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

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Abstract

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

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

Acronyms

AXs: Arabinoxylans

AXOS: arabinoxylooligosaccharides

BSG: brewers' spent grain

GI: Glycemic Index

MAX: small molecular arabinoxylans

NSP: non-starch polysaccharides

PWMB: brewers' spent grain

SWE: subcritical water extraction

SCFAs: short chain fatty acids

UAX: unmodified arabinoxylans

1. Introduction

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

Particular by-products, like the ones derived from cereal processing industries, are potentially a rich source of high-added value molecules (Díaz-Montes and Castro-Muñoz 2021), which are either difficult to chemically synthesize or produce (Roberto Castro-Muñoz et al. 2021). This is the case of arabinoxylans (AXs), which is a complex fiber providing various health benefits regulated thanks to the chemical composition which are naturally present in specific parts of cell walls of distinct grains including corn, wheat, rice, rye, sorghum, oats, barley and other plants. AXs are polysaccharides presenting various d-Xylose molecules arranged in linear backbone, which are joined due to β (1→4) bonds, while α-L-arabinofuranosyl residues molecules are also chemically attached to the specific d-Xylose molecules (Lapierre et al. 2018). Their isolation has been successful, showing that the different molecular weight compositions are affected directly by their source and extraction methods and hence impacting on their functionality. AXs have shown functional properties acting as a nutraceutical agent; as soluble fiber aids in controlling diabetes mellitus (specially type II), and enhancing the metabolism of the three main macronutrients (carbohydrates, proteins and lipids) (Nie et al. 2018). AXs have also exhibited a role as a prebiotic agent since they stimulate bacterial growth, making them a beneficial and important factor on the microbial gut health. Being able to improve microbial health has been linked to reducing risk in diseases caused by shifts within the gut. Other health benefits, such as hepatoprotective and immunomodulatory activities, postprandial glucose and cholesterol control, improving absorption of calcium and magnesium, enhancing colon function and lower risk of colon cancer, have also been found (Fadel et al. 2018). However, these compounds not only provide benefits to humans, but also to animals. Therefore, they can also be valuable as feed additives for livestock (Siddiqui et al. 2022).

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

2. Extraction strategies to recover arabinoxylans from food wastes

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

2.1. Alkaline extraction method with defatted and dried maize

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

2.2. Hydrothermal treatment

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

In recent years, the use of brewers’ spent grain (BSG) has been a novel source of AXs due to the large amount of biomass generated by this agro-industrial process. The BSG is a by-product left after barley malting and separation of the wort during the brewing process (Jaguey-Hernández et al. 2022). In their study, Pérez-Flores et al. (2019) obtained a yield near 65% using alkaline extraction method, representing the amount of AXs in the BSG-AX compared to the total AX amount to the original sample, but a yield of 72% of pure AX. The BSG-AX contained glucose (ca. 17.94%), arabinose (ca. 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 too high while presenting strong alkali taste which affect the quality (Lihua, Xin, and Jiayang 2018). It has been proved to reduce the bioactivity and antioxidant properties of AXs since the long extraction time, exposes AX to longer periods of constant high temperatures and pressure, leading into depolymerization of the molecules (Jaguey-Hernández et al. 2022; Daniela D. Herrera-Balandrano et al. 2018; Schmidt, Wiege, and Hollmann 2021; Pérez-Flores et al. 2019; Rudjito et al. 2019).

