and abdominal obesity to 1.41 and 1.38, respectively, compared to non-consumption [10]. Among various fried products, individuals with the highest consumption of high-starch fried foods exhibited a 45% higher risk of obesity and a 49% higher risk of abdominal obesity [10].

According to Mellema (2003), various techniques have been demonstrated to reduce oil absorption in fried food, and one of these approaches involves the application of edible coatings [6]. The most important function of edible coatings in fried food is to inhibit oil absorption and prevent the migration of water to and from the fried food [11]. Hydrocolloids stand out as the mainly used materials for edible coating in fried food due to their ability to act as a lipid barrier by forming an invisible and tasteless thin film [11]. Hydrocolloid coatings enhance the surface properties of fried products by making them stronger and more brittle with fewer voids, thereby reducing surface permeability and preventing the replacement of evaporated water with oil during frying [11, 12]. Moreover, hydrocolloids can also inhibit oil migration into and water migration out of fried food by altering surface hydrophobicity through their thermogelling properties [11, 13]. Hydrocolloids such as hydroxypropyl methylcellulose (HPMC) and xanthan gum are commonly used as coating materials and have been proven to significantly reduce oil absorption in various fried products, particularly high-starch fried products (French fries, potato strips, and potato balls) [14–17].

While most of the prior studies have focused on examining the impact of each HPMC and xanthan gum on the characteristics of the resulting fried foods, the influence of variations between types of hydrocolloids with diverse concentrations on fried food characteristics has yet to be extensively studied. Variability in sample treatment might affect the quality of final products and their commercial value. In order to assess the effect of variability on sample properties, a statistical design such as a two-stage nested design can be applied. This statistical design is referred to as a multifactor assessment that has a hierarchical structure, where the levels of one factor (factor B) are nested under the levels of another similar but not identical factor (factor A) [18–20]. The variability introduced at each hierarchy layer is evaluated compared to the layer below it [21].

Studies regarding the application of nested design to assess the influence of treatment variations on food products are still limited. Hence, this study was conducted to assess the effects of different concentrations (factor B) nested within hydrocolloid types (factor A) on the characteristics of cassava sticks. To ensure the reliable application of the hydrocolloid coating, additional evaluations of immersion time, stick dimension, and frying temperature were conducted to minimize potential variability unrelated to hydrocolloid factors. The characteristics measured were moisture content, oil absorption, crude fat content, hardness, and colour properties of the samples. Furthermore, a PCA plot was also performed to understand the nested relationship between factors. This study will likely provide information about using nested design to assess the quality of the final product, specifically high-starch fried food.

Materials and methods

Materials

Yellow-flesh cassava roots (*Manihot esculenta* Crantz) were purchased from a local market in Malang, Indonesia. The hydrocolloids used in this study were HPMC (food grade) and xanthan gum (food grade). HPMC was purchased from Shin-Etsu Chemical Co., Ltd. (Japan), while xanthan gum was purchased from Halim Sarana Cahaya Semesta Co., Ltd. (Indonesia). A food-grade calcium chloride ($CaCl_2$) was purchased from Brataco Co., Ltd. (Indonesia). Palm oil (Salim Ivomas Pratama Co., Ltd, Indonesia) as the cooking oil was purchased on the same day as the frying process from a supermarket in Surabaya, Indonesia. Other reagents used for analysis were analytical grade.

Preparation of cassava sticks

Cassava sticks were prepared based on our previous study [4]. Cassava roots were thoroughly washed twice with tap water, peeled, and cut into sticks of 4 × 1 × 1 cm using a knife, following the dimensions of a stainless steel mold. The cassava sticks were soaked in 0.1% (w/v) $CaCl_2$ for 15 min and then steamed in a stainless steamer (40 × 28 cm) for 15 min at 98°C prior to the coating application. Next, the cassava sticks were cooled to room temperature for about 20 min. The cassava sticks were then immersed in the HPMC (0.4; 0.6; 0.8; 1% w/v) and xanthan gum (0.4; 0.6; 0.8; 1% w/v) solutions with the ratio of cassava stick: hydrocolloid solution was 3:4 (w/v) for 10 min. Hydrocolloid solutions were made by dissolving HPMC or xanthan gum in distilled water. The cassava sticks were drained using a stainless-steel strainer to allow the removal of excess surface solution for about 10 min. The samples were then pre-fried for 30 s at 170°C using a deep fryer (Fritel Professional 35 SICO, Belgium) in cassava sticks: cooking oil ratio of 1:7 (w/v); then, samples were vacuum packed in a polypropylene plastic using a vacuum sealer (Maksindo DZ300, Indonesia) and stored in a chest freezer (Modena MD 45, Italy) at -20°C. Before every analysis procedure, the frozen cassava sticks were thawed in a water bath (15 min) and fried for 2 min at 170°C. The frying sieve was then immediately shaken to remove the excess oil, and the fried cassava sticks were drained for 5 min on the frying sieve.

Evaluation of process variables affecting coating performance

To further support the main experimental design, additional evaluations were performed to evaluate the potential influence of process variables, including immersion time, stick dimension, and frying temperature on the coating performance. Cassava sticks coated with 1% (w/v) xanthan gum were subjected to variations in immersion duration (1, 2, 5, 10, and 15 min), stick dimensions ($4\times1\times1$ cm, $5\times1\times1$ cm, $6\times1\times1$ cm, $7\times1\times1$ cm, and $8\times1\times1$ cm), and frying temperatures (170 °C, 180 °C, and 190 °C). The impact of these process variables was assessed by measuring moisture content and oil absorption.

Moisture content

A thermogravimetric method by the Association of Official Analytical Chemists (AOAC) [22] was used to examine the moisture content of cassava sticks. The cassava sticks were minced and immediately analysed using a hot air oven (Venticell 55, Germany) at 105°C.

Oil absorption

The oil absorption of cassava sticks was determined according to the method of Rashed et al. (2021) [23] and Trisnawati et al. (2023) [4] with minor modifications. Approximately 5 g of pre-fried and fried cassava stick samples were minced and dried in a hot air oven at 105 °C. Then, samples were weighed until the stable weight of each sample was obtained. The oil absorption of cassava sticks was calculated using the following equation:

$$Oil\ absorption\ (\%) = \frac{Weight\ of\ dried\ fried\ sample\ (g) - Weight\ of\ dried\ pre-fried\ sample\ (g)}{Weight\ of\ dried\ fried\ sample\ (g)}$$

Crude fat content

The crude fat content of cassava sticks was analysed using a Soxhlet method, as described by AOAC (2005) [22]. The solution used for fat extraction in this study was n-hexane.

