

## Arabinoylans: A review on protocols for their recovery, functionalities and roles in food formulations

Fernanda Jimena Hernández-Pinto<sup>1</sup>, Juan Daniel Miranda-Medina<sup>2</sup>, Abril Natera-Maldonado<sup>3</sup>, Óscar Vara-Aldama<sup>4</sup>, Mary Pily Ortueta-Cabranes<sup>4</sup>, Jorge A. Vázquez del Mercado-Pardiño<sup>4</sup>, Mohammad Saeed Kharazmi<sup>8</sup>, Roberto Castro-Muñoz<sup>9,10\*</sup>, Seid Mahdi Jafari<sup>5,6,7\*</sup>

<sup>1</sup>Tecnologico de Monterrey, Campus Querétaro. Av. Epigmenio González 500, Tecnológico, 76130, Santiago de Querétaro, Qro., Mexico

<sup>2</sup>Tecnologico de Monterrey, Campus Guadalajara, Av. General Ramón Corona 2514, Zapopan, 45138, Jalisco, Mexico

<sup>3</sup>Tecnologico de Monterrey, Campus Chihuahua, Av. H Colegio Militar 4700, Nombre de Dios, Chihuahua, Chih., Mexico

<sup>4</sup>Tecnologico de Monterrey, Campus Monterrey. Av. Eugenio Garza Sada Sur 2501 Sur, Tecnológico, 64849 Monterrey, N.L., Mexico

<sup>5</sup>Department of Food Materials and Process Design Engineering, Gorgan University of Agricultural Science and Natural Resources, Gorgan, Iran

<sup>6</sup>Universidade de Vigo, Nutrition and Bromatology Group, Department of Analytical Chemistry and Food Science, Faculty of Science, E-32004 Ourense, Spain

<sup>7</sup>College of Food Science and Technology, Hebei Agricultural University, Baoding 071001, China

<sup>8</sup>Faculty of Medicine, University of California, Riverside, CA 92679, USA

<sup>9</sup>Tecnologico de Monterrey, Campus Toluca. Av. Eduardo Monroy Cárdenas 2000 San Antonio Buenavista, 50110 Toluca de Lerdo, México

<sup>10</sup>Gdansk University of Technology, Faculty of Civil and Environmental Engineering, Department of Sanitary Engineering, 11/12 Narutowicza St., 80-233, Gdansk, Poland

\*Corresponding Author:

*E-mail: [food.biotechnology88@gmail.com](mailto:food.biotechnology88@gmail.com); [roberto.castro-munoz@pg.edu.pl](mailto:roberto.castro-munoz@pg.edu.pl); [castromr@tec.mx](mailto:castromr@tec.mx)*

## 28 Abstract

29 Arabinoxylans (AXs) are compounds with high nutritional value and applicability, including  
30 prebiotics or supplementary ingredients, in food manufacturing industries. Unfortunately, the  
31 recovery of AXs may require advanced separation and integrated strategies. Here, an analysis of the  
32 emerging techniques to extract AXs from cereals and their by-products is discussed. This review  
33 covers distinct methods implemented over the last 2-3 years, identifying that the type of method,  
34 extraction source, AX physicochemical properties and pre-treatment conditions are the main factors  
35 influencing the recovery yield. Alkaline extraction is among the most used methods nowadays, mostly  
36 due to its simplicity and high recovery yield. Concurrently, recovered AXs applied in food  
37 applications is timely reviewed, such as potential bread ingredient, prebiotic and as a wall material  
38 for probiotic encapsulation, in beer and non-alcoholic beverage manufacturing, complementary  
39 ingredient in bakery products and cookies, improvers in Chinese noodles, 3D food printing and  
40 designing of nanostructures for delivery platforms.

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**Keywords:** Arabinoxylan; Purification; Gelling properties; Cereals; Dietary fiber; Functional foods.

## 101 Acronyms

102 AXs: Arabinoxylans

103 AXOS: arabinoxylooligosaccharides

104 BSG: brewers' spent grain

105 GI: Glycemic Index

106 MAX: small molecular arabinoxylans

107 NSP: non-starch polysaccharides

108 PWMB: brewers' spent grain

109 SWE: subcritical water extraction

110 SCFAs: short chain fatty acids

111 UAX: unmodified arabinoxylans

## 58 1. Introduction

59 As of 2022, many global trends lean into the search for new and innovative techniques towards  
60 the development of environmentally conscious processes. Ongoing climate change has created a  
61 heightened need for re-designing the use and obtaining high-value-added compounds from by-  
62 products of the food industry. Many abundantly available by-products end up as waste (Roberto  
63 Castro-Muñoz et al. 2018); thus, the present-day demand for emerging applied technologies for their  
64 management (Valencia-Arredondo et al. 2020; Roberto Castro-Muñoz 2020a). This not only  
65 represents an opportunity in a much-needed favourable time for taking care of the environment, but  
66 also **opens a new opportunity** for the food industry to improve and make the most out of its protocols  
67 and processes in multiple areas. Recovering by-products not only influences the economic spectrum  
68 of the protocol but also gives out a chance for finding, studying, and investigating new benefits from  
69 previously discarded materials (Castro-Muñoz, Gontarek-Castro, and Jafari 2022; Castro-Muñoz and  
70 García-Depraect 2021) .

71 Particular by-products, like the ones derived from cereal processing industries, are potentially  
72 a rich source of high-added value molecules (Díaz-Montes and Castro-Muñoz 2021), which are either  
73 difficult to chemically synthesize or produce (Roberto Castro-Muñoz et al. 2021). This is the case of  
74 arabinoxylans (AXs), which is a complex fiber providing various health benefits regulated thanks to  
75 the chemical composition which are naturally present in specific parts of cell walls of distinct grains  
76 including corn, wheat, rice, rye, sorghum, oats, barley and other plants. **AXs are polysaccharides**  
77 **presenting various d-Xylose molecules arranged in linear backbone, which are joined due to  $\beta$  (1→4)**  
78 **bonds, while  $\alpha$ -L-arabinofuranosyl residues molecules are also chemically attached to the specific d-**  
79 **Xylose molecules** (Lapierre et al. 2018). Their isolation has been successful, showing that the  
80 different molecular weight compositions are affected directly by their source and extraction methods  
81 and hence impacting on their functionality. AXs have shown functional properties acting as a  
82 nutraceutical agent; as soluble fiber aids in controlling diabetes mellitus (specially type II), and  
83 enhancing the metabolism of the three main macronutrients (carbohydrates, proteins and lipids) (Nie

84 et al. 2018). AXs have also exhibited a role as a prebiotic agent since they stimulate bacterial growth,  
85 making them a beneficial and important factor on the microbial gut health. Being able to improve  
3 86 microbial health has been linked to reducing risk in diseases caused by shifts within the gut. Other  
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6 87 health benefits, such as hepatoprotective and immunomodulatory activities, postprandial glucose and  
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8 88 cholesterol control, improving absorption of calcium and magnesium, enhancing colon function and  
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11 89 lower risk of colon cancer, have also been found (Fadel et al. 2018). However, these compounds not  
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13 90 only provide benefits to humans, but also to animals. Therefore, they can also be valuable as feed  
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15 91 additives for livestock (Siddiqui et al. 2022).

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18 92 This review timely identifies potential sources containing AXs such as food by-products, as  
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20 93 well as to elucidate the updated strategies and methods applied for AX recovery. Knowing their  
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23 94 advantages and disadvantages including details on the techniques and protocols used, we will declare  
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25 95 the most appropriate processes for AXs separation. Therefore, an explicit **search for understanding** of  
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28 96 recent scientific literature (over the last 2-3 years) has been done. Knowing the implications of the  
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30 97 molecules of interest and their potential use in new formulations within the industry, we review the  
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33 98 latest research studies focused on AX exploitation for new food formulations or helping to improve  
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35 99 the existing ones, including their importance to the industry.

