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Influence of Tapioca, Corn, and Potato Starches on Physical and Textural Characteristics of Puffed Starch Crackers

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ABSTRACT

Puffed products have become increasingly popular, prompting this study to determine how various types of starches such as tapioca, potato, and corn influence the physical, textural, and microstructural properties of starch-based puffed crackers. The physicochemical properties of the starches, including amylose content, water holding capacity (WHC), and oil holding capacity (OHC), as well as the physical properties, texture, and microstructure of the resulting crackers were evaluated. Results indicated that all starches had similar WHC and OHC values. Crackers made with corn starch (FCS) had the lowest oil content (8.65%) and the highest rehydration ratio (1.12). After frying, tapioca and potato starches produced significantly crispier crackers compared to corn starch, with a strong positive correlation (r=0.986) between crispiness and volume expansion. Potato starch-based crackers (FPS) exhibited longer cooling periods due to lower specific heat capacity. Scanning electron microscopy (SEM) images revealed that tapioca starch caused more pronounced changes in microstructure due to its porosity, which explained differences in volume expansion and texture. The study highlighted how different starch sources impacted the texture and microstructure of puffed crackers, providing insights for producing crackers with desired properties.

Keywords: Puffed cracker, Corn starch, Potato starch, Tapioca starch

Tapyoka, Mısır ve Patates Nişastalarının Şişirilmiş Nişastalı Krakerlerin Fiziksel ve Dokusal Özellikleri Üzerindeki Etkisi

ÖZ

Puf ürünler giderek daha popüler hale gelmiş olup, bu durum çeşitli nişasta türlerinin (tapyoka, patates ve mısır) nişasta bazlı puf krakerlerin fiziksel, dokusal ve mikro yapısal özellikleri üzerindeki etkisini inceleyen bu çalışmayı teşvik etmiştir. Çalışmada, nişastaların amiloz içeriği, su tutma kapasitesi (WHC) ve yağ tutma kapasitesi (OHC) gibi fizikokimyasal özellikleri değerlendirilmiş; ayrıca elde edilen krakerlerin fiziksel özellikleri, dokusu ve mikro yapısı incelenmiştir. Bulgular, tüm nişastaların benzer WHC ve OHC değerlerine sahip olduğunu göstermiştir. Mısır nişastası içeren krakerlerin (FCS) en düşük yağ içeriğine (%8,65) ve en yüksek yeniden su alma oranına (1,12) sahip olduğu belirlenmiştir. Kızartma işlemi sonrasında, tapyoka ve patates nişastası içeren krakerler, mısır nişastası içerenlere kıyasla önemli ölçüde daha gevrek bulunmuş ve gevreklik ile hacim genişlemesi arasında güçlü bir pozitif korelasyon (r=0,986) tespit edilmiştir. Patates nişastası bazlı krakerlerin (FPS) spesifik ısı kapasitesinin daha düşük olması nedeniyle soğuma süresinin daha uzun olduğu gözlemlenmiştir. Taramalı elektron mikroskobu (SEM) görüntüleri, tapyoka nişastasının gözenekliliği nedeniyle mikro yapıda daha belirgin değişikliklere yol açtığını ve bu durumun hacim genişlemesi ile doku farklılıklarını açıkladığını ortaya koymuştur. Çalışma, farklı nişasta kaynaklarının puf krakerlerin doku ve mikro yapısı üzerindeki etkilerini vurgulamakta olup, istenen özelliklere sahip krakerlerin üretilmesine yönelik önemli bilgiler sunmaktadır.

Anahtar Kelimeler: Puf kraker, Mısır nişastası, Patates nişastası, Tapyoka nişastası

INTRODUCTION

Snack production and consumption have increased worldwide in recent years. A snack is defined as a light meal consumed between main meals or instead of meals. Foods such as biscuits, crackers, cakes, soft drinks, ice cream, candy, chips, and popcorn are classified as snacks [1]. According to Statista Research Department report, the cookies and crackers segment is expected to have the highest production of 29.9 billion kilograms in 2029 [2]. This growing demand for snack options has led to significant research into the development of innovative food products, including puffed crackers. Particularly, puffed starchy crackers have been popular in recent years due to their appealing texture and potential for customization with various servicing options [3].

Puffing is an atmospheric pressure process and takes place by evaporation of water when the product is exposed to high temperature or sudden pressure drop [4]. Air puffing, sand puffing, oil puffing, and roller puffing are examples of atmospheric pressure treatment [5]. Steps involved in the oil puffing can be sorted as water loss from the internal cells, formation of water vapors associated with volume expansion, and creation of pore networks starting from the surface of the food and continuing towards the center after the pore development [6]. Puffed starchy crackers can be made by using different pulses such as red lentil, yellow pea or flours such as rice flour or starches isolated from plants such as sweet potato [7]. Previously, Guraya and Toledo [4] investigated the hot air puffing properties of the non-fat starch-based snack containing tapioca flour and sweet potato puree. They revealed that after puffing the starch gelatinization occurred by 93% and puffed volume increased to 490%. Nath et al. [5] developed a potato-based ready-to-eat (RTE) puffed snack with a high-temperature short-time air puffing process and optimized the parameters by investigating the quality attributes such as expansion ratio, hardness, ascorbic acid loss, and overall acceptability of the products. These studies revealed that starch plays a crucial role in defining the physical and textural properties of puffed products primarily owing to its distinctive characteristics in gelatinization and water absorption capacity. Moreover, Vaan Der Sman and Broeze [8] reviewed the studies about the structure of expanded snacks based on potato content and noted the scarcity of scientific literature on the subject. Recently, our group has investigated the effect of different starch types (corn, potato, and tapioca) on the rheological and textural properties of potato powder containing starch cracker dough [3]. Therefore, this study aims to extend those findings by focusing on the production of puffed crackers from potato powder containing dough using tapioca, corn, and potato starches and analyzing their physical, textural, and microstructural properties.

MATERIALS and METHODS

Materials

Potato (PS), tapioca (TS), and corn (CS) starches were purchased from Ingro Food Co., Ltd. (Karaman, Türkiye), and proximate compositions are shown in Table 1. Potatoes (*Solanum tuberosum* L.), sunflower oil (Migros, İstanbul, Türkiye), salt (Billur Tuz, İzmir, Türkiye), and sugar (Nar, Aydın, Türkiye) were obtained from a local market in Izmir, Türkiye. Distilled water (1 µS/cm) was used for all preparations.

