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Valorization of Fruit and Vegetable Processing Wastes as Prebiotics: A Review

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Abstract

Although fruit and vegetable processing wastes are a great source of several macro/micronutrients and nutraceutical ingredients, in most cases, they are discarded or underutilized. Given the advancements in technology and the increasing awareness about the prospects of resource recovery, it is indeed a sustainable approach to effectively valorize such biomasses for both food and non-food applications. One promising concept is their prebiotic potential. Particularly, these agro-processing wastes are rich in dietary fiber and an array of bioactive compounds, making them an excellent substrate for probiotics, which are valued for their numerous health benefits. The effective extraction and inclusion of prebiotic fibers, oligosaccharides and bioactives from processing residues into a variety of functional foods, beverages, and supplements has been made possible by advancements in food technology. Considering the increasing research interest in this area, this review presents the fundamental concepts, expands on compositional merits, provides commodity-specific advantages, and concludes with the relevance and rising thrust of sustainability and the circular food economy. The sector benefits from the synergy between the circular economy policies and increased industry focus on waste valorization strategies, which further improve commercial viability. With consumers placing a greater emphasis on sustainability, clean-label products, and vegan-friendly options, plant-based prebiotics, including

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those made from fruit and vegetable byproducts, dominate market shares. Emphasis is placed on recent insights and innovations. With promising prospects and a keen focus on a circular food economy, the approach must consider scalability and commercialization, as many waste streams require pretreatment, the heterogeneous nature of waste makes process optimisation difficult and can lead to scalability issues

Abbreviations

OS	Oligosaccharides
NDOs	Nondigestible Oligosaccharides
CAGR	Compound Annual Growth Rate
ROS	Reactive Oxygen Species
TCA	Tricarboxylic Acid cycle (or Krebs cycle)
GSTs	Glutathione S-transferases
SCFAs	Short-Chain Fatty Acids
GPR	G Protein-Coupled Receptor
IMO	Isomaltooligosaccharides
GalA	Galacturonic Acid
HG	Homogalacturonan
RG	Rhamnogalacturonan
DP	Degree of Polymerization
XOS	Xylose-oligosaccharides
AXOS	Arabinoxylo-oligosaccharides
MOS	Mannan-oligosaccharide
COS	Cello-oligosaccharides
WPP	Watermelon Peel Powder
BPP	Banana Peel Powder
RSP	Rosehip Seed Powder
PCP	Pineapple Crown Powder
TPC	Total Phenolic Content
PP	Pomegranate Peel
HHP	High Hydrostatic Pressure
LAB	Lactic Acid Bacteria
SDGs	Sustainable Development Goals

Introduction

Globally, every year, over 0.9 billion tonnes of fruits and 1.2 billion tonnes of vegetables are produced.[1] Although such figures are enormous, a sizable portion gets wasted or lost, with levels varying from country to country. Over time, agro-food processing solutions have been continuously explored to address this issue. However, even during the processing and value addition of these commodities, significant levels, ranging from 40 to 50%, are collected as 'wastes' and 'discards'.[2] This waste can be cumulative of peels, seeds, pomaces, shells, rags, stones, pods, vines, skins, etc. Unfortunately, current practices fall far short of the concept of 'zero discards'; massive volumes of organic materials are often regarded as garbage and are burned, broken down anaerobically, or composted to provide energy, heat, and fertilizers, or sent as animal feed. Although not well reported, a sizable fraction ends up in landfills or is discarded in water bodies, making rotting biomass a pressing environmental concern. Furthermore, these processing waste streams are highly perishable, making them susceptible to microbial contamination, including mold growth and the introduction of aflatoxins into the food system. Over time, this can be utilized as a fertilizer in agriculture, as live feed in aquaculture, and as a biogas production source in renewable energy. However, these are considered waste by the food industry. Currently, the world is moving towards sustainability and the circular economy, so there is an urgent need to develop solutions that maximize the value of these waste materials, thereby achieving social, environmental, and financial benefits.