## 400 401 **2. Extraction strategies to recover arabinoxylans from food wastes**

402 To date, different methods have been applied for extracting AXs present in distinct sources,  
403 including sugarcane bagasse, wheat bran, corn, barley, among some others. These extraction methods  
404 include but are not limited to enzymatic and alkaline extraction. Initially, **it is obvious that selecting**  
405 **the adequate source of recovery is a key variable to obtain a higher yield, however, it is worth**  
406 **mentioning that the recovery strategy is planned and strongly depends on the initial physicochemical**  
407 **composition of the AXs source.** Maize bran is a primary source of election, mostly due to the  
408 quantities produced globally, resulting in an ease of availability (Ayala-Soto et al. 2014).

### 9 **2.1. Alkaline extraction method with defatted and dried maize**

110 When studying the extraction and recovery of AXs with defatted and dried maize, Herrera-  
111 Balandrano et al. (2018) achieved an 8.23% recovery with an alkaline extraction method, meanwhile  
112 Paz-Samaniego et al. (2016) obtained a 46% yield but when using maize wastewater or “nejayote” as  
113 a primary source with acid hydrolysis extraction method, a percentage that can be interpreted as a  
114 good source of recovery for AXs (Roberto Castro-Muñoz 2020b; Ramírez-Jiménez and Castro-  
115 Muñoz 2020). **Another alternative source to extract AXs is wheat bran, a by-product of different  
116 wheat processes, which has a significant nutrient content, such as dietary fiber and protein, and makes  
117 it a product with value-added in the current market.** Concurrently, as being one of the biggest food  
118 products in the world, there is nowadays an environmental concern from the under-consumed wheat  
119 (Liu et al. 2020).

## 2.2. Hydrothermal treatment

121 By using hydrothermal treatment and on mesoporous silica catalyst, it has been reported the  
122 simultaneous extraction and recovery of AXs from detached wheat bran; in this study, Sánchez-  
123 Bastardo et al. (2017) observed that extracting large quantities of small fractions of AXs is promoted  
124 in a short extraction time while maintaining high temperature, catalyzed with extreme acidity values.  
125 For instance, when extracting at optimum conditions of 180 °C, 10 minutes, the total AX yield  
126 extracted was 78% AXs (expressed as the ratio of total AXs contained in liquid extract and raw  
127 material), while Li et al. (2020) reported lower recovery rates (approximately 17.98%), representing  
128 a more attractive source compared with maize bran.

129 In recent years, the use of brewers’ spent grain (BSG) has been a novel source of AXs due to the  
130 large amount of biomass generated by this agro-industrial process. The BSG is a by-product left after  
131 barley malting and separation of the wort during the brewing process (Jaguey-Hernández et al. 2022).  
132 In their study, Pérez-Flores et al. (2019) obtained a yield near 65% using alkaline extraction method,  
133 representing the amount of AXs in the BSG-AX compared to the total AX amount to the original  
134 sample, but a yield of 72% of pure AX. The BSG-AX contained glucose (ca. 17.94%), arabinose (ca.  
135 33.74%), and xylose (ca. 37.90%).

### 2.3. Saccharification and fermentation process

On the other hand, Lynch et al. (2021) used a simultaneous saccharification and fermentation process on several BSG samples obtaining an average concentration of 23.5%, where they performed different treatment processes in order to obtain diverse samples containing different content of soluble AX differing in structural characteristics, including polymerization and substitution degree.

A source of recent interest for AXs extraction is the sugarcane bagasse; this source represents a high waste stream arising from sugar and alcohol industries. According to Campbell et al. (2019), bagasse exhibits different functional properties to take into consideration when choosing the method of extraction, since bagasse has a reduced solubility and greater susceptibility to enzyme action. They also evaluated an extraction of AXs from two different sources: sugarcane and wheat bread, obtaining a total recovery of 34% and 11.5%, respectively. On the other hand, Solier et al. (2022) were able to obtain a higher yield of precipitated hemicellulose (ca. 85%), corresponding to the treatment performed at high alkalinity with no use of peroxide.

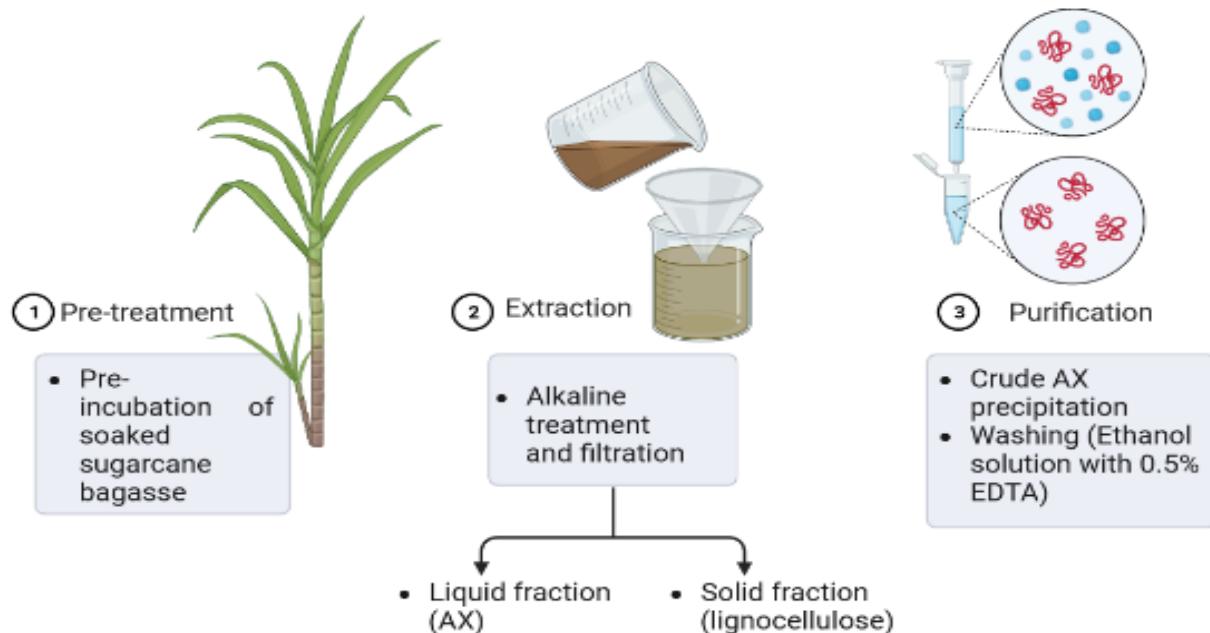
Preliminarily, by analyzing the current strategies used for AX extraction, alkaline extraction is likely to be the most prominent method, mostly due to its simplicity and equipment needed, with adequate yields and concentrations depending on the primary source used. This method was described for the first time in 1998 by Zilliox and Debeire (1998), who established the use of organic solvents, such as acetic acid (also known as ethanoic acid) and ethanol, to precipitate AXs. Several washing steps are required until reaching a neutral pH; after this, an alkaline treatment is performed with a certain concentration of KOH. However, this protocol has been adapted several times in order to obtain higher concentrations of AXs. The alkaline treatment is generally followed by a liquid fraction (see **Fig. 1**) to obtain AX or even a solid fraction if it is desired to obtain lignocellulose. Alkaline extraction method has a substantial operation time between 2 and 8 h depending on the solution used; unfortunately, among its disadvantages are the hydrolysis of polysaccharides destroying its structure and when there is an improper concentration of alkali, it can break glycosidic bonds, generating many impurities and thus difficult to further process (e.g., filtration). Also, extraction solution viscosity is

162 too high while presenting strong alkali taste which affect the quality (Lihua, Xin, and Jiayang 2018).  
163 It has been proved to reduce the bioactivity and antioxidant properties of AXs since the long  
164 extraction time, exposes AX to longer periods of constant high temperatures and pressure, leading  
165 into depolymerization of the molecules (Jaguey-Hernández et al. 2022; Daniela D. Herrera-  
166 Balandrano et al. 2018; Schmidt, Wiege, and Hollmann 2021; Pérez-Flores et al. 2019; Rudjito et al.  
167 2019).