Table 1. Proximate composition of starches used (%)

Type	Starch	Protein	Lipid	Moisture	Ash
Corn	84.0	0.50	0.15	13.1	2.25
Potato	82.2	0.60	1.20	15.9	0.10
Tapioca	82.0	0.00	3.90	12.7	1.40

Preparation of Crackers

The preparation of cracker dough from different starches followed the procedures detailed by Berk et al. [3]. Throughout the study, potatoes from the same batch were used to ensure consistency. The potatoes were first washed, peeled, and boiled. After cooling, they were mashed and dried in a hot air circulation oven (JP Selecta, Barcelona, Spain). The dried potatoes were then ground into powder using a knife mill (Gringomix GM200, Retsch, Germany). For dough preparation, 150 g of starch, 30 g of potato powder, ~150 mL of water (varied by formulation), 3.5 mL of sunflower oil, 2 g of salt, and 2 g of sugar were mixed and kneaded for about 5 min until a medium-firm consistency was achieved. Then, the dough was shaped into 40 mm diameter cylinder molds , refrigerated for 1 h at ~5ºC, and blanched in boiling water (~97-99ºC) for 30 min. After cooling, the dough was stored in the refrigerator at 4ºC for 18 h and then sliced to a thickness of 1 mm with an adjustable slicer. The slices were dried at 80ºC for 4 h in an air circulation oven.

To obtain puffed crackers, the dried samples were deep-fried in 2 L of sunflower oil at 190ºC for 10 seconds using an electric fryer (Arcelik Fritty, Istanbul, Turkey) [9]. The metal basket was gently shaken intermittently to ensure uniform heating and gently tapped to drain excess oil at the end of frying time. The fried samples were placed on paper towels to remove the excess surface oil and packed for further analysis. Three different batches of dough for each starch type were prepared accordingly.

Physical Properties of Starches

A phase contrast microscope (Novex, K-range, Arnhem, The Netherlands) was used to analyze the shape, size, and appearance of starch granules. The captured images were processed with the software package Image-Pro Plus 4.5.1 (Media Cybernetics Inc., Silver Spring, MD, USA). Randomly selected 100 starch granules were counted, and their diameters were recorded. Amylose contents of the starches were determined in a previous study [3]. Water holding capacities (WHC) of CS, PS, and TS were determined using the method described by Mishra and Rai [10]. A 1% (w/v) starch suspension in distilled water was prepared in a 2 mL centrifuge tube and incubated for 1 h at 25 ºC with intermittent shaking. Then, the tube was centrifuged (Centurion Scientific, Lancing, West Sussex, UK) at 10,080x*g* for 15 min at 25ºC, and the supernatant was removed carefully. The wet starch was weighed. Oil holding capacity (OHC) was determined by the method of Olu-Owolabi et al. [11] with some modifications. 0.05 g of starch was added in 5 mL of sunflower oil and mixed for 1 min. After the 60-minute holding period, the sample was centrifuged at 10,080x*g* for 15 min. The supernatant was decanted, and the remaining part was weighed. WHC and OHC were calculated by the following equations.

$$WHC\ (\frac{g\ H_2O}{g\ starch}) = \frac{m_{wet\ starch} - m_{dry\ starch}}{m_{dry\ starch}} \quad (1)$$

$$OHC\ \left(\frac{g\ oil}{g\ starch}\right) = \frac{m_{sample} - m_{dry\ starch}}{m_{dry\ starch}} \quad (2)$$

Moisture and Oil Contents, Water Activity, and Rehydration Rate of Crackers

The moisture content of dried and puffed cracker samples was determined by the AOAC method 925.10 [12]. The water activity (a_w) of the samples was measured with a water activity analyser (Hygrolab C1, Rotronic, Bassersdorf, Switzerland) at room temperature.

To determine the amount of oil absorbed by the samples, the puffed cracker samples were weighed, crushed in a mortar and mixed with 15 mL of petroleum ether as an organic solvent. The mixture was filtered by using filter paper, and 5 mL more of petroleum ether was again added to the sediment. The solvent was evaporated at 50ºC for 15 min, and the final weight of the solid material left after evaporation was recorded [13].

For the rehydration ratio, approximately 5 g of cracker samples were weighed and submerged in 100 mL of water. After 30 min duration and 10 min draining period, the final weight of the samples was recorded [14]. The percentage of total oil content (TOC) of samples and rehydration ratio were calculated by Equations 3 and 4;

$$TOC\ (\%) = \frac{oil\ content\ after\ extraction}{oil\ content\ after\ extraction + weight\ of\ sample\ after\ extraction} \quad (3)$$

$$Rehydration\ ratio = \frac{m_{after\ rehydration} - m_{initial}}{m_{initial}} \quad (4)$$

Color

Color parameters (L*, a*, and b* values) of the samples were measured using a colorimeter (CR-400, Minolta Sensing, Osaka, Japan) according to [15] with some modifications. For this purpose, three different crackers and three different points on the surface of each cracker type were determined, and average L*, a* and b* values were calculated after measurement.

The browning index (BI) was calculated based on the CIE values of L*, a*, b* according to Equations 5 and 6 [16];

$$BI = \frac{X - 0.31}{0.17} \cdot 100 \quad (5)$$

$$X = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \quad (6)$$

Texture Analysis

Texture analysis of each cracker was performed using a TA-XT plus texture analyzer (Stable Micro System, Surrey, UK) equipped with a spherical probe (P/0.5S) with a crisp fracture support ring (HDP/CFS) for the hardness (N) and crispiness (dimensionless) at room temperature. Force vs time curves were generated by placing the sample centrally onto the crisp fracture rig where the distance between points was 10 mm. The test commenced in compression mode with a 50 kg load cell with pretest, test, and posttest speeds of 1.0, 0.5, and 5.0 mm/s, respectively. The target mode was selected as a distance of 4 mm and the trigger force was set as 5 g. The breaking maximum peak force (N) represented the hardness of the cracker, and the number of peaks (n) was measured as crispiness. An average of seven measurements with three replicates for each frying cracker produced with different starch types was reported.

Volume Expansion

The volume expansion of the crackers was determined by the seed displacement method with black cumin seed (AACC, Method 10-05.01) [17]. Crackers were placed in a beaker that was filled with black cumin. Then, the beaker was tapped several times to fill the gaps on irregular surfaces. The overflow volume of the black cumin was recorded. Volume expansion was calculated from the ratio of the volume difference between the dried cracker and the puffed cracker to the volume of the puffed cracker.

