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Research Article

Characterization of Dietary Fibers from Corn Cobs as A Potential Functional Ingredient in Muffin

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ABSTRACT

Dietary fiber (DF) has gained significant attention due to its potential health benefits. Corn cobs, a by-product of corn that is rich in minerals and low in protein, represent a valuable source of DF. This study investigated the fiber content of corn cobs and evaluated its potential use in bakery products to provide enhanced nutritional options. The physicochemical properties of the extracted fiber, including Fourier transform infrared spectroscopy, water-holding capacity (WHC), oil-holding capacity (OHC), swelling capacity (SC), glucose adsorption capacity (GAC), and cholesterol adsorption capacity (CAC), were assessed. Three extraction methods were employed: water, acid, and alkali. Water extraction yielded the highest total DF at 98.12% (p<0.05) and the highest insoluble DF at 69.40%, excelling in OHC, SC, and CAC. Alkali-extracted fiber demonstrated superior WHC, while acid-extracted fiber showed the highest GAC. Muffins enriched with fiber extracted using these methods were compared to the control group (without fiber), revealing no significant differences in texture, except for cohesiveness. In conclusion, water extraction is the most advantageous method, providing the highest yields, enhanced safety, and a muffin texture comparable to those made with fiber from acid and alkali extraction without compromising quality.

Key words: Corn by-products, fiber extraction, functional ingredients, physicochemical analysis, textural properties

INTRODUCTION

Corn (*Zea mays* L.; family: Poaceae) is one of the most adaptable new cereal crops, with a wide range of adaptations to various climatic conditions. It is the third most important cereal crop after wheat and rice (Ramessar *et al*., 2008). Various types of corn are cultivated around the world, such as dent corn, flint corn, sweet corn, popcorn, flour corn, pod corn, and waxy corn. In Malaysia, corn is widely cultivated, with approximately 80% of the total primary production originating from several states, including Perak, Johor, and Sarawak (US Department of Agriculture, 2021).

The corn processing industry produces various products, such as corn starch for thickening, corn oil for frying and biodiesel, corn syrup and dextrose as sweeteners, corn grits and flour for cooking, corn gluten meal for animal feed, corn steep liquor as fertilizer, ethanol as a biofuel, and nixtamalized corn products like masa for traditional dishes (Jiao *et al*., 2022). However, during this process, several by-products or waste materials are generated, including corn cobs, which are high in fiber. Corn cobs contain approximately 81.24% total dietary fiber (TDF), comprising 78.53% insoluble dietary fiber (IDF) and 2.71% soluble dietary fiber (SDF) (Njideka *et al*., 2020). Previously, agro-waste such as corn cobs was utilized as animal feed or organic fertilizer, left to decompose naturally in fields, or disposed of through burning. However, due to the large volume of waste generated by the industry and the decreased demand for certain products, such as raw materials and packaging, as well as by-products from corn processing, current practices involving on-farm burning, burial, stockpiling, and landfilling are harmful to both humans and the environment (Agamuthu, 2009). Therefore, a more sustainable waste management approach that emphasizes reduction, reuse, and recycling practices is gaining increased attention nowadays.

Fiber is a vital nutrient that the body cannot produce or digest, and its consumption is associated with various health benefits. It can be incorporated into various functional foods including baked goods, drinks, beverages, and meat products. The bakery industry has experienced the most rapid growth in the use of dietary fiber (DF), with sales expected to reach approximately 110 kilotons by 2026 (Ahuja & Malkani, 2024). Additionally, DF is often used as a food additive to enhance specific characteristics of food products (Ma *et al*., 2015; Baye *et al*., 2017). It can also extend the shelf life of high-fat food products by increasing the antioxidant capacity of emulsions (Elleuch *et al*., 2011). The demand for edible fiber is projected to reach USD 2,701.45 billion in 2022 and USD 4,434 billion by 2033 (Taj, 2022). Despite the increasing demand for fiber, the utilization of fibers from alternative sources remains underexplored. Unlocking the potential of underutilized products, such as corn cobs, to produce edible fiber can effectively address the waste problem, particularly in the corn industry.

The separation of DF into its constituents presents a challenge, as there are limited techniques available for this process. Previous studies have employed extraction methods using water, ethanol, alkali, and acid to extract fiber from various plant

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wastes, such as wheat straw (Qasim *et al*., 2020), orange peel (Wang *et al*., 2015), and apple pomace (Fidriyanto *et al*., 2023). It has been reported that different extraction methods can have varying impacts on the properties of the resulting fiber. Therefore, it is essential to evaluate multiple extraction methods for their efficiency on particular plant sources and the yield of fiber that can be extracted. Following the extraction process, the resulting fiber should undergo several analyses of its physicochemical parameters to gain a better understanding of its behavior when incorporated into food applications. By utilizing waste materials like corn cobs in the production of various food products, this approach helps address waste management issues while maximizing the nutritional potential of these by-products. Therefore, to explore this potential, this study aims to evaluate the effects of different extraction methods (water, acid & alkali) on the physicochemical properties of the DF derived from corn cob waste. The resulting DFs were assessed for their potential as a functional ingredient in bakery products, specifically muffins, through a series of texture profile analyses, as the texture is a critical quality attribute that influences consumer acceptance and marketability.

