Comparative study of cross- and uncross-linked arabinoxylans extracted from maize bran with special reference to their structural and antioxidant potential

Muhammad Ahtisham Raza¹, Farhan Saeed ², Muhammad Afzaal³, Ali Imran⁴, Bushra Niaz⁴, Muzzamal Hussain⁴, Amara Rasheed⁴, Muhammad Kashif Mukhtar⁵, Muhammad Waleed⁴, and Entessar Al Jbawi⁶⁺

¹Department of Food Science, Government College University Faisalabad, Pakistan; ²National Institute of Food Science and Technology (NIFSAT), University of Agriculture Faisalabad, Pakistan; ³Agricultural Extension Directorate, MAAR, Damascus, Syria

ABSTRACT
Maize bran is a by-product obtained after the milling of maize kernels and separated as by-product. The current research aimed to extract and characterize the arabinoxylans (AXs) and their gels from maize bran. Initially, maize bran was evaluated for its proximate composition and dietary fiber profile. Then, AXs were extracted through alkali extraction method, and in vitro gelation of AXs was performed through enzymes (laccase from Termitis versicolor). Their structure was characterized through Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM). Further, the phenolic compounds and their activity was assessed through three different assays including diphenyl picryl hydrazyl (DPPH), ferric reducing antioxidant power (FRAP), and ABTS⁺. The results regarding the chemical composition of maize bran showed that maize bran majorly comprised moisture, ash, crude fat, fiber, crude protein and nitrogen-free extract with 10.13 ± 0.46, 1.87 ± 0.15, 1.26 ± 0.26, 7.53 ± 1.00, 12.67 ± 0.75, and 66.54 ± 0.82 g/100 g of the sample. Further, dietary fiber profile showed that maize bran comprised 6.97 ± 0.5 and 35.20 ± 4.1% soluble and insoluble fractions of dietary fibers. Then, the structural characterization of maize bran through FTIR spectroscopy showed a typical spectrum and presented the peaks at different wavelengths, which was similar to structural features as described in previous studies. Surface morphology of gel through SEM showed micrographs with small pores, which according to our information was formed due to laccase (enzymes) activity. However, quantification of polyphenols including total phenolic content and total flavonoid content showed the results including 6.42 ± 0.18 GAE/g and 1.84 ± 0.66 CE/g and their activity assessed through DPPH, FRAP, and ABTS⁺ assays showed the values including 31.62 ± 0.16, 34.87 ± 0.18, and 14.21 ± 0.18 μmol TE/g, respectively. The results in this study showed that maize bran AXs and their gels showed an interesting trend in their structural and antioxidant potential.

ARTICLE HISTORY
Received 23 September 2022
Revised 28 October 2022
Accepted 29 October 2022

KEYWORDS
Hydrogels; Arabinoxylans; Structural properties; Antioxidant potential; Fourier transform infrared spectroscopy; Scanning electron microscopy

CONTACT Entessar Al Jbawi (dr.entessara@nmail.sy) Agricultural Extension Directorate, MAAR, Damascus, Syria; Farhan Saeed (f.saeed@gcuf.edu.pk) Department of Food Science, Government College University Faisalabad, Pakistan; Muzzamal Hussain (muzzamalhussain24@gcuf.edu.pk) Department of Food Science, Government College University Faisalabad, Pakistan.

© 2022 Muhammad Ahtisham Raza, Farhan Saeed, Muhammad Afzaal, Ali Imran, Bushra Niaz, Muzzamal Hussain, Amara Rasheed, Muhammad Kashif Mukhtar, Muhammad Waleed and Entessar Al Jbawi Published with license by Taylor & Francis Group, LLC. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Introduction

Cereals are used as a staple diet since the ancient times due to the presence of essential nutrients along with bioactive moieties which are reported to have the therapeutic potentials on human health and combat various chronic diseases like diabetes, cancer, atherosclerosis, cardiovascular diseases, and Alzheimer disease.\textsuperscript{1,2} Biologically active fractions of maize bran, such as arabin-xylans (AXs), ferulic, di-ferulic, and \textit{p}-coumaric acids have many nutritional, functional, and rheological properties, and maize bran is considered as a rich source of ferulic acid among other cereal brans.\textsuperscript{3} Further, the dimers and trimers of ferulic acid are cross linked with AXs and form feruloylated AXs, which have a significant role in the synthesis of cross-linked AXs (hydrogels).\textsuperscript{4}