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

2.4. Subcritical water extraction

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

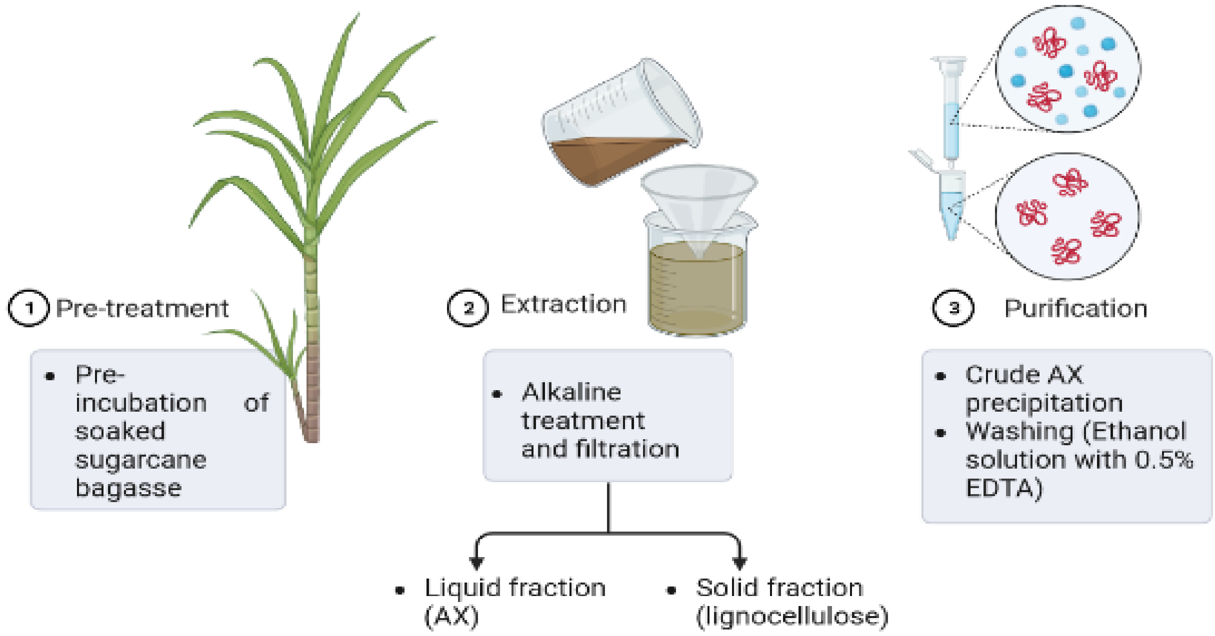

Fig. 1. Graphical illustration of AX extraction contained in sugarcane bagasse using alkaline treatment (de Figueiredo et al. 2017).

According to de Figueiredo et al. (2017), the alkalinization can be successfully done with a solution composed of KOH (24% m/V) and $NaBH_2$ (1% m/V), which was subsequently blended with the extraction source (8% m/v) for 3 h at 35 °C. After this, the resulting liquid fraction was then pre-filtered using gauze until obtaining a liquid lacking in visible solids. In a subsequent step, the AXs contained in such liquid fraction were precipitated by mixing with an organic mixture containing ethanol (60% v/v), acetic acid (6.7% v/v) and AXs (33.3% v/v). The precipitated matter, identified as AXs, was recovered using centrifugation (for short time 15 min at 4000 g). Finally, the obtained AX fraction was washed in proportional ratio (1:1 v/v) using ethanolic solution containing ethanol (50%) and EDTA (0.5%) in deionized water, subsequently, the AX fraction was subjected to drying (at 60 °C).

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

2.5. Milling

Also, there are a variety of emerging technologies based on mechanical treatment, including milling which offer many advantages representing an ecofriendly and economically feasible option to obtain a homogeneous dispersion when blended with biopolymers. Such technologies provide other advantages in terms of less environmental impact, controlled degradation reactions regulated by high temperatures, enhanced compatibility of blends lacking in miscibility, the promotion of mechano-chemical reactions and an appropriate handling of thermolabile active molecules (Gorrasi and Sorrentino 2015).

2.6 . Extrusion

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

2.7. Ultrasound and microwave-based technologies

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

2.8. Stream-pressure

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

As discussed previously, the protocols dedicated to the extraction and purification of AX depend on the source of recovery, in which the extraction may imply the combination of two or more different methods. In most of the protocols, chemical or biological factors, such as KOH concentration, enzymatic concentration, extraction temperature, exposure time, solvent for precipitation (e.g., acetic acid, ethanol) and its ratio, and number of washes, varied according to the needs of the investigation. According to **Table 1**, available studies demonstrated acceptable recovery efficiencies toward AX, pointing out that alkaline extraction can offer a yield of up to 72%, which is comparable with hydrothermal synthesis with an AX yield = 78%.