MATERIALS AND METHODS

Materials

Fresh corn, approximately three months old, was purchased from a local farm in Chuping, Perlis, located in the northern region of Malaysia. All reagents used in the experiments, including hydrochloric acid (HCl), sodium hydroxide (NaOH), ethanol, distilled water, glucose solution, and 3,5-Dinitrosalicylic acid (DNS) reagent, were purchased from Sigma-Aldrich (Darmstadt, Germany). These reagents were of analytical grade and were used without further purification. Meanwhile, all the ingredients used in the preparation of muffins, including wheat flour, sugar, whole eggs, baking powder, sunflower oil, milk, and DF from corn cobs, were purchased from a local supermarket.

Preparation of corn cob powder

Before preparation, the corn kernels were removed from the corn to obtain the corn cobs. On average, corn kernels measure 7–12 mm in length and 5–10 mm in width, weighing between 0.3 and 0.5 g. The corn cobs when then cut into 5 cm pieces and frozen in a deep freezer at -18°C before being dried in a dryer (QLD-380, QRLab) at 50°C for 24–48 hr until the weight remained constant. To produce corn cob flour, the freeze-dried corn cobs were finely ground in a heavy-duty blender (Waring, USA), sieved through 150 mesh screens, and stored in an airtight container at room temperature (25°C).

Extraction of corn cob fiber

Extraction with water

The extraction method followed the procedure of Twarogowska *et al*. (2020) with slight modifications. First, 25 g of corn cob powder was mixed with 250 mL of distilled water, along with adjustments to the concentration of NaOH, soaking duration, and ethanol precipitation. The mixture was then heated at 90°C in a water bath (Sigma-Aldrich, Darmstadt, Germany). The liquid and solid parts were separated through filtration. The filter residue was washed with pure water (95%) three times. Subsequently, it was oven-dried at 60°C until a constant weight was achieved, resulting in water-extracted insoluble dietary fiber (W-IDF). The precipitation step involved the addition of 95% ethanol, which was made up to the volume of the filtrate. After 24 hr of incubation at room temperature (25°C), the precipitate was collected by centrifugation (Thermo Fisher Scientific, Waltham, MA, USA) for 10 min at 4,910 rpm. The precipitate was dried in the oven (Thermo Fisher Scientific, Waltham, MA, USA), yielding water-extracted soluble dietary fiber (W-SDF). The extraction yield was determined using the following equation, in which the value of W was replaced by the weight of W-IDF or W-SDF.

Extraction with acid

The extraction method was modified based on the work of Ajanth Praveen *et al*. (2019). First, 25 g of corn cob powder was soaked twice for 3 hr in 250 mL of 1% (v/v) HCl at 4°C. The mixture was then filtered to separate the liquid and solid parts. The filter residue was washed with pure water (95%) until neutral. Subsequently, it was dried using hot air at 60°C until a constant weight was achieved, resulting in the production of acid-extracted insoluble dietary fiber (AC-IDF). The filtrate was neutralized with an equal amount of 1% (w/v) NaOH. Following this, 95% (v/v) ethanol was made up to the volume of the filtrate obtained, leading to the formation of a precipitate. After 24 hr at room temperature (25°C), the precipitate was separated by centrifugation (Thermo Fisher Scientific, Waltham, MA, USA) for 10 min at 4,910 rpm. The acid-extracted soluble dietary fiber (AC-SDF) was obtained after dialysis against water and lyophilization. The extraction yield was determined using the equation.

$$Y\ (\%) = \frac{W}{W_{cp}} \times 100\%$$

Where W is the weight of AC-IDF or AC-SDF and W_{cp} is the weight of the corn cob powder.

Extraction with alkali

The extraction method was conducted according to Wang *et al*. (2021) with slight modifications to the concentration of NaOH, soaking duration, and ethanol precipitation. First, 25 g of corn cob powder was soaked twice for 3 hr in 250 mL of 4% (w/v) NaOH (1:40, w/v) at 4°C. The mixture was then filtered to separate the liquid and solid parts. The filter residue was washed with pure water (95%) until neutral, followed by oven-drying at 60°C until a constant weight was achieved, resulting in alkali-extracted insoluble dietary fiber (AL-IDF). The filtrate was neutralized with an equal amount of 1% (v/v) HCl. Subsequently, 95% ethanol was added to the volume of the filtrate obtained to form a precipitate. After 24 hr at room temperature (25°C), the precipitate was separated by centrifugation (Thermo Fisher Scientific, Waltham, MA, USA) for 10 min at 4,910 rpm. The alkali-extracted soluble dietary fiber (AL-SDF) was obtained after dialysis against water and lyophilization. The extraction yield was determined using a similar equation to that of acid extraction, in which the value of W was replaced by the weight of AL-IDF or AL-SDF.

Characterization of the extracted corn cob fiber

Fourier transform infrared spectroscopy

The Fourier transform infrared (FTIR) spectra of DF samples were obtained using the Thermo Scientific Nicolet iS50 FTIR spectrometer (Waltham, MA, USA). Before conducting FTIR scanning in the frequency range of 4000–400 cm^{-1}, the dried extracted fiber was ground with potassium bromide (KBr) powder and pressed into pellets, using a ratio of 2 mg of DF sample to 200 mg of KBr for each pellet. Fourier transform infrared spectroscopy was used to identify the organic functional groups and assess the molecular structures of the corn cob fibers.

