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Unlocking the prebiotic carbohydrates: Insights into the types, preparation, health benefits and future utilizations of selected Indonesian exotic fruit seeds as a potential source of prebiotics

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ABSTRACT

The human gastrointestinal tract, particularly the colon, is densely populated with microflora, primarily *Bifidobacteria* and *Lactobacilli* that are responsible for maintaining diet-based human health. Prebiotics, which are non-living dietary components, selectively stimulate the growth and activity of these beneficial gut microorganisms, offering numerous health benefits. This paper aims to explore the feasibility of utilizing Indonesian exotic fruit seeds as a potential source of prebiotic carbohydrates for functional foods and dietary additives. There are seven Indonesian exotic fruits that have large seed portions and are rich in various carbohydrates that function as prebiotics. These prebiotic carbohydrates, particularly oligosaccharides, can be extracted directly from fruit seeds or produced through enzymatic, fermentation, chemical, or thermal processes, each of which influences the prebiotic composition and effectiveness. Incorporating prebiotic carbohydrates into human health care and functional food production could reduce reliance on synthetic antibiotics. Furthermore, repurposing fruit seed residues for prebiotic production not only contributes to economic growth but also promotes environmental sustainability by minimizing waste.

1. Introduction

Over the past few decades, diet-related diseases such as obesity, hypertension, cancer, inflammatory bowel diseases, and micronutrient deficiencies have significantly impacted global health. Functional foods offer medicinal benefits beyond basic nutrition (Damián et al., 2022). The gastrointestinal (GI) system, with the largest surface area of any organ in the human body, is essential for nutrient absorption, selective processing, maintaining fluid and electrolyte balance, and facilitating waste excretion while simultaneously providing introductory defense in opposition to any toxins, pathogens, and other harmful agents (Le Gall et al., 2019). The native gut microflora constructs the complicated ecosystem within the GI lumen, facilitating interactions between the external environment and the host. The composition of GI microflora varies based on diet, environment, gender, and genetics (Crnčević et al., 2022). Mostly, the stomach's microflora primarily consists of gram-positive and aerobic microorganisms at a low concentration of 10^3 CFU mL^{-1}. The amount of microflora rises significantly from the sparsely colonized to the highly-populated colon (10^{12} CFU mL^{-1}) (Dieterich et al., 2018).

Most of the time, the concentrations of facultative anaerobes and aerobic bacteria in the small intestine is between 10^3 and 10^5 CFU mL^{-3}. *Coliforms* and *Bacteroides* are not present very often. Then, this microflora concentration drastically increases to a concentration of 10^{11}–10^{12} CFU g^{-1} in the colon (Dieterich et al., 2018). It is estimated that this bacterial load constitutes up to 50 % of the total colonic volume. Despite colonic microflora comprises over 400 distinct species, they are mainly anaerobic (97 %) including *Bacteroides*, *Bifidobacterium*, *Enterobacter, Fusobacterium*, *Lactobacillus*, and coliforms (Antza et al., 2018). Some others are facultative anaerobic microflora, namely *Staphylococcus* and *Candida* species. These microflorae play vital functions in sustaining mucosal integrity, converting superfluous cholesterol in the large

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intestine to coprostanol, fermenting carbohydrates to produce short-chain fatty acids (SCFAs), converting proteins to sterols and bile acids to demolish possible mutagenic substances of the consumed foods, and suppressing pathogenic bacteria (Cagnasso et al., 2024; Juste & Gérard, 2021). Therefore, the idea of exploiting microflora to improve the favorable facets of the GI tract has come to be a more targeted attempt. Particular dietary fibers and polysaccharides that are not broken down in the upper GI tract are perfect food components to function as substrates for the growth of advantageous gut microflora through fermentation (Fu et al., 2022). This novel idea concerning such polysaccharides is called prebiotics. Prebiotics vary in type depending on their source and chemical composition. Research has classified inulin, fructo-oligosaccharides (FOSs), galacto-oligosaccharides (GOSs), pectic-oligosaccharides (POSs), lactulose, and polydextrose as common prebiotics, while isomalto-oligosaccharides (IMOs), xylo-oligosaccharides (XOSs), and lactitol are considered emerging prebiotics (Figueroa-González et al., 2011; Sabater-Molina et al., 2009). Additionally, mannitol, maltodextrin, raffinose, lactulose, and sorbitol have been recognized for their beneficial health effects (Bamigbade et al., 2022).

Many countries, specifically in South East Asia, Pacific, South America and Africa, which enjoy tropical climates have been linked with the growing cultivation of various tropical fruit plants that the harvested fruits exhibit excellent potential for prevention of the aforementioned diet- associated diseases (Wanapat et al., 2024). Located in Southeast Asia, the archipelagic and tropical climate of Indonesian land (1.9 million km^2), which covers approximately 20 % of its total area, has established the nation one of the most biodiverse in the world (Geospatial Information Agency, 2018). Literally, Indonesia is a habitat for around 30,000 to 40,000 species of seed plants *(spermatophyta),* which includes a diverse range of fruits. In regard to this fact, the Indonesian Agency for Research and Development (IARD) has documented that in excess of 592 fruit species display a great prospective market (Kumoro et al., 2020). Based on their annual statistics data, BPS-Statistics Indonesia (2024) reported that mango, durian, avocado, jackfruit, cempedak, guava, and tamarind, are the most abundant and popular seeds containing fruits in Indonesia with annual total production exceeding 6.5 million tonnes, from which more than 2.4 million tonnes of seed can be generated every year. In addition to containing an embryonic (baby) plant, the seed also contains a food supply – known as the endosperm – that is richly loaded with nutritional, including starch, carbohydrates, proteins, fats or lipids, minerals, vitamins, and various metabolites to maintain the seed nutrified and permit its embryo to grow during germination. Carbohydrate and protein function as an energy source, supplying carbon and nitrogen for the germination of seeds and following seedling initiation (Chandrasekaran et al., 2022; Yan et al., 2014). The carbohydrate present in these seeds is also regarded as a prebiotic, as it is believed to offer various health benefits when incorporated into food (Vaidya & Sheth, 2011).

Over time, technological advances have changed the traditional methods of consuming natural foods such as fruits and vegetables and utilizing their by-products, especially seeds. Interestingly, the seed components separated from the fruit pulp are rich in oligosaccharides that have significant prebiotic potential, often surpassing commercial synthetic prebiotics (Palaniappan et al., 2017). Prebiotic compounds such as FOSs and POSs are found in abundance in mango, durian and guava seeds (Baraheng & Karrila, 2019; Islam et al., 2020; Mandha et al., 2021). In addition, raffinose-oligosaccharides (ROSs) are also found in jackfruit, tamarind, and guava seeds (Guízar-Amezcua et al., 2022; Islam et al., 2020; Li et al., 2022). Given the limited prebiotics in modern foods, it is important to further identify and develop new sources for large-scale production by utilizing the Indonesian popular exotic fruit seeds. Although various studies have explored the extraction of prebiotics from various sources, this review is important because, to our knowledge, no previous review has investigated the potential of Indonesian popular exotic fruit seeds as a source of prebiotics. In full, this paper reviews the carbohydrate composition, health benefits and future potential of selected Indonesian popular exotic fruit seeds as raw materials for the development of functional foods, especially prebiotics.

2. Prebiotics

Because the feasibility of live bacteria in food products and on their way to their final excretion through the gastrointestinal tract (GIT) may be uncertain, the prebiotic idea has been established. Therefore, the prebiotic approach recommends a proper intake of non-viable entities and intends to address survival issues related to native bacteria in the upper GIT. Prebiotics promote the beneficial proliferation of a select group of health-enhancing microflora residing in the colon, specifically *lactobacilli* and *bifidobacteria* (Mazziotta et al., 2023). Previous research confirmed that human breast milk oligosaccharides (HMOs) are regarded as unique prebiotics since they facilitate the beneficial proliferation of *lactobacilli* and *bifidobacteria* in the colon of breastfed newborn infants. Indeed, this phenomenon may well elucidate many immunological and other health benefits that are possessed by breast-fed infants (Tadesse, 2012).