3. Potential applications of recovered AXs in food formulations

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

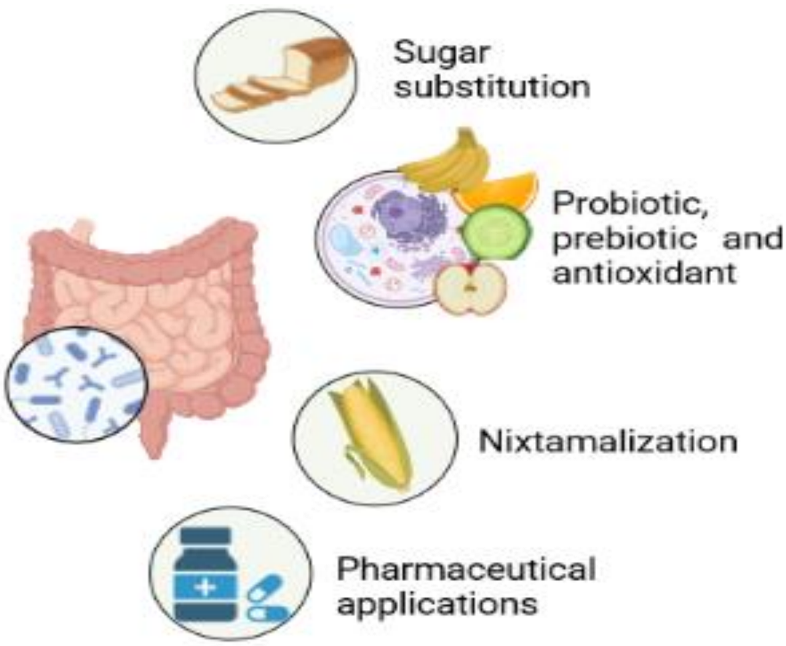

Fig. 2. Main health benefits of AXs.

Table 1. Arabinoxylan extraction techniques and outcomes.

Molecule	Source	Technique	Operating conditions	Yield (%)	Reference
BSG-AX	Barley	Alkaline extraction	**Temperature:** 25°C **Time:** 8 h, complete darkness **Stirring:** 150 rpm **Solvent:** NaOH 0.5 mol L-1 (pH 11-12)	72	(Pérez-Flores et al. 2019)
BSG-AX	Barley	Alkaline extraction	**Temperature:** 25°C **Time:** 8h, complete darkness **Stirring:** Yes, 100 rpm **Solvent:** NaOH 0.5 mol L-1 (pH 11-12)	**-**	(Jaguey-Hernández et al. 2022)
BSG-AX	Barley	Saccharification +water treatment	**Temperature:** 90°C **Time:** 6 h **Solvent:** water	21.9	(Lynch et al. 2021)
Sugarcane AX	Sugarcane bagasse	Alkaline extraction	**Temperature:** 55°C **Time:** 4 h **Stirring:** Yes, 200 rpm **Solvent:** NaOH 5 mol/L and 5−10 drops of antifoaming agent	-	(Solomou et al. 2022)
Native and acetylated AX	Wheat bran	-Pretreated by α-amylase. -Subcritical water extraction (SWE) of AX from destarched wheat bran	**Temperature:** 90 ◦C for **Time:** 17 h **Solvent:** 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	**Temperature:** 70 °C **Time:** 5-30 min **Power:** 200-600 W **Solvent:** NaOH 0.15-0.35 mol/L pH= 4.5 **Stirring:** 4000 rpm, 20 min	25	(Jiang et al. 2019)
Feruloylated AXs	Wheat bran	Subcritical water treatment. Microwave heating extraction system	**Temperature:** 120-180 °C **Time:** 10-120 min **Solvent:** 10% (w/v) aqueous suspension pH 4-10	17.98	(J. Li and Du 2019)
Feruloylated AXs	Maize bran	Alkaline extraction	**Temperature:** 37 °C **Time:** 2-6 h **Solvent:** 0.5 N NaOH solution	8.23	(Herrera-Balandrano et al. 2019)
Maize waste water AXs	Maize wastewater “nejayote”	Acid hydrolysis extraction	**Temperature:** 120 °C **Time:** 2 h **Solvent:** 2 N trifluoroacetic acid	46	(Paz-Samaniego et al. 2016)
Arabinose/Xylose	Wheat bran	Hydrothermal synthesis assisted by heterogenous catalyst	**Temperature:** 140-180 °C **Time:** 10-20 min **Mesoporous silica:** MCM-48/Al-MCM-48 With or without Ruthenium catalyst ($RuCl_3$)	78	(Sánchez-Bastardo, Romero, and Alonso 2017)