168 In view of this problem, different extraction strategies and methods have emerged to reduce such  
169 a limitation.

## 170 2.4. Subcritical water extraction

171 For instance, subcritical water extraction (SWE) is an alternative method that has demonstrated  
172 to decrease the extraction time with significant recovery yields depending on the operating extraction  
173 conditions. Since this technique uses water instead of a buffer solution for de-starching the source,  
174 SWE offers better yields and less environmental impacts (Rudjito et al. 2019).



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According to de Figueiredo et al. (2017), the alkalization can be successfully done with a solution composed of KOH (24% m/V) and NaBH<sub>2</sub> (1% m/V), which was subsequently blended with

182 the extraction source (8% m/v) for 3 h at 35 °C. After this, the resulting liquid fraction was then pre-  
183 filtered using gauze until obtaining a liquid lacking in visible solids. In a subsequent step, the AXs  
184 contained in such liquid fraction were precipitated by mixing with an organic mixture containing  
185 ethanol (60% v/v), acetic acid (6.7% v/v) and AXs (33.3% v/v). The precipitated matter, identified  
186 as AXs, was recovered using centrifugation (for short time 15 min at 4000 g). Finally, the obtained  
187 AX fraction was washed in proportional ratio (1:1 v/v) using ethanolic solution containing ethanol  
188 (50%) and EDTA (0.5%) in deionized water, subsequently, the AX fraction was subjected to drying  
189 (at 60 °C).

190 Following with the extraction methods of AXs, Lazaridou et al. (2008) described a protocol using  
191 water treatment which consist in the solubilization of AXs by immersing the grain fragments in hot  
192 water varying between 45-90 °C; observing that the higher the temperature, the shorter the exposure  
193 time. This method could preserve the native structure of AX. However, the water-soluble property of  
194 AXs was to some extent dependent on the type of grain and its germination degree, location within  
195 the grains and chemical nature of the carbohydrate fractions present in the grain. All these aspects  
196 greatly determine the overall recovery yield of AXs via water extraction (Zannini et al. 2022). To  
197 some extent, Lazaridou´s protocol seem to be feasible enough for AX extraction, however, it depends  
198 on the type of grain used. Importantly, the removal of starch and other carbohydrates using specific  
199 enzymes may be required. Even though, the nature of the polysaccharides may result as a main  
200 limiting factor when chemically crosslinked AXs to other polymer fractions (from grain cell wall)  
201 are not efficiently separated and thus inherently limits the extraction efficiency.

## 202 2.5. Milling

203 Also, there are a variety of emerging technologies based on mechanical treatment, including  
204 milling which offer many advantages representing an ecofriendly and economically feasible option  
205 to obtain a homogeneous dispersion when blended with biopolymers. Such technologies provide  
206 other advantages in terms of less environmental impact, controlled degradation reactions regulated  
207 by high temperatures, enhanced compatibility of blends lacking in miscibility, the promotion of



208 mechano-chemical reactions and an appropriate handling of thermolabile active molecules (Gorrasi  
209 and Sorrentino 2015).

## 210 **2.6. Extrusion**

211 For instance, extrusion stands out as a preferred technique for the preparation of extruded  
212 foods with high acceptability, while impacting specific properties of the product, including water  
213 solubility, water and oil absorption, expansion indices of extruded formulations and their bulk  
214 density, as well as the dough viscosity (Alam et al. 2015). Demuth et al. (2020), for example,  
215 performed an extraction of AX using a milling and exclusion; their results showed that this  
216 mechanical treatment helped to boost the recovery yield due to more extractable AXs.

## 217 **2.7. Ultrasound and microwave-based technologies**

218 Ultrasound and microwave-based technologies are other successful approaches for valuable  
219 solutes extraction, such as AXs. According to their principles, the use of these technologies can not  
220 only result in shortened extraction times but also contributes to obtaining high recovery yield towards  
221 a targeted compound. Moreover, these technologies exhibit a reduction of solvent usage (if required)  
222 as cavitation bubbles pressure may disrupt the cell wall (Görgüç, Bircan, and Yılmaz 2019; Cako et  
223 al. 2022) and thus result into enhanced transfer of mass in the extraction process (Jiang et al. 2019).

## 224 **2.8. Steam-pressure**

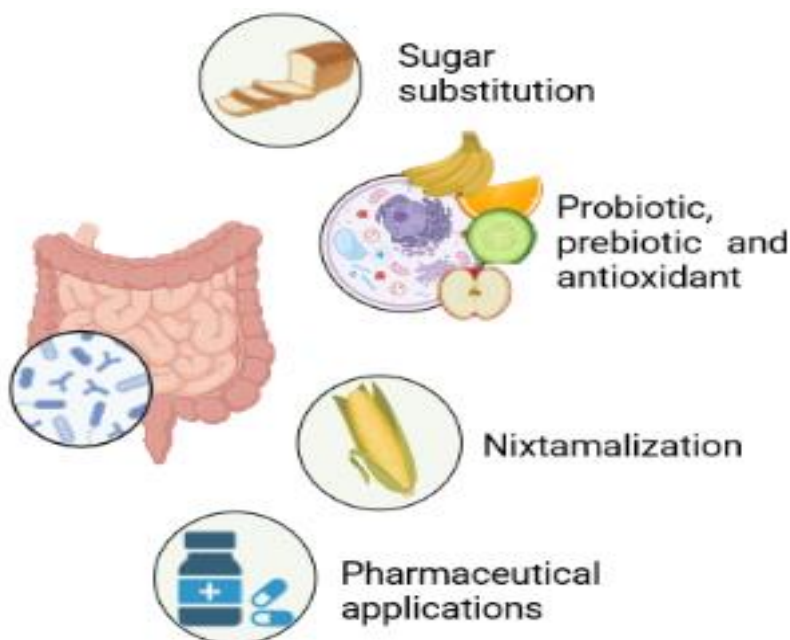
225 Steam-pressure application positively affects AX's extractability. Sui et al. (2018), for  
226 instance, evaluated the applicability of steam pressure for insoluble fiber extraction, which could be  
227 potentially transformed into a soluble one boosting its extraction with water.

228 As discussed previously, the protocols dedicated to the extraction and purification of AX depend  
229 on the source of recovery, in which the extraction may imply the combination of two or more different  
230 methods. In most of the protocols, chemical or biological factors, such as KOH concentration,  
231 enzymatic concentration, extraction temperature, exposure time, solvent for precipitation (e.g., acetic  
232 acid, ethanol) and its ratio, and number of washes, varied according to the needs of the investigation.  
233 According to **Table 1**, available studies demonstrated acceptable recovery efficiencies toward AX,

234 pointing out that alkaline extraction **can offer** a yield of up to 72%, which is comparable with  
235 hydrothermal synthesis with an AX yield = 78%.

### 236 237 **3. Potential applications of recovered AXs in food formulations**

238 As represented in **Fig. 2**, AXs have been attributed with multiple functionalities for costumers  
239 as sugar substitute, probiotic and prebiotic, antioxidant, bioactive compounds for lowering  
240 cholesterol, and as a nutraceutical in pharmaceutical formulations. Several studies have shown that  
241 AXs greatly promote the nutritional health of the digestive system as a dietary fiber and prebiotic.  
242 This molecule is contained in foods, particularly cereals as the main ingredient. Such molecules are  
243 targeted for human consumption or animal feed due to their great impact in terms of different  
244 biological activities, such as the synergic effect with phenolics, prebiotic activity due to fermentation,  
245 cholesterol control because of the generation of short chain fatty acids (SCFAs) (Y. Zhao et al. 2017),  
246 regulation of blood sugar for patients with diabetes and as a booster of the intestinal microbiota  
247 composition improving the immune response (Ashaolu 2020).



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**Fig. 2.** Main health benefits of AXs.