Hydrogels are colorless product derived from the modification of complex carbohydrates polymers with high hydration capacity and viscosity.\textsuperscript{5} Several methods are used to synthesize hydrogels including chemical extraction, enzymatic extraction, high shear, and peroxide treatment. These hydrogels are being used in various food industries due to their technological and functional applications. This highly cross-linked polymeric structure was firstly synthesized in Germany during the study of kinetic of cross-linking ability of bio-polymers. Recently, these are being used in the biomedical application, which are majorly extracted from agro-industrial wastes. Many natural polymers such as heparin, chitosan, fibrin, collagen, gelatin, hyaluronic acid, alginates, pectin, and others are also being used to prepare hydrogels and utilized in biomedical industries for targeted drug delivery.\textsuperscript{6}

Hydrogels are “jelly-like” three-dimensional structure which are now commonly used in biomedical applications including contact lenses, solid air fresheners, jiggle desserts, and bay diapers.\textsuperscript{7} Pilot study of these hydrogels ease the researchers to understand their chemistry; however, their food applications have also been observed since the past few decades due to their structural and rheological attributes on final product.\textsuperscript{8,9} Biomedical applications of these hydrogels gained significance in targeted drug delivery, tissue engineering, and various biomedical applications due to their biocompatibilities. Further, these gels of AXs have the ability to entrap the large amount of water and other biological fluid as well as bioactive moieties, which are further used for biomedical applications.\textsuperscript{10} Recently, the utilization of maize bran AXs and hydrogels impart in food recipes to develop the end-product with desired textural and structural attributes. The current research aimed to extract the maize bran AXs and synthesize their gel through \textit{in vitro} gelation using enzymes, i.e. laccase from \textit{Termites versicolor}, and assessed their morphological features and antioxidant potential through three commonly used antioxidant assays.
Material and method

Procurement of raw material

Maize bran (Pioneer-3062) was procured from Rafhan Maize Pvt. Ltd. Chemicals (sodium chloride, hydrochloric acid and citrate phosphate buffer) were procured from Sigma-Aldrich and Merck Pvt Ltd. All the chemicals were analytical grade. Enzymes (laccase from Termites versicolor) were kindly provided by the Department of Chemistry, Government College University, Faisalabad.

Proximate composition of maize bran

Moisture content of the maize bran was quantified through hot air oven (Memmert, Germany) at 105 ± 5°C through the standard method of AACC method No. 44-15A, ash content was assessed through DAIHAN Scientific Muffle furnace through AACC method No. 08-01. The nitrogenous bases in bran samples were quantified through Kjeldahl method using the protocol prescribed by AACC method No. 46-10. Soxhlet apparatus was used to quantify the crude fat content through method No. 30-25 described by AACC. Further, crude fiber content was determined with Method No. 32-10. Nitrogen-free extract was quantified on difference basis using the following formulae.

\[ \text{NFE}\% = 100 - (\text{Moisture} + \text{ash} + \text{crude fat} + \text{Crude fiber} + \text{Protein}) \]

Dietary fiber profile (total, soluble, and insoluble)

Dietary fiber profile of the bran sample was analyzed through AACC method No. 32-05.01 for total dietary fibers, method No. 32-07.01 for soluble and insoluble dietary fibers’ determination.

Alkali extraction of AXs

Maize bran sample, for the extraction of AXs, was subjected by following the protocol demonstrated by Carvajal-Millan et al. and Kale et al. with slight modifications. Briefly, maize bran was grinded to 120 μm particle size using a lab scale mill (Hammer-type mill 120 Perton). Maize bran (100 g) was suspended in ethanol (500 ml) and agitated on a rotatory shaker (100 rpm) for 12 h at 25°C to remove lipophilic components. The ethanol treated bran was then filtered through a 2.7-mm pore size filter (Millipore). The bran sample was then dried in hot air oven at 45°C to evaporate the solvent residues and subjected the sample for starch gelatinization and enzymes inactivation by boiling (30 min in 1000 ml of water). After boiling, bran sample was centrifuged (8000 rpm for 15 min) to recover the solid residue, which was further treated with 500 ml of (0.5 N) NaOH solution at 25°C in darkness for 2 h in a shaker (100 rpm). After the alkali treatment, residual solids were then eliminated through centrifugation (12,096 g, 4°C, 15 min) and, supernatant was acidified to pH 4 with 3 N HCl solution and placed for 15 mins. The acidified solution was finally centrifuged (12,096 g, 4°C, 15 min), supernatant was recuperated and precipitated in 65% (v/v) ethanol (4 h at 4°C). Precipitates were then recovered and lyophilized to obtain the dried AXs.