Alkali- insoluble cellulose-rich AX (CAX)	Wheat Bran	Alkaline and water extraction	**Temperature:** 95 °C **Time:** 6 h **Solvent:** α-amylase, ethanol	16.97	(Kaur et al. 2021)
AXs	Sugarcane bagasse and wheat bran	Alkaline and enzyme extraction	For alkaline: **Temperature:** 50 °C **Time:** 4 h **Solvent:** 2% H_2OH For enzymatic: **Temperature:** 37 °C **Time:** 2 h	For sugarcane: 34 For wheat bread: 11.5	(Campbell et al. 2019)(Campbell et al. 2019)
AXs	Sugarcane bagasse	Alkaline extraction	**Temperature:** 35 °C **Time:** 3 h **Solvent:** 250 mL of a 24% (m/v) KOH and 1% (m/v) $NaBH_2$ solution	17.5	(de Figueiredo et al. 2017)
BSG-AX	Barley	Water extraction	**Temperature:** 45-90 °C **Time:** 11 h **Solvent:** water	28	(Lazaridou et al. 2008)
Water- extractable AX (WEAX)	Wheat bran	Water extraction	**Temperature:** 60-95 °C **Time:** 6 h **Solvent:** water	73.72	(Demuth, Betschart, and Nyström 2020)

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

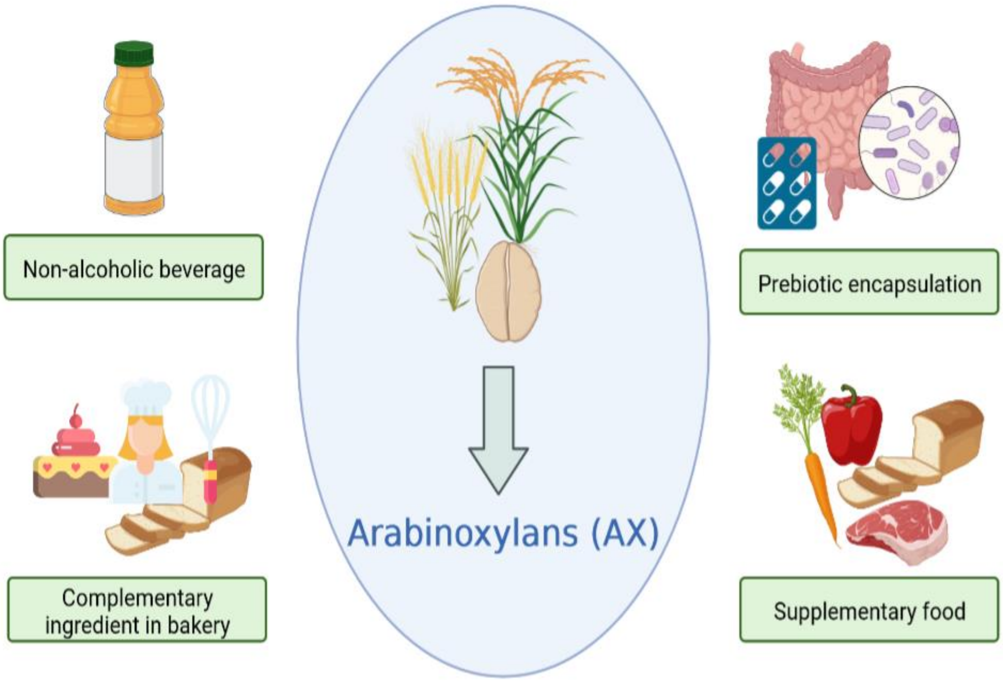

Fig. 3. Potential sources and uses of recovered AXs.