Probiotic bacteria are live microorganisms that, when administered in sufficient amounts, confer health benefits to the host.[3] Probiotics such as *Bifidobacterium* spp and *Lactobacillus* spp. support human health in many ways.[4] The beneficial substances produced by probiotics during their growth that impart gut health are named postbiotics. Although they may be given as supplements, several indigenous fermented foods are also known to be rich in probiotics. As a practical approach, promoting the growth of these existing microbes through increased dietary intake of prebiotics can also improve the health-promoting activities of these microorganisms.[5] The nondigestible food materials linked by glucosidic bonds that have a β-configuration are selectively metabolized by these beneficial organisms and are termed prebiotics. These act as a substrate for probiotics to stimulate their growth. Prebiotics possess certain characteristic features[6] and these are summarized in Figure 1.

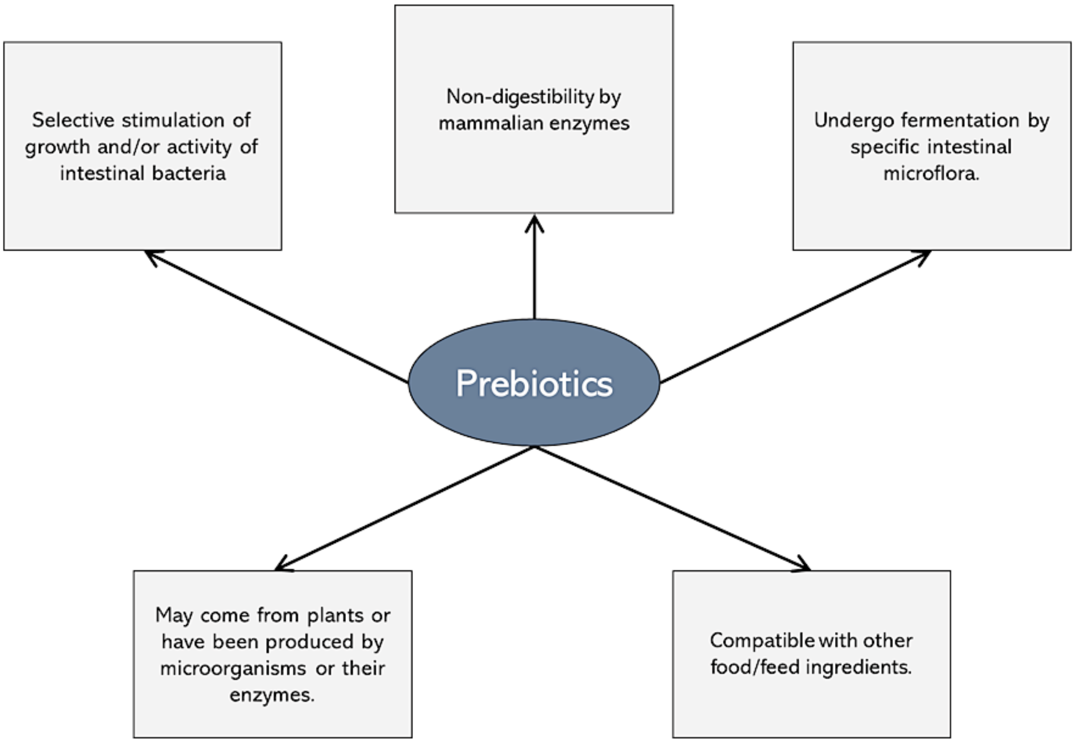

Fig. 1: Characteristic features of prebiotics

Apart from their significance to probiotics, which is most widely recognized, prebiotics render diverse health benefits. Therefore, there has been tremendous focus on identifying prebiotic substances that can bring about the most effective solutions for commercial-scale applications. Asparagus, sugar beet, garlic, chicory, onion, Jerusalem artichoke, wheat, honey, banana, barley, tomato, rye, soybean, human's and cow's milk, peas, and beans are the natural sources of prebiotics and are low in concentration; hence, conventionally, these prebiotics are sourced from lactose, sucrose, and starch as raw material.[7] However, considering the requirements listed in Figure 1 and the wide availability of fruit and vegetable wastes, trends indicate that these agro biomasses can be exploited as prebiotic materials (Figure 2).