Hardness

In this study, the hardness of cassava sticks was measured using a texture analyser (Stable Micro-System TA-XT Plus, U.K.). One cassava stick for each treatment was placed on the sample holder and compressed with a three-point bend rig probe. The probe was programmed to move 10 mm at a speed of 0.5 mm/s. The hardness of each sample was indicated by the maximum force required to compress the sample (in kg).

Colour properties

Colour parameters (L, a, b) of each sample were measured using a colour reader (Konica Minolta CR-10, Japan). The instrument was calibrated with a standard white plate before each replication. The colour difference (ΔE) of samples during the frying process was calculated based on the equation described by Zhang et al. (2021) [24].

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

where L*, a*, and b* were the colour values of the pre-fried cassava sticks, while L, a, and b were the colour values of the fried cassava sticks.

Statistical analysis

The statistical model used in this study was a two-stage nested design [18, 19, 25], as illustrated in Fig. 1. The observation is labelled as Y_{ijk}, where i is the hydrocolloid type (HPMC and xanthan gum), j is the hydrocolloid concentration (0.4, 0.6, 0.8, and 1% w/v), and k is the number of replications (five replications). The sample with 0% (w/v) of hydrocolloid coating served as a control sample. The linear statistical model was set at $\alpha = 0.05$ and fitted to the two-stage nested design according to Montgomery (2020) [19] is shown below:

$$Y_{ijk} = \mu + \tau_i + \varphi_{j(i)} + \varepsilon_{(ij)k}.$$

In this model, Y represents the observed variable, μ denotes the true mean, τ captures the effect of different hydrocolloids, and φ signifies the impact of various concentrations within different hydrocolloids. The subscript j(i) indicates that the jth level of factor B is nested within the ith level of factor A, where factor A pertains to the variability among different hydrocolloids and factor B relates to the variability among hydrocolloid concentrations within different hydrocolloids. Replicates are nested within the combined level of A and B, denoted by the subscript (ij)k for the error term (ε). Additionally, the effects of immersion time, stick dimension, and frying temperature on moisture content and oil absorption were analyzed separately using one-way ANOVA. One-way ANOVA was selected to assess

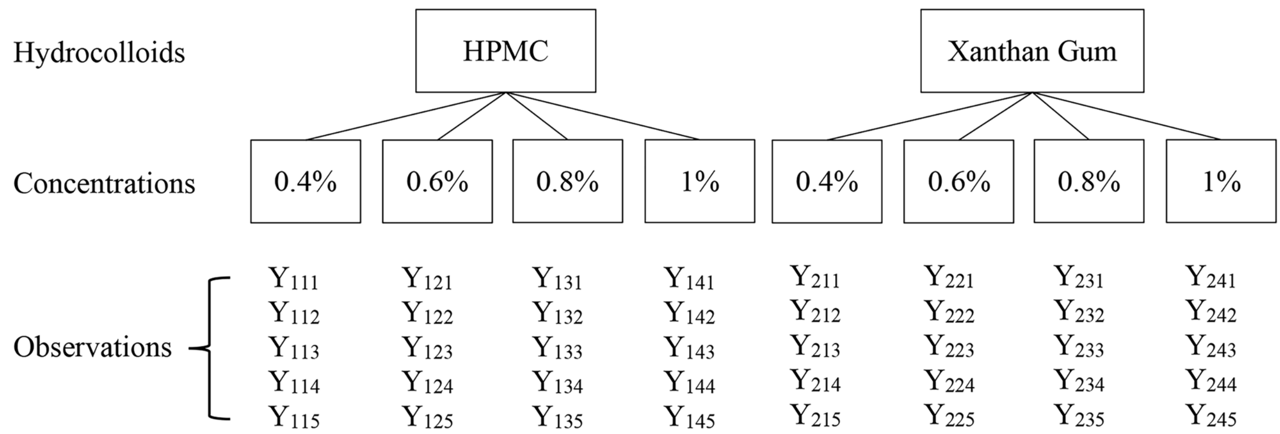

Fig. 1 An illustration of two-stage nested design used in the study

the independent effects of each variable without considering nested structures [19]. The statistical computations were calculated using SPSS for Windows (version 24.0, SPSS Inc., USA) [26]. The significant differences of each sample, either from the main (types of hydrocolloids) and nested effects (levels of hydrocolloid concentration) or from the additional evaluations (immersion time, stick dimension, and frying temperature), were determined at $P<0.05$ using Fisher's Least Significant Difference (LSD) test [27].

Principal component analysis (PCA) was performed to visualise properties that underlie group differences of hydrocolloid variations for the coated cassava sticks. The PCA plot was obtained using the correlation matrix method in Origin 2018 (OriginLab Corps., USA) for moisture content, oil absorption, crude fat content, hardness, and ΔE of cassava sticks.

Results and discussion

Effect of process variables on coating performance

The experimental data presented in Fig. 2 elucidate the relationship between various processing parameters and the efficacy of hydrocolloid coatings in fried cassava sticks. This analysis examines the influence of immersion time, stick dimensions, and frying temperature on moisture content and oil absorption, with statistical significance determined through one-way ANOVA. Variations in immersion time (1, 2, 5, 10, and 15 min), stick dimensions (4 × 1 × 1 cm, 5 × 1 × 1 cm, 6 × 1 × 1 cm, 7 × 1 × 1 cm, and 8 × 1 × 1 cm), and frying temperatures (170 °C, 180 °C, and 190 °C) were assessed to understand their impact on coating performance. The results from these evaluations were used as a reference for selecting the appropriate processing conditions for the main two-stage nested design experiment.

Hydrocolloid immersion time

As shown in Fig. 2(a), immersion time significantly affected both the moisture content and the oil absorption of cassava sticks. Moisture content progressively increased with longer immersion, from 30.82% at 1 min to 44.01% at 10 min and 43.92% at 15 min, with different superscript letters indicating significant differences ($P<0.05$) among treatments. Conversely, oil absorption exhibited an inverse trend, with the highest oil uptake at 0 min (31.10%) and 1 min (30.49%) and the lowest (24.66–24.88%) after 10–15 min. A similar trend has also been reported by Torabi et al. (2017) [28], that increasing immersion time led to higher moisture content and lower oil absorption in fried potato chips. Immersion time plays a critical role in determining the effectiveness of hydrocolloid coating treatments, as it directly influences the formation and uniformity of protective layers on the food surface [29]. Longer immersion periods allow more hydrocolloid molecules to adhere and interact with the surface, enhancing the structural integrity of the coatings. This improved adhesion is closely linked to the water-binding properties of hydrocolloids, which are capable of forming hydrogen bonds with water molecules [30]. Through these interactions, hydrophilic polymers not only promote moisture retention but also reduce surface tension and form cohesive films that act as effective barriers during thermal processing [6, 31].