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

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

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

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

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

Application	Targeted product	Description	Reference/Patent number
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	CNI103549606A
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	CN1045228llA
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	CNI04544137A
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 β-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

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)

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3.2. Arabinoxylans as prebiotics

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

3.3. Arabinoxylans in beer manufacturing

AXs are able to cause several issues credited to the increment of wheat employed for brewing the wheat beer, which could compromise the quality of the obtained wheat beer, including the high viscosity of the wort, the haze formation, and the sensorial properties and wheat beer foam performance. Langenaeken et al. (2020) confirmed the significance of AXs and its degree of polymerization for a better mouthfeel attribute of produced beverages, such as alcohol-free beer, low-alcohol content beers and light beers as it increases the viscosity values of the beer. Experimentally, those beers were brewed replacing barley malt grits (20%) with weather oat, non-malted barley, or rye in comparison with a control. As for the one brewed with rye, a substantial increase (ca. 53 %) in AXs presence was observed while increasing the degree of polymerization from 29 to 50. In comparison with the control beer presenting a viscosity = 1.48 mm²/s, this property was observed to increase in the rye beer (ca.1.85 mm²/s). It is worth mentioning that the highest viscosity in beer was shown by the non-malted rye, this latter phenomenon was credited to the presence of high molecular weight AXs in the final beer. During sensory analysis, the beer, containing rye (30%), was found to as the fullest beer, emphasizing the AXs relevance and their related polymerization degree in the fullness and viscosity of low-alcohol beers, presenting this approach as a viable solution to improve mouthfeel characteristics and postulating that the improved viscosity is attributed to the delivery of higher molecular weight AXs from un-malted cereals than the ones that could be obtained from malted cereals (Langenaeken, De Schutter, and Courtin 2020).

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

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

3.4. Arabinoxylans for probiotic encapsulation

Maize is one of the major sources of food in Mexico. To improve its nutritional value, the maize kernel is subjected to nixtamalization processes (Roberto Castro-Muñoz and Yáñez-Fernández 2015; R Castro-Muñoz et al. 2015), in which maize is exposed to an alkali treatment generating large volumes of wastewater which contain gelling AX (Roberto Castro-Muñoz, Fíla, and Durán-Páramo 2019). Therefore, there is an interest focused in the rheological, structural and microstructural characteristics of this bio-based material. The capability of maize wastewater enriched in AX (MWAX) to encapsulate probiotics has been studied (Paz-Samaniego et al. 2016). Nixtamalization, as it is called the alkali cooking in Mexico, is widely used to have a better texture and for the addition of nutritional value to the maize and the wastewater generated from the maize processing is known as “Nejayote", which is considered as highly alkaline with high chemical and biological oxygen demand. Throughout the nixtamalization procedure, once maize bran is removed from the kernel, AXs and cell wall components are partially solubilized in Nejayote, formerly described as a source of gelling AX (Ayala-Soto et al. 2014). Among the most significant findings, is the encapsulation of probiotic *Bifidobacterium* in MWAX gels with a 10% (w/v) where the ones containing and maintaining the maximum probiotic content with a $1x10^7\ \mathrm{CFU/mL}$. Thus, because of the pore size of the matrix that surrounds it, the capsule was about 11 times smaller than the probiotic (Paz-Samaniego et al. 2016).