**Table 1.** Arabinoxylan extraction techniques and outcomes.

<b>Molecule</b>	<b>Source</b>	<b>Technique</b>	<b>Operating conditions</b>	<b>Yield (%)</b>	<b>Reference</b>
BSG-AX	Barley	Alkaline extraction	<b>Temperature:</b> 25°C <b>Time:</b> 8 h, complete darkness <b>Stirring:</b> 150 rpm <b>Solvent:</b> NaOH 0.5 mol L <sup>-1</sup> (pH 11-12)	72	(Pérez-Flores et al. 2019)
BSG-AX	Barley	Alkaline extraction	<b>Temperature:</b> 25°C <b>Time:</b> 8h, complete darkness <b>Stirring:</b> Yes, 100 rpm <b>Solvent:</b> NaOH 0.5 mol L <sup>-1</sup> (pH 11-12)	-	(Jaguey-Hernández et al. 2022)
BSG-AX	Barley	Saccharification +water treatment	<b>Temperature:</b> 90°C <b>Time:</b> 6 h <b>Solvent:</b> water	21.9	(Lynch et al. 2021)
Sugarcane AX	Sugarcane bagasse	Alkaline extraction	<b>Temperature:</b> 55°C <b>Time:</b> 4 h <b>Stirring:</b> Yes, 200 rpm <b>Solvent:</b> NaOH 5 mol/L and 5–10 drops of antifoaming agent	-	(Solomou et al. 2022)
Native and acetylated AX	Wheat bran	-Pretreated by $\alpha$ -amylase. -Subcritical water extraction (SWE) of AX from destarched wheat bran	<b>Temperature:</b> 90 °C for <b>Time:</b> 17 h <b>Solvent:</b> Sodium phosphate buffer (pH= 7.0)	FAX: 7.5 NAX: 31.1	(Yilmaz-Turan et al. 2020)
Water un-extractable AX	Corn bran	Ultrasonic-Microwave	<b>Temperature:</b> 70 °C <b>Time:</b> 5-30 min <b>Power:</b> 200-600 W <b>Solvent:</b> NaOH 0.15-0.35 mol/L pH= 4.5 <b>Stirring:</b> 4000 rpm, 20 min	25	(Jiang et al. 2019)
Feruloylated AXs	Wheat bran	Subcritical water treatment. Microwave heating extraction system	<b>Temperature:</b> 120-180 °C <b>Time:</b> 10-120 min <b>Solvent:</b> 10% (w/v) aqueous suspension pH 4-10	17.98	(J. Li and Du 2019)
Feruloylated AXs	Maize bran	Alkaline extraction	<b>Temperature:</b> 37 °C <b>Time:</b> 2-6 h <b>Solvent:</b> 0.5 N NaOH solution	8.23	(Herrera-Balandrano et al. 2019)
Maize waste water AXs	Maize wastewater “nejayote”	Acid hydrolysis extraction	<b>Temperature:</b> 120 °C <b>Time:</b> 2 h <b>Solvent:</b> 2 N trifluoroacetic acid	46	(Paz-Samaniego et al. 2016)
Arabinose/Xylose	Wheat bran	Hydrothermal synthesis assisted by heterogenous catalyst	<b>Temperature:</b> 140-180 °C <b>Time:</b> 10-20 min <b>Mesoporous silica:</b> MCM-48/Al-MCM-48 With or without Ruthenium catalyst (RuCl <sub>3</sub> )	78	(Sánchez-Bastardo, Romero, and Alonso 2017)

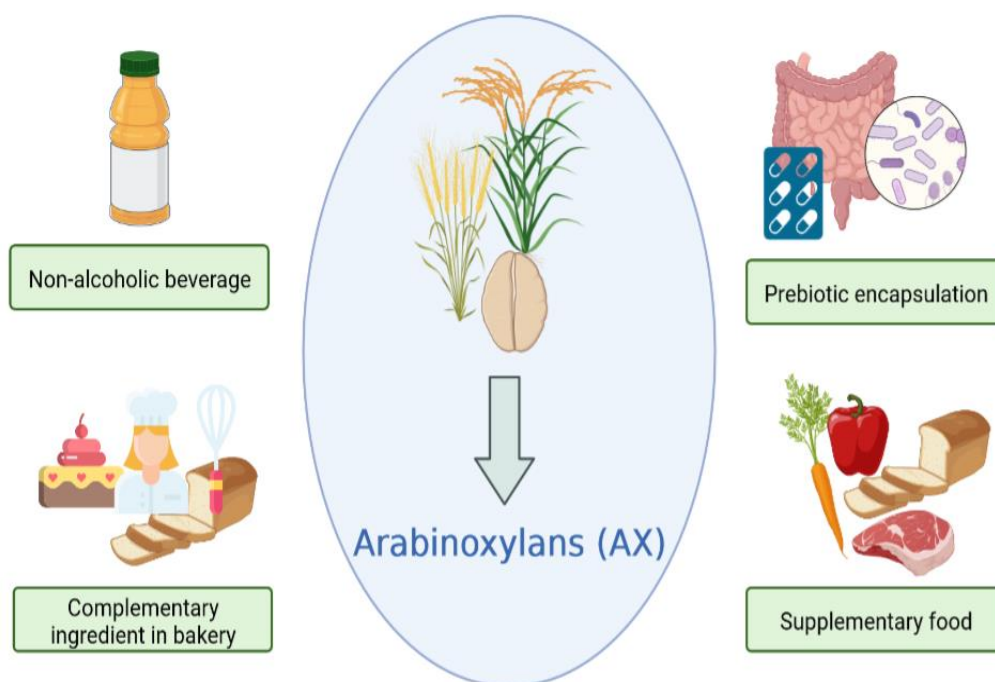
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Alkali- insoluble cellulose-rich AX (CAX)	Wheat Bran	Alkaline and water extraction	<b>Temperature:</b> 95 °C <b>Time:</b> 6 h <b>Solvent:</b> α-amylase, ethanol	16.97	(Kaur et al. 2021)
AXs	Sugarcane bagasse and wheat bran	Alkaline and enzyme extraction	For alkaline: <b>Temperature:</b> 50 °C <b>Time:</b> 4 h <b>Solvent:</b> 2% H <sub>2</sub> O For enzymatic: <b>Temperature:</b> 37 °C <b>Time:</b> 2 h	For sugarcane: 34 For wheat bread: 11.5	(Campbell et al. 2019)(Campbell et al. 2019)
AXs	Sugarcane bagasse	Alkaline extraction	<b>Temperature:</b> 35 °C <b>Time:</b> 3 h <b>Solvent:</b> 250 mL of a 24% (m/v) KOH and 1% (m/v) NaBH <sub>2</sub> solution	17.5	(de Figueiredo et al. 2017)
BSG-AX	Barley	Water extraction	<b>Temperature:</b> 45-90 °C <b>Time:</b> 11 h <b>Solvent:</b> water	28	(Lazaridou et al. 2008)
Water- extractable AX (WEAX)	Wheat bran	Water extraction	<b>Temperature:</b> 60-95 °C <b>Time:</b> 6 h <b>Solvent:</b> water	73.72	(Demuth, Betschart, and Nyström 2020)

253 According to Damen et al. (2011), a combination of partially enzymatic hydrolyzed water  
 254 unextractable and extractable AXs and arabinoxylo-oligosaccharides (AXOS) led to an increase of  
 255 SCFAs. Likewise, the fermentation of these polysaccharides helped to lessen the intestinal pH making  
 256 an inappropriate environment for pathogens while increasing the *Bifidobacteria* activity. In the same  
 257 way, different formulations were tested, and an important synergic effect was found with the  
 258 replacement of the proportions between the ingredients showing that the combination of the water  
 259 unextractable AX (40% purity), water extractable AX (81% purity) and AXOS, together increased  
 260 the butyrate levels. In the following subsections, we report some of the findings in literature dealing  
 261 with the use of AXs in food formulations, along with the main implication on the resultant product.  
 262 In general, **Fig. 3** overviews the main applications in food technology in which AXs are involved.