Laccase-induced gelation

Dried AXs powder (2% w/v) was added in 0.05 M citrate phosphate buffer with pH 5. Laccase from Termites versicolor (1.675 nkat/mg AXs) was added in the solution and incubated for 4 h at 37°C.
Structural characterization of AX gels

Fourier transform infrared spectroscopy
The sample of powdered AXs was subjected for Fourier transform infrared (FTIR) spectroscopy to evaluate the structural model and presence of functional groups, by following the instructions stated in instruction manual IR Prestige-21. The FTIR (Cary 630-Agilent Technologies) spectroscopy was used to determine the chemical structure, functional groups, and molecular bonding. For the purpose, sample for scanning was passed through infrared beam and detected by infrared radiations. The device was connected with computer-based detector, which plots the spectrum of the subjected sample. Mid-IR spectrum was used which generally ranges between 650 and 4000 cm\(^{-1}\).

Scanning electron microscopy
For the morphological characterization of AXs and their gels, scanning electron microscopy (SEM) was used as valid approach. The sample on scanning electron microscope (cube series company, Emcraft) for scanning was placed on stubs at 5-kV accelerating voltage.\(^{[14]}\) and their micrographs were further used to understand their structural properties.

Functional properties

Total phenolic content
Total phenolic contents (TPCs) were determined as reported by Sengul et al.\(^{[15]}\) using gallic acid equivalent (gallic acid/g). The absorbance was measured at 760 nm using a spectrophotometer (IRMECO, U2020). Briefly, the Folin–Ciocalteu reagent oxidized 100 \(\mu\)L of extracts and the reaction was neutralized with sodium carbonate and the solution was diluted with distilled water up to 10 mL. The solution was given 2 h for reaction. Then, the absorption was measured at 760 nm after 2 h of incubation, and for the purpose of measuring the level of phenol, standard gallic acid was used as internal standard. Milligrams per gram (\(\mu\)mol GAE/g) of sample gallic acid equivalent was used to express the results.

Total flavonoid content
Total flavonoid contents (TFCs) of AXs and their gels were determined by following the method used by Turkmen et al.\(^{[16]}\) and Ali and Naz.\(^{[17]}\) Briefly, 1 g of sample was added in 10 ml of ethyl alcohol, placed in shaker and then, filtered. One millilitre of extracted sample in ethyl alcohol was mixed in 0.3 ml of sodium nitrite (5% NaNO\(_2\)) and diluted 6 times with distilled water. Then, 0.3 ml of aluminum chloride (10%) was added in solution and incubated for 5 min. Then, 2 mL sodium hydroxide (1 M NaOH) was added in solution and gave 2 h as reaction time. The absorbance of sample was measured at 517 nm through double-beam spectrophotometer (IRMECO, U2020). Catechin calibration curve was used to determine TFC, and the results were expressed as \(\mu\)mol CE/g.

Diphenyl picryl hydrazyl assay
The radical scavenging potential of AXs and AX-based hydrogels were determined by using the standard method used by Turkmen et al.\(^{[16]}\) and Ali and Naz.\(^{[17]}\) Briefly, 1 g of dried sample was added in 10 ml of absolute ethyl alcohol (99%) to form a solution and then placed in shaker (IKA-WERKE, Germany) at 300 rpm for 120 min. Alcohol extracted (0.1 ml) sample was mixed with already prepared diphenyl picryl hydrazyl (DPPH) (3.9 ml, 0.025 g/L of methanol) solution. At ambient temperature, mixture was incubated in darkness for 30 mins. By spectrophotometer (IRMECO, U2020) the absorbance of the mixture was measured at 517 nm and the results were presented in the form \(\mu\)mol TE/g. The samples were analyzed in triplicates and the results were written in the form of mean and their standard deviation (SD).
**Ferric reducing antioxidant power assay**