3.5. Arabinoxylans in bakeries and confectioneries

AXs, as soluble fibers, are mostly present in the endosperm of cereals. Most of their physicochemical properties have been potentially exploited, for example as baking additives, to enhance several properties in the final products, such as consistency property of the dough, loaf volume increase, improve crumb structure, or decrease in the bread staling. So far, AXs have been described as palatable ingredients, in which the AX-enriched foods present excellent acceptability by consumers. For example, AXs, especially the ones present in hard wheat varieties, are widely known and chosen to provide better loaf volume in bread, which also enrich the protein intake and gluten strength (Kiszonas et al. 2015). Several studies have reported positive effects of AXs in different cookies, where the use of flours in combination with these soluble fibers results in a product with a low spread radio, a decrease in diameter and a firm consistency, which are phenotypic characteristics of great importance for a quality product. The non-starch polysaccharide fraction in wheat flour cookie-making was studied by Guttieri, Souza, and Sneller (2008). It was documented that higher arabinose/xylose ratio demonstrated a tendency in the depletion of water absorption contained in entire grain flour leading to a soft cookie. Also, the influence of substituting small quantity of sugar, or fluor, by AX oligosaccharides in cookies was analysed. According to Pareyt et al. (2011), when the flour was replaced, the cookie diameter was somewhat decreased while the hardness behaved opposite. Likewise, it was reported that AXs in cakes have potential benefits, although it has not been extensively studied (Oliete et al. 2010). To some extent, it is recommended to select the flours based on the concentration of the soluble pentosan which must be high. However, the use of xylans has been highlighted as a quality bran-enriched cake improver (Lebesi and Tzia 2011). Furthermore, when baking with high content AX flours, the air cell in final products is smaller which is best viewed by consumers (Moza and Gujral 2017). Particularly, they conclude that when AXs are present, there are multiple favourable effects on batter stability, cake cell density and consistency. Thus, it improves 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, and/or salt. Given the evidence of diet-related noncommunicable disease risk and obesity, the World Health Organization (WHO) and other authoritative bodies have stepped in to shape policies for regulating unhealthy beverages marketing and reduce the impact in children specially (Boyland et al. 2022; Ngqangashe et al. 2022). This is why conducting biotechnological research to find new strategies for enhancing the functionality of non-alcoholic drinks is a big opportunity for the industry. In this field, AXs have a potential to increase the value of these drinks, as mentioned on the (Basinskiene et al. 2016) approach for non-alcoholic beverages called "Kvass", which is a typical cereal-based beverages manufactured from fermented barley malt and rye, or stale rye bread in eastern European countries (e.g., Lithuania). AX-derived arabinoxylooligosaccharides (AXOS), represent an emerging food ingredient as prebiotics thanks to their exceptional stimulation of the growth of beneficial microflora, as mentioned in the previous section. Concluding that extruded rye, along with xylanolytic enzymes and LAB bacteria, could be interestingly employed within the manufacture of new, safe and higher-value-added non-alcoholic beverages (Basinskiene et al. 2016).

3.7. Arabinoxylans for the improvement of Chinese noodles

Being dietary fiber as an important element in human diet and AX a main component of both soluble/insoluble roughage, they indeed provide numerous health benefits such as antioxidant properties. Several works have evidenced that AXs improve substantially the quality of flour and bread since they increment the water absorption capacity as well as dough formation (Guttieri, Souza, and Sneller 2008). Reports have proven that noodles account for 30 up to 35%, of the total produced wheat flour, as they are known to be a popular food in China. With this in mind, Fan et al. (2016) used ultrasonication to treat unmodified AX (UAX) for obtaining small molecular AXs (MAX) and later studied the effect on the color, water properties, cooking characteristics, chemical interactions between free sulfhydryl chemical groups and generated disulfide bonds, and texture of this classic meal. When AX content increased, the dough sheet appeared to be darker, while the texture of the prepared noodles improved but it was worsened with higher content than 1% AXs (Buksa, Nowotna, and Ziobro 2016)(Zhang et al. 2011). Apart from that, the presence of free sulfhydryl chemical functionalities varied, e.g., they decreased by 15.4% and 19.3% when incorporated UAX and MAX, (0.5%), respectively. Finally, findings on the water absorption improvement and cooking loss rate were observed to decrease up to 1.0% of AX addition. In this study, the authors confirmed that by incorporating lower AXs (between 0.25–1.0%) in the final wheat flour, h to improve the quality and nutritional value of Chinese noodles.

3.8. Starch-arabinoxylans in 3D food printing

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

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) tunning 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).