**Fig. 3.** Potential sources and uses of recovered AXs.

### 3.1. Arabinoxylans as a potential bread ingredient

**Table 2** enlists the reported implementations and patents of AXs in the food science aimed at improving the nutritional value of existing food items, as well as improving specific physicochemical properties. The dietary fiber obtained from wheat bran can offer several health benefits including disease prevention and antitumor activity. Although the addition of wheat bran to bread can improve

271 the nutritional value, it can also detriment the overall quality of the bread baking causing lower  
272 volume dough, bitter taste, hard crumbing and a darker color (Biliaderis et al. 1995). The relevance  
273 of AXs on these effects lies in them being the main dietary fiber component of wheat bran, even if  
274 water-soluble AXs can be generally beneficial for loaf volume and crumb structure. It is known that  
275 the **water insoluble** AXs could be the main source of spoiling, since this type of AX competes for  
276 water molecules affecting the gluten formation. According to Biliaderis et al. (1995), AXs exhibit  
277 hydrophilic nature translated to high water affinity and thus compete for water molecules against  
278 other compounds present in food matrices. Furthermore, AXs present a unique capability to capture  
279 water molecules thanks to “oxidative gelation” and considering the influence of these on water  
280 relations, based on hydrogen bonding or other specific interactions. As for food processing properties,  
281 they depend on the availability and content of water; AXs certainly become relevant in the final  
282 physicochemical properties and quality of wheat. Since AXs are able to bind or capture a relatively  
283 high quantity of water, this increases the moisture level, together with the molecular chain mobility  
284 of starch, resulting in an improved rate of starch retrogradation (Michniewicz et al. 1992; Biliaderis  
285 et al. 1995).

286 It has been known for years that water-insoluble AXs can be released via alkaline or xylanase  
287 enzyme treatment to give alkali-**solubilized** AXs or enzyme-**solubilized** AXs (Courtin and Delcour  
288 2002). The investigation made by Xue et al. (2020) demonstrated that the quality of the bread  
289 containing high quantities of wheat bran could be substantially tuned by arranging the AX structure,  
290 which can be done by an enzyme treatment enriched with arabinofuranosidase to enhance the  
291 efficiency of degradation while eliminating the arabinose units from the AX structure. Indeed, Wang  
292 et al. (2003) explained that AXs negatively affect the formation of gluten and consequently may result  
293 in a worsened gluten yield because water-unextractable solids, which include water-insoluble AXs.  
294 Also, according to their water competition, AXs somehow provoked a diminished gluten yield, since  
295 they limited the molecular chain motion and capability of the gluten formation by the gliadin and  
296 glutenin.

297 The enzyme cocktail of TmAra and XynB can improve both the nutritional content and  
298 processing functionality of wheat bran, exhibiting a synergetic response to the rheologic properties  
299 of the dough and bread quality. Additionally, it displays promising applicability within emerging  
300 areas for extracting antioxidants, conferring a higher added value in functional foods, nutraceuticals  
301 and pharmaceutical applications.

302 Reducing dietary Glycemic Index (GI) while equilibrating high levels of carbohydrate intake  
303 could be a great option for the betterment of health issues, such as being overweight, obesity and the  
304 risk to acquire diabetes, especially type II. As (Hodge et al. 2004) mentioned, a promising pathway  
305 to possibly achieve this relies on the possibility to replace white bread with low-GI bread. In refined  
306 cereals, the contained glucose tends to be more available in the metabolic digestion which can  
307 provoke insulin resistance, as continuous fluctuations of blood sugar levels may result in responses  
308 to high insulin. Interestingly, AXs obtained from trifluoroacetic acid, ultrasonication processing and  
309 xylanase-aided treatments could be potentially employed to regulate specific GI values desired in  
310 distinct baked products (Y. Liu et al. 2020).

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**Table 2.** Up-to-date developments of AXs in the food products.

<b>Application</b>	<b>Targeted product</b>	<b>Description</b>	<b>Reference/Patent number</b>
Significantly improve the added value of wheat sprouts and wolfberry	Wheat malt juice wolf- berry drink	Mix the wort, wolfberry juice and softened water, add auxiliary materials, and sterilize	CN1103549606A
Added value stimulates the growth of beneficial colonic microflora.	Kvass: cereal-based and non-alcoholic beverage	Extruded rye, xylanolytic enzymes and LAB can be used for production of novel, safe and higher value non-alcoholic beverages	(Basinskiene et al. 2016)
Enhance the nutritional and technological functionality of dough rheology and steamed bread quality	Wheat bran, having a synergetic effect on the dough rheology and steamed bread	Enzyme treatment enriched with arabinofuranosidase to enhance the efficiency of degradation and modifying the AX structure	(Xue et al. 2020)
Reducing dietary GI substituting white bread with low-GI breads.	Bread	AXs obtained from trifluoroacetic acid, ultrasonication and xylanase treatments under specific conditions can be used to modulate different baked products for the desired GI	(Y. Liu et al. 2020; Hodge et al. 2004)
Quality bran-enriched cake improver	Bakery products and cookies	Favourable effects on batter stability, cake cell density and consistency. Improves the water binding properties which helps to maintain the desired crumb moist.	(Moza and Gujral 2017)
Relieving intestine symptoms, as well as psychobiotics with a beneficial effect on microbiome-brain axis and anti-inflammatory effect.	Novel food prototypes with prebiotic applications	Water-soluble extractable AXs in vitro and confirmed in vivo, increasing the number of SCFAs in the intestine, growing the beneficial bacteria in vitro and in vivo, while decreasing the pathogens in the profile of intestinal microorganisms	(C. Paesani et al. 2019; Candela Paesani et al. 2020)
Encapsulating probiotics, better texture and addition of nutritional value to the wastewater	Nejayote: wastewater generated from the maize processing	Maize wastewater enriched in AX (MWAX) to encapsulate probiotics.	(Ayala-Soto et al. 2014)
It is rich in biological activity of wheat and has a good flavor	Wheat polysaccharide drink	Treated with organic acid and then hydrolyzed, adjust the flavor, fill and sterilize	CN104522811A
Moisturize the intestines, control blood sugar and blood lipids, regulate human immunity and prevent colon cancer	Wheat bran dietary fiber	Alkaline extraction and alcohol precipitation are combined with steam explosion and compound enzyme hydrolysis	CN104544137A
Increase the storage period of the yellow peach and preserve the good flavor of the yellow peach	Yellow peach fresh- keeping treatment liquid	Dissolve vegetable oil, sucrose, iron sulfate, and kusatrol in water, and add modified AX, clove, and astragalus mixed powder	CN108935654A
Simulate the mouthfeel of sugar to improve the quality of low- calorie beverage	Composition for im- proving the taste of beverages	Add hydrolyzed $\beta$ -glucan and AX to a low-calorie or zero- calorie beverage	CN109843086A
Improve the storage effect and edible effect of the composite probiotic product	Compound probiotic products	Add heat protection agent, then the probiotics are embedded with AX and soy protein	CN110623066A
The product not only has the rich fragrance of instant tea, but also can effectively assist in lowering blood sugar	Hypoglycemic instant tea	The product is composed of AX, hop extract, orange peel extract, Pu'er tea extract	CN110897023A
Extend the shelf life of bread and steamed	AX to extend the shelf life of	Modified AX is produced by enzymatic hydrolysis and debranching,	CN110938664A



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bread, and an efficient and healthy flour improver	bread and steamed bread	which is added to the dough	
Inhibit the growth of ice crystals and protect the dough network structure	AX to improve the quality of frozen dough	Modified by enzymes and added to frozen dough	CN110938665A
Increase the plasticity of the dough and reduce the baking time	Cookies	Reduce water absorption of flours with lower WE-AXc and sucrose solvent retention capacity	(Guttieri, Souza, and Sneller 2008)
Adding WE-AX can increase the volume of bread, reduce rejuvenation and extend the shelf life of bread	Bread	Higher WE-AX generally leads to higher loaf volume and quality, whereas higher WU-AXd has the opposite effect	(Courtin and Delcour 2002)
Low-alcohol beer brewed with rye has a higher viscosity and fullness, and a better taste	Mouthfeel contributor in beer	Grind the raw materials, add saaz hops after the saccharification bath; after sterilization, yeast is added for fermentation	(Langenaeken, De Schutter, and Courtin 2020)
Using 0.25-2.0% (w/w) of AX in wheat flour, for improving the quality. Thus, corroborate that using the percentage of AX in wheat flour, both, the nutrition and quality increase in the Chinese noodles	Chinese noodles	The use of UAX in AX from wheat bran flour and bread quality, due to the increment in the water absorption as well as dough formation of noodles	(Fan et al. 2016)
Development of accessible nutritional blends for 3D printing with AX as the basis	3D food printing	Aqueous solutions of starch-mango AX blends to preserve the properties related to the viscoelasticity were prepared with the addition of mineral water to incorporate them in 3D food	(Montoya et al. 2021)