Thermal Properties of Crackers

Differential scanning calorimetry (DSC) (Q10, TA Instruments, New Castle, DE, USA) analysis was performed on both dried and fried samples. Approximately 6 mg of sample was enclosed in a hermetically sealed aluminum pan. The indium-calibrated system was purged with nitrogen gas at a 50 mL/min flow rate. From -20ºC to 100ºC at the rate of 10ºC/min, samples were scanned. In the calculation of specific heat (c_p), linear portions of the data were used, and the formula is given in Equation 7.

$$c_p = \frac{|Q_s - Q_b|}{h_r \cdot m} \cdot 60 \left(\frac{J}{g \cdot K}\right) \quad (7)$$

Where Q_s is the sample heat flow (mW), Q_b is the blank heat flow (mW), h_r is the heating rate (ºC/min), and m is the sample weight (mg).

Cooling Rate Evaluation

The cooling rate of the crackers was determined with a thermal camera (FLIR C5, FLIR System Inc., Wilsonville, Oregon, USA) having 160×120 pixels resolution and 8-14 µm spectral range. It had an accuracy of ±3ºC and an image frequency of 8.7 Hz. The temperature distribution of the cracker surfaces was observed at 30-130ºC for 90 s, and surface images of crackers were captured at every 30 s intervals immediately after frying.

Microstructure of Crackers

The cross-sectional morphologies of dried and fried puffed crackers were examined to analyze the volume expansion and textural changes of the crackers by using a scanning electron microscope (SEM, 250 Quanta FEG, FEI Company, Waltham, Massachusetts, USA). Fried samples were immersed in petroleum ether for 4 h after frying to remove the surface oil. Samples were gold-coated with a sputter coater (Emitech K550X, Quorum Technologies Inc., Laughton, East Sussex, UK) under 10 mA for 30 s.

Statistical Analysis

ANOVA was conducted to determine differences in the parameters for crackers formulated using different starch types (p≤0.05), and a Pearson correlation test was applied to analyze the relation between texture and volume expansion data using Minitab with a confidence level of 95% (ver.18.1, Minitab Inc., United Kingdom). All experiments were done in triplicate, each with duplicate measurements.

RESULTS and DISCUSSION

Physical Properties of Starches

In the microscopy, starches exhibited distinct shapes as polyhedral for CS, ellipsoid for PS, and spherical for TS as given in Figure 1a-c. From the obtained images, the particle size distribution of the starch granules was determined. The particle size profiles are given in Figure 1d. The mean particle size of the starches was found to be 11.62 µm, 92.36 µm and 58.08 µm for corn, potato and tapioca, respectively. Compared to corn starch granules, potato and tapioca starches had larger granules. Mishra and Rai [10] observed similar trends of the morphological properties of corn, potato, and tapioca starches, aligning with our microscopy results.

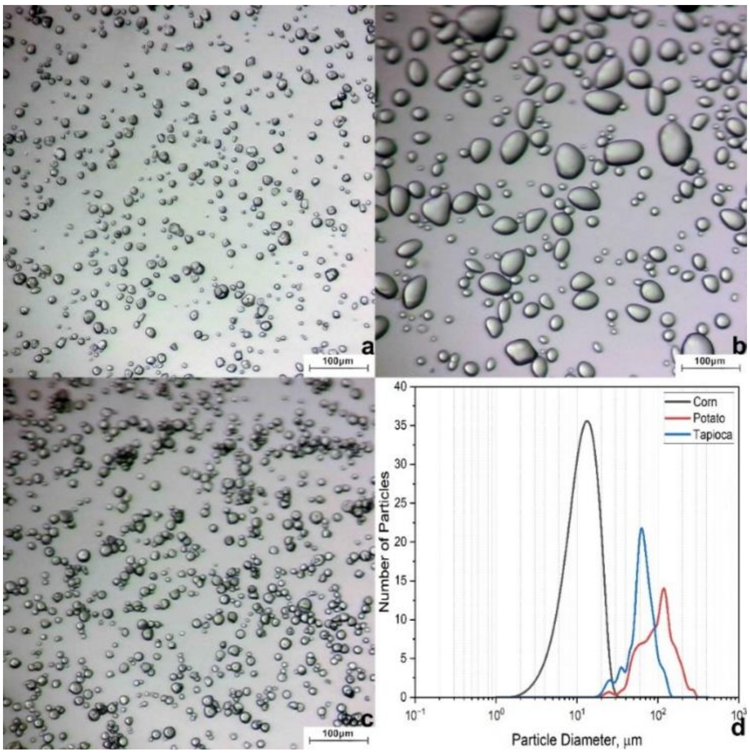

Figure 1. Starch granules of (a) corn, (b) potato, and (c) tapioca (Magnification: 10×, Scale bar: 100 µm), (d) Particle size distribution of the starches

Crystalline and amorphous forms of starches lead to different morphological shapes and sizes [18]. The measurement of crystallinity in starches is determined by their amylose/amylopectin content [19]. In our previous study, the amylose content was reported in the following order: potato > corn > tapioca, indicating that tapioca starch exhibited a higher crystalline state compared to the other starches [3]. The amylose content influences starch solubility and the degree of gelatinization [20]. The ratio of amylose to amylopectin is crucial for starch gelatinization. A higher amylose content delays gelatinization, resulting in the formation of harder and less expanded products [8]. Therefore, starches with lower amylose content are preferred to produce puffed crackers to achieve a crispier structure.

WHC and OHC results of starches are summarized in Table 2. WHC indicates the presence of water-binding sites, which are hydroxyl groups in starch chains that form covalent and hydrogen bonds [10]. Higher WHC values indicate greater moisture retention in products and facilitate starch gelatinization and dough formation. WHC is also positively correlated with amylose content in starch [20]. Our findings showed similar WHC values among starches. Additionally, all starches demonstrated similar OHC (approximately 1.00 g oil/g starch). OHC is a critical factor in starch gelatinization, as oils form complexes with amylose that inhibit granule swelling, thereby delaying gelatinization [20]. The researchers [20] investigated the physicochemical and functional properties of extracts from tubers such as cassava and sweet potato, reporting OHC values ranging from 0.962 to 1.152 g oil/g starch. Hence, the determination of WHC and OHC provides a better understanding of the puffing phenomena of cracker doughs.