According to the results, the success of hydrocolloid coatings in reducing oil absorption strongly depends on controlling key processing steps [32]. In particular, the immersion process plays a vital role in forming a uniform coating layer, enhancing moisture retention, and reinforcing the barrier that prevents oil from penetrating during frying. Therefore, a 10-minute immersion time was considered for subsequent treatments, as it resulted in optimal outcomes

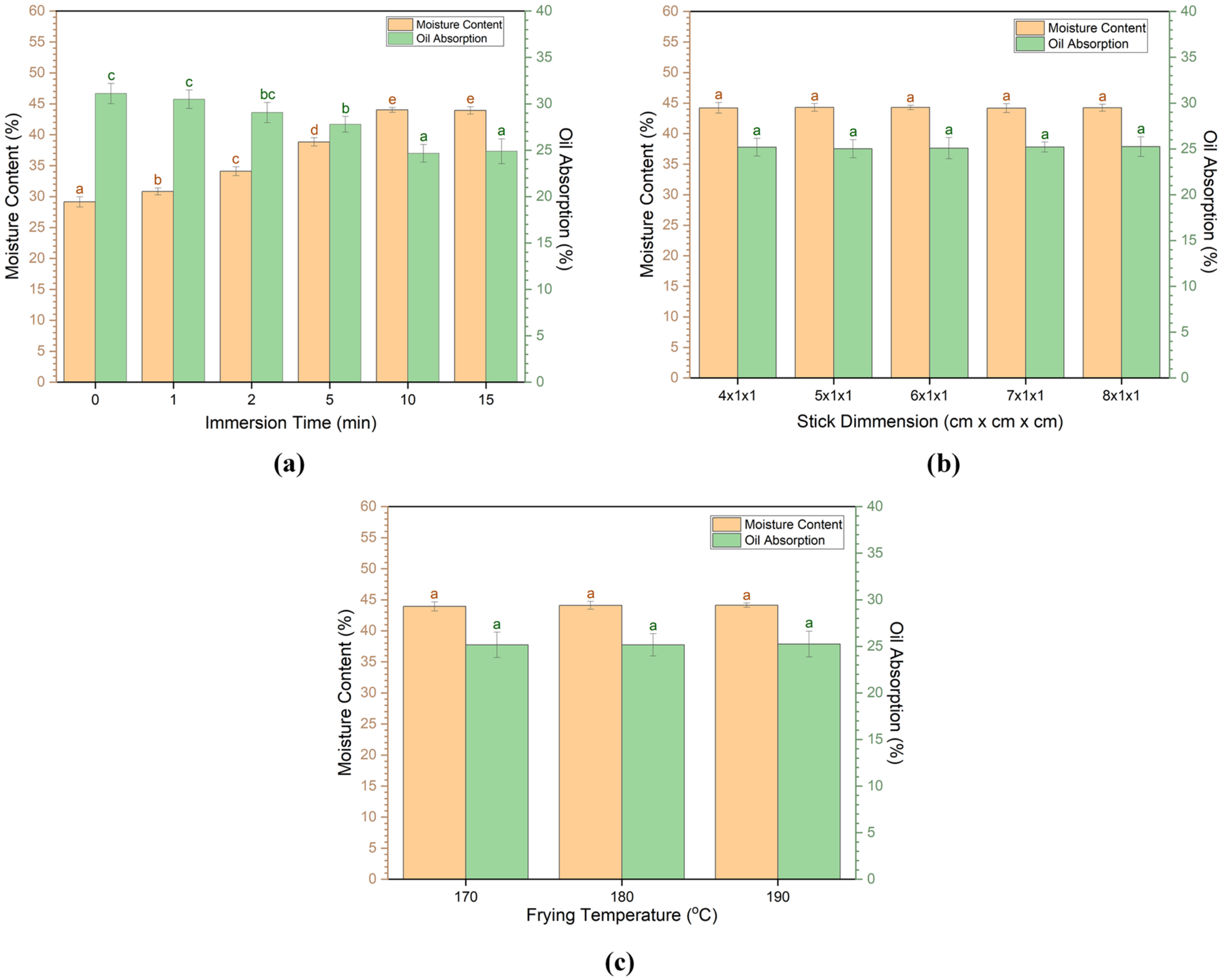

Fig. 2 Moisture content and oil absorption of cassava sticks coated with 1% (w/v) xanthan gum as influenced by (**a**) immersion time, (**b**) stick dimension, and (**c**) frying temperature

[a]Means ± standard deviation with different lowercase letters indicate significant differences between samples based on one-way ANOVA followed by post-hoc comparison ($P<0.05$)

for both moisture content and oil absorption. Extending the immersion period beyond 10 min did not yield significant improvements, indicating that 10 min was sufficient to ensure effective coating performance.

Cassava sticks dimension

Figure 2(b) illustrates the effect of stick dimension on the moisture content and oil absorption of cassava sticks coated with hydrocolloid. The results indicate that varying the stick dimensions (4 × 1 × 1 cm, 5 × 1 × 1 cm, 6 × 1 × 1 cm, 7 × 1 × 1 cm, and 8 × 1 × 1 cm) did not significantly affect ($P>0.05$) the moisture content and oil absorption of cassava sticks. Moisture content across all dimensions remained consistently at 44.16–44.28%, while oil absorption values were stable within 25.02–25.24%. These findings indicate that although stick size may contribute to some extent, its impact on coating performance is relatively minor compared to more influential factors such as coating thickness, formulation, and application method [15, 33]. As long as the coating is uniformly applied, its protective effect appears consistent across various product sizes.

Although Fig. 2(b) shows no statistically significant differences in coating performance among the different stick dimensions, the 4 × 1 × 1 cm size was considered in this study to optimize material use and surface area exposure. Smaller dimensions offer a higher surface area-to-volume ratio, which may enhance coating efficiency while avoiding processing issues commonly associated with larger geometries. Standardizing sample size is also a widely adopted approach to minimize variability. For example, Gaurav et al. (2023) standardized fish dimensions before coating and frying to control for size as a confounding factor [34]. Similarly, this study adopts the 4 × 1 × 1 cm to ensure uniformity and consistency throughout the experimental process.