Ferric reducing antioxidant power (FRAP) of both samples was assessed using the method of Benzie and Strain,\(^{[18]}\) with some amendments. Briefly, 0.1 mL of the extract was added in the FRAP reagent. The FRAP regent was prepared by using 0.1 M acetate buffer, 10 mM TPTZ (2,4,6-tri (2-pyridyl)-1,3,5 triazine solution) and 20 mM ferric chloride were added with the proportion of (10:1:1 v/v/v). Then, 1.9 mL of reagent was added in 0.1 mL of extract. The solution was then placed in dark for 35 min. The absorption was measured using a spectrophotometer at the wavelength of 593 nm. Trolox was used as an internal standard and the results were written in the form of μmol TE/g. All the samples were assessed in triplicates and the results were written in the form of mean ± SD.

**Azino-bis-3-ethylbenzothiazoline-sulfonic acid (ABTS) assay**

The scavenging potential of AXs and their gels were assessed using the method used by Malunga and Beta,\(^{[19]}\) with modifications. Briefly, ABTS\(^+\) radical solution was prepared by reacting the 7 mmol/L aqueous solution of 3 mL azino-bis-3-ethylbenzothiazoline-sulfonic acid with 3 mL of potassium persulfate 2.45 mmol/L solution. Then, the solution was placed in dark for 12–14 h at room temperature (37°C). Then, the ABTS\(^+\) radical solution was diluted with distilled water (250 mL) to obtain the absorbance at 734 nm wavelength using a double-beam spectrophotometer (IRMECO, U2020). Then, 0.1 mL of the sample was mixed with 1.7 mL ABTS\(^+\) solution in a 2 mL amber centrifuge tube. The mixture was vortexed and placed in dark for 35 min, after which the solution was poured in cuvette for measuring the absorbance and results were presented in the form of mean and their SD.\(^{[20]}\)

**Statistical analysis**

Analyses were accomplished in triplicate to investigate the different parameters of the sample. The data were analyzed statistically by completely randomized design using Statistix 8.1 software. The results were shown in the form of mean ± SD.

**Results and discussion**

**Chemical composition of maize bran**

The proximate composition of maize bran has been presented in Table 1, and the results showed that maize bran primarily composed of moisture, protein, crude fiber, and nitrogen-free extract (carbohydrates) with 10.13 ± 0.46, 12.67 ± 0.75, 7.53 ± 1.00, and 66.54 ± 0.82 g/100 g, respectively, whereas, ash and crude fat contents were found in trace amount with the values including 1.87 ± 0.15 and 1.26 ± 0.26 g/100 g, respectively. However, soluble (6.97 ± 0.5) and insoluble (35.20 ± 4.1) fractions of dietary fiber in maize bran showed the results which are closely corroborated with the findings of Hussain et al.,\(^{[21]}\) who reported that maize bran is chiefly composed of 41–42% insoluble and 3–4%

| Biochemical composition                  | Percentage (%) |
|------------------------------------------|----------------|
| Moisture                                 | 10.13 ± 0.46   |
| Ash                                      | 1.87 ± 0.15    |
| Crude fat                                | 1.26 ± 0.26    |
| Crude protein                            | 12.67 ± 0.75   |
| Crude fiber                              | 7.53 ± 1.00    |
| Nitrogen-free extract                    | 66.54 ± 0.82   |
| Total dietary fibers                     |                |
| Soluble dietary fibers                   | 6.97 ± 0.5     |
| Insoluble dietary fibers                 | 35.20 ± 4.1    |

\(^{[18]}\) Benzie, I.C., and Strain, J.J., 1996. Analysis of ABTS radical cation formation using a double-beam spectrophotometer. Am. J. Clin. Nutr. 64, 1317–1321. \(^{[19]}\) Malunga, M.C., and Beta, T., 2017. Antioxidant activity and chlorogenic acid content of avocado (Persea americana Mill.) peels. Food Sci. Technol. 4, 1–5. \(^{[20]}\) Statistix 8.1 software. \(^{[21]}\) Hussain, M.Z., et al., 2022. The proximate composition and antioxidant activity of maize bran. J. Food Sci. Technol. 66, 2499–2503.
soluble fractions of dietary fibers. Herrera-Balandrano et al.\cite{22} reported soluble and insoluble dietary fibers content with 4.40 ± 0.05 and 54.91 ± 0.06, respectively. The variation in results regarding the insoluble fraction of dietary fiber could be due to nixtamalized nature of maize bran.