Water-holding capacity

The water-holding capacity (WHC) procedure was conducted following the methodology of Wang *et al*. (2015) with slight modifications to the sample weight, volume of distilled water, incubation time, centrifugation speed, and duration. First, 0.2 g of extracted fiber was weighed and mixed with 5 mL of distilled water. The mixture was then incubated at room temperature (25°C) for 2 hr. Subsequently, the mixture was centrifuged for 10 min at 4,910 rpm. Finally, the collected sediment was weighed, and the WHC was calculated using the equation.

$$WHC\ (g/g) = \frac{W_2 - W_1}{W_1}$$

Where W_1 is the initial weight of water (g) and W_2 is the weight of water after centrifugation (g).

Oil-holding capacity

The oil-holding capacity (OHC) procedure was conducted following the methods established by Zhang *et al*. (2009). First, 0.2 g of extracted fiber was weighed and mixed with 5 mL of sunflower oil. The mixture was then incubated at room temperature (25°C) for 2 hr. After incubation, the mixture was centrifuged for 10 min at 4,910 rpm. Finally, the residue that was separated from the supernatant was weighed, and the OHC was calculated using the equation.

$$OHC\ (g/g) = \frac{O_2 - O_1}{O_1}$$

Where O_1 is the initial weight of oil (g) and O_2 is the weight of oil after centrifugation (g).

Swelling capacity

The swelling capacity (SC) procedure was modified based on the methodology described by Qiao *et al*. (2021), with adjustments made to the sample weight, volume of distilled water, incubation time, and centrifugation speed. An accurate 0.5 g of extracted fiber was weighed and transferred into a measuring tube containing 5 mL of distilled water. The initial volume was then recorded. The samples were left to set for 24 hr at room temperature (25°C). Finally, the final volume of the extracted fiber was recorded, and the SC was calculated using the equation.

$$SC\ (mL/g) = \frac{V_2 - V_1}{V_1}$$

Where V_1 is the volume of the hydrated fiber (mL) and V_2 is the volume of the fiber before hydration (g).

Glucose adsorption capacity

The glucose adsorption capacity (GAC) procedure was modified based on the methodology described by Chen *et al*. (2013), with adjustments made to the sample weight, glucose solution concentration, centrifugation speed, and duration. Approximately 0.1 g of the extracted fiber was mixed with 10 mL of glucose solution (50 mmoL/L). The mixture was shaken for 2 hr at 37°C and 120 rpm before being centrifuged for 15 min at 4,000 rpm. In a graduated test tube, 1.0 mL of supernatant was collected and combined with 1.5 mL of DNS reagent. The mixture was then submerged in boiling water for 15 min. After cooling to room temperature (25°C), the corn cob powder volume was made up with distilled water. A control sample was prepared without the addition of the extracted fiber in the solution, and the absorbance was measured using a spectrophotometer (Thermo Scientific, MA, USA) at 550 nm. The GAC was calculated using the equation.

$$GAC\ (mmol/g) = \frac{(A_i - A) \times v}{m}$$

Where A is the reducing sugar content (g/100 g), A_i is the reduced sugar content in the blank group (g/100 g), v is the volume of the solution, and m is the weight of the sample (g).

Cholesterol absorption capacity

The cholesterol absorption capacity (CAC) was analyzed using the method described by Daou *et al*. (2014) with slight modifications, including adjustments to the sample weight, pH, and incubation conditions. Egg yolk and distilled water were combined in a 1:9 volume ratio and thoroughly mixed to create a uniform diluted yolk solution. Approximately 0.8 g of the extracted fiber was then added to 10 mL of the diluted yolk solution, and the pH of the mixture was adjusted to 7. Afterward, the mixture was incubated at 37°C in a shaker water bath (Sigma-Aldrich, Darmstadt, Germany) for 2 hr. A diluted yolk solution without the extracted fiber served as the blank. The mixture was centrifuged at 4,910 rpm for 10 min, and a control group was prepared in the absence of the extracted fiber in the solution. The absorbance of the supernatant was measured at 535 nm. The CAC was calculated using the equation.

$$CAC\ (mg/g) = \frac{C_b - C_d}{W}$$

Where C_d is the cholesterol content in the diluted yolk containing DF (mg), C_b is the blank diluted yolk without DF (mg), and W is the weight of the sample (g).

Preparation of muffins

The fiber-enriched muffins feature a harmonious blend of ingredients, including wheat flour (70 g), sugar (45 g), whole egg (3 5g), baking powder (3.5 g), sunflower oil (30 g), and milk (55 mL). Specifically, 2% of the total wheat flour weight was replaced with the DF extracted from corn cobs and added to each batch of muffins. The muffins were then baked in an oven (EPRC-9860E/SS; ELBA) at a temperature of 180°C for 25 min. Their readiness was determined using the toothpick method, and they were carefully removed from the oven upon confirmation.

Textural profile analysis

The evaluation of the muffin's texture followed the methodology outlined by Matos *et al*. (2014). Crumb cubes measuring 12.5 mm^3 underwent texture profile analysis employing a texture analyzer (Stable Micro Systems, Godalming, UK) equipped with a 5 kg load cell. A double compression test was conducted using a flat-ended cylindrical probe (P/75) with a diameter of 77 mm. The samples experienced compression at a rate of 1 mm/s for a duration of 5 sec or until they reached 50% of the original muffin height. Utilizing Exponent software (Stable Micro Systems, Godalming, UK), calculations were performed to derive values for stiffness, springiness, cohesion, and chewiness.

Statistical analysis

All measurements were carried out in triplicate. The experimental data were analyzed using one-way analysis of variance with GraphPad Prism Version 9 (GraphPad Software, Boston, USA). The data were assumed to meet normality and homogeneity of variances without requiring transformation. Post hoc analysis was conducted using Tukey's test to compare means between groups, with statistical significance set at $p \leq 0.05$.