Basically, a prebiotic is an indigestible food substance that beneficially enhances host health by specifically stimulating the growth and/or activity of specific bacteria in the colon. Hence, it is probably viable to obtain prebiotics in a more natural way by consuming an appropriate diet. Various fruits and vegetables accommodate prebiotic oligosaccharides such as FOSs. Nonetheless, their levels in these foods are too low to bear any pronounced influence.

Food components can be regarded as prebiotics if they restrain host digestion, adsorption, and absorption processes; are fermented by the GI microflora; and particularly promote the growth and/or activity of specific bacteria within the GIT. Even though each prebiotic criterion is equivalently significant, the most important and possibly hardest to achieve is selectively improving the growth and/or activity of certain bacteria. As stated by many publications, nowadays, a substantial amount of components are recognized to evade enzymatic hydrolysis in the small intestine. Nevertheless, only a limited number of components meet the established criteria for prebiotics in promoting the proliferation of particular bacteria.

2.1. Principal eligibilities of prebiotic compounds

Bamigbade et al. (2022) summarized that a compound can be considered as a prebiotic if it is highly tolerant to gastric acidity, hydrolysable by mammalian enzymes, taken in the GIT, digestible by intestinal microflora, and capable of specifically stimulating the growth and activity of intestinal microflora. It's important to note that not all prebiotics constitute polysaccharides, as some derive from fiber. These two prebiotics can be strictly distinguished based on two reference points. First, fibers are sugars that have a minimum degree of polymerization (DP) of three. Second, fibers are not hydrolysable by enzymes that are naturally found in the GIT. The solubility and fermentability of dietary fibers depend on their structural characteristics, which influence their interactions with water molecules (Capuano, 2017). Long linear fibers with regular (semi)-crystalline conformation structures, such as cellulose and lignin have limited solubility in water. In contrast, branched fibers such as pectin, gum, and oligosaccharides are more likely to interact with water molecules, making them more soluble in water (Capuano, 2017). The fermentability of fibers is strongly affected by their molecular structure and size as well as the presence of bacteria with the enzymes needed to digest the bonds within the fiber structure (Williams et al., 2019). Factors such as the chemical composition, molecular size, and structural arrangement of dietary fibers determine their fermentation rate and the resulting SCFA profiles (Wang et al., 2019). Additionally, the availability of specific bacterial species capable of colonizing and degrading these fibers plays a crucial role in their fermentability (Williams et al., 2019).

Alongside prebiotic carbohydrates, there are also numerous secondary metabolite compounds contained in our daily diet that are non-digestible by the gut enzymes (Shondelmyer et al., 2018). Surprisingly, they display prebiotic functions by promoting the proliferation of lactic acid bacteria, destroying pathogenic bacteria, neutralizing reactive species, and mitigating inflammation for the achievement of a healthy gut (Davani-Davari et al., 2019). Hence, these compounds may not exhibit polysaccharide attributes, but they meet the prebiotic criteria. For that reason, these compounds are regarded as non-prebiotic carbohydrates, which include anthocyanin, curcumin, flavanols, licorice, polyphenols, and other minor phytochemicals (Anand et al., 2022). Among others, flavanols from cocoa, anthocyanins from blueberry, sweet potatoes, carrots, cauliflower, and cabbage, glycyrrhizin from licorice, curcumin from turmeric and piperine from black pepper are a good example of non-prebiotic carbohydrates.

To date, researchers have mostly concentrated on investigating the influence of flavanols on the growth of lactic acid bacteria by doing tests both in living things and in test tubes (Tzounis et al., 2011). To achieve this goal, dietary polyphenols are applied to interact with gut microflora in a way that either enhances the proliferation of helpful bacteria or restricts the growth of harmful bacteria (Bindels et al., 2015). These polyphenols employ the distinct characteristics of gut microflora to produce the secondary metabolites utilized by human metabolism (Blumberg et al., 2013). According to Al-Thubiani and Khan (2017), prebiotics can include any dietary components that enter the colon, including lipids, indigestible polysaccharides, or proteins. Based on this idea, it is presumable that these lipids and proteins are glycolipids and glycoproteins, respectively. Since this paper focuses only on prebiotic carbohydrates, non-prebiotic carbohydrate compounds are not elaborated in this paper.

2.2. Prebiotic carbohydrates

After being invented in 1995, the concept of a prebiotic has evolved. In 2016, the International Scientific Association for Probiotics and Prebiotics (ISAPP) established the current agreed definition of prebiotics as "a substrate that is selectively utilized by host microorganisms conferring a health benefit" (Gibson et al., 2017; Johnson et al., 2020). Particular foods found in the colon, called prebiotic carbohydrates, act as biosynthetic building blocks for the activity of microbiota in humans. It can have health benefits, mostly related to preventing obesity and type II diabetes. The existing definition has widened the context of discussing prebiotics beside carbohydrate substrates in BIT by respecting the prospective for non-GI locations and non-carbohydrate compounds to allow selective fermentation. Despite the definition expanding to include more than dietary carbohydrates, most prebiotic research has focused on these, therefore, this article focuses on fruit seeds that are rich in carbohydrate content. Prebiotic carbohydrates can be classified according to their sugar subunits, DP, and bond framework. Dietary fiber and sugar alcohols (SAs) are the two primary categories of prebiotic carbohydrates found in nature (Roberfroid, 2007). Dietary fiber comprises of resistant starch (RS) and non-starch polysaccharides (cellulose, hemicellulose, inulin, pectin, and oligosaccharides, such as GOSs, FOSs, ROSs, and XOSs). Meanwhile, the common SAs comprise sorbitol, mannitol, xylitol, isomalt and hydrogenated starch hydrolysates (Godswill, 2017; Roberfroid, 2007). Prebiotic carbohydrates play a fundamental role in numerous health advantages by enhancing satiety, regulating cholesterol levels, and managing post-meal blood glucose levels (Beserra et al., 2015). Studies have shown that prebiotics such as inulin and FOSs contribute to increased satiety by stimulating the production of gut-derived hormones like peptide YY (PYY) and glucagon-like peptide-1 (GLP-1), which regulate appetite (Kellow et al., 2014; Slavin, 2013). Additionally, prebiotics have been linked to improvements in lipid metabolism, helping to reduce total cholesterol and low-density lipoprotein (LDL) cholesterol levels, which can lower the risk of cardiovascular disease (Russo et al., 2010; Sheng et al., 2023). Furthermore, they support glycemic control by slowing glucose absorption and promoting beneficial gut microbiota, which influence insulin sensitivity (Dewulf et al., 2011; Holscher, 2017).

Prebiotic carbohydrates, primarily derived from natural sources such as fruits, legumes, and vegetables, vary significantly in their concentrations, ranging from trace amounts to relatively high levels depending on the plant species, maturity, and processing methods (Johnson et al., 2020). Common prebiotics include inulin and FOSs found in onions, garlic, bananas, and chicory root, as well as GOSs present in legumes like lentils and chickpeas (Carlson et al., 2018).

2.3. The classifications of prebiotic carbohydrates

Although prebiotic carbohydrates consist of numerous groups, oligosaccharides round off the biggest portion of the whole prebiotic members (Davani-Davari et al., 2019). Table 1 tabulates the well-established prebiotic groups with particular compounds.