### 313 **3.2. Arabinoxylans as prebiotics**

314 As a nondigestible fiber, AXs stimulates specific gut microbial species, specially the  
315 *Bifidobacterium* spp. and *Lactobacillus* spp., having great potential as a prebiotic with health benefits  
316 including the prevention of dysbiosis effect of gut microbiota, countering the proliferation of  
317 pathogens as well as mitigating specific gastrointestinal disorders (Duan et al. 2022). As mentioned  
318 previously, AX structure can differ depending on cereal type, the part of the grain from which it is  
319 extracted, and the method of recovery. The AX structure becomes relevant regarding the way in which  
320 it is degraded and fermented by the gut microbiota. Because of the structural diversity, there is still a  
321 lot to learn from each function/use that could have. The most studied structures are the wheat-based  
322 AXs, which have shown development of microbial species and their substantial proliferation, but  
323 there is much more to know about other types of cereal grains, such as rice, oatmeal and corn  
324 (Schupfer et al. 2021). However, Paesani et al. (2019) mentioned the potential of novel food  
325 formulations and ingredient prototypes such as AXs and probiotics for relieving intestine symptoms,  
326 as well as the possible use as psychobiotics exhibiting a positive effect on microbiome-brain axis.  
327 Punctually, this study revealed that *Lactobacillus reuteri* ATCC23272 had anti-inflammatory  
328 activity, and its synergistic effect with AXs, opens a new window of developing new food  
329 formulations. Another development was presented by Paesani et al. (2020), who studied the prebiotic  
330 activity of water-soluble extractable AXs *in vitro* and proved *in vivo* test, showing a higher prebiotic  
331 capacity by raising the number of SCFAs in the intestine, growing the health-promoting bacteria in  
332 both assays, while mitigating the number of pathogens in the total profile of microorganisms present  
333 in the intestine.

### 335 **3.3. Arabinoxylans in beer manufacturing**

6 AXs are able to cause several issues credited to the increment of wheat employed for brewing  
7 the wheat beer, which could compromise the quality of the obtained wheat beer, including the high  
8 viscosity of the wort, the haze formation, and the sensorial properties and wheat beer foam  
9 performance. Langenaeken et al. (2020) confirmed the significance of AXs and its degree of

340 polymerization for a better mouthfeel attribute of produced beverages, such as alcohol-free beer, low-  
341 alcohol content beers and light beers as it increases the viscosity values of the beer. Experimentally,  
342 those beers were brewed replacing barley malt grits (20%) with weather oat, non-malted barley, or  
343 rye in comparison with a control. As for the one brewed with rye, a substantial increase (ca. 53 %) in  
344 AXs presence was observed while increasing the degree of polymerization from 29 to 50. In  
345 comparison with the control beer presenting a viscosity = 1.48 mm<sup>2</sup>/s, this property was observed to  
346 increase in the rye beer (ca. 1.85 mm<sup>2</sup>/s). It is worth mentioning that the highest viscosity in beer was  
347 shown by the non-malted rye, this latter phenomenon was credited to the presence of high molecular  
348 weight AXs in the final beer. During sensory analysis, the beer, containing rye (30%), was found to  
349 as the fullest beer, emphasizing the AXs relevance and their related polymerization degree in the  
350 fullness and viscosity of low-alcohol beers, presenting this approach as a viable solution to improve  
351 mouthfeel characteristics and postulating that the improved viscosity is attributed to the delivery of  
352 higher molecular weight AXs from un-malted cereals than the ones that could be obtained from  
353 malted cereals (Langenaeken, De Schutter, and Courtin 2020).

354 In recent years, pure wheat malt beer (PWMB) has risen in popularity due to its imaginably  
355 functional properties, such as aroma and taste (Schneiderbanger et al., 2016). As non-starch  
356 polysaccharides (NSPs), including the AXs, are the main component in wheat beer, it has been stated  
357 by Li et al. (2020) that NSPs can certainly enhance the body of beers and can favorably have an  
358 impact on the haze and foam retention of beers, being crucial indicators for consumers to determine  
359 whether the beer has a good or bad quality.

360 The potential health value and functional properties of NSPs in PWMB were studied by Díaz  
361 et al. (2023), who found out that its antioxidant, prebiotic activities, hypoglycemic and hypolipidemic  
362 effects arise. Likewise, Michiels et al. (2023) confirmed the impact of AXs on the brewing process  
363 contributing to the palate fullness of beers. This concluded that this promising tunable cereal  
364 component, depending on the arabinose units where most often, a low AX concentration is sought to  
365 reduce wort viscosity and consequently eliminate wort and beer filtration complications (Sadosky et.,  
366 2002).

### 367 **3.4. Arabinoxylans for probiotic encapsulation**

368 Maize is one of the major sources of food in Mexico. To improve its nutritional value, the  
369 maize kernel is subjected to nixtamalization processes (Roberto Castro-Muñoz and Yáñez-Fernández  
370 2015; R Castro-Muñoz et al. 2015), in which maize is exposed to an alkali treatment generating large  
371 volumes of wastewater which contain gelling AX (Roberto Castro-Muñoz, Fíla, and Durán-Páramo  
372 2019). Therefore, there is an interest focused in the rheological, structural and microstructural  
373 characteristics of this bio-based material. The capability of maize wastewater enriched in AX  
374 (MWAX) to encapsulate probiotics has been studied (Paz-Samaniego et al. 2016). Nixtamalization,  
375 as it is called the alkali cooking in Mexico, is widely used to have a better texture and for the addition  
376 of nutritional value to the maize and the wastewater generated from the maize processing is known  
377 as “Nejayote”, which is considered as highly alkaline with high chemical and biological oxygen  
378 demand. Throughout the nixtamalization procedure, once maize bran is removed from the kernel,  
379 AXs and cell wall components are partially solubilized in Nejayote, formerly described as a source  
380 of gelling AX (Ayala-Soto et al. 2014). Among the most significant findings, is the encapsulation of  
381 probiotic *Bifidobacterium* in MWAX gels with a 10% (w/v) where the ones containing and  
382 maintaining the maximum probiotic content with a  $1 \times 10^7$  CFU/mL. Thus, because of the pore size  
383 of the matrix that surrounds it, the capsule was about 11 times smaller than the probiotic (Paz-  
384 Samaniego et al. 2016).