Frying temperature

Figure 2(c) shows the effect of frying temperature on the moisture content and oil absorption of cassava sticks coated with hydrocolloids. Frying temperatures were set at 170 °C, 180 °C, and 190 °C to assess the influence of thermal processing conditions on water retention and oil migration within the product. Previous studies have reported that the typical frying temperature range for most food products lies between 170 °C and 190 °C, offering a suitable balance between heat transfer efficiency, product quality, and safety [9, 35]. The results demonstrate that frying temperature has no significant effect ($P > 0.05$) on the moisture content and oil absorption of cassava sticks. Moisture contents remained consistent between 43.92% and 44.12%, while oil absorption values ranged from 25.16 to 25.24%. These findings indicate that hydrocolloid coatings effectively preserved their barrier function across the evaluated temperature range. Although previous studies by Ghaderi et al. (2018) have shown that higher frying temperatures may influence oil uptake [36], Kassama and Ngadi (2016) noted that oil absorption tends to reach a plateau or quasi-equilibrium state, resulting in minimal changes with further temperature increases [37]. The presence of a hydrocolloid coating further limits oil penetration, which may explain the lack of significant differences observed in this study.

Based on these findings, 170 °C was considered as the standard frying temperature for subsequent treatments. Frying at this temperature helped to prevent excessive browning and the formation of undesirable compounds, while still maintaining sufficient moisture retention and low oil absorption [38, 39]. Furthermore, frying at 170 °C is more energy-efficient, requiring less energy input than higher temperatures.

Table 1 ANOVA of the variation of hydrocolloid concentration nested in hydrocolloid types on each parameter

Parameter	Sig[a]		Observed power[a]	
	Hydrocolloid Types	Hydrocolloid Concentrations*	Hydrocolloid Types	Hydrocolloid Concentrations*
Moisture content, pre-fried	0.138^{NS}	0.000^{S}	0.315	1.000^{H}
Moisture content, fried	0.000^{S}	0.000^{S}	1.000^{H}	1.000^{H}
Oil absorption	0.000^{S}	0.000^{S}	1.000^{H}	1.000^{H}
Crude fat content	0.000^{S}	0.000^{S}	0.997^{H}	1.000^{H}
Hardness	0.002^{S}	0.000^{S}	0.888^{H}	1.000^{H}
Colour, pre-fried, lightness	0.255^{NS}	0.000^{S}	0.203	1.000^{H}
Colour, pre-fried, redness	0.831^{NS}	0.999^{NS}	0.055	0.074
Colour, pre-fried, yellowness	0.677^{NS}	0.000^{S}	0.069	1.000^{H}
Colour, fried, lightness	0.132^{NS}	0.000^{S}	0.324	1.000^{H}
Colour, fried, redness	0.571^{NS}	0.000^{S}	0.086	1.000^{H}
Colour, fried, yellowness	0.251^{NS}	0.000^{S}	0.206	1.000^{H}
Colour difference	0.985^{NS}	0.045^{S}	0.050	0.791

[a] $\alpha = 0.05$, *nested within hydrocolloid types, ^{NS} not significant, ^{S} significant, ^{H}power >0.8

Assessment of hydrocolloid variations

In this study, the influence of hydrocolloid coating variations on the observed parameters was assessed statistically using a two-stage nested design. The variations consisted of four distinct concentrations of hydrocolloid (0.4, 0.6, 0.8, and 1%), which were nested within two different types of hydrocolloids (HPMC and xanthan gum). This statistical design suited the objectives of the study, as the effect of concentration under HPMC on cassava sticks is not the same as the concentration under xanthan gum. The nesting design accounted for sources of variability in the hierarchical layers (concentration within the types of hydrocolloids), allowing for a more precise assessment of their influence on cassava sticks characteristics [19–21, 26].

Table 1 shows the ANOVA of the treatments on all observed parameters. The primary factor, namely the types of hydrocolloids, exerted a significant impact ($P < 0.05$) on the moisture content ($P = 0.000$), oil absorption ($P = 0.000$), crude fat content ($P = 0.000$), and the hardness ($P = 0.002$) of fried cassava sticks. On the other hand, the moisture content of pre-fried cassava sticks was not significantly different ($P = 0.138$). Other factors, such as colour properties were not significantly different ($P > 0.05$) between samples. The results are preferable because coating fried products with hydrocolloids effectively prevents the exchange of evaporated water with oil during frying due to its protective layer [40], but it does not alter their physical appearance in this term colour of the products.

Based on the findings presented in Table 1, the nested factor, represented by the concentrations nested in hydrocolloids, significantly influenced ($P < 0.05$) all parameters investigated in this study. These results indicate that increasing hydrocolloid concentration enhances its ability to inhibit the transfer of water and oil during frying, consequently increasing the moisture content and lowering oil absorption. The escalation in coating concentration prolongs the time required for the cassava stick to reach 100°C [5], resulting in less water evaporating during frying. The increase in hydrocolloid concentration also impacts the visible characteristics, specifically the colour of the fried cassava stick. However, the redness of pre-fried cassava sticks showed a non-significant result ($P=0.999$), likely due to the short frying period during pre-frying, which lasted for 30 s. The redness of fried products is primarily attributed to the Maillard reaction, which occurs during prolonged frying periods at higher oil temperatures (>150 °C) [41, 42].

The observed power in Table 1. provides insight into the study's ability to detect actual effects within the hierarchical structure of the two-stage nested design. Statistical power represents the probability of correctly rejecting the null hypothesis when it is false, thus minimizing the risk of Type II errors [43]. According to the results, parameters such as moisture content (fried), oil absorption, crude fat content, and hardness exhibit low P-values ($P<0.05$) and high observed power (power > 0.800), indicating that the nested design effectively captured significant effects of hydrocolloid types and concentrations. These results confirm that the study had sufficient power to detect meaningful differences, reinforcing the validity of the findings. Conversely, several colour parameters, including pre-fried sample redness (power = 0.069), fried sample redness (power = 0.086), and colour difference (power = 0.050 for hydrocolloid types), show both non-significant ($P>0.05$) P-values and low observed power (power < 0.800). These findings indicate that although the nested design helps manage variability within samples, it may also lead to decreased sensitivity in identifying minor differences, especially for parameters that naturally exhibit high variability, like the colour parameters [44, 45].

Table 2 Significance of hydrocolloid types on the mean of each observed parameter.