Table 2. Water holding capacity (WHC) and oil holding capacity (OHC) results of starches

Starch Type*	WHC, g H_2O/g starch	OHC, g oil/g starch
S	0.81±0.16^{A}	1.04±0.08^{A}
PS	0.72±0.06^{A}	1.18±0.17^{A}
TS	0.69±0.08^{A}	1.05±0.12^{A}

*Mean ± standard deviation within a column followed by different letters is significantly different (p≤0.05). CS, PS, and TS denote for corn starch, potato starch, and tapioca starch, respectively.

Moisture and Total Oil Contents, Water Activity, and Rehydration Ratio of Crackers

The TOC, a_w and rehydration ratio of fried crackers are shown in Table 3. Drying is one of the intermediate steps used in the production of puffed crackers by providing micro pores in the matrix before expansion during frying. The moisture content of the dried crackers prepared using corn (D_{CS}), potato (D_{PS}), and tapioca starches (D_{TS}) was determined as 1.83±0.26, 1.66±0.15, and 5.19±0.05%, respectively. In their work, van der Sman and Broeze [8] stated that the puffing ability of the fried product proportionally increased with the moisture content of the product before puffing. Our results were consistent with this statement. Fried crackers prepared using potato starch (F_{TS}) exhibited greater puffing ability and volume expansion. The a_w of the dried crackers prepared using CS, PS, and TS was determined as 0.554, 0.476, and 0.482, respectively (data not shown). After frying (puffing with high temperature), the a_w values decreased by 1.6-fold for CS and 1.3-fold for both PS and TS, respectively. Similarly, Guraya and Toledo [4] also found a small moisture content change (1.03-fold) after puffing the sweet potato-tapioca mixture starch-based product. Therefore, the frying process resulted in a decrease in a_w values of puffed crackers.

During frying, oil uptake and moisture loss occurred simultaneously. Moreira et al. [13] described this phenomenon by attributing it to capillary force. The heat was transferred from the hot oil to the cracker surface while the moisture inside the cracker moved to the surface as vapor. The pores were formed by this intensive evaporation and some of the vapor could be trapped in these pores due to intercellular diffusion. After the cracker was removed from the fryer, due to the large temperature gradient the vapor was condensed in these pores to create positive capillary pressure. Thus, the oil was relocated with water vapor. Our results showed that the highest TOC value was measured for fried crackers prepared using potato starch (F_{PS}) (15.05%) and the lowest for fried crackers prepared using potato starch (F_{CS}) (8.65%) whereas the TOC value of F_{TS} (11.47%) was found in between. According to these results, the high oil content of puffed crackers with PS can be explained by their relatively high OHC value (Table 2). There was no significant difference between puffed crackers with CS and TS (p>0.05). The observed result might be attributed to an increase in pore size and surface area rather than capillary forces which can enhance oil absorption. The extent of this effect could influence by the composition of the cracker, as well as temperature and time, which impact the degree of bubble formation [21].

The rehydration ratio determines the extent of regeneration and sample damage resulting from processes such as drying and radio frequency treatment [14]. Table 3 shows that F_{CS} exhibited the highest rehydration ratio followed F_{TS} and F_{PS} that were similar to each other. Hence, CS was exposed to greater degradation compared to others, and alterations in the starch structure resulted in an increased solubility of the CS. Furthermore, structural damage in starch may result in a reduced degree of puffing due to solubility [22]. Xie et al. [14] indicated that different processing methods including radiofrequency (RF), hot air (HA), vacuum freezing (VF), and microwave (MW) alter the rehydration ratio of purple sweet potato chips. The highest rehydration ratios were observed with RF (3.42) and MW (3.16), while VF resulted in the lowest ratio (0.09). Therefore, blanching, drying and frying processes lead to a little structural damage to crackers at the end of production, and the rehydration ratio can serve as an indicator of puffing ability.

Table 3. Physical and textural properties of fried crackers with corn starch (F_{CS}), potato starch (F_{PS}), and tapioca starch (F_{TS})

Properties*	F_{CS}	F_{PS}	F_{TS}
TOC (%)	8.65 ± 0.40^{B}	15.1 ± 2.20^{A}	11.5 ± 2.96^{AB}
Water Activity, a_w	0.35 ± 0.003^{A}	0.37 ± 0.005^{A}	0.37 ± 0.006^{A}
Rehydration Ratio (%)	1.12 ± 0.04^{A}	1.07 ± 0.05^{AB}	1.02 ± 0.02^{B}
L*	73.57±4.81^{A}	70.21±8.74^{A}	67.71±0.51^{A}
a*	-4.00±1.07^{A}	-2.97±2.66^{A}	-3.84±0.15^{A}
b*	29.88±3.11^{A}	27.09±6.20^{A}	21.86±0.83^{B}
BI	46.89±9.96^{A}	46.67±20.6^{A}	33.64±5.85^{A}
Hardness (N)	11.6 ± 2.53^{B}	30.5 ± 3.90^{A}	15.2 ± 3.19^{B}
Crispiness (n)	10.6 ± 1.18^{B}	16.3 ± 3.36^{A}	17.6 ± 3.29^{A}
Volume Expansion (%)	206.89 ± 68.65 ^{A}	302.38 ±139.24^{A}	352.35 ± 82.5 ^{A}

Mean ± standard deviation within a row followed by different letters is significantly different ($p \leq 0.05$). F_{CS}, F_{PS}, and F_{TS} denote the fried puffed crackers prepared with corn starch, potato starch, and tapioca starch, respectively. TOC: Total oil content, L: lightness; a*: redness-greenness; b*: blueness-yellowness; BI: browning index

Color

The color characteristics of puffed crackers are shown in Table 3, indicating slight differences in color values among crackers containing different starches. The L* values, which indicate the brightness of an object on a scale from 0 (black) to 100 (white) were found in a ranged between 67.21 and 73.57. The a* and b* values, which indicate the chroma of an object and range from -120 to +120, represent redness-greenness and blueness-yellowness, respectively [16]. For the crackers, the a* values for F_{CS}, F_{PS}, and F_{TS} were -4.00, -2.97, and -3.84, respectively, while the b* values ranged from 20.00 to 30.00. Kim, Yun, and Jeong [23] reported comparable findings in their study on the effect of corn, potato, and tapioca starches on the quality of gluten-free rice breads with L* values ranging from 62.67 to 69.24 and the b* values between 17.57 and 25.3. Consequently, the color values of crackers made with CS, PT, and TS were comparable after frying.