2.3.1. Fructans

Fructans encompass inulins and FOSs. Chemistry wise, the molecular structure of fructans consists of linearly ordered fructose chains linked with β(2,1) bonds. In fact, insulins are larger carbohydrate polymers than FOSs, having a DP of around 60, whereas FOSs have a DP of less than 10. (Louis et al., 2016). Although more than 36,000 plants have been reported to contain naturally occurring FOSs, their concentrations are sufficient for exhibiting prebiotic capacity (Havenaar et al., 1999). Up to now, numerous prior investigations have demonstrated the capacity of fructans to selectively promote the growth of LAB. Additionally, Scott et al. (2014) discovered that the chain length of fructans significantly determines which bacteria are suitable to ferment them.

2.3.2. Galacto-oligosaccharides (GOSs)

Numerous in vitro and in vivo assays on animals and humans have proven the prebiotic potential of GOSs (Torres et al., 2010). Generally, GOSs can be obtained from the expansion of lactose molecules, a disaccharide mostly contained in milk and numerous agricultural products. In fact, GOS are divided into GOS with excess galactose connected to the 3rd, 4th, or 6th carbon atom and GOS synthesized from enzymatic trans-glycosylation of lactose.

When lactose is trans-glycosylated, it can create a trans-galacto-oligosaccharide (TOS), which is made up of penta-saccharides with a DP of 3 to 5 and galactose at β (1,6), β (1,3), and β (1,4) bonds (Davani-Davari et al., 2019). Usually, GOSs function to enhance the proliferation of *Lactobacilli* and *Bifidobacteria,* making them perfect agents to be incorporated in infant's diets (Davani-Davari et al., 2019). Furthermore, GOSs have also been proven to be stimulate Bacteroides and Firmicutes to a lower extent than probiotics, such as *Bifidobacteria* (Louis et al.,

Table 1
Various groups of prebiotic carbohydrates.

Groups	Compounds	Functions	References
Fructans	Inulin FOSs	Selective stimulation of lactic acid bacteria	(Louis et al., 2016)
GOSs	Lactose-based GOSs Galactose-based GOSs ROSs	Stimulation of *Bifidobacteria* & *Lactobacilli*	(Davani-Davari et al., 2019)
Starch- and Glucose-derived Oligosaccharides	Resistant starch Polydextrose	Butyrate production Stimulation of *Bifidobacteria*	(Magne et al., 2020)
POSs	Pectin-based GOSs	Stimulation of *Bifidobacteria*	(Wongkaew et al., 2022)
XOSs	Xylose-based GOSs	Stimulation of *Bifidobacteria* & *Lactobacilli*	(Valladares-Diestra et al., 2023)

2016). Lactulose, an isomer of lactose, can serve as an effective raw material for certain GOSs. Structurally, lactulose is a lactase undigestible disaccharide made up of fructose and galactose molecules connected by a chemical bond. Lactulose retards food digestion in the upper intestine and cannot be absorbed by the small intestine. Nonetheless, it goes through fermentation to generate SCFAs, CO_2, and H_2, leading to improved fecal acidity (Pranami et al., 2017).

Furthermore, lactulose-derived GOSs also demonstrate prebiotic activity (Gibson et al., 2010). Even though some GOSs have been reported to originate from sucrose, which are called ROSs, their prebiotic activity has yet to be confirmed (Johnson et al., 2013).

2.3.3. Starch- and glucose-derived oligosaccharides

Starch-derived oligosaccharides, particularly RS, and glucose-derived oligosaccharides, such as polydextrose, differ in their structural complexity, fermentation patterns, microbial selectivity, and physiological benefits. RS, a form of dietary fiber that resists enzymatic digestion in the small intestine, reaches the colon largely intact, where it serves as a substrate for specific gut microbiota (Magne et al., 2020). The fermentation of RS leads to the production of significant amounts of SCFAs, particularly butyrate, which plays a crucial role in maintaining gut integrity, modulating inflammation, and supporting metabolic health (DeMartino & Cockburn, 2020; Haenen et al., 2013). RS fermentation is primarily driven by *Ruminococcus bromii*, a keystone species essential for breaking down RS into smaller oligosaccharides, enabling further utilization by secondary fermenters such as *Eubacterium rectale* and *Bifidobacterium adolescentis* (Ze et al., 2012).

In contrast, glucose-derived oligosaccharides like polydextrose have a different structural configuration, consisting of randomly branched glycosidic linkages that provide resistance to enzymatic breakdown in the small intestine (Rastall & Gibson, 2015). Unlike RS, polydextrose is more broadly utilized by various gut bacteria, particularly *Bifidobacteria*, leading to its well-documented bifidogenic effect (Hooda et al., 2012). While RS selectively supports butyrate-producing bacteria and Firmicutes, polydextrose contributes to a more general modulation of gut microbiota, with increased lactate and acetate production rather than butyrate (Carlson et al., 2018; Herfel et al., 2011). Furthermore, RS has been shown to improve insulin sensitivity and lipid metabolism, likely due to its ability to enhance SCFA production and modulate the gut-liver axis (Davani-Davari et al., 2019).

Overall, both starch- and glucose-derived oligosaccharides are good for gut health. However, RS has a more focused effect on SCFA production and Firmicutes abundance, while polydextrose has a broader, less targeted effect on bifidogenic response. Their differing mechanisms suggest that dietary inclusion should be tailored based on desired health outcomes—RS for metabolic and anti-inflammatory benefits and polydextrose for general prebiotic effects and digestive health support.

2.3.4. Pectic-oligosaccharides (POSs)

Pectin, being a polysaccharide, serves as an excellent source of diverse oligosaccharides (Davani-Davari et al., 2019). Such oligosaccharides originating from pectin are simply named as POSs. Based on their production method, either from the extension of galacturonic acid or rhamnose. POSs can be classified into homogalacturonan and rhamnogalacturonan I, respectively (Davani-Davari et al., 2019). Moreover, they discovered that carboxyl groups can undergo substitution through methyl esterification, leading to the acetylation of the POSs structure at the second or third carbon. Generally, the side chains of these POSs are linked with ferulic acid or sugars, including arabinose, galactose and xylose (Yoo et al., 2012). Gullón et al. (2013) observed through their experimental inquiry that the source of the POSs strongly affects the disparity in their structures.

Previous study proved that POSs are efficient in providing various health benefits, such as promoting bifidogenic microflora, modulating blood cholesterol and triglyceride level, stimulating apoptosis of colon cancer cells, defending colonic cells against pathogenic Shiga toxins (Stx) produced by (*Escherichia coli* O157:H7), and exhibiting strong antioxidant activity (Wongkaew et al., 2022). A higher molecular mass of POSs has been proven to demonstrate as greater the inhibitory activity, which can be the result of an improved access to the receptor-binding sites on the toxin (Olano-Martin et al., 2003).

2.3.5. Xylo-oligosaccharides (XOSs)

Regarded as effective prebiotics, XOSs are non-digestible small oligomers made up mostly of (2−10) xylose units with confirmed health benefits through adjusting gut microbiota and few aftereffects (Manicardi et al., 2023). As a consequence of their existence of β-1,4-xylosidic bonds, XOSs are exceptionally persistent to GI enzymes and gastric juices, enabling them to traverse the upper GIT undigested until they arrive the lower intestine, where they are metabolized by probiotic bacteria, predominantly from the *Lactobacillus* and *Bifidobacterium* genus, leading to enhanced growth and proliferation of these bacteria (Holscher, 2017; Valladares-Diestra et al., 2023). An XOSs-enriched diet enhances host health through the immunomodulatory, anticancer, antibacterial, antioxidant, growth-regulating, and other significant bioactivities of XOSs (Gupta et al., 2022). Recently, XOSs enjoy a strong demand in the global market as a result of their growing food and feed applications (Food Market Insight, 2022).

The naturally XOSs can be obtained from some botanical and animal sources, namely fruits, bamboo shoots, honey, milk, and certain vegetables. Nevertheless, the extraction of these prebiotics from their natural sources suffers from low yield and concentration, which restricts their industrial applications (Gupta et al., 2022). Therefore, new sources for extracting and developing XOSs production methods have been looked for, mostly focusing on the huge potential of lignocellulosic biomass as a promising raw material.