**Structural characterization of AXs and their gel**

**FTIR spectroscopy**

In the current study, AXs were extracted from maize bran and their structure was confirmed using FTIR spectroscopy technique. The spectra showed a narrow to wide range of stretching at different wavelengths from which the structure of AXs was confirmed which will give a new insight according to our information to predict the structural characteristics of biopolymer. The FTIR spectra of AXs have been presented in Figure 1, which was recorded from 650 to 4000 cm\(^{-1}\). The peak at 3447 cm\(^{-1}\) typically corresponds the hydroxyl group of polysaccharide and water involves in hydrogen bond as described by Zhang et al.\cite{23} The absorption peaks in the fingerprint region ranging from 800 to 1500 cm\(^{-1}\) showed typical spectra of AXs with functional groups including C–C, C–O–C, C–O, and C–OH among which peak at 1017 cm\(^{-1}\) represents the glycosidic linkage interconnects with xylan backbone. Further, the stretching at 1500–1700 cm\(^{-1}\) represents the ferulic acid which is crucial in the gel-forming mechanism.

According to previous research by Ren et al.,\cite{24} the spectra of arabinogluconoxylan due to ring vibrations, C–OH of side groups, and C–O–C glycosidic bond vibration were observed which shows the peaks at 1162/1152, 1037/1027 cm\(^{-1}\). It has been proved that the maize bran polysaccharide is constituted of β-xylene in pyranose form in the backbone and both α-arabinose in furanose form and β-xylene in sidechains substituting on C-3 or/and C-2. The current results showed that xylose is substituted by arabinose and forms a highly branched AXs structure. The spectra of AXs from 1020 to 920 cm\(^{-1}\) range reflect the A/X and substitution of xylan backbones. These band shifts may be rationalized with the strong 1017 cm\(^{-1}\) interactions probably due higher degree of cross-linking.

**Scanning electron microscopy**

SEM technique is used to assess the surface morphology of the developed structure through which the functional properties of the specimen could be assessed. High energy beam of electrons pass from the specimen and the nature of the nanomaterials can be probed on a fine scale.

In the current study, AXs and their gels were structurally characterized and the results showed an interesting trend which have been presented in Figure 2. The result showed that the surface

![Figure 1. FTIR spectra of arabinoxylans.](image-url)
morphology of AXs (a) presented a rough pattern of heterogenous sheets, whereas their gels (b) presented a uniform arrangement of particles in a definite manner with a hexagonal structure. Micropores on the surface of gels enhance the swallowing ratio due to its water holding capacity, which could be a technological aspect to improve the textural and sensorial properties in the food applications. Previous literature supports the statement that ferulic acid moieties in tridimensional polymeric network of hydrogels formed compact gel network due to esterification of ferulic acid with polysaccharide chain. Moreover, increased aggregation in samples could be due to drying method as, lyophilization formed the hydrophilic interaction between powder particle, which ultimately leads toward aggregation of gel powder, which could clearly be seen in the micrograph (b). Furthermore, the Flory–Huggins theory related to the thermodynamic properties of the biopolymers stated that compatibility and elasticity is related with thermodynamic elasticity of the polymer surface, which is dependent on the elastic forces present in the biopolymers. Flory stated about the modulus of elasticity in his model, which was due to presence of retractive forces present in the gaussian surface of the biopolymer.

Previous literatures reported that alkali treatment (nixtamalization) of maize bran for the extraction of AXs loosen the bioactive moieties, which are bound with polymeric structures, and develop the compact gel structure. A similar study by Martínez-López et al. reported that nixtamalized maize bran extracted AX-based hydrogels presented the compact gel structure as compared to non-nixtamalized maize bran.

**Total polyphenols**

Phenolics are imperative class of phytochemicals which are reported to have the redox potential due to the presence of hydroxyl group (–OH) and scavenge free radicals, reported to contain better scavenging potential. Phenolic compounds are widely distributed among the plant species, and their structures greatly dependent upon the origin, and harsh climatic conditions, and plants secrete them as secondary metabolites to combat environmental stress.