The BI reflects the extent of non-enzymatic browning reactions such as the Maillard Reaction and caramelization in baked and fried products [24]. Table 3 shows BI values for the puffed crackers. The degree of browning varied among cracker types, with F_{CS}, F_{PS}, and F_{TS} exhibiting decreasing levels of browning, respectively. Specifically, crackers made with corn and potato starches tended to exhibit almost 1.4-fold more browning during frying compared to those made with tapioca starch, likely due to differences in molecular composition. The Maillard reaction is a type of non-enzymatic browning reaction between reducing sugars and proteins, and forms melanoidins (brown color products) at the end [25]. The formation of melanoidins leads to an increase in BI value. Corn and potato starches contain 0.5 g and 0.6 g of protein, respectively, whereas tapioca starch does not contain any protein (Table 1). In that regard, corn and potato starches were found more susceptible to the Maillard reaction, whereas the browning observed in tapioca starch might be attributed to a different non-enzymatic reaction [26].

Texture Analysis and Volume Expansion

The texture analysis results of each cracker prepared with CS, PS and TS are shown in Table 3. After frying, crackers prepared with PS exhibited approximately twice the hardness compared to those made with CS and TS. Conversely, PS and TS showed higher crispiness values than CS. Despite the high moisture content (15.9%) and WHC (0.78), the high amylose rich starch content (82.2%) with mean particle size of 92.36 µm, lipid content (1.2%) and low OHC (0.62 g/g) of PS resulted in a coarse, less aerated dough structure, leading to less effective puffing and a denser, harder cracker with moderate crispiness. Similarly, Nath et al. [5] reported that an increase in moisture content beyond a certain level during the air puffing process of potato snacks adversely affected the expansion of the snack by increasing the hardness. Otherwise, they indicated that good retention of water aids in better puffing, creating a larger surface area and softer texture up to a certain limit. On the other hand, amylose content also plays a critical role in gelatinization; higher levels of free amylose exhibit moderate elasticity, which can retard puffing (bubble expansion) during frying [8]. However, soluble solids or oil content are undesirable as they can interfere with starch gelatinization and thus affect puffing performance [4]. As such in CS, the high starch content (84%) and adequate WHC (0.78) should give better puffing performance, but CS results in a softer, less crispy cracker due to containing moderate protein (0.5%) and high ash content (2.25%). Also, CS had the smallest particle size (11.62 µm), leading to less cohesive structure with reduced textural properties. On the other hand, moderate starch content (82%) with intermediate particle size (58.08 µm), lower moisture content (12.7%) and WHC (0.67) of TS suggested less water retention, which might lead to a slightly drier dough, but the highest lipid content (3.9%) and higher OHC (0.82) balanced the texture, contributing to intermediate hardness and high crispiness. Thus, for achieving the desired textural quality in puffed crackers, these results help to select the appropriate starch type for further operations.

Table 3 presents the volume expansion results of crackers prepared with different starches. The standard deviation observed in the volume expansion data was relatively high, which can be attributed to the inherent variability of the puffing process. During puffing, each sample expands to a different extent, resulting in variations in final product size. The puffing ability of the starches appeared to follow a decreasing order of tapioca>potato>corn. This variation might be attributed to differences in starch and protein content among the crackers. Wang et al.[27] investigated the influence of banana flour substitution for cassava starch on the texture, color, and sensory attributes of crackers. They highlighted that the type of starch and protein content significantly affect cracker expansion due to the gelatinization process of starches, rapid vaporization within the starch matrix, and the inhibitory effect of proteins on amylopectin expansion. Hence, we can conclude that tapioca starch exhibits superior gelatinization, rapid vaporization, and higher amylopectin content compared to potato and corn starches in fried crackers.

A similar trend was observed between volume expansion and crispiness of crackers (Table 3). Higher crispiness correlated positively with greater volume expansion of crackers (Pearson correlation coefficient, r=0.986, p=0.05). Consequently, crackers made with F_{TS} demonstrated the highest crispiness and largest volume expansion. This correlation has also been noted by other researchers. Guttifera et al. [28] found a correlation between volume expansion and hardness in puffed fish crackers. Wang et al. [27] examined the porosity and bulk density of puffed crackers containing green banana flour-substituted cassava starch with minced fish, confirming that higher expansion results in greater porosity and preferred crispiness among consumers.

Thermal Properties of Crackers

The thermograms obtained from DSC analysis are given in Figure 2.

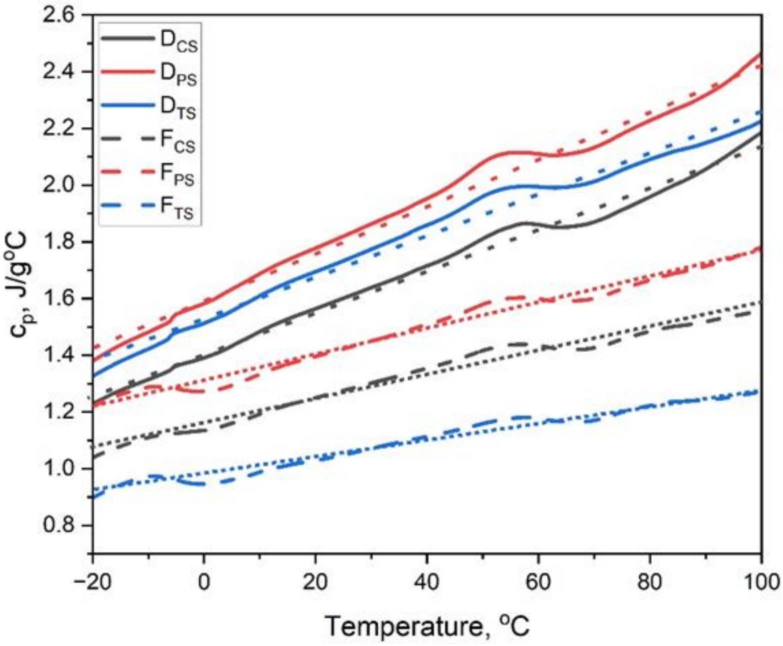

Figure 2. Thermograms of dried and fried samples. D_{CS}, D_{PS} and D_{TS} denote dried crackers prepared with corn, potato and tapioca starches, respectively. F_{CS}, F_{PS} and F_{TS} denote fried crackers prepared with corn, potato and tapioca starches, respectively

The specific heat equation from linear fitting of the data is given in Table 4. In the dried samples, the most temperature-dependent c_p value PS the containing formulation. CS and TS containing dried samples have the same temperature dependency. The order of c_p values at 0ºC is PS>TS>CS, meaning that the PS containing dried cracker requires more heat to elevate the temperature by 1 unit. After frying, the c_p values of all samples decreased due to moisture loss and increased oil content [29]. The lowest c_p value was observed in the TS containing sample due to high expansion and rapid evaporation of water as explained in the study of Sahin et al. [30].