RESULTS AND DISCUSSION

Extraction yield

The yields of TDF, SDF, and IDF of corn cobs extracted using different extraction methods are presented in Table 1. The results indicate that the SDF yield ranged from 25.28% to 32.62%. Among the SDF yields, alkali extraction produced the highest yield ($p<0.05$), followed by water extraction and acid extraction. In contrast, the yield of IDF ranged between 45.73% and 69.4%, with water extraction producing the highest yield ($p<0.05$), followed by acid extraction and alkali extraction. These findings are consistent with a previous study conducted by Wang *et al*. (2022).

The alkali extraction method demonstrated a high yield of SDF while producing lower amounts of IDF. This trend aligns with findings from previous research, which employed a 5% NaOH solution to extract DFs from papaya peel and papaya seed (Feng *et al*., 2024). The study also reported high yields of SDF but lower yields of IDF, attributing this outcome to the alkali's ability to break down cell wall structures. Specifically, the current study utilized a 4% NaOH solution, which proved sufficient to solubilize hemicellulose and facilitate the conversion of IDF to SDF. The mechanism involves the disruption of ether and ester linkages in lignin, allowing for the solubilization of hemicellulose and other structural components. This process enhances the yield of SDF, as the alkali effectively compromises the rigid cell wall architecture. Thus, the findings corroborate existing literature that recognizes alkali treatment as an efficient technique for extracting DFs from plant materials.

Table 1. Yield of SDF, IDF, and TDF of corn cob powder extracted using different extraction methods

Extraction Methods	Yield (%)		
	SDF	IDF	TDF
Water	28.71 ± 0.60^b	69.40 ± 0.90^a	98.12 ± 0.35^a
Acid	25.28 ± 0.31^c	58.43 ± 0.92^b	76.76 ± 0.18^b
Alkali	32.62 ± 0.19^a	45.73 ± 1.50^c	76.24 ± 2.03^b

All values are expressed as mean value (n=3) ± standard deviation, and different alphabets in the same column denote a significant difference ($p<0.05$).

Moreover, acid extraction yielded the lowest amount of SDF. This outcome is attributed to the acid solution, which disrupts polysaccharides by breaking glycosidic bonds and hydrolyzing the SDF. Consequently, the oligosaccharides and monosaccharides formed remained in solution and were not precipitated by the additional volume of 95% ethanol (Wang *et al*., 2022). On the other hand, water extraction produced the highest yield of IDF, which is most likely due to the lignocellulosic composition of corn cobs that typically contain cellulose, hemicellulose, and lignin. These three types of fibers are known to be less soluble in water and are responsible for categorizing DF into two groups: water-insoluble or less fermented fibers (e.g., cellulose, hemicellulose, and lignin) and water-soluble fibers (e.g., pectin, gums & mucilage) (Dhingra *et al*., 2011).

It is also noteworthy that water extraction yielded the highest TDF. The water extraction technique typically results in the greatest quantity of extracted fiber, as it effectively breaks down the plant cell wall and releases the fiber. Elevated temperatures up to 90°C, especially when using water, facilitate the breakdown of the structural components of the plant material, including cellulose, hemicellulose, and pectin. This process contributes to a higher yield of extracted fiber (Leszczyński&, Roman 2023).. Moreover, water is not an ideal solvent for fibers, as it has limitations in extracting DFs from plant materials. Its polar nature, potential for hydrolysis, and issues related to gel formation contribute to its inefficiency as a solvent for certain types of DF extraction (Reyes *et al*., 2020). Consequently, this results in a higher yield of extracted fibers, as the fibers remain intact and are more effectively separated from the plant material during extraction.

Conversely, both acid and alkali extraction methods resulted in significantly lower TDF yields compared to water extraction. The high solubility of acidic and alkaline solutions in water facilitates the dissolution of certain fibers during extraction. As a result, these fibers may not be completely recovered in the final product, remaining either dissolved or suspended in the extraction solution (Ntenga *et al*., 2022). Therefore, different extraction methods contribute to variations in the yield of DF produced.

Physicochemical properties of extracted corn cob fiber

Fourier transform infrared

Figure 1 shows the FTIR spectra for the extracted fibers. Each extraction was divided into two groups: SDF and IDF. Fourier transform infrared spectroscopy was used to identify the organic functional groups and assess the molecular structures of the corn cob fibers. The dissociation of intermolecular hydrogen bonds in polysaccharides likely caused variations in the intensity of some peaks, depending on the extraction techniques used. In general, the IR spectra of all samples exhibited common characteristics associated with polysaccharides. However, variations in the intensities and positions of specific bands were noted, indicating changes in the characteristic features of the spectra. All extracted fibers displayed prominent signals in the range of 3408.44–3435.97 cm^{-1}, which signify the vibration or elongation of hydrogen bonds (O-H) primarily linked to the hydroxyl groups within the polysaccharides (Dai *et al*., 2023). Moreover, a peak observed at approximately 2919.48–2923.96 cm^{-1} indicated the presence of -CH stretching bands in the polysaccharides.

The peak observed in the range of 2127.48–2134.99 cm^{-1} corresponds to the C≡C stretching associated with the alkyne group in polysaccharides, such as xylan (Huang *et al*., 2013; Liu *et al*., 2023). This functional group is present in the spectra of acid-extracted soluble fiber and also water-extracted soluble and insoluble fibers.