Fig. 1 illustrates how different prebiotic carbohydrates—such as fructans, GOSs, starch- and glucose-derived oligosaccharides, POSs, and XOSs—selectively stimulate beneficial gut microbiota, primarily Lactobacillus and Bifidobacterium. Each type of carbohydrate undergoes fermentation in the colon, producing distinct metabolites such as SCFAs, gases (CO_2, H_2), and antioxidant compounds. These metabolic processes result in a variety of health benefits, including improved gut health, anti-inflammatory effects, enhanced immune modulation, antioxidant activity, and modulation of fecal acidity. Collectively, these prebiotic mechanisms underscore the importance of including a variety of non-digestible carbohydrates in the diet to enhance microbial diversity and support targeted physiological outcomes for overall health.

3. Exotic fruit seeds

Fruit seed, along with the core, leaves, pomace, rind, and stem, is regarded as the leading by-product of the fruit processing industry. Naturally, the seeds within a specific fruit differ in size, number, and weight (Kumoro et al., 2020). As already mentioned in Part 1, mango, durian, avocado, jackfruit, cempedak, guava, and tamarind, are the most abundant and popular seeds containing exotic fruits in Indonesia with high annual productivity (BPS-Statistics Indonesia, 2024). Based on a thorough literature survey, the aforementioned exotic fruit kernels are consumable following appropriate processing. Numerous research has been performed on the nutritional composition of seven Indonesian exotic fruit seeds, which subsequently revealed that the fruits bear a diverse nutritional content when the fruit plants are planted with different varieties and cultivating conditions. For that reason, their nutritional composition (on a weight basis), including carbohydrate, protein, lipid, fiber, moisture, and ash contents summarized in Table 2 demonstrates their wide potential applications, especially in the food sector. In addition to their edible pulp and rind, the seeds of the selected exotic fruits also possess magnificent promise as prominent source of highly-valuable food ingredients, particularly staple food and prebiotics.

Although various fruit residues possess great potential as prebiotics, this paper focuses on the prebiotic carbohydrates of the seed from

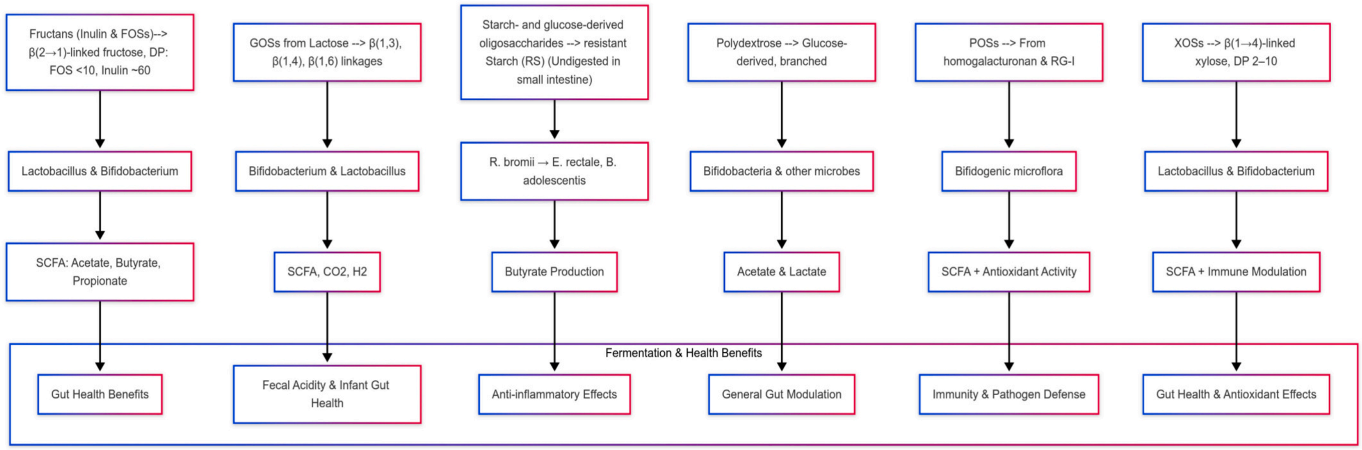

Fig. 1. Prebiotic mechanism of carbohydrates.

Table 2
Proximate composition (% wt.) in raw prebiotic-rich fruit seeds.

Nutrients	Mango[a]	Durian[b]	Jackfruit[c]	Cempedak[d]	Tamarind[e]	Guava[f]	Avocado[g]
Moisture	9.89	51.0–64.5	40.82	52.9–72.8	10.75	8.06	13.09
Crude protein	6.02	6.60–7.04	16.50	9.9–11.2	23.06	8.41	2.64
Total lipids	11.55	0.40–0.43	1.31	0.8–2.4	4.30	15.35	1.1–1.6
Crude fiber	10.60	1.0–1.5	3.19	3.9–7.1	7	46.21	2.87
Ash	2.58	0.9–1.2	2.32	3.2–5.1	2.6	1.43	3.82
Carbohydrate	59.34	25.8–38.4	38.2	2.8–3.5	53.66	28.60	64.9

References [a]Mutua et al. (2017), [b]Swami et al. (2012), [c]Ulloa et al. (2017), [d]Lim et al. (2011), [e]Geethalaxmi et al. (2024), [f]El Anany (2015), [g] Bangar et al. (2022)

Table 3
Carbohydrate composition (% wt.) in raw prebiotic-rich fruit seeds.

Carbohydrates	Mango[a]	Durian[b]	Jackfruit[c]	Cempedak[d]	Tamarind[e]	Guava[f]	Avocado[g]
Simple sugars							
Pentose							0.33
Ribose						0.008	
Hexose							0.0.9
Glucose	2.9	37.1–45.1				0.009	0.562
Fructose						0.011	1.293
Sucrose						0.117	0.786–1.85
Mannoheptulose							1.051–6.38
Raffinose - oligosaccharides							
Raffinose			0.031		3.25	0.003	
Stachyose						0.014	
Fructo-oligosaccharides							
Total starch	58–80	46.2	70–85	30	72.2–85.7	12	58.37
Resistant starch	73.73	5 (4.53)	8.0 (29.83)	29.72 (16.12)	55.8		44.1
Readily digestible starch	6.35		–		9.5		
Slowly digestible starch	19.92		33		34.7		
Insoluble fiber	34.6		7.9	12.44		63.94	
Soluble fiber	5.07		3.2	16.0			
Pectic-oligosaccharides							
Arabinose		0.58–3.41					4.12
Galactose		48.6–59.9				0.008	
Xylose		0.3–3.21					
Pectin	0.8				32.45	0.58	
Sugar alcohols							
Sorbitol						0.191	
Mannitol							
Xylitol							
Inositol					7.27		
Perseitol							1.254–8.83
Inulin						0.043	
Non-starch polysaccharides					65–73		

References: [a]Mandha et al. (2021), [b]Baraheng & Karilla (2019), [c]Li et al. (2022), [d]Lim et al., (2011), [e]Guízar-Amezcua et al. (2022), [f]Islam et al. (2020), [g]Bangar et al. (2022)

selected Indonesian seasonal exotic fruits, which are still underutilized and require more intensive feasibility studies. As a minor part of diets by people in several tropical countries, exotic fruit seeds, serve as excellent sources of prebiotic carbohydrates. Table 3 displays the naturally occurring prebiotic carbohydrates stored in the selected Indonesian exotic fruit seed kernels.