Parameter	Hydrocolloid Types	
	HPMC	Xanthan Gum
Moisture content, pre-fried (%)	50.81 ± 3.08[a]	51.09 ± 3.44[a]
Moisture content, fried (%)	36.71 ± 4.33[a]	37.92 ± 5.18[b]
Oil absorption (%)	28.76 ± 1.61[a]	26.92 ± 2.53[b]
Crude fat content (%)	13.31 ± 1.45[a]	12.58 ± 2.15[b]
Hardness (kg)	1.10 ± 0.14[a]	0.99 ± 0.21[b]
Colour, pre-fried, lightness	74.58 ± 1.52[a]	74.25 ± 1.68[a]
Colour, pre-fried, redness	0.70 ± 0.24[a]	0.68 ± 0.23[a]
Colour, pre-fried, yellowness	33.98 ± 1.19[a]	34.06 ± 1.01[a]
Colour, fried, lightness	67.51 ± 1.26[a]	67.16 ± 1.53[a]
Colour, fried, redness	3.66 ± 0.36[a]	3.64 ± 0.39[a]
Colour, fried, yellowness	33.57 ± 1.06[a]	33.44 ± 1.04[a]
Colour difference	7.77 ± 0.95[a]	7.77 ± 0.81[a]

[a]Means ± standard deviation with different letters indicate significant differences ($P<0.05$)

Effect of hydrocolloid variations on the observed parameters

Moisture content

Table 2. shows the effect of hydrocolloid types on the moisture content of pre-fried and fried samples. Even though the moisture content of the pre-fried cassava stick coated with xanthan gum (51.09%) was slightly higher than the sample coated with HPMC (50.81%), it did not differ significantly ($P>0.05$). However, after the frying process, the moisture content of both xanthan gum (37.92%) and HPMC (36.71%) coated samples were significantly different ($P<0.05$). A similar result was also reported by Akdeniz et al. (2006) [32], adding xanthan gum to the coating batter significantly improved the moisture content of fried carrot slices compared to HPMC. The difference in moisture content of samples with different hydrocolloid coatings is due to the different barrier properties and gel formation ability, which are related to hydrocolloid structure and functionality [14, 15, 17, 46]. Xanthan gum has the ability to produce a higher viscosity in coating solutions than HPMC due to its rigid double-helix structure, which stabilized by non-covalent bonds [47]. Higher viscosity of xanthan gum coating solutions can act as an insulating material, reducing the rate of heat transfer and consequently minimizing water evaporation [48]. According to Lumanlan et al. (2021) [49] and Akdeniz et al. (2006) [32], the ability of xanthan gum to maintain moisture during frying is also due to its thermal stability and high-water binding capacity. On the other hand, the thermo gelation properties of HPMC improve the moisture retention of fried cassava sticks during the frying process [31, 32].

The effect of concentrations nested in different hydrocolloid coatings was also studied, as the data are presented in Table 3. The moisture content of samples coated with xanthan gum and HPMC was significantly increased ($P<0.05$) with the increased level of hydrocolloids. Control cassava stick (without coating) had the lowest moisture content among other pre-fried and fried samples. These results indicate that coating cassava sticks using higher concentrations of hydrocolloids significantly reduced moisture loss. Hydrocolloid coating treatment on fried products contributes to forming a thicker and less porous surface structure so that it can serve as a film to retain moisture within the product and avoid the migration of oil during the frying process [17, 31, 50, 51].

Table 3 Effect of concentrations nested in hydrocolloids on moisture content, oil absorption, and crude fat content

Treatment	Moisture Content, Pre-fried (%)	Moisture Content, Fried (%)	Oil Absorption (%)	Crude Fat Content (%)
Control	46.13 ± 0.73^{aA}	29.98 ± 0.25^{aA}	30.98 ± 1.58^{aA}	15.49 ± 0.31^{aA}
HPMC 0.4%	49.24 ± 0.22^{b}	34.60 ± 0.15^{b}	28.97 ± 0.76^{b}	13.94 ± 0.11^{b}
HPMC 0.6%	50.84 ± 0.35^{c}	36.79 ± 0.16^{c}	28.16 ± 1.19^{b}	13.12 ± 0.14^{c}
HPMC 0.8%	53.30 ± 0.31^{d}	40.18 ± 0.48^{d}	27.96 ± 0.95^{b}	12.73 ± 0.15^{c}
HPMC 1%	54.56 ± 0.43^{e}	41.98 ± 0.17^{e}	27.75 ± 1.15^{b}	11.28 ± 0.34^{d}
XG 0.4%	48.92 ± 0.68^{B}	35.07 ± 0.67^{B}	26.89 ± 0.62^{B}	13.64 ± 0.18^{B}
XG 0.6%	51.28 ± 0.68^{C}	38.43 ± 0.49^{C}	26.45 ± 1.25^{B}	12.48 ± 0.73^{C}
XG 0.8%	53.83 ± 0.97^{D}	41.89 ± 1.19^{D}	25.79 ± 0.62^{BC}	11.96 ± 0.27^{C}
XG 1%	55.29 ± 0.86^{E}	44.22 ± 0.63^{E}	24.46 ± 1.92^{C}	9.33 ± 0.87^{D}

aMeans ± standard deviation with different lowercase letters indicate significant differences ($P < 0.05$) between control and HPMC-coated samples

AMeans ± standard deviation with different capital letters indicate significant differences ($P < 0.05$) between control and xanthan gum-coated samples

Oil absorption and crude fat content

The results in Table 2 indicate that using different hydrocolloids as edible coatings significantly influenced ($P < 0.05$) the oil absorption of fried cassava sticks. Cassava sticks coated with HPMC (28.76%) showed higher oil absorption than those coated with xanthan gum (26.92%). A similar trend was observed in the crude fat content of the fried cassava sticks. The crude fat content of cassava sticks coated with HPMC (13.31%) was significantly higher ($P < 0.05$) than that of samples coated with xanthan gum (12.58%). These findings indicate that the type of hydrocolloid used influences the amount of oil absorbed by fried products, likely due to the hydrocolloid film's properties, which reduce the tendency of the cassava stick to absorb oil during frying [17, 52]. Moreover, the effectiveness of hydrocolloids in reducing oil absorption depends on mechanical and barrier properties associated with the chemical composition, formula, and structure of the hydrocolloid coatings [31]. Xanthan gum was found statistically more effective than HPMC in reducing oil content in cassava fries. The thermal-gelation capabilities of xanthan gum may contribute to the low porosity of the areas where most oil adheres, resulting in lower oil absorption and fat content [49]. Meanwhile, HPMC also forms a solid gel upon heating, though this gelation process is reversible upon cooling. This property may help prevent oil absorption into the product's pores and cracks during the chilling phase [31, 53, 54].

Table 3. shows that concentrations nested within hydrocolloid types showed significant differences ($P < 0.05$). A higher concentration of hydrocolloids was more effective in hindering oil absorption in cassava sticks than in uncoated ones. Increasing the concentration of HPMC (0.4–1%) decreased the oil absorption of cassava sticks; however, the reduction was not statistically significant ($P > 0.05$) among the HPMC samples. In contrast, coating cassava sticks with xanthan gum at concentrations of 0.8% and 1% significantly ($P < 0.05$) reduced oil absorption to 25.79% and 24.26%, respectively. As a result, the fat content of cassava sticks coated with HPMC (13.94–11.28%) and xanthan gum (13.64–9.33%) was significantly lower ($P < 0.05$) than the control sample (15.49%). Applying hydrocolloids as coatings impedes efficient heat transfer, thereby reducing oil absorption by limiting water-to-oil transfer from the surface of the food via convection and conduction from the surface to the interior [5, 55]. In addition to acting as a barrier to inhibit water and oil exchange during frying, hydrocolloid coatings may also decrease the surface roughness of fried products. Moreno et al. (2010) found a direct relationship between oil retention and surface roughness, whereby reducing surface roughness may increase oil retention in the crust, leading to lower oil absorption and fat content [56]. Furthermore, coatings may also reduce the surface tension and increase the contact area between oil and food, thereby reducing oil absorption during frying [31].