Table 4. Temperature-dependent specific heat values of the dried and fried samples of corn starch (CS), potato starch (PS) and tapioca starch (TS) containing samples

Sample	Specific heat (c_p) of dried samples (J/gºC)*	Specific heat (c_p) of fried samples (J/gºC)
CS	1.4038+0.0073T; R^2=0.9906	1.1582+0.0042T; R^2=0.9769
PS	1.5947+0.0083T; R^2=0.9884	1.3088+0.0046T; R^2=0.9829
TS	1.5312+0.0073T; R^2=0.9831	0.9753+0.0031T; R^2=0.9747

*T denotes temperature in °C and R^2 denotes the coefficient of determination for the temperature-dependent specific heat values equations.

Cooling Rate

The temperature distribution and cooling rate of crackers at different time intervals are illustrated in Figure 3. The central region of the crackers serves as the hot spot, with cooling progressing from the outer layers towards the center. Crackers made with tapioca starch exhibit more pronounced hot spots at the center compared to those made with potato and corn starches, as evidenced by the layered temperature distribution of F_{TS} (Figure 3g-i). Consequently, the sequence of cooling rates can be ordered as potato, corn, and tapioca, respectively. This variation in cooling heat transfer may be attributed to differences in geometric properties. Higher moisture content enhances puffing and promotes the formation of a larger surface area, but it also leads to non-uniform cooling and prolonged cooling periods as areas with higher moisture content retain heat longer, resulting in uneven cooling and potentially affecting the final texture and structural integrity of the puffed crackers [31]. Similarly, Mao et al. [31] observed a linear relationship between moisture content (15–55%) and heating rate of purple sweet potato chips during radio frequency (RF) heating, but an inverse relationship with heating uniformity. Xie et al. [14] studied the effects of RF heating on puffing of the of purple sweet potato chips that have different thicknesses ranging from 1 to 3 mm, and moisture content (40-60%) finding that the heating rate increases proportionally with moisture content while decreasing with sample thickness in RF heating. Therefore, controlled cooling can contribute to maintaining desirable textural properties of puffed crackers.

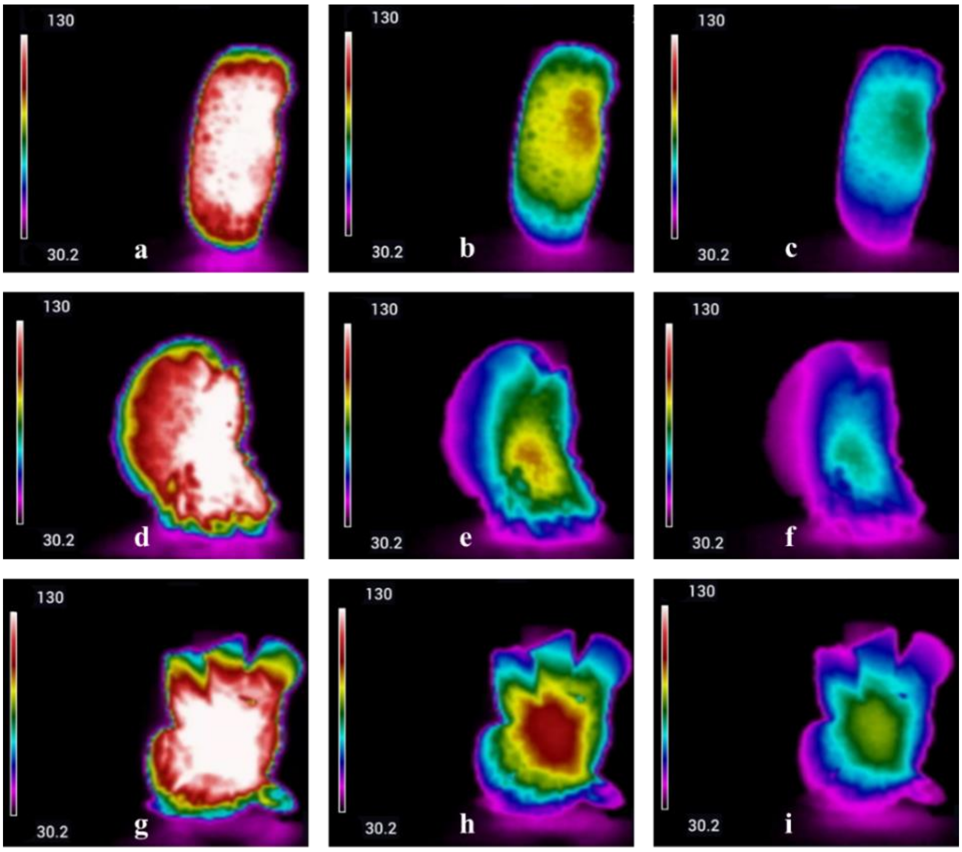

Figure 3. Thermal camera images of F_{CS} at (a) 30 s, (b) 60 s and (c) 90 s; F_{PS} at (d) 30 s, (e) 60 s and (f) 90 s; F_{TS} at (g) 30 s, (h) 60 s and (i) 90 s. F_{CS}, F_{PS}, and F_{TS} denote the fried crackers prepared with corn starch, potato starch, and tapioca starch, respectively

Microstructure of Crackers

Heat and mass transfer during the frying process cause microstructural changes in the food matrix that affect the texture properties [32]. Microstructural properties such as pore size, pore distribution, and porosity should be known to improve the texture of the food and to determine the heat transfer patterns [32,33]. In this study, the effect of puffing with the frying process for crackers prepared using corn, potato, and tapioca starches on microstructural properties was investigated by SEM. The cross-sectional images of dried crackers are shown in Figure 4a-c and fried crackers are shown in Figure 4d-f.