Additionally, C=C stretching and aromatic C-H bending were detected in all extracted fibers, observed at 1632–1650 cm^{-1}, and 609.42 cm^{-1} and 587.46 cm^{-1}, respectively, and these peaks represent lignin, which is commonly found in lignocellulosic materials (Poletto *et al*., 2013).

Hydration properties: water-holding capacity and swelling capacity

The WHC of DF refers to the fiber's ability to retain free and bound water, which is influenced by physical and physicochemical interactions within the fiber matrix. This capacity is determined by environmental conditions and the intrinsic properties of the fiber, such as ionic strength, surface area, and morphological structure (Cui *et al*., 2021). Enhanced WHC is associated with improved food quality, particularly by reducing syneresis, a characteristic that is critical in the development of functional foods (He *et al*., 2019).

As shown in Figure 2(a), alkali extraction methods applied to corn cob fibers demonstrate significant potential for enhancing WHC, thereby improving food quality by retaining moisture and stabilizing texture (Wang *et al*., 2022). Moreover, the SC of DF, which is defined as the fiber's ability to absorb and retain water or other liquids, is another key functional property. Although SC shares some similarities with WHC, it differs in that the absorbed water is not permanently retained, which influences its applications in various food formulations (Xu *et al*., 2020). The SC influences fiber behavior within food matrices, impacting viscosity, mouthfeel, and satiety when incorporated into food products (Bai *et al*., 2021).

The findings presented in Figure 2(a) and Figure 2(d) indicate that the TDF obtained through alkali extraction yielded the highest WHC ($p<0.05$), while the TDF from water extraction showed the highest SC. A study conducted by Catherine and Venkatachalam (2020) found that both alkali and water extraction methods were most effective in yielding substantial amounts of cellulose and hemicellulose from corn cobs. Cellulose and hemicellulose are renowned for their water absorption properties and are integral components of the fiber. The extraction process not only reveals functional groups like -OH and -COOH but also enhances the fiber's WHC. Moreover, the removal of hemicellulose and lignin during extraction further increases the fiber's ability to retain water. Therefore, the high WHC and SC are likely attributed to the specific characteristics of the fiber obtained from corn cobs through alkali and water extraction, respectively, which include the presence of cellulose and hemicellulose, as well as the functional groups.