### 385 **3.5. Arabinoxylans in bakeries and confectioneries**

386 AXs, as soluble fibers, are mostly present in the endosperm of cereals. Most of their  
387 physicochemical properties have been potentially exploited, for example as baking additives, to  
388 enhance several properties in the final products, such as consistency property of the dough, loaf  
389 volume increase, improve crumb structure, or decrease in the bread staling. So far, AXs have been  
0 described as palatable ingredients, in which the AX-enriched foods present excellent acceptability by  
1 consumers. For example, AXs, especially the ones present in hard wheat varieties, are widely known  
2 and chosen to provide better loaf volume in bread, which also enrich the protein intake and gluten  
3 strength (Kiszonas et al. 2015). Several studies have reported positive effects of AXs in different

394 cookies, where the use of flours in combination with these soluble fibers results in a product with a  
395 low spread ratio, a decrease in diameter and a firm consistency, which are phenotypic characteristics  
396 of great importance for a quality product. The non-starch polysaccharide fraction in wheat flour  
397 cookie-making was studied by Guttieri, Souza, and Sneller (2008). It was documented that higher  
398 arabinose/xylose ratio demonstrated a tendency in the depletion of water absorption contained in  
399 entire grain flour leading to a soft cookie. Also, the influence of substituting small quantity of sugar,  
400 or flour, by AX oligosaccharides in cookies was analysed. According to Pareyt et al. (2011), when  
401 the flour was replaced, the cookie diameter was somewhat decreased while the hardness behaved  
402 opposite. Likewise, it was reported that AXs in cakes have potential benefits, although it has not been  
403 extensively studied (Oliete et al. 2010). To some extent, it is recommended to select the flours based  
404 on the concentration of the soluble pentosan which must be high. However, the use of xylans has  
405 been highlighted as a quality bran-enriched cake improver (Lebesi and Tzia 2011). Furthermore,  
406 when baking with high content AX flours, the air cell in final products is smaller which is best viewed  
407 by consumers (Moza and Gujral 2017). Particularly, they conclude that when AXs are present, there  
408 are multiple favourable effects on batter stability, cake cell density and consistency. Thus, it improves  
409 the water binding properties which helps to maintain the desired crumb moist.

Very recently, Molina et al. (2021) evaluated the effect of isolated AXs in preparing model  
flours. The refined flour was added with both extractable and water unextractable AXs. In this  
investigation, AXs showed a meaningful impact on the mechanical properties, especially elasticity,  
increasing the starch gelatinization degree from 24 up to 36%.

### **3.6. Arabinoxylans in non-alcoholic beverages**

Nowadays, the producers of non-alcoholic drinks aim to distinguish their products in the  
market of beverages with additional health benefits and functionality. This category is already sought  
and commercialized on global markets by healthy lifestyle consumers. They choose to buy fortified  
drinks, e.g., water enriched with minerals/vitamins and fruits, and more interested on the functionality  
features of ready-to-drink food items (Busuricu et al. 2022). Also, non-alcoholic beverage marketing  
is pervasive across multiple media predominantly promoting products with high content in fat, sugar,

421 and/or salt. Given the evidence of diet-related noncommunicable disease risk and obesity, the World  
422 Health Organization (WHO) and other authoritative bodies have stepped in to shape policies for  
423 regulating unhealthy beverages marketing and reduce the impact in children specially (Boyland et al.  
424 2022; Ngqangashe et al. 2022). This is why conducting biotechnological research to find new  
425 strategies for enhancing the functionality of non-alcoholic drinks is a big opportunity for the industry.  
426 In this field, AXs have a potential to increase the value of these drinks, as mentioned on the  
427 (Basinskiene et al. 2016) approach for non-alcoholic beverages called “Kvass”, which is a typical  
428 cereal-based beverages manufactured from fermented barley malt and rye, or stale rye bread in eastern  
429 European countries (e.g., Lithuania). AX-derived arabinoxylooligosaccharides (AXOS), represent an  
430 emerging food ingredient as prebiotics thanks to their exceptional stimulation of the growth of  
431 beneficial microflora, as mentioned in the previous section. Concluding that extruded rye, along with  
432 xylanolytic enzymes and LAB bacteria, could be interestingly employed within the manufacture of  
433 new, safe and higher-value-added non-alcoholic beverages (Basinskiene et al. 2016).

### 3.7. Arabinoxylans for the improvement of Chinese noodles

434 Being dietary fiber as an important element in human diet and AX a main component of both  
435 soluble/insoluble roughage, they indeed provide numerous health benefits such as antioxidant  
436 properties. Several works have evidenced that AXs improve substantially the quality of flour and  
437 bread since they increment the water absorption capacity as well as dough formation (Guttieri, Souza,  
438 and Sneller 2008). Reports have proven that noodles account for 30 up to 35%, of the total produced  
439 wheat flour, as they are known to be a popular food in China. With this in mind, Fan et al. (2016)  
440 used ultrasonication to treat unmodified AX (UAX) for obtaining small molecular AXs (MAX) and  
441 later studied the effect on the color, water properties, cooking characteristics, chemical interactions  
442 between free sulfhydryl chemical groups and generated disulfide bonds, and texture of this classic  
443 meal. When AX content increased, the dough sheet appeared to be darker, while the texture of the  
4 prepared noodles improved but it was worsened with higher content than 1% AXs (Buksa, Nowotna,  
5 and Ziobro 2016)(Zhang et al. 2011). Apart from that, the presence of free sulfhydryl chemical  
6 functionalities varied, e.g., they decreased by 15.4% and 19.3% when incorporated UAX and MAX,  
7

448 (0.5%), respectively. Finally, findings on the water absorption improvement and cooking loss rate  
449 were observed to decrease up to 1.0% of AX addition. In this study, the authors confirmed that by  
450 incorporating lower AXs (between 0.25–1.0%) in the final wheat flour, h to improve the quality and  
451 nutritional value of Chinese noodles.

### 3.8. Starch-arabinoxylans in 3D food printing

452 3D-food printing materials, such as isolated proteins, carbohydrates (alginate), and fats, are emerging  
453 alternatives in homemade cookies in recent years. Apart from their advantages for complex  
454 geometries, modifications in texture and specified nutritional contents are desired (Baiano 2022). In  
455 this emergent field, Montoya et al. (2021) developed accessible nutritional blends for 3D printing  
456 with the help of starch, lyophilized fruit as basis and AXs. In the case of AXs, they were proposed  
457 since they own specific characteristics, including adhesive properties, thickener stabilizer,  
458 emulsification properties, and film-forming properties (Ayala-Soto, Serna-Saldívar, and Welti-  
459 Chanes 2016). By adding AXs, the preparation of blends containing small starch concentration was  
460 done intentionally while aiming to preserve specific attributes related to the viscoelasticity. In this  
461 study, the first batch of starch-mango aqueous mixtures (0/100, 25/75, 50/50, 75/25, 100/0) were  
462 prepared, and second batch contained starch-AX mixtures (50/50, 75/25, 100/0) with the addition of  
463 mineral water in first place, and then starch portion, and lastly followed by AXs fraction, as shown  
464 in **Table 3**. The three starch-AX blends, identified as 100/0, 75/25, 50/50 ratio, were selected for  
465 further 3D printing protocol to determine the best blend with the maximum printed height. Especially,  
466 the one with 75/25 formulation displayed a pseudoplastic and shear thinning viscous properties  
467 similar to pure starch. Thus, they concluded that appropriate starch/AXs combinations could also  
468 form hydrogels, or reticulated natural composites, that are dependent on the starch ratio; when having  
469 a 50% of this, they are in the form of hydrogels, on the contrary, become complex composites. At  
470 this point, it was proven that high contents in starch-AX blends are very suitable and then suggested  
1 for 3D food printing due to its nutritional value (Liu et al. 2018).

3 **Table 3.** Composition of the different starch-mango and AX blend formulations.