Hardness

The effect of different hydrocolloids on the texture of fried products has not yet been extensively studied. In this study, the texture of the cassava stick was represented by hardness, defined as the force required to change the sample's shape due to its resistance to resist deformation [57]. Based on the result shown in Table 2., it is evident that the type of hydrocolloid coating impacts the hardness of cassava sticks. Samples coated with HPMC (1.10 kg) required a significantly higher force ($P < 0.05$) to deform compared to those coated with xanthan gum (0.99 kg). This difference in hardness may be explained by the formation of thermogelling film by HPMC, which creates a stronger but more brittle coating and promotes the formation of a smaller number of larger punctures with low capillary pressure [6, 14].

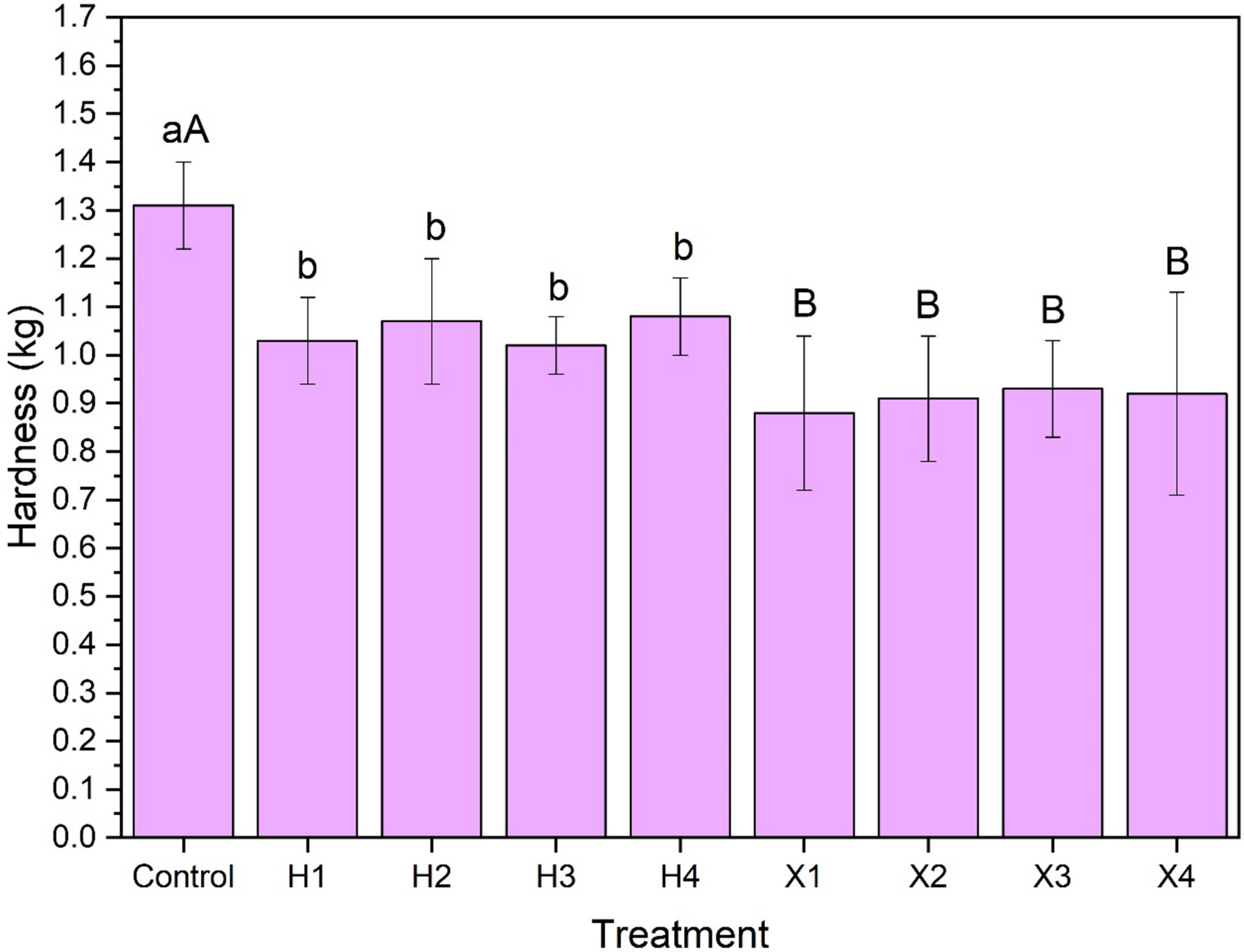

Fig. 3 Effect of concentrations nested in hydrocolloid types on the hardness of cassava sticks. [a]Means ± standard deviation with different lowercase letters indicate significant differences ($P<0.05$) between control and HPMC-coated samples (H1-H4). [A]Means ± standard deviation with different capital letters indicate significant differences ($P<0.05$) between control and xanthan gum-coated samples (X1-X4). (Control: uncoated sample, H1: HPMC 0.4%, H2: HPMC 0.6%, H3: HPMC 0.8%, H4: HPMC 1%, X1: xanthan gum 0.4%, X2: xanthan gum 0.6%, X3: xanthan gum 0.8%, X4: xanthan gum 1%)

Figure 3. illustrates the influence of hydrocolloid concentration nested within each hydrocolloid type. The uncoated cassava stick (control) exhibited the highest hardness (1.31 kg) among other cassava stick samples. The control sample also had a significant difference ($P<0.05$) compared to samples coated with HPMC and xanthan gum. These results are aligned with the findings of Sahin et al. (2005), Akdeniz et al. (2006), Bouaziz et al. (2016), and Herawati et al. (2019), who reported that hydrocolloid coatings reduce rigidity and improve the texture of chicken nuggets [58], deep-fat fried carrot [32], potato chips [59], and cassava stick [60]. According to Mellema (2003) and Weerasekera et al. (2015), the film-forming abilities of hydrocolloids play an essential role in reducing the hardness of the product structure while enhancing the crispiness of the product [6, 61].