The current study aimed to enumerate the phenolic compounds present in AXs and their gels extracted from maize bran and the results depicted that total phenolic and flavonoid contents in maize
barn AXs were 6.42 ± 0.18 and 5.29 ± 0.02 GAE/g and 1.84 ± 0.66 and 1.54 ± 0.01 CE/g, respectively. In a study, Hussain et al. reported the flavonoids content in two different varieties of maize bran with 1.11 ± 0.13 mg RE/g and 0.93 ± 0.14 mg RE/g and Mehta et al. reported the total flavonoids, i.e. 1.02 ± 0.02 mg rutin/g in rice bran which shows the presence of bioactive compounds in different cereals, which strengthen the findings of our study.

**Scavenging potential of hydrogels**

The current study aimed to explore the antioxidant potential of AXs and laccase-induced cross-linked AXs using three commonly used antioxidant assays, and the results are presented in Table 2. The results depicted that AXs showed the higher antioxidant potential as compared to their cross-linked structure. Previous study of Mendez-Encinas et al. reported that gelation reduced the antioxidant potential of AXs which was assessed through FRAP assay, up to 61–64% and reported that cross- and uncross-linked AXs showed the antioxidant potential including 16.83 ± 0.83 and 48.41 ± 1.07 μmol TE/g, respectively. However, the current findings support the statement that antioxidant activity is greatly dependent on the availability of polyphenols, and in maize bran, ferulic acid is a major phenolic acid which is reported to contain better antioxidant potential. Further, the gel formation mechanism is also dependent on the quality and form of ferulic acid. In the current study, it was observed that cross-linking of ferulic acid limited the scavenging potential of cross-linked AXs, and our current findings are closely corroborated with those of Mendez-Encinas et al., who reported the similar results but their proliferation evaluation depicted that both AXs and their gels are compatible for colon cell lining. In cross-linking mechanism, substitution of the AXs bound the ferulic acid, which ultimately leads toward the lowering in vitro antioxidant activity due to unavailability of ferulic acid but, it would be better for in vivo digestion.

A comparative study on AXs esterified with hydroxycinnamic acids and reported the formation of superior gel structure from maize-based AXs. It would be a better recommendation that cross-linking of bioactive moieties with AXs would be beneficial to release them at targeted site, as, the protective effect of maize bran based cross-linked AXs against chemically induced reactive oxygen species.

**Conclusion**

Maize bran is generally used as animal feed due to some undesirable properties (textural and sensorial) on the end products. Our findings, in the current study, showed that maize bran contain 42% dietary fibers with bounded bioactive moieties, which upon the extraction of AXs, esterified with AXs structure. The FTIR spectra showed the multiple functional groups with dense peaks at 836 and 1017 cm⁻¹, which correspond the arabinose and xylose interaction. Further, SEM micrographs showed distinct surface morphology from which AXs showed a rough surface, whereas, their cross-linked showed a definite pattern of microparticles, which according to our information was due to enzymatic activity. The scavenging potential of maize bran AXs and their gels was assessed through three different assays, and the results showed that, maize bran AXs showed the higher antioxidant potential as compared to their gels. However, the decline in antioxidant potential was due to unavailability of ferulic acid, due to cross-linking. Conclusively, the current study presented the interesting insights of in vitro hydrolysis of biological polymers and their cross-linking, which are helpful in the assumption.

| Antioxidant assays | Arabinoxylans (uncross-linked) | Hydrogels (cross-linked) |
|--------------------|-------------------------------|-------------------------|
| TPC (GAE/g)        | 6.42 ± 0.18                  | 5.29 ± 0.02             |
| TFC (CE/g)         | 1.84 ± 0.66                  | 1.54 ± 0.01             |
| DPPH (μmol TE/g)   | 39.52 ± 0.63                 | 13.62 ± 0.16            |
| FRAP (μmol TE/g)   | 34.87 ± 0.18                 | 10.87 ± 0.08            |
| ABTS (μmol TE/g)   | 72.64 ± 0.32                 | 14.21 ± 0.18            |
of in-vivo digestion of these polymers and their potential to preserve the gut health, which would be important in the development of gut-friendly functional foods as well.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Farhan Saeed http://orcid.org/0000-0001-5340-4015
Muhammad Afzaal http://orcid.org/0000-0001-9047-9075
Muzzamal Hussain http://orcid.org/0000-0001-6508-1962
Entessar Al Jbawi http://orcid.org/0000-0002-1804-1770