3.1. Mango seeds

Mango (*Mangifera indica* L.) is regarded as one of the most popular tropical fruits globally for its attractive features, delightful odor, rich nutritional content, and unique taste. In 2022, the Food and Agriculture Organization (FAO) declared that global mango production was as high as 59.15 million tons, with India, Indonesia, and China as the leading mango producers, contributing 26.3, 4.1, and 3.8 million, respectively. Mango processing enterprises worldwide have documented that about 35–60 % of every single mango fruit is disposed of as waste. The predominant waste from mango fruit is the seed, accounting for about 1 million tons/year. (Torres-León et al., 2016). Jahurul et al. (2015) documented that as a biowaste, mango seed contains various bioactive compounds, including dietary fiber, carotenoids, phenolic compounds, vitamin A, C, and E. The existence of bioactive compounds in mango seed justifies that the seed could function in minimizing oxidative stress and subsequently providing health benefits. Saito et al. (2008) confirmed that the ethanol-based extract of mango seed possesses significant antioxidant activity. Furthermore, Maisuthisakul and Gordon (2009) observed that mango seed extracts have plenty of polyphenols, namely gallotannins and condensed tannins. This fact favors the prebiotic benefits of mango seeds, since polyphenols are crucial in controlling gut microflora (Plamada & Vodnar, 2022). They affect the growth of intestinal microflora and immediately hinder cell function.

In addition, FOSs, also known as prebiotics in mango seeds, selectively stimulate probiotic bacteria (Mandha et al., 2021). However, other oligosaccharides in mango seeds have not been fully studied. The presence of complex polysaccharides and dietary fiber suggests the potential prebiotic properties present in mango seeds. These compounds can survive digestion in the upper gastrointestinal tract and reach the large intestine, where they serve as substrates for probiotic fermentation, producing SCFAs. SCFAs contribute to gut health by lowering pH, inhibiting pathogenic bacteria, and serving as an energy source for colonocytes (Parhi et al., 2024).

3.2. Durian seeds

It is indisputable that, as the king of fruit, the durian *(Durio zibethinus* Murr.*)* is the most famous tropical fruit in Southeast Asia. According to Fang et al. (2022) around 75,000 t of durian seeds are thrown away each year, a figure projected to escalate with the growing global demand for durians. Predominantly, durian seeds comprise mucilage or gum (53.8 %) and starch (46.2 %) (Baraheng & Karrila, 2019). Following their investigation, Amid and Mirhosseini (2012) found that the yield of durian seed gum (DSG) obtained from aqueous extraction is approximately 56 % of the weight of durian seed flour (DSF). Amid et al. (2012) identified that DSG had attributes that influence the configuration of monosaccharide and glycoside linkages. As a dietary fiber, durian seed gum is made up of protein-polysaccharide complexes making it not easily digested by small bowel enzymes and capable of imbibing considerable amounts of water indicating its function as a hydrocolloid (Amid et al., 2012; Amid & Mirhosseini, 2012). Amid and Mirhosseini (2012) also disclosed that galactose, glucose, arabinose, and xylose predominantly contribute to the carbohydrate content of DSG by (48.6–59.9 %), (37.1–45.1 %), (0.58–3.41 %) and (0.3–3.21 %), respectively. Meanwhile, the plentiful amino acids are alanine, leucine, glycine, lysine, glutamic and aspartic acids, serine, proline, isoleucine, valine, threonine, and phenylalanine (Amid et al., 2012). Extraction of durian seed yielded 10.1 % starch (dry basis), which contains about 23 % amylose and 5 % RS (Tongdang, 2008). Additionally, every 100 g of DSF bears 20 mg fructan (inulin + fructo-oligosaccharides), a carbohydrate compound within the group of prebiotics Varichanan et al. (2023). According to their results, Varichanan et al. (2023) concluded that the carbohydrates of durian seed consist of starch and non-starch polysaccharides.

Previous research on chemical extraction carried out by Amid et al. (2012) proved that DSF contains abundant non-digestible carbohydrates that could exhibit prebiotic functions. An in vitro assay demonstrated by Varichanan et al. (2023) confirmed that durian seed flour contains a substantial quantity of potentially prebiotic substances. They also validated that the crude polysaccharide extracted from DSF displays a remarkable capacity to resist gastric juice and enzyme digestion. Further, Varichanan et al. (2023) predicted that about 85 % of crude polysaccharide extract reaches the colon. Moreover, the crude polysaccharide extracts also demonstrated better capacity than commercial prebiotic inulin to stimulate the growth of probiotics, including *Lactobacillus acidophilus* ATCC 4356, *Lactobacillus casei* BCC 13300, and *Lactobacillus rhamnosus* TBRC 374. Therefore, both DSF and crude polysaccharide extract display their capacity to act as prebiotics and can be utilized as raw materials in functional food development.

3.3. Jackfruit seeds

Tongdang (2008) extracted jackfruit (*Artocarpus heterophyllus* Lam.) seed and results in 18.2 % starch (dry basis), which contains approximately 24.40 % amylose and 29.83 % RS. Surprisingly, Zhang et al. (2016) obtained 18.92 % – 22.86 % of starch (based on dry basis) from the seed of five jackfruit cultivars grown in Malaysia and China, which contains 26.41–38.24 % amylose and 77.60 % RS (Zhang et al., 2019). RS helps to prevent lifestyle diseases, such as hypercholesterolemia, cardiac problems, diabetes, cancer, obesity, etc. by modulating blood glucose level and maintain intestinal microbial balance that keeps the gut remains healthy (Ranasinghe et al., 2019; Waghmare et al., 2019). From their research, Dasaesamoh and Seechamnanturakit (2014) attained highest yield of crude polysaccharide and non-reducing sugar (oligosaccharide) from extraction of jack fruit seed gum at 50 °C employing 50 % aqueous ethanol and distilled water, respectively.

Previously, Appukuttan and Basu (1987) found that in jackfruit seeds, the primary storage polysaccharides consist predominantly of guar-galactomannan. Jackfruit seed is also richer in fiber than the edible pulp, which is about 7.1 % (Babu et al., 2018). Dietary fiber is related to a decreased likelihood of cardiovascular disease and mortality (Barber et al., 2020; Swami et al., 2012). The findings offer important insights into the prospective application of jackfruit seed gum and starch as materials for prebiotics.

3.4. Cempedak seeds

Cempedak (*Artocarpus integer*) is also a species of the *Moraceae family*, like jackfruit. Its seed bears 2.44 %, 24.55 %, and 29.72 % of crude fiber, carbohydrate and RS, respectively. After primary processing into flour, the cempedak seed flour (CSF) contains respectively 2.35 %, 79.74 %, and 14.77 % of crude fiber, carbohydrate and RS (Zabidi & Aziz, 2009). In a later study, Aziz and Zabidi (2011) found that CSF possesses a greater insoluble dietary fiber (IDF) content (23.93 %) and a diminished RS content (14.77 %) than the original IDF and RS contents of raw cempedak seed, which are 12.44 % and 29.72 % respectively. They also documented that the soluble dietary fiber (SDF) in raw cempedak seed and CSF accounts for 16.0 % and 9.6 % of the total dietary fiber, respectively. SDF comprises viscous fibers, which include β-glucans, fructans (fructo-oligosaccharides and inulin), gum, mucilage, pectin, and non-viscous fibers, which mainly comprise hemicellulose. SDF absorbs water, resulting in gel formation that prolongs food transit time, postpones stomach emptying, reduces nutrient absorption, and decelerates digestion. Additionally, they also assist reduce cholesterol level because they are unsusceptible to hydrolysis by human small bowel enzymes, however are fermented by the gut bacteria in the large bowel into SCFA, which induces intestinal microbiota changes and reduces cholesterol synthesis in the liver. Generally, the IDF consist of various hemicelluloses, celluloses, and lignin. In contrast to SDF, the IDF reduces transit time and improves fecal bulk, and thus aids to alleviate constipation. An appropriate intake of dietary fiber provides advantageous physiological reactions, which include the prevention of three preeminent degenerative ailments as a result of its prospective in attenuating the risks of colorectal cancer, ischemic heart diseases and type 2 diabetes (Li & Ma, 2024). Extraction of cempedak seed yielded 17.5 % starch (dry basis), which roughly comprises 22.64 % amylose and 16.12 % RS. The above information ascertains that extensive processing of starchy foods induces microstructural degradation of the seeds as indicated by considerably lower RS content in CSF and starch compared with the raw cempedak seed. Indeed, cempedak and durian seed starches contain very similar amylose content, while jackfruit seed starch bears a slightly higher amylose content (Tongdang, 2008). Jackfruit and cempedak seed starches are 6.6 and 3.6 times richer in RS than the durian seed starch.