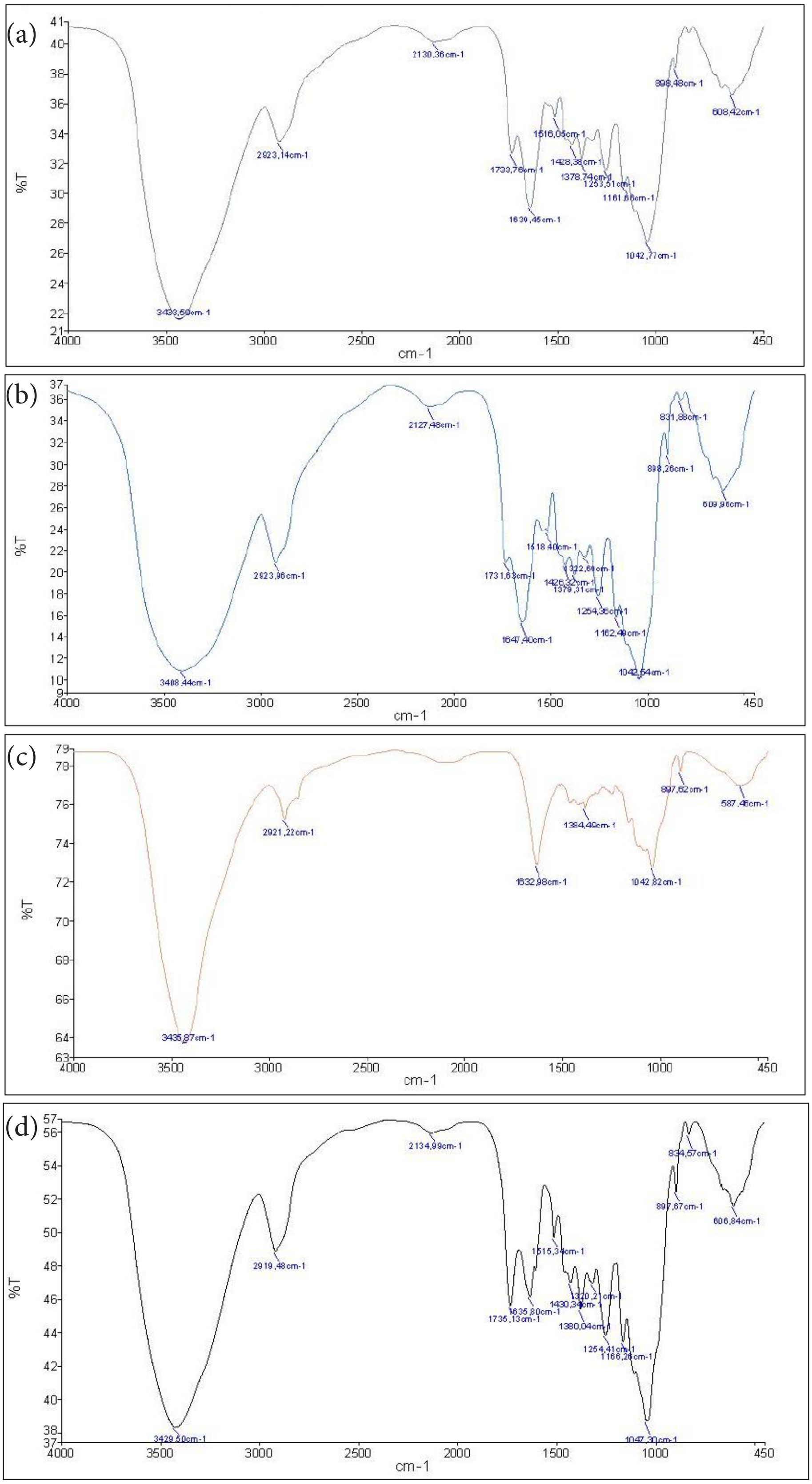

Fig. 1. Fourier transform infrared spectra of soluble and insoluble fibers obtained through different extraction methods: a) FTIR spectra of SDF by water extraction, b) FTIR spectra of SDF by acid extraction, c) FTIR spectra of SDF by alkali extraction, d) FTIR spectra of IDF by water extraction, e) FTIR spectra of IDF by acid extraction, and f) FTIR spectra of IDF by alkali extraction.

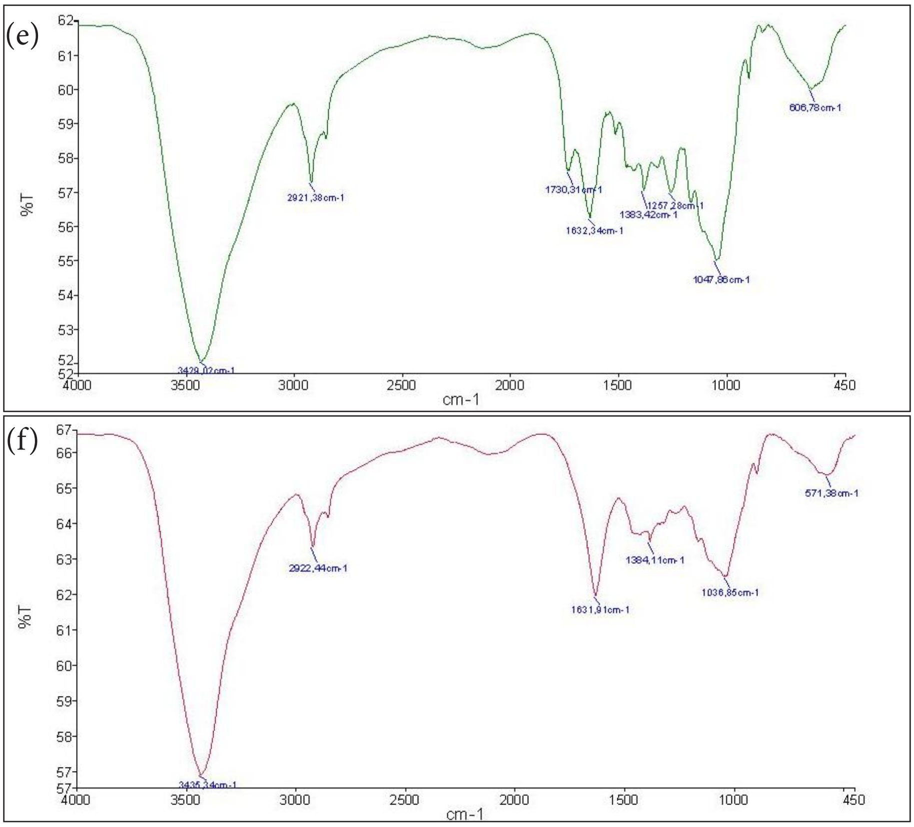

Fig. 1. Continued. Fourier transform infrared spectra of soluble and insoluble fibers obtained through different extraction methods: a) FTIR spectra of SDF by water extraction, b) FTIR spectra of SDF by acid extraction, c) FTIR spectra of SDF by alkali extraction, d) FTIR spectra of IDF by water extraction, e) FTIR spectra of IDF by acid extraction, and f) FTIR spectra of IDF by alkali extraction.