References

[1] Calinoiu, L. F.; Vodnar, D. C. Whole Grains and Phenolic Acids: A Review on Bioactivity, Functionality, Health Benefits and Bioavailability. Nutrients. 2018, 10(11), 1615. DOI: 10.3390/nu10111615.
[2] Martinez, T. M.; Meyer, R. K.; Duca, F. A. Therapeutic Potential of Various plant-based Fibers to Improve Energy Homeostasis via the Gut Microbiota. Nutrients. 2021, 13(10), 3470. DOI: 10.3390/nu13103470.
[3] Ramirez-Jiménez, A. K.; Castro-Muñoz, R. Emerging Techniques Assisting Nixtamalization Products and by-products Processing: An Overview. Crit. Rev. Food Sci. Nutr. 2021, 61(20), 347–3420. DOI: 10.1080/10408398.2020.1798352.
[4] Marquez-Escalante, J. A.; Carvajal-Millan, E. Feruloylated Arabinoxylans from Maize Distiller’s Dried Grains with Solubles: Effect of Feruloyl Esterase on Their Macromolecular Characteristics, Gelling, and Antioxidant Properties. Sustainability. 2019, 11(22), 6449. DOI: 10.3390/su11226449.
[5] Xiong, S.; Sun, W.; Chen, R.; Yuan, Z.; Cheng, X. Fluorescent dialdehyde-BODIPY Chitosan Hydrogel and Its Highly Sensing Ability to Cu2+ Ion. Carbohydr. Polym. 2021, 273, 118590. DOI: 10.1016/j.carbpol.2021.118590.
[6] Shariatinia, Z.; Barzegari, A. Polysaccharide Hydrogel films/membranes for Transdermal Delivery of Therapeutics. In S. Maiti & S. Jana (eds.) Polysaccharide Carriers for Drug Delivery; Woodhead Publishing, 2019; pp 639–684. 9780081025536.
[7] Guo, Y.; Bae, J.; Fang, Z.; Li, P.; Zhao, F.; Yu, G. Hydrogels and hydrogel-derived Materials for Energy and Water Sustainability. Chem. Rev. 2020, 120(15), 7642–7707. DOI: 10.1021/acs.chemrev.0c00345.
[8] Ewens, H.; Metilli, L.; Simone, E. Analysis of the Effect of Recent Reformulation Strategies on the Crystallization Behaviour of Cocoa Butter and the Structural Properties of Chocolate. Carr Res. Food Sci. 2021, 4, 105–114. DOI: 10.1002/j.cfrs.2021.02.009.
[9] Marangoni, A. G.; Van Duynhoven, J. P.; Acevedo, N. C.; Nicholson, R. A.; Patel, A. R. Advances in Our Understanding of the Structure and Functionality of Edible Fats and Fat Mimetics. Soft Matter. 2020, 16(2), 289–306. DOI: 10.1039/C9SM01704F.
[10] Robert, B.; Chenthamara, D.; Subramaniam, S. Fabrication and Biomedical Applications of Arabinoxylans, Pectin, Chitosan, Soy Protein, and Silk Fibroin Hydrogels via laccase-Ferulic Acid Redox Chemistry. Int. J. Biol. Macromol. 2021, 201, 539–556. DOI: 10.1016/j.ijbiomac.2021.12.103.
[11] AACC. American Association of Cereal Chemists (AACC). In Approved Method of the AACC. St; The Association: Paul, MN, 2000.
[12] Carvajal-Millan, E.; Rascón-Chu, A.; Márquez-Escalante, J. A.; Micard, V.; de León, N. P.; Gardea, A. Maize Bran Gum: Extraction, Characterization and Functional Properties. Carbohydr. Polym. 2007, 69(2), 280–285. DOI: 10.1016/j.carbpol.2006.10.006.
[13] Kale, M. S.; Hamaker, B. R.; Campanella, O. H. Alkaline Extraction Conditions Determine Gelling Properties of Cornt Bran Arabinoxylans. Food Hydrocoll. 2013, 31(1), 121–126. DOI: 10.1016/j.foodhyd.2012.09.011.
[14] Wang, J.; Somasundaran, P. Study of Galactomannose Interaction with Solids Using AFM, IR and Allied Techniques. J. Colloid Interface Sci. 2007, 309(2), 373–383. DOI: 10.1016/j.jcis.2006.10.086.
[15] Sengul, H.; Surek, E.; Niflufer-Erdil, D. Investigating the Effects of Food Matrix and Food Components on Bioaccessibility of Pomegranate (Punica Granatum) Phenolics and Anthocyanins Using an in-vitro Gastrointestinal Digestion Model. Food Res. Int. 2014, 62, 1069–1079. DOI: 10.1016/j.foodres.2014.05.055.
[16] Turkmen, F. U.; Takci, H. A. M.; Sekeroglu, N. Total Phenolic and Flavonoid Contents, Antioxidant and Antimicrobial Activities of Traditional Unripe Grape Products. Indian J. Pharm. Educ. Res. 2017, 51, 489–493. DOI: 10.5530/ijper.51.3s.72.
Cytotoxicity