Based on their in vitro evaluation, Taweerodjanakarn et al. (2020) noted that cempedak starch had considerable prebiotic action, resilient to simulated GI stressors. It displayed 16.66 %, 14.85 %, and 13.00 % hydrolysis level following the consecutive contact with the upper GIT, namely in the stomach at pH 1, 2, and 3 and the duodenum (pancreatic α-amylase) for 4 and 6 h, respectively. Recently, Wong et al. (2021) posited that the hydrolysis levels of cempedak seed extract by gastric juice at pH 1, 2, 3, and 4 were respectively 6.14 %, 7.12 %, 8.98 %, and 10.23 %. Generally, food is held in the human stomach, where the gastric juice with pH 2 to 4 is secreted for no longer than 2 h. Meanwhile, the enzymatic hydrolysis levels of cempedak seed extract and inulin at pH 7 were 0.16 % and 0.09 %, respectively. In vitro studies suggest that roughly 90 % of cempedak seed extract is likely to reach the intestines within 4 h post-consumption. These extremely low levels of enzymatic hydrolysis show that both carbohydrate polymers exhibit resistance to enzymatic digestion and may reach the small bowel with negligible content loss. Further, they predicted that no less than 60 % of the cempedak seed extract consumed by humans would arrive in the colon because some of it was hydrolyzed by α-amylase (0.16 %), by gastric juice (10 %), and by brush-border enzymes in the small bowel (30 %). Based on their recent in vitro digestion experiment, Wong et al. (2021) reported that the cempedak seed extract demonstrates its potential as a good candidate for prebiotics because it is capable of resisting gastric juice digestion and enzymatic hydrolysis. Additionally, the cempedak seed extract had an analogous impact to inulin in promoting the proliferation of *Lactobacillus acidophilus* and *Lactobacillus casei* that use cempedak seed extract as a carbon source. In conclusion, cempedak seed extract demonstrated parallel prebiotic activity to the commercial inulin.

3.5. Tamarind seeds

Tamarind (*Tamarindus indica* L.) seed accounts for approximately 30–34 % of the whole fruit, containing up to 72 % wt. of the polysaccharides (Khounvilay & Sittikijyothin, 2012). The whole seed and the seed kernel contain a high level of carbohydrates (57.7 %), whereas the seed coat contains a lower carbohydrates level (40.1 %). Conversely, the seed coat bears a higher crude fiber level (21.6 %) than both whole seed and seed kernel that contain 7.6 % and 3.2 % crude fiber, respectively (El-Gindy et al., 2015).

Tamarind seed polysaccharides (TSPs) are energy depository units in the tamarind seeds making up about 65 % of the whole seed constituents, which are usually recovered from the seeds through acid or alkaline hydrolysis (Majeed et al., 2019). TSPs possess the prebiotic characteristics, specifically anti-obesity and anti-inflammation activities (Li et al., 2020). The xyloglucans combine in cross-like and parallel-like connections, and result in rope-like structures (Kozioł et al., 2015). As a galactoxyloglucan, the molecular structure of TSPs comprises a cellulosic skeleton of β-(1,4)-D-glucan backbone with side chains of -(1,4)-D-xylopyranose and (1,6) linked [β-D-galactopyranosyl-(1,2)-α-D-xylopyranosyl] to the extra glucose fragments, wherein glucose, xylose, and galactose units are present in a ratio of 3:1:1 as sugar monomer units (Zhang et al., 2020). Hexoses, such as mannose (17.35 %), glucose (11.8 %), fructose (6.16 %), and galactose (4.75 %) make up the predominant soluble sugars, while pentoses contribute to about 20 % of the total sugars comprising ribose (10.89 %), xylose (6.89 %), and arabinose (1.54 %). Other soluble sugars in the tamarind seed kernel are disaccharides, such as sucrose (5.23 %) and maltose (1.84 %). Meanwhile, inositol, the sugar alcohol, which is generally associated with phosphorous as phytate in seeds also exists at 7.27 %. Raffinose (3.25 %) and a lower level of stachyose constitute the oligosaccharides of tamarind seed kernel (Marangoni et al., 2006).

Previous research has proven that TSPs demonstrate appreciable antidiabetic activity by lowering blood sugar levels (Joseph et al., 2012). Besides, TSPs also display gel-forming capacity when utilized together with sugar or alcohol, confirming them as a promising raw material that can form gels similar to pectins in the food structure (Shukla et al., 2018). Additionally, tamarind seed extracts also exhibit antimicrobial and antioxidant activities. An in vitro investigation conducted by Utami et al. (2022) proved that tamarind seeds could function as prebiotics for the growth of lactic acid bacteria when incubated at 70 °C for 180 min. The existence of xylose sugar monomers in tamarind seed kernels renders them a perfect substitute for food-grade starch (Abiraami et al., 2021). For instance, a functional yogurt prepared from tamarind seed kernel powder exhibited prebiotic capacity.

3.6. Guava seeds

Guava (*Psidium guajava* L.) byproducts consist of 15–50 % little seeds (Mantovani et al., 2004). Inherently, seeds carry nutrient supplies for plant embryo development. Hence, they are abundant in carbs, lipids, and proteins. Guava seeds bear mostly 63.94 total dietary fiber, 13.93 % total lipids, 11.19 % protein, 6.68 %, moisture, 3.08 % carbohydrate, 1.18 % ash and 0.17 % starch (Uchôa-thomaz et al., 2014). They also found pectin and reducing sugar (fructose) in guava seeds, with their contents are 0.58 % and 0.29 %, respectively. In fact, guava seeds contain a high content of cellulose (40.22 %), but very low RS and soluble carbohydrate content (Ling & Chang, 2017). Nevertheless, the high dietary fiber content and the existence of antinutritional components restrict the utilization of guava seeds as a food raw material attributable to its poor digestibility and safety. According to the 2021 guidelines from the United States Food & Drug Administration, the daily value for dietary fiber in a 2000-cal diet is 28 g. For that reason, Ling and Chang (2017) investigated the effect of germination on the total soluble carbohydrates, starch, and cellulose levels in guava seeds. The findings demonstrated that germination improves the total soluble carbs while attenuating digestible starch and cellulose contents.

Recently, Lin and Lin (2020) studied the fractionation and characterization of guava seed polysaccharides, from which they acquire 3 glycoproteins or proteopolysaccharides, and named them as guava seed fractions (GSF). Stemming from their monosaccharide-protein proportion and molecular weight, GSF1 was designated as a storage polysaccharide, GSF2 as a skeletal polysaccharide and GSF3 as a mucoprotein of guava seeds. Predominately, the monosaccharide component of GSF comprised galactose, galacturonic acid, glucose, and xylose, whereas minor amounts of arabinose, fucose, gluconic acid, mannose, rhamnose, and ribose contributed to the lesser monosaccharide portion of GSF3. A careful in vitro examination proved that GSF3 displays greater anti-inflammatory and immunomodulatory functions than both GSF1 and GSF2.