Colour properties

Table 2. presents the effect of hydrocolloid types on the colour parameters (L, a, b, and ΔE) of pre-fried and fried cassava sticks. No significant differences were observed across all colour parameters ($P>0.05$), indicating that hydrocolloid types did not affect the colour changes in cassava sticks, resulting in similar colour characteristics. However, different concentrations within each hydrocolloid type yielded significant results ($P<0.05$) for all colour parameters of pre-fried and fried cassava sticks, except the redness (a) of pre-fried samples, as shown in Table 4.

The lightness (L) of pre-fried and fried samples decreased as the hydrocolloid concentration increased, while the highest lightness was observed in the control sample. This result aligns with the findings from Izadi et al. (2015) and Torabi

Table 4 Effect of concentrations nested in hydrocolloids on colour properties

Treatment	Pre-fried			Fried			ΔE
	Lightness	Redness	Yellowness	Lightness	Redness	Yellowness	
Control	76.66 ± 0.73^{aA}	0.66 ± 0.38	35.62 ± 0.74^{aA}	68.95 ± 0.74^{aA}	4.27 ± 0.05^{aA}	34.72 ± 0.60^{aA}	8.65 ± 1.05^{aA}
HPMC 0.4%	75.02 ± 1.18^{b}	0.76 ± 0.11	34.27 ± 0.33^{b}	68.39 ± 0.48^{a}	3.78 ± 0.04^{b}	34.23 ± 0.25^{ab}	7.30 ± 1.19^{b}
HPMC 0.6%	74.12 ± 0.87^{bc}	0.66 ± 0.21	33.44 ± 1.06^{bc}	67.25 ± 0.81^{b}	3.59 ± 0.06^{c}	33.81 ± 0.55^{b}	7.55 ± 0.82^{b}
HPMC 0.8%	73.86 ± 1.35^{bc}	0.72 ± 0.16	33.20 ± 0.43^{c}	66.99 ± 0.88^{bc}	3.41 ± 0.12^{d}	33.10 ± 0.24^{c}	7.40 ± 1.09^{b}
HPMC 1%	73.26 ± 0.79^{c}	0.70 ± 0.32	33.37 ± 1.23^{bc}	65.97 ± 0.59^{c}	3.26 ± 0.07^{e}	31.97 ± 0.41^{d}	7.97 ± 0.51^{ab}
XG 0.4%	74.52 ± 0.88^{B}	0.70 ± 0.20	34.13 ± 0.31^{B}	67.87 ± 1.19^{B}	3.77 ± 0.08^{B}	34.07 ± 0.30^{B}	7.33 ± 0.66^{B}
XG 0.6%	73.74 ± 1.17^{BC}	0.70 ± 0.16	34.00 ± 0.23^{B}	67.13 ± 0.83^{B}	3.58 ± 0.11^{C}	33.62 ± 0.44^{B}	7.24 ± 0.55^{B}
XG 0.8%	73.26 ± 1.55^{BC}	0.64 ± 0.28	33.63 ± 0.70^{BC}	66.09 ± 1.56^{C}	3.36 ± 0.16^{D}	32.41 ± 0.41^{C}	7.85 ± 0.85^{AB}
XG 1%	73.08 ± 1.08^{C}	0.72 ± 0.13	32.93 ± 0.28^{C}	65.76 ± 0.69^{C}	3.23 ± 0.22^{D}	32.37 ± 0.50^{C}	7.78 ± 0.36^{AB}

aMeans ± standard deviation with different lowercase letters indicate significant differences ($P < 0.05$) between control and HPMC-coated samples

AMeans ± standard deviation with different capital letters indicate significant differences ($P < 0.05$) between control and xanthan gum-coated samples

et al. (2017), where a higher concentration of hydrocolloids reduced the lightness of coated fried shrimp [62] and potato chips [28]. While hydrocolloid coatings did not significantly ($P > 0.05$) affect the redness (a) of the pre-fried sample, redness decreased with increased concentration after the frying process. The yellowness of pre-fried and fried cassava sticks was significantly lower than that of the control sample and decreased as hydrocolloid concentration increased. These changes in colour parameters can likely be attributed to the Maillard reaction between reducing sugars and amino group-containing compounds (amino acids, proteins, and peptides) naturally present in the product [59, 63]. The Maillard reaction is recognized as the primary reaction responsible for food browning in fried products, leading to colour changes that significantly impact consumer perception and acceptance [9, 64]. Increased redness caused by browning reaction is generally considered a less preferable colour attribute in fried foods due to the darker colour it imparts [65, 66]. In contrast, yellowness (b) is the most preferable colour attribute in fried foods [51, 66]. According to Wang et al. (2023), consumers' subjectivity tends to prefer a fried product that has a golden-brown colour, rather than low lightness, high redness (dark brown) or high lightness and yellowness (pale-yellow) [67]. Therefore, changes in L, a, and b values of cassava sticks are likely to influence consumer preferences due to the difference in the product's colour from the usual expectations (golden-brown colour).

Furthermore, colour changes between pre-fried and fried cassava sticks were assessed using the ΔE value. According to Bal et al. (2011), pre-treatment methods involving heating, such as pre-frying, decrease product water activity, which can trigger non-enzymatic browning [63]. This can be seen by the ΔE value of the control sample, which was significantly higher than other hydrocolloid coated samples. Akdeniz et al. (2006) stated that the ability of hydrocolloid to bind moisture inhibits dehydration during the heating process and prevents the Maillard reaction from occurring [32].

Principle component analysis

Principal components (PC) are calculated from the eigenvectors of the correlation matrix of the observations [68, 69]. The biplot of PC1 versus PC2, which includes both the loading plot and the score plot, is shown in Fig. 4. The eigenvalues for PC1 and PC2 are found as 4.03 and 1.60, respectively. PC1 accounts for 67.11% of the variance, primarily distinguishing samples based on moisture content (pre-fried and fried) and ΔE on the positive side, whereas crude fat, oil absorption, and hardness align with the opposing side. PC2 contributes 26.61% of the variance and positively correlates with all variables. Thus, the cumulative variance covered by PC1 and PC2 is 93.72%, indicating that the information captured by these PCs effectively summarizes the overall variability in the samples.

Although no specific sample classification was expected before the analysis, the biplot reveals some clustering based on hydrocolloid type. Cassava sticks coated with 0.4%, 0.6%, and 0.8% HPMC are grouped on the positive side of PC2, distinguished from other samples by higher oil absorption, hardness, and crude fat content. Meanwhile, samples coated with 0.4% and 0.6% xanthan gum group on the negative sides of both PC1 and PC2, suggesting lower oil absorption and hardness. Samples with 0.8% and 1% xanthan gum are positioned in the positive PC1 and negative PC2 quadrants, indicating higher moisture retention and reduced oil uptake. Notably, the 1% HPMC-coated sample appears as an outlier in the top right quadrant, possibly due to higher oil absorption and hardness values, deviating significantly from other HPMC-coated cassava sticks.