The pore sizes taken from the SEM micrographs are shown in Table 5. When the dried samples were compared, D_{TS} and D_{PS} had similar pore sizes that were almost 2.4-fold higher than D_{CS}. However, after frying, while the pore size increased by 10.4-fold and 10.7-fold for F_{CS} and F_{TS}, respectively, it showed a 4.7-fold increase for F_{PS}. It appears that dried crackers showed a much more compact and less porous structure compared with fried crackers. Also, among all samples, it was determined that the pore distribution on the F_{PS} was more regular. The pore expansion was more obvious in F_{TS}, which could be related to vapor expansion and pore disruption due to low c_p measured. Under similar thermal conductivity and density range, lower c_p value means that the material has greater thermal diffusivity and yield with faster heating. Depending on these findings, the largest pore sizes could be related to rapid heating. Additionally, it was previously stated that pore enlargement increased air and oil penetration as well as crispiness [32]. Accordingly, F_{TS} is expected to have the crispiest texture as found in section Texture Analysis and Volume Expansion. Lastly, since the puffing event did not occur homogeneously at every point, a large deviation was observed between the pore size data.

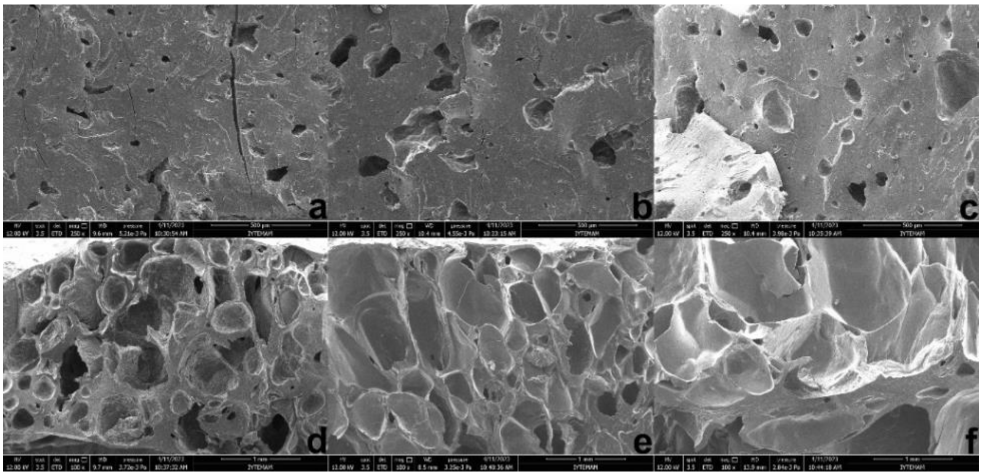

Figure 4. Cross-sectional morphology of crackers: (a) D_{CS}; (b) D_{PS}; (c) D_{TS} (Magnification: 250×, Scale bar: 500 µm); (d) F_{CS}; (e) F_{PS}; (f) F_{TS} (Magnification: 100×, Scale bar: 1 mm). D_{CS}, D_{PS}, and D_{TS} denote the dried crackers prepared with corn starch, potato starch, and tapioca starch, respectively. F_{CS}, F_{PS}, and F_{TS} denote the fried crackers prepared with corn starch, potato starch, and tapioca starch, respectively

Table 5. Pore sizes of dried and fried crackers prepared with corn, tapioca and potato starches

Samples*	Pore size (µm)
D_{CS}	58.6±38.3^{D}**
D_{PS}	144.3±46.1^{C}
D_{TS}	141.0±90.8^{C}
F_{CS}	610.9±249.5^{B}
F_{PS}	674.0±351.0^{B}
F_{TS}	1537.0±233.2^{A}

*D_{CS}, D_{PS}, and D_{TS} denote the dried crackers prepared with corn starch, potato starch, and tapioca starch, respectively. F_{CS}, F_{PS}, and F_{TS} denote the fried crackers prepared with corn starch, potato starch, and tapioca starch, respectively. **Means ± standard deviation within a column followed by different letters are significantly different (p≤0.05).

CONCLUSION

In this study, the effect of different starch types on some of the physical and textural properties of starch-based puffed crackers was investigated. The puffing ability of starches showed a proportional increase with the initial moisture content of dried crackers, but the high amylose content caused a decrease in puffing. After frying dried crackers, the volume expansion of puffed crackers was found to be positively correlated with crispiness. The low c_p value of F_{TS} led to rapid heating during frying and the largest pores. Additionally, the difference in the microstructural level of crackers was visually seen and related to the different porosity behavior of starches. Thus, this study provides valuable insights into optimizing the formulation and processing conditions for producing high-quality potato-based puffed crackers. Although the present work focused on only three types of starch and the laboratory-scale experiments, future work will be required to include additional starch types and scale up to commercial production levels. The outcomes of this work will be beneficial in revealing the effect of different starches on the puffing of starch-based crackers.

AUTHOR CONTRIBUTIONS

Conceptualization was done by YSC. Investigation, methodology, data curation and writing-original draft were done by YSC, BB and EÇ. Also, data curation was done by EK and HY. Review and editing were done by SÜ. SÜ had supervised the entire research work. All authors of this research read the manuscript and agreed to publish it.

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REFERENCES

[1] Forbes, S.L., Kahiya, E., Balderstone, C. (2016). Analysis of snack food purchasing and consumption behavior. *Journal of Food Products Marketing*, 22(1), 65-88.

[2] Statista Research Department. (2022). Snack Food Market Volume By Segment Worldwide 2027.

[3] Berk, B., Cankal, Y.S., Köroğlu, E., Yorulmaz, H., Çavdaroğlu, E., Ünlütürk, S. (2024). The effect of starch types on extensional, linear and nonlinear rheological properties of starch cracker dough. *International Journal of Biological Macromolecules*, 277(Part 1), 133848.

[4] Guraya, H.S., Toledo, R.T. (1994). Volume expansion during hot air puffing of a fat-free starch-based snack. *Journal of Food Science,* 59(3), 641-643.

[5] Nath, A., Chattopadhyay, P.K., Majumdar, G.C. (2007). High temperature short time air puffed ready-to-eat (RTE) potato snacks: Process parameter optimization. *Journal of Food Engineering*, 80(3), 770-780.

[6] Shah, Y., Takhar, P.S. (2022). Pressure development and volume changes during frying and post-frying of potatoes. *LWT*, 172, 114243.