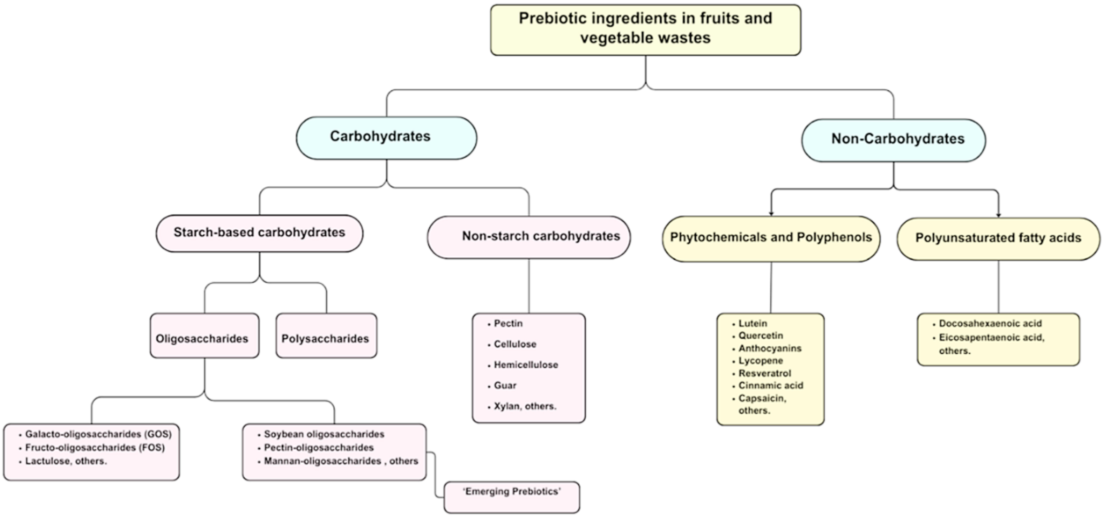

Fig. 2: Examples of prebiotic constituents from fruit and vegetable wastes

Overall, this review covers scientific evaluations of the utilisation of waste generated from fruit and vegetable fractions as prebiotics, which are crucial for probiotics. This approach serves two purposes: to address the rising concerns in waste management within agro-processing industries more effectively and to effectively utilise a widely available resource that is often discarded as 'zero-value waste.'

Prebiotics and Global Markets

Until recently, all recognized prebiotics were carbohydrates, mainly oligosaccharides (OS). Nondigestible oligosaccharides (NDOs) belong to carbohydrate-type prebiotics and reach the colon intact by escaping the upper gut due to their nondigestible nature, and are fermented by intestinal microorganisms and produce volatile fatty acids. These, in turn, express several health benefits.[8] A variety of non-carbohydrate materials, such as polyunsaturated fatty acids and polyphenols, are emerging prebiotics.[9] There are more than 8000 recognized polyphenols in fruits, vegetables, and plants. Many make it to the colon unharmed and intact, where they are used by the microbes that live there.[10] A few polyphenols have demonstrated prebiotic efficacy, such as extracts high in cranberries that stimulate *Akkermansia muciniphila* or offer pathogen-fighting antimicrobial activity.[11]

The market for prebiotics is not limited to humans but extends to animal health applications. With increasing awareness, several industrial sectors are finding increasingly expanding avenues for prebiotic substances. The main sectors involved in prebiotic synthesis are the food and beverage, pharmaceutical and healthcare, biotech, and animal feed industries.[12] Prebiotics, as a functional ingredient, are used in many food industries; dairy products, confectionery, infant formulas, whole wheat bread, cereal bars, chocolate, and meat products are a few among them.[13] Trends predict the prebiotic market to boom and fetch a profit of approximately $20.89 billion by 2030; the market was $6.71 billion in 2022 and will grow at a CAGR of 15.24% over the forecast period 2023-2030.[14] Similarly, it is estimated that the market will grow at a CAGR of 12.30% from 2024 to 2034, from a market size of USD 8.97 billion in 2024 and USD 10.08 billion in 2025, to reach approximately USD 28.62 billion by 2034.[15]

Plant Polysaccharides, Bioactives, and their Prebiotic Potential

The most researched prebiotic component found in waste and byproducts from agro-food production operations is nondigestible carbohydrates. These are made of plant polysaccharides, which can be used as water-retaining substances (alginates and pectins), structural components (cellulose, hemicellulose, and pectin), or calorie reserves (starch