Correlation analysis revealed a significant positive correlation among variables positioned in similar directions. Oil absorption and crude fat are positively correlated ($r = 0.763$), suggesting that samples with higher oil absorption also exhibit higher crude fat content. Similarly, ΔE positively correlates with moisture content in pre-fried ($r = 0.794$) and fried samples ($r = 0.771$), implying that higher moisture retention is associated with greater colour changes.

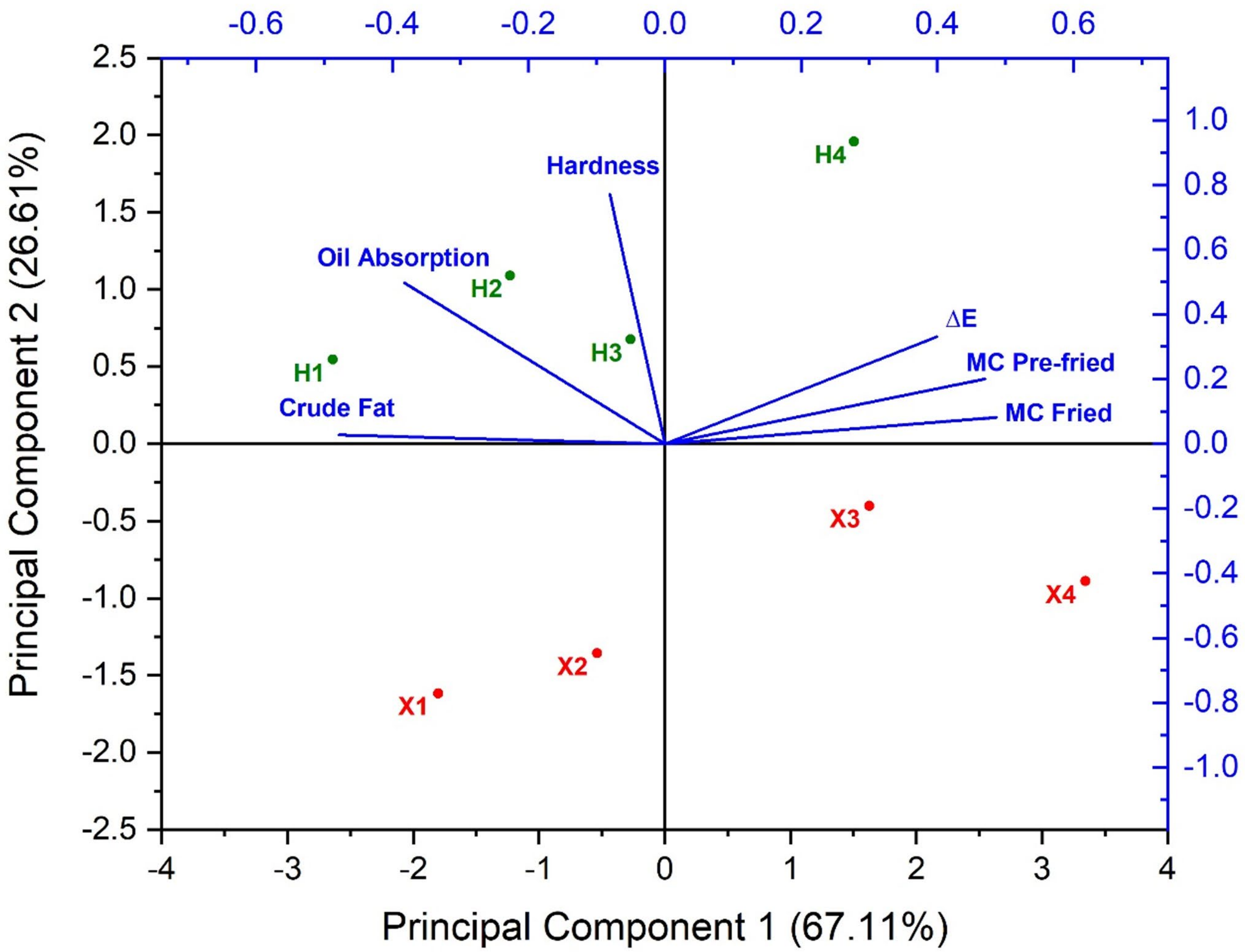

Fig. 4 Biplot of PCA of cassava sticks coated with different variations of hydrocolloids, describing 67.11% of data variation for PC 1 and 26.61% for PC 2 (H1: HPMC 0.4%, H2: HPMC 0.6%, H3: HPMC 0.8%, H4: HPMC 1%, X1: xanthan gum 0.4%, X2: xanthan gum 0.6%, X3: xanthan gum 0.8%, X4: xanthan gum 1%)

In contrast, negative correlations are evident between the moisture content of fried samples and oil absorption ($r = -0.669$) or crude fat ($r = -0.922$), meaning that cassava sticks with higher moisture content tend to have lower oil absorption and fat content.

Conclusions

In summary, this study highlights the importance of processing variables in optimizing the performance of hydrocolloid coatings for fried cassava sticks. Immersion time significantly affected both moisture content and oil absorption, with 10 min identified as the optimal duration for achieving higher water retention and lower oil uptake. In contrast, variations in stick dimensions and frying temperature showed no significant influence, suggesting their limited impact on coating effectiveness under the conditions tested. The systematic evaluation and standardisation of these processing parameters were crucial for ensuring experimental reliability. By identifying and controlling these variables, potential confounding factors were minimized, allowing for more precise assessment of hydrocolloid type and concentration effects on product quality. The two-stage nested design further demonstrated the significant influence of hydrocolloid types and their concentrations on the physicochemical properties of cassava sticks. Application of HPMC and xanthan gum at varying concentrations led to notable differences in moisture content, oil absorption, crude fat content, texture, and colour. Higher concentrations of hydrocolloids generally improved moisture retention and reduced oil absorption, with xanthan gum proving more effective than HPMC due to its strong water-binding capacity and thermal stability. In terms of texture, HPMC coated samples exhibited higher hardness values, while xanthan gum resulted in softer, more desirable textures. Colour parameters were more strongly affected by concentration than hydrocolloid type, with higher concentrations leading to reduced lightness and yellowness but minimal changes in redness. PCA results supported these findings, with the first two principal components accounting for 93.72% of total variance. The biplot showed differentiation based on hydrocolloid type and concentration, with HPMC samples clustering along the positive side of PC2 and xanthan gum samples mainly on the negative side of both PC1 and PC2. Although commercial-scale application of nested designs may face logistical challenges, this study offers practical insights for developing healthier fried food products by controlling critical formulation and processing variables.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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