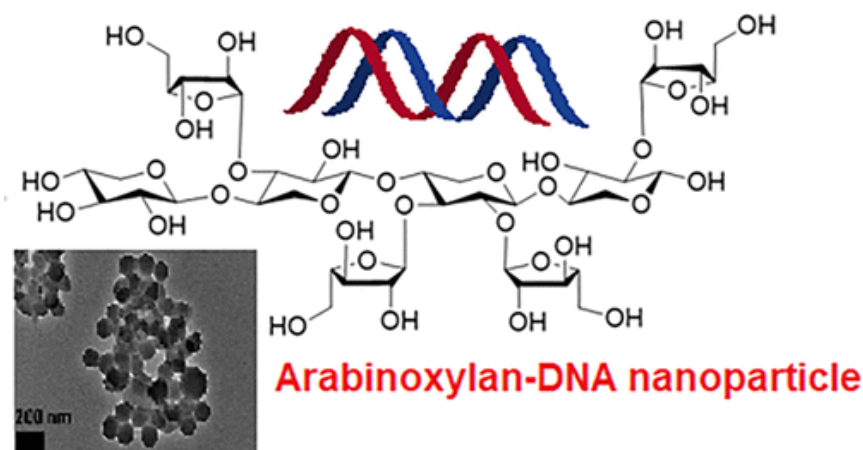
Formulation	Water %	Starch %	Mango %	AXs%
Starch (100)	80	20	0	0

Starch/Mango (75/25)	80	15	5	0
Starch/Mango (50/50)	80	10	10	0
Starch/Mango (25/75)	80	5	15	0
Starch/Mango (0/100)	80	0	20	0
Starch/AXs (75/25)	80	15	0	5
Starch/AXs (50/50)	80	10	0	10

### 3.9. Arabinoxylans in nanodelivery platforms

It is known that the food industry is likely to be one of the main fields demanding large quantities of water and energy consumption. As there is an abrupt increase in global population, the future perspective is to meet higher agricultural sources while mitigating any possible negative impact on the natural resources (e.g. water bodies) and environment (Schneider et al. 2021). Also, climate change plays an important role in future agricultural production, while temperature effects become relevant for policy-makers, farmers, agriculturalists, and crop breeders, who need to guarantee worldwide food systems. To some extent, developing sustainable crop systems and adaptation strategies for specific regions are crucial to guarantee the future food supply chain of an increased global population (C. Zhao et al. 2017). In this regard, Sarker et al. (2020) presented a sustainable idea of using chemically modified AXs, which were successfully obtained from agro-food waste and by-products, as portable materials for gene delivery in agrochemical area. Particularly, nanocarriers should offset the three main identified drawbacks of modern delivery methods in plant systems: (i) as a specific nanoparticle size can permeate through the cell wall, (ii) tuning and adjusting the surface properties (such as charge, hydrophilic/hydrophobic) to carry diverse compounds and cargo, and (iii) extended applicability in plant-based systems (Cunningham et al. 2018). It was proven that AXs, especially the ones present in wheat bran, are analogs with similar chemical properties like the ones to obtained from wheat flour and therefore can be used to construct DNA polyplexes with cationically derivatized AXs, as described in **Fig. 4**. These biodegradable nanocarriers with an average size of 150–200 nm can be used as delivery platforms with facilitated transport ability of protein and nucleic acid fractions in plants (Sarker et al. 2020).





**Fig. 4.** Nanocarriers based on wheat bran obtained from AXs for nucleic acid delivery. Taken from (Sarker et al. 2020).

### 3.10. Structure-function relationship of AXs and their application within food systems

Throughout the years, cereals grains have been extensively studied due to their wide range of ingredients with a varying degree of structural and functional complexity. The characterization of the proteins and starches, major components in cereals, has allowed to demonstrate its irrefutably functional role. The interest in the study of cereal cell wall polysaccharides stems from the recognition of the role of these minor components which affects to a degree human nutrition, physical and chemical properties, processing behavior and shelf life. Despite the diverse non-starch polysaccharides that form the cell walls of cereal grains,  $\beta$ -glucans and AXs molecular structures have received the most attention as well as oligosaccharides derived from these polymers. Due to it, endo- $\beta$ -xylases and endo- $\beta$ -glucanases have permitted structural examination of these cereal cell wall at its finest detail.

Both polysaccharides afterward mentioned display halfway dissolvability in water and thus in the human diet, notwithstanding the physiological impacts related to the consumption of insoluble fiber. In food systems,  $\beta$ -glucans and AXs may likewise modify the texture, water binding properties and tangible characteristics of a food product (Eliasson et al. 1996). From a wholesome and practical perspective, cereal foods rich in non-starch polysaccharides meet the description of “functional foods” as they give some of the ordinary quality characteristics of a food, like sustenance and texture.

As an example, there is a wide range of studies on the role of AXs in the bread-making process that seek to expound on the effects of AXs on properties such as water adsorption of dough, loaf

518 volume and firmness. Once the studies were run, the one in which water-soluble AXs were added to  
519 bread formulations, demonstrated an increase in the water adsorption of the dough and improved the  
520 loaf volume of wheat and rye bread. Therefore, the conclusions point that the improvement in the loaf  
521 volume of bread is dependent on the AX's concentration in the dough system and it was importantly  
522 debated that the concentration which ideally upgrades the loaf volume is related to factors such as the  
523 quality of the bread flour along with the molecular weight and same structure indicating that the  
524 higher the concentration is compared to the optimum of AX can cause viscosity built up in the dough  
525 and thereby hinder the loaf expansion (Izydorzyc & Biliaderis, 2000).

### 3.11. Potential of purified/isolated AX in food systems

526 There are many studies reporting on the functional role of pentoses (the main forming structure of  
527 AXs), particularly as it relates to the breadmaking process giving rise to various experimental findings  
528 that are attributed to diverse factors, to mention some are the method of isolation, degree of purity,  
529 composition of pentosan preparation and baking systems. Nonetheless, with most proof  
530 recommending that the functional properties of pentosans are primarily due to the AX components.  
531 When AX is added to wheat flour, these last certainly compete with the dough water (Izydorzyc et  
532 al., 1991 & Biliaderis).

## 4. Concluding remarks and perspectives

533 The purpose of this comprehensive review is to reveal the up-to-date findings on the AXs  
534 extraction, their health benefits, and applications in food products. This review reports, for the first  
535 time, the main efforts of the scientific community on the different strategies and methods for the  
536 extraction, separation, and recovery of AXs from distinct sources and by-products (e.g.,  
537 nixtamalization wastewaters). From this review, it can be concluded that AX purification is directly  
538 affected by the type of source, germinating state, location in the grain, pre-treatment, source  
539 conditioning and finally the extraction technique. However, a detailed description of the extraction  
540 conditions of AXs may be useful to overcome the main constraints during the purification protocols

544 and to obtain reproducible data from different studies. AXs have potential health benefits, including  
545 SCFAs modulation in colon tissue, increased antioxidant activity, as well as reduced glycaemic  
546 response through a variety of mechanisms. The chemical structure of AXs has a decisive influence  
547 on the physical properties when contained in foods; generally, AXs, exhibiting low molecular weight  
548 and high solubility properties, seems to be suitable for better food systems. Unfortunately, the pre-  
549 treatment strategies, extraction and purification techniques and used food manufacture parameters  
550 greatly dictate the resulting properties of AXs and their performance in food formulations, suggesting  
551 that the functionality properties of isolated AX could be tuned to meet the quality needed for the end-  
552 products. To date, alkaline extraction has been the most used method for AX extraction, especially  
553 due to its simplicity, the easy to implement facilities and the operation time (between 2 to 8 h).  
554 Unfortunately, the main inconvenience of this method relies on reducing the bioactivity and  
555 antioxidant properties of AXs (Jaguey-Hernández et al. 2022; Pérez-Flores et al. 2019; Daniela D.  
556 Herrera-Balandrano et al. 2018; Rudjito et al. 2019). Regarding the probiotic encapsulation, once the  
557 *Bifidobacterium* was already studied and its efficacy has been proven, AXs represent an opportunity  
558 for future studies proposing another probiotic models, such as *Lactobacillus* or a mixture of both,  
559 giving rise to a healthier gut population microbiota in the consumer. Concerning the effect of AXs in  
560 bakery products and cookies, findings lead to possible approaches reducing sugar levels while  
561 increasing fiber content, obtaining enriched cookies with high plasticity in the dough and more  
562 efficient baking (Pareyt et al. 2011).

563 Furthermore, up-to-date developments of AXs in food products were described, in which the  
564 modification of AXs by enzymes results in having a positive effect on the shelf life of a variety of  
565 cereals, to mention just a few. They act as a protection for the dough network structure, enhancers of  
566 viscosity, water absorption, foam stabilizers, among others. Thus, these polysaccharides'  
567 considerable importance in cereal-based processes has been widely accepted and studied due to their  
568 nutritional benefits and properties giving rise to an increasing demand for arabinoxylan-enriched  
569 products.

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576 **Conflict of Interest**

577 The authors declare no conflict of interest.

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