[7] He, Y., Ye, F., Zhang, Z., Zou, Y., Li, S., Chen, J., Zhao, G. (2023). Unraveling the regulating mechanisms of moisture content in the puffing of sweet potato starch gel. *International Journal of Biological Macromolecules*, 233, 123490.

[8] Van Der Sman, R.G.M., Broeze, J. (2013). Structuring of indirectly expanded snacks based on potato ingredients: A review. *Journal of Food Engineering*, 114(4), 413-425.

[9] Kantrong, H., Klongdee, S., Jantapirak, S., Limsangouan, N., Pengpinit, W. (2022). Effects of extrusion temperature and puffing technique on physical and functional properties of purpled third-generation snack after heat treatment. *Journal of Food Science and Technology*, 59(6), 2209-2219.

[10] Mishra, S., Rai, T. (2006). Morphology and functional properties of corn, potato and tapioca starches. *Food Hydrocolloids,* 20(5), 557-566.

[11] Olu-Owolabi, B.I., Afolabi, T.A., Adebowale, K.O. (2011). Pasting, thermal, hydration, and functional properties of annealed and heat-moisture treated starch of sword bean (*Canavalia gladiata*). *International Journal of Food Properties*, 14(1), 157-174.

[12] AOAC (2005). Official Method 925.10 – Moisture in Flour (by Air-Oven). in: W. Horwitz, G. Latimer (Eds.), Off. Methods Anal., 18th edition, Gaithersburg, Maryland, USA.

[13] Moreira, R.G., Palau, J., Sweat, V.E., Sun, X. (1995). Thermal and physical properties of tortilla chips as a function of frying time. *Journal of Food Processing and Preservation*, 19(3), 175-189.

[14] Xie, Y., Liu, Q., Mao, C., Pang, H., Ye, P., Cui, B., Chen, X., Fu, H., Wang, Y., Wang, Y. (2024). Radio frequency puffing of purple sweet potato nutritious snacks. *Journal of Food Engineering*, 367 (December 2023).

[15] Ciemniewska-Żytkiewicz, H., Bryś, J., Bryś, A., Sujka, K., Koczoń, P. (2014). Effect of roasting process on moisture content and colour of polish inshell hazelnuts. *Akademik Gıda,* 12(1), 6-10.

[16] Pathare, P.B., Opara, U.L., Al-Said, F.A.-J. (2013). Colour Measurement and analysis in fresh and processed foods: A review. *Food and Bioprocess Technology*, 6(1), 36-60.

[17] AACC (2010). Method 10-05.01. Guidelines for Measurement of Volume by Rapeseed Displacement. in: Approv. Methods Anal., 11th edition, St. Paul, Minesota, USA.

[18] LeCorre, D., Bras, J., Dufresne, A. (2011). Influence of botanic origin and amylose content on the morphology of starch nanocrystals. *Journal of Nanoparticle Research*, 13(12), 7193-7208.

[19] Lemos, P.V.F., Barbosa, L.S., Ramos, I.G., Coelho, R.E., Druzian, J.I. (2018). The important role of crystallinity and amylose ratio in thermal stability of starches. *Journal of Thermal Analysis and Calorimetry*, 131(3), 2555-2567.

[20] Azima, F., Nazir, N., Efendi, H.C. (2020). Characteristics of physico-chemical and functional properties of starch extracts from tubers. *Journal of Physics: Conference Series*, 1469, 012002.

[21] Chang, H., Chen, H. (2013). Association between textural profiles and surface electromyographic (sEMG) behaviors of microwavable cassava cuttlefish crackers with various expansion ratios. *Food Research International*, 53(1), 334-341.

[22] Huang, J., Zhang, M. (2016). Effect of three drying methods on the drying characteristics and quality of okra. *Drying Technology*, 34 (8), 900-911.

[23] Kim, M., Yun, Y., Jeong, Y. (2015). Effects of corn, potato, and tapioca starches on the quality of gluten-free rice bread. *Food Science and Biotechnology*, 24(3), 913-919.

[24] Köprüalan, Ö., Elmas, F., Bodruk, A., Arikaya, S., Koç, M., Koca, N., Kaymak-Ertekin, F. (2021). Impact of pre-drying on the textural, chemical, color, and sensory properties of explosive puffing dried white cheese snacks. *LWT*, 154, 112665.

[25] Ke, C., Li, L. (2023). Influence mechanism of polysaccharides induced Maillard reaction on plant proteins structure and functional properties: A review. *Carbohydrate Polymers*, 302, 120430.

[26] Pantoa, T., Pongpaew, P., Thirathumthavorn, D., Prabsangob, N.,Udomrati, S. (2024). Heat-drying and size reduction-treated tapioca flour stabilized oil-in-water emulsion-loaded eugenol: Physical properties, stability, and in vitro gastrointestinal digestion. *Future Foods*, 9, 100358.

[27] Wang, Y., Zhang, M., Mujumdar, A. (2012). Influence of green banana flour substitution for cassava starch on the nutrition, color, texture and sensory quality in two types of snacks. *LWT*, 47, 175-182.

[28] Guttifera, Rahmawati, L., Sari, S.R., Pratama, F., Widowati, T.W. (2022). Traditional puffed fish cracker ('kemplang Palembang') by microwave-oven method: Physical properties and microstructure evaluation. *Czech Journal Food Sciences,* 40(3), 202-209.

[29] Sahin, S., Sumnu, S.G. (2006). Physical Properties of Foods. Springer, New York, USA.

[30] Sahin, S., Sastry, S.K., Bayindirli, L. (1999). Heat transfer during frying of potato slices. *LWT*, 32(1), 19-24.

[31] Mao, C., Ye, P., Liu, T., Song, M., Xie, Y., Pang, H., Wang, Y., Chen, X., Wang, K. (2024). Evaluation of mechanical properties, heating rate and radio frequency explosive puffing (RFEP) quality of purple

sweet potato under different moisture contents and moisture equilibrium process. *Innovative Food Science and Emerging Technologies*, 93, 103611.

[32] Alam, T, Takhar, P.S. (2016). Microstructural characterization of fried potato disks using X-ray Micro computed tomography. *Journal of Food Science*, 81(3), E651-E664.

[33] Zhang, J., Liu, Y., Fan, L. (2020). Effect of pore characteristics on oil absorption behavior during frying of potato chips. *Innovative Food Science & Emerging Technologies*, 66, 102508.