3.7. Avocado seeds

As a member of the *Lauraceae* family, avocado (*Persea americana* Mill.) is a popular tropical exotic fruit that originates from Central America and Mexico. The seeds carry a considerable amount of carbohydrate and crude fiber content, which are 64.9 % and 2.87 %, respectively (Bangar et al., 2022). However, the maximum polysaccharides yield obtained from the avocado seed ranges from 19.54–20.1 % wt. In fact, about 7.8–29.3 % (on a dry basis) of the isolated carbohydrate is starch with 41.95–49.46 % amylose content (Frasson et al., 2023). Meanwhile, Bangar et al. (2022) reported that the avocado seed kernel contains 8.00 % total sugar comprising fructose (1.293 %) and glucose (0.562 %) as the reducing sugars, and hexose (0.19 %) and sucrose (0.786–1.85 %) as the non-reducing sugar components. In addition, the seed also bears 1.051–6.38 % D-mannoheptulose), and 1.24–8.83 % soluble sugar alcohol (perseitol) of dry weight (DW).

Based on the animal assay in rats, Uchenna et al. (2017) observed the partial influences of avocado seed flour dose in the rats' diets on their feeding and growth accomplishments. Their cholesterol levels were reduced and the blood glucose levels were suppressed, while the liver glycogen storage was enhanced after the avocado seed incorporation into the diets. On that account, the avocado seed flour is able to regulate the carbohydrate and lipid metabolisms and enhances glycogen storage ability of liver, so that it can be incorporated into the diet of hyperglycemia and/or hypercholesterolemia patients. With regard to the dietary and crude fiber content of the avocado seed, Pahua-Ramos et al. (2012) also found the hypocholesterolemia and the low-density lipoprotein (LDL) cholesterol lowering activities in the hypercholesterolemic model mice. Moreover, the supplementation of avocado seed powder to the regular diet enhanced the kidney and liver functions of the culled female quail (Tugiyanti et al., 2019). Indeed, the dietary fiber rich avocado seeds demonstrate numerous health benefits, which include cardioprotective, hypoglycemia, hypocholesterolemia (Hu & Yu, 2013), early satiety (Kristensen & Jensen, 2011), prebiotics (Slavin, 2013), and excretion and retention of bile juices (Kristensen et al., 2012).

4. Prebiotic Carbohydrates Preparation

So far, numerous oligosaccharides have been observed to function as prebiotic carbohydrates. Fructans, FOSs and inulin are the long-time leaders of prebiotics market in Europe and the USA. Nevertheless, GOSs also contribute prebiotic market in both regions at a smaller scale. In response to the limited availability of naturally occurring prebiotic carbohydrates than can be directly extracted from the fruit seeds, prebiotic carbohydrates can also be synthesized from their respective sugar either using chemical, enzymatic, fermentation or thermal methods. Table 4 presents the generally employed commercial prebiotic carbohydrates and their production methods.

As the major oligosaccharides, the prebiotic activity of raffinose and stachyose have been tested in humans. Although the effects experienced by volunteers varied, overall, raffinose showed a considerably strong prebiotic activity. IMOs, lactosucrose, lactulose, and XOSs have also been proven to be effectual prebiotics. FOSs are short- and medium-length chains of β-D-fructans, where fructosyl units are tied by β-2-1 glycosidic connections. Some polysaccharides naturally produced by numerous plants, including bananas, garlic, honey, leeks, onions, and wheat, also include glucose as the primary constituent. As long-chain fructans, inulin and frutafit are commonly extracted from chicory root. After a careful isolation, these fructans can be partially hydrolyzed using enzymes to produce FOSs. Normally, inulin possesses a high number (10–60) of fructose monomers, while its oligofructose derivatives possess a low (3–7) number of fructose monomers. However, FOSs can also be obtained from tranfructosylation of sucrose using enzymes generated by *Aspergillus niger*. Thus far, various countries have commercially manufactured FOSs for incorporation in miscellaneous food products, including biscuits, breakfast cereals, drinks, table spreads, sweeteners and yoghurts. GOSs are non-digestible oligosaccharides originated from lactose that are typically present in human milk and comprise galactose monomers chains of the form Glu α1-4β $[\text{Gal } 1\text{–}6]_n$ where $n = 2\text{–}5$. These prebiotics contribute favorable influences in the GIT by stimulating the growth of distinct intestinal microbiota, especially bifidobacteria. GOSs, whether used independently or in conjunction with FOS, are largely incorporated into infant food to enhance the microbiota composition to resemble that achieved through breastfeeding during both milk feeding and the weaning phase.

5. Health Benefits of Prebiotic Carbohydrates

Animal assays and human trials have proven that prebiotics exhibit prudent physiological changes. Indeed, prebiotics have been connected with diverse health benefits, such as augmentation of the bioavailability of valuable minerals, prevention of gastrointestinal infection incidences, and regulation of metabolic disorders linked to obesity, hepatic encephalopathy, and reduced cancer risk. Previous studies also proved that the biological effects of prebiotics are largely determined by their effect on the gut microbiota composition, the resulting metabolites, molecular structure and direct action. For instance, the molecular structure of GOSs may resemble the pathogen binding sites that overlay the surface of gastrointestinal epithelial cells and consequently may retard enteric pathogen adhesion and infection. Furthermore, these prebiotics have advantageous influences on the GIT by promoting the proliferation of particular intestinal microbiota members (i.e. *bifidobacteria* and *lactobacilli*) demonstrate numerous functional attributes, such as modulating

Table 4
Composition, production methods and DP of commercial prebiotic carbohydrates.

Prebiotics	Composition	Production Method	DP*	Refs.
Inulin	β(2-1) fructans	Hot water extraction (70–85 °C for 30–60 min) from asparagus root, banana, barley, chicory root, dandelion root, garlic, Jerusalem artichoke, leek, onion, rye, and wheat	11–65	(Hadji & Bouchemal, 2022)
FOS	β(2–1) fructans	Tranfructosylation of sucrose or enzymatic hydrolysis of inulin or polyfructose, naturally available in artichoke, bananas, dahlia tubers, garlic, onions, wheat, etc.	2–10	(Gonçalves et al., 2023)
GOS	Oligo-galactose (85 %)	Transglycosylation of lactose by microbial β-galactosidases or enzymatic conversion of acid whey lactose using β-galactosidases	3–5	(Ji et al., 2021; Teng et al., 2024)
Soya-oligosaccharides (SOSs)	Raffinose	(F-Gal-G)* and stachyose (F-Gal-Gal-G)* extracted from soya bean whey and tofu wastewater	3–4	(Y. Wang et al., 2022)
XOSs	β(1–4)-linked xylose	Hydrolysis of xylan from bamboo shoots, fruits, vegetables, wheat bran, straw, sugarcane residues, maize cobs, rice straw, etc., using chemical, physical, or enzymatic methods. Hydrothermal pretreatment and alkali treatment	2–4	(Fuso et al., 2022; Huang et al., 2022)
Pyrodextrins	Glucose containing oligosaccharides	Pyrolysis of potato or maize starch	diverse	(Barbosa-Martín et al., 2024)
IMOs	α(1–4) glucose & branched α(1–6) glucose	Transgalactosylation of maltose	2–8	(Tiangpook et al., 2023)

* DP: degree of polymerization, F: fructose. Gal: galactose, G: glucose.

gut microbiota, preventing pathogen adhesion and colonization, induction of anti-inflammatory responses, reducing food intake, regulating bowel habits and altering lipid and glucose metabolism. Predominantly, these biological functions stem from their resistance to mammalian digestive enzymes and their capability to promote the growth of useful bacteria (e.g. *bifidobacteria* and *lactobacilli*) in the colon and to enhance the formation of SCFAs with various biological functions. GOSs also demonstrate immune functions as the result of the stimulated modification on the gut microbiota and/or the influences of the created SCFAs through attachment to SCFA receptors on leucocytes. Previous studies revealed that SCFAs play significant role in controlling intestinal lipid absorption because butyrate weakens lipid transfer in vitro. Moreover, inulin and inulin-type fructans are categorized as dietary soluble fiber, and immediately regulate bowel routines, decelerating gastric draining, extending intestine transit time, slowing down glucose absorption and enhancing changes in glucose metabolism.