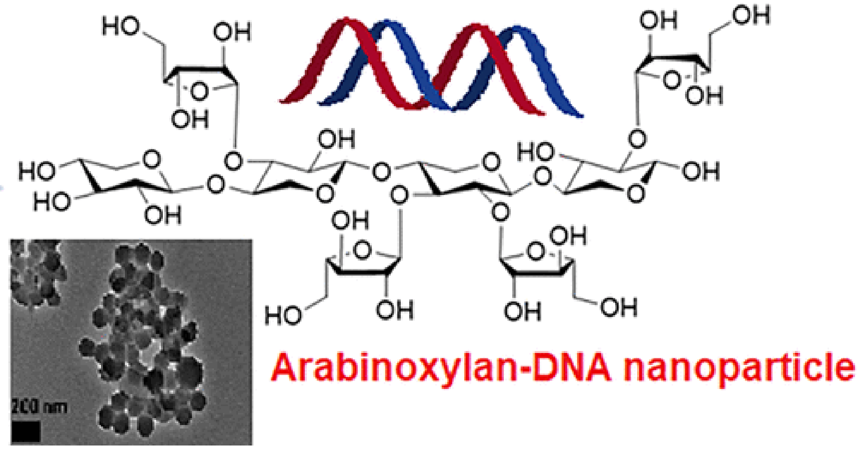

Fig. 4. Nanocarriers based on wheat bran obtained from AXs for nucleic acid delivery. Taken from (Sarker et al. 2020).

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, ß-glucans and AXs molecular structures have received the most attention as well as oligosaccharides derived from these polymers. Due to it, endo-ß-xylases and endo-ß-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, β-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 volume and firmness. Once the studies were run, the one in which water-soluble AXs were added to bread formulations, demonstrated an increase in the water adsorption of the dough and improved the loaf volume of wheat and rye bread. Therefore, the conclusions point that the improvement in the loaf volume of bread is dependent on the AX's concentration in the dough system and it was importantly debated that the concentration which ideally upgrades the loaf volume is related to factors such as the quality of the bread flour along with the molecular weight and same structure indicating that the higher the concentration is compared to the optimum of AX can cause viscosity built up in the dough and thereby hinder the loaf expansion (Izydorczyk & Biliaderis, 2000).

3.11. Potential of purified/isolated AX in food systems

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

4. Concluding remarks and perspectives

The purpose of this comprehensive review is to reveal the up-to-date findings on the AXs extraction, their health benefits, and applications in food products. This review reports, for the first time, the main efforts of the scientific community on the different strategies and methods for the extraction, separation, and recovery of AXs from distinct sources and by-products (e.g., nixtamalization wastewaters). From this review, it can be concluded that AX purification is directly affected by the type of source, germinating state, location in the grain, pre-treatment, source conditioning and finally the extraction technique. However, a detailed description of the extraction conditions of AXs may be useful to overcome the main constraints during the purification protocols and to obtain reproducible data from different studies. AXs have potential health benefits, including SCFAs modulation in colon tissue, increased antioxidant activity, as well as reduced glycemic response through a variety of mechanisms. The chemical structure of AXs has a decisive influence on the physical properties when contained in foods; generally, AXs, exhibiting low molecular weight and high solubility properties, seems to be suitable for better food systems. Unfortunately, the pre-treatment strategies, extraction and purification techniques and used food manufacture parameters greatly dictate the resulting properties of AXs and their performance in food formulations, suggesting that the functionality properties of isolated AX could be tuned to meet the quality needed for the end-products. To date, alkaline extraction has been the most used method for AX extraction, especially due to its simplicity, the easy to implement facilities and the operation time (between 2 to 8 h). Unfortunately, the main inconvenience of this method relies on reducing the bioactivity and antioxidant properties of AXs (Jaguey-Hernández et al. 2022; Pérez-Flores et al. 2019; Daniela D. Herrera-Balandrano et al. 2018; Rudjito et al. 2019). Regarding the probiotic encapsulation, once the *Bifidobacterium* was already studied and its efficacy has been proven, AXs represent an opportunity for future studies proposing another probiotic models, such as *Lactobacillus* or a mixture of both, giving rise to a healthier gut population microbiota in the consumer. Concerning the effect of AXs in bakery products and cookies, findings lead to possible approaches reducing sugar levels while increasing fiber content, obtaining enriched cookies with high plasticity in the dough and more efficient baking (Pareyt et al. 2011).

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

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Conflict of Interest

The authors declare no conflict of interest.

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