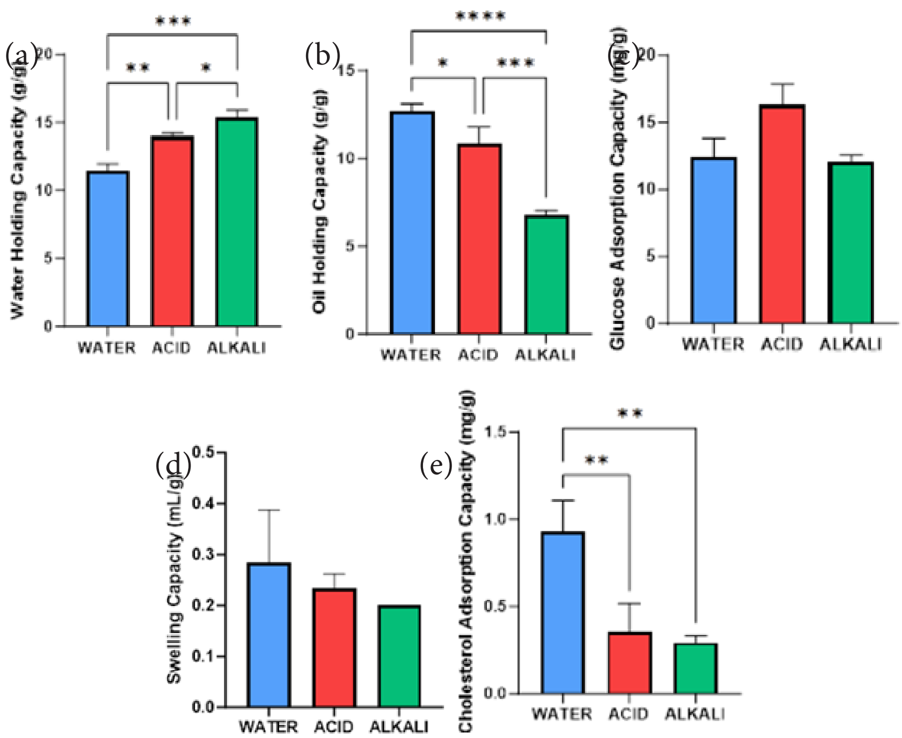

Fig. 2. Properties of extracted corn cob fibers using different extraction methods: a) WHC, b) OHC, c) GAC, d) SC, and e) CAC (pH 7) of the extracted corn cob fibers. Significant differences are denoted by * for p < 0.05, ** for p < 0.01, *** for p < 0.001, and **** for p < 000.1.

Oil-holding capacity

Dietary fibers with a high OHC improve baked goods by enhancing moisture retention, texture, and flavor release, creating a softer, more appealing product (Sharma & Kumar, 2020). Additionally, these fibers serve as fat replacers, offering a lower-calorie alternative while maintaining mouthfeel and crumb structure (Silva *et al*., 2021). Furthermore, OHC reduces fat migration, which contributes to the preservation of product integrity and freshness over time (Kaur & Das, 2019). Figure 2(b) displays the OHC of corn cob fibers extracted using different extraction methods. The findings indicate that the TDF obtained through water extraction exhibited the highest OHC, followed by acid and alkali extraction. The SDF present in the corn cob fibers derived from water and acid extraction demonstrated exceptional performance. It is suggested that water and acid treatments enhanced and preserved the hydrophobic elements or groups within the material, indicating that the treated fibers possess characteristics that repel or resist water. This phenomenon occurs because DF can interact with water through various mechanisms, such as polar and hydrophilic interactions, hydrogen bonding, and enclosure (Chaplin, 2003). The nature of these interactions is influenced by the flexibility of the fiber surface. When the fiber is insoluble or forms junction zones, it can lead to significant changes in the surrounding water. These interactions have the potential to influence the structure and solvation properties of water not only near the immediate surfaces but also in more extensive areas (Chaplin, 2003). Consequently, the fiber's affinity for oil can be influenced by this hydrophobicity. Therefore, the presence of these hydrophobic groups facilitates the penetration of oils into the soluble dietary molecules extracted from the fiber, preventing oil loss. This explains why OHC is not solely related to the viscosity, surface properties, total charge density, and thickness of DF (Wang *et al*., 2022).

Glucose adsorption capacity

Glucose absorption capacity refers to the ability of certain fibers or ingredients in baked goods to absorb glucose, slowing its release during digestion. High-GAC ingredients are beneficial for regulating blood sugar and managing post-meal glucose spikes, making them beneficial for diabetic diets (Raza *et al*., 2021). Figure 2(c) displays the GAC of the corn cob fibers extracted using different methods. The findings indicate that the TDF obtained through acid extraction yielded the highest GAC, followed by water extraction but not significant (p>0.05). The fibers demonstrated effectiveness in adsorbing glucose across different extraction methods. Consequently, the high capacity for glucose adsorption observed with acid extraction may be attributed to the degradation of the fiber surface. Moreover, acid extraction removes lignin and other non-cellulosic components, leaving cellulose and hemicellulose as the primary constituents in the resulting fiber. It is well-known that cellulose and hemicellulose are recognized for their ability to absorb glucose (Jiang *et al*., 2022). During acid extraction, the interactions among the fiber components can be weakened, leading to the exposure of additional -OH and -COOH groups. These functional groups can form bonds with glucose molecules, enhancing the fiber's capacity to adsorb glucose.

Cholesterol adsorption capacity

The CAC measurement underscores the beneficial effects of DF on lowering blood pressure and lipid levels, promoting the development of functional foods with cardiovascular benefits. This study demonstrated that the TDF obtained through water extraction exhibited a significantly higher CAC (p<0.01) than acid- and alkali-extracted fibers, as presented in Figure 2(e). These results align with those of Wang *et al*. (2022), who observed that water extraction enhanced the functional properties of DFs. This suggests that SDF tends to more readily form a gel-like consistency upon water swelling. This characteristic enhances its effectiveness in binding cholesterol from food, making it particularly effective in cholesterol adsorption.

Textural profile of muffins

The corn cob fibers produced from the three extraction methods were incorporated into a bakery product (i.e., muffins) to evaluate their potential as a functional ingredient. The muffins were enriched with 1.4 g of extracted fiber from the three distinct extraction methods and evaluated for their textural profile, including firmness, cohesiveness, chewiness, and springiness. These properties were compared to a control group that did not contain corn cob fiber. The findings indicated that the values for all muffins with added extracted fiber, regardless of the extraction method used, were higher than those of the control group. A noteworthy finding reported by Rawat and Indrani (2014) showed that the determination of textural parameters, such as firmness, cohesiveness, chewiness, and springiness of the energy bars, revealed that these attributes exhibited higher values when fiber was incorporated compared to protein. This observation underscores the impact of fiber supplementation on the textural characteristics of the final product, providing valuable insights into the relationship between ingredients and their effects on various quality parameters. Figure 3 shows the results of the textural profile analysis conducted on the muffins incorporated with the extracted corn cob fibers from three different methods.

Firmness

The firmness of a muffin refers to its stiffness or hardness, which is indicated by the maximum force exerted during initial compression. The firmness of the product was significantly influenced by both the degree of sugar/fat reduction and also the specific type of added fiber (Harastani *et al*., 2021). Other research also shows that replacing wheat flour by up to 4% may reduce height and increase hardness without significantly affecting sensory acceptance (Heo *et al*., 2019). Furthermore, it was observed that muffins with a 30% reduction in sugar content, enriched with DFs, exhibited increased firmness. This enhancement is attributed to the superior water-binding capacity of DFs, which increases capacity and restricts the availability of water for other ingredients, such as starch, affecting the characteristics of the final product (Struck *et al*., 2016). Although no significant difference was observed (p>0.05), it is shown in Figure 3(a) that the alkali-extracted fiber exhibited the highest firmness.

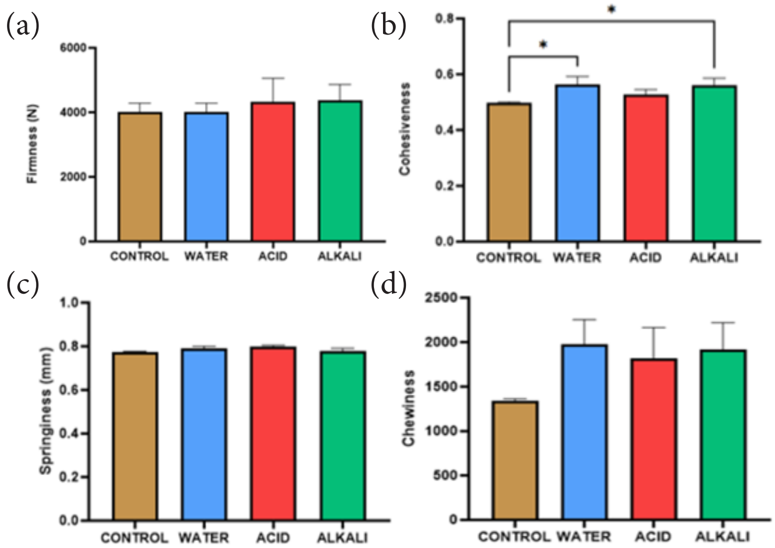

Fig. 3. Textural profile of muffins incorporating fibers extracted from different methods: a) firmness, b) cohesiveness, c) springiness, and d) chewiness of muffins incorporating different extracted fibers. Significant differences are denoted by * for $p<0.05$.

Subjecting fibers to alkali treatment has the potential to enhance both tensile strength and modulus, resulting in increased firmness (Luqman *et al.*, 2023). The increase in firmness resulting from alkali treatment is commonly associated with the removal of non-cellulose impurities, including lignin and hemicellulose, which improves the bonding capacity of the materials (Aravindh *et al.*, 2022).

Cohesiveness

Cohesiveness measures the internal resistance within the food structure, indicating its capacity to adhere to itself. Additionally, cohesiveness is related to the energy required for the second compression, providing insights into sensory crumbliness and the energy required for chewing the food. Figure 3(b) shows a marginal increase in cohesiveness values for each type of extracted fiber compared to the control group, as only about 2% of fiber was added to the muffin. Water- and alkali-extracted fibers exhibited significantly higher cohesiveness ($p<0.05$) compared to the control group. The fiber content in muffins can be influenced by interactions with other ingredients, such as gluten, which contribute to the development of a more cohesive crumb structure in muffins (Aydoğdu *et al.*, 2017).

Springiness

Springiness refers to the ability of a muffin to recover its original shape after being deformed. It indicates how well the crumb rebounds to its original height after the second compression. Findings from Martínez-Cervera *et al.* (2013) indicated that a high fiber content in muffins is associated with a reduction in springiness. However, in the current study, the addition of fiber did not significantly affect springiness ($p>0.05$). This suggests that incorporating 2% fiber is optimal for maintaining the springiness of the muffins.

Chewiness

Chewiness refers to the force required to break down a product in a manner suitable for swallowing. It is also influenced by the textural characteristics that measure a muffin's resistance to deformation when bitten or chewed. This sensory attribute is significant as it can influence the overall consumer acceptance and satisfaction with the product (Akinwande *et al.*, 2020). Figure 3(d) shows that the addition of fiber to the muffin resulted in higher chewiness compared to the control group, although this difference was not statistically significant ($p>0.05$). It was observed that muffins enriched with DF exhibited increased chewiness at higher concentrations of DF, possibly due to water absorption (Heo *et al.*, 2019).

CONCLUSION

In conclusion, alkali extraction yielded the highest SDF, while water extraction excelled in producing the highest IDF and TDF. The characteristics of the fibers extracted using various methods demonstrated significant differences in WHC, OHC, and CAC. Notably, the addition of fiber did not affect the texture of the muffins, as there was no significant difference compared to the control group ($p>0.05$). Furthermore, fiber extracted through water extraction is considered the most advantageous, as it offers higher yields, and enhanced safety, and produces a muffin texture profile comparable to that obtained through acid and alkali extraction methods. This suggests that the fiber extracted from corn cob possesses promising characteristics for incorporation into baked goods, potentially improving daily fiber intake without significantly affecting the overall quality of the products.

ETHICAL STATEMENT

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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