The concentration of RS in food is often minimal and is influenced by the botanical origin of the starch, as well as the methods of processing and storage. The development of RS during the processing of carbohydrate-dense foods is affected by several parameters, including moisture content, heating duration and temperature, frequency of heating and cooling cycles, pH, freezing, and drying.

6. General Insight on Prebiotic Carbohydrates and Their Food Applications

Currently, research output concerning the health application prospects of prebiotic carbohydrates is steadily growing. Based on their animal assay regarding the beneficial functions of prebiotic carbohydrates in obese mice, Everard et al. (2011) revealed that prebiotic carbohydrates intake attenuated firmicutes population, improved glucose tolerance level, reduced lipid level, and brought down oxidative stress and inflammation. More than a decade later, Megur et al. (2022) published their literature survey, in which they concluded that an appropriate intake of prebiotic carbohydrates prompted the modification of gut microflora and enhanced glucose homeostasis, which may be utilized in diabetes mellitus treatment. Nonetheless, thorough clinical investigations remain necessary to study different influential factors that have been employed to cause the experimental rats to become obese.

Basically, prebiotic carbohydrates have demonstrated both essential technological and delightful nutritional attributes in food applications. However, to ensure their suitability as functional food materials, prebiotic carbohydrates must be chemically and thermally stable to food processing conditions, such as heating, exposure to harsh pH, and Maillard reaction. To date, there is a lot of information on the stability of prebiotic carbohydrates, especially GOSs, FOSs, and inulin, obtained from experiments using food product models. Commonly, GOSs have considerable stability at acidic environments and elevated temperatures. Hence, they can potentially be introduced to various acidic or heated foods, such as bakery products, buttermilk, fermented milk, pasteurized fruit juices and yoghurts. Conversely, in an acidic environment or high temperatures, inulin and FOSs exhibit lower stability than other oligosaccharides. Their stability is even lower under acidic and high temperatures. This is because under extremely low pH, the β (2–1) bonds between the fructose units in inulin and FOSs structures are more susceptible to partial hydrolysis.

Meanwhile, information on prebiotic carbohydrates stability in real foods is still very rare. Therefore, major commercial implementations of FOSs, GOSs and inulin are still limited to infant foods. Table 5 summarizes the proposed applications of prebiotic carbohydrates in functional food preparation.

Indeed, prebiotic carbohydrates can potentially influence the physicochemical and organoleptic characteristics of food products. For instance, previous research reported that the DP considerably affects the physicochemical characteristics of inulin. As expected, inulin having a longer carbon chain (DP > 10) exhibits a stronger gel and consequently leads to improved body and mouthfeel. This phenomenon can be associated with the reduced water solubility of longer-chain polysaccharides, resulting in their more rapid crystallization. FOSs demonstrate higher aqueous solubility than inulin (up to 85 % soluble at ambient temperature). Commonly, they are utilized as sugar substitutes because they are relatively sweet (30–35 % of sucrose sweetness) and possess similar physical characteristics to sucrose and glucose syrups (Jackson et al., 2023). Because FOSs can create bulk with a lower energy content and improve the functional value of products without altering their taste and mouthfeel, they have been popularly implemented in numerous dairy products (Martins et al., 2019). FOSs are also utilized as sugar substitutes in the manufacture of baked foods and breads as well as to preserve the moisture in the resulting food products. So far, very few commercial food products have been reported to contain GOSs. Nevertheless, the incorporation of GOSs into commercial food products has been explored, especially in dairy products. For example, studies on the addition of GOSs to yogurt and examining its effects on the physicochemical and sensory properties of the product (Mosquera-Martínez et al., 2023). However, the overall number of commercial food products enriched with GOSs is still relatively limited. Similar to FOSs, GOSs are also perfect raw materials in the preparation of bread, baked products and fruit juice because they exhibit high moisture retention capacity and acid stability.

Table 5
Food applications of prebiotic carbohydrates.

Applications	Functional characteristics
Yoghurts and desserts	Alternative to sugar, enhances texture and mouthfeel, provides dietary fiber, and prebiotic elements
Beverages and drinks	Sugar replacement, improves mouthfeel, stabilizes foam, and includes prebiotics
Breads and fillings	Replaces lipids or sugar, enhances texture, adds fiber, and includes prebiotic benefits
Meat products	Acts as a lipid replacement, improves stability and texture, and adds fiber
Dietetic products	Substitutes lipids or sugar, incorporates fiber, and offers prebiotic benefits
Cake and biscuits	Sugar alternative, retains moisture, provides fiber, and includes prebiotics
Chocolate	Replaces sugar, resists heat, and adds fiber
Sugar confectionary	Acts as a sugar alternative, incorporates fiber, and prebiotic benefits
Soups and sauces	Sugar substitute, includes prebiotic ingredients
Baby & infant foods	Enhances texture, body, and mouthfeel, adds fiber, stability, and prebiotics

In relation to the increasing global life expectancy of the world's population (Wise, 2024), that indicates population aging, enhanced prevention and treatment options for various communicable, maternal, neonatal, and nutritional diseases, and increasing rates of obesity and metabolic disorders, there is also an expanding opportunity for the application of prebiotic carbohydrates in food products. Based on the fact that the elderly population has enjoyed various types of food products with various culinary attributes, such as physical state, appearance, colors, aroma, tastes, flavor, textures and serving sizes throughout their life (Liu et al., 2022), the future development of prebiotic carbohydrates-enriched foods should not only focus on their effects on health benefits, but also on how these food products satisfy their eating preferences. In addition, the resulting prebiotic carbohydrates-enriched food products must also be easy to package, carry, store, safe, durable and affordable for everyone.

7. Conclusions

Commonly, abandoned fruit residue in the field and waste dumps cause health and environmental problems through generation of air and water pollution as a consequence of their natural decomposition, attracting pest and disease vector insects as well as becoming an ideal growing medium for pathogenic microbes. However, the application of appropriate technology to fruit seeds residue can produce prebiotic carbohydrates aimed at maintaining healthy gut microflora. The negligible adverse reactions of prebiotics validate their potential as prebiotics that are capable of enhancing the GIT dwelling microflora. More well-planned experiments should be carried out to validate prebiotic carbohydrates potential of various fruit seed residues, thus research on prebiotic carbohydrates production and application will keep progressing. Since the level of naturally occurring prebiotic carbohydrates in fruit seed is usually lower than their prebiotic influential level threshold, their preparation through physical, chemical, enzymatic and biological methods is becoming a paramount challenge for functional food researchers worldwide. The application of prebiotic carbohydrates in human health care and functional food production has also been suggested, thereby declining the extensive utilization of chemically manufactured antibiotics in human health care programs. Finally, the production of diverse prebiotic carbohydrates from fruit seed residue will not only foster the global economy, but also strongly support the efforts of environmental issues minimization.

CRediT authorship contribution statement

Andri Cahyo Kumoro: Writing – review & editing, Writing – original draft, Supervision, Data curation. **Dyah Hesti Wardhani:** Writing – original draft, Validation, Supervision. **Tutuk Djoko Kusworo:** Writing – review & editing, Methodology, Data curation. **Yusuf Ma'rifat Fajar Azis:** Project administration, Methodology, Formal analysis. **Misbahudin Alhanif:** Writing – review & editing, Software, Data curation. **Tan Chin Ping:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

If needed, the data of this research will be available to readers upon direct request to the corresponding author: Andri Cahyo Kumoro through andrewkomoro@che.undip.ac.id.

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