Brown-Bojorquez, DOI: 10.1006/abio.1996.0292.

Malung, L. N.; Beta, T. Antioxidant Capacity of Arabinoxylan Oligosaccharide Fractions Prepared from Wheat Aleurone Using Trichoderma Viride or Neocallimastix Patriciarum Xylanase. Food Chem. 2015, 167, 311–319. DOI: 10.1016/j.foodchem.2020.105737.

Hussain, M.; Saeed, F.; Niaz, B.; Afzaal, M.; Ikram, A.; Hussain, S.; ... Anjum, F. M. Biochemical and Nutritional Profile of Maize Bran-enriched Flour in Relation to Its End-use Quality. Food Sci. Nutr. 2021, 9(6), 3336–3345. DOI: 10.1002/fsn3.2323.

Herrera-Balandrano, D. D.; Báez-González, J. G.; Carvajal-Millán, E.; Muy-Rangel, D.; Urias-Orona, V.; Martínez-López, A. L.; Niño-Medina, G. Alkali-extracted Feruloylated Arabinoxylans from Nixtamalized Maize Bran Byproduct: A Synonymous with Soluble Antioxidant Dietary Fiber. Waste Biomass Valorization. 2020, 11(2), 403–409. DOI: 10.1007/s12649-018-0462-z.

Ren, Y.; Yakubov, G. E.; Linter, B. R.; MacNaughtan, W.; Foster, T. J. Temperature Fractionation, Physicochemical and Rheological Analysis of Psyllium Seed Husk Heteroxylan. Food Hydrocolloids. 2020, 104, 105737. DOI: 10.1016/j.foodhyd.2020.105737.

Zhang, X.; Chen, T.; Lim, J.; Gu, F.; Fang, F.; Cheng, L.; Hamaker, B. R. Acid Gelation of Soluble laccase-crosslinked Corn Bran Arabinoxylan and Possible Gel Formation Mechanism. Food Hydrocolloids. 2019, 92, 1–9. DOI: 10.1016/j.foodhyd.2019.01.032.

Martínez-López, A. L.; Carvajal-Millan, E.; Rascón-Chu, A.; Márquez-Escalante, J.; Martínez-Robinson, K. Gels of Ferulated Arabinoxylans Extracted from Nixtamalized and non-nixtamalized Maize Bran: Rheological and Structural Characteristics. CyTA-J. Food. 2013, 11(sup1), 22–28. DOI: 10.1080/19476337.2013.781679.

Mehta, D.; Yadav, K.; Chaturvedi, K.; Shivhare, U. S.; Yadav, S. K. Impact of Cold Plasma on Extraction of Polyphenol from De-Oiled Rice and Corn Bran: Improvement in Extraction Efficiency, in Vitro Digestibility, Antioxidant Activity, Cytotoxicity and Anti-Inflammatory Responses. Food Bioproc. Tech. 2022, 15, 1142–1156. DOI: 10.1007/s11947-022-02801-8.

Mendez-Encinas, M. A.; Carvajal-Millan, E.; Rascón-Chu, A.; Astiazarán-Garcia, H.; Valencia-Rivera, D. E.; Brown-Bojorquez, F.; Velazquez, C. Arabinoxylan-based Particles: In Vitro Antioxidant Capacity and Cytotoxicity on a Human Colon Cell Line. Medicina. 2019, 55(7), 349. DOI: 10.3390/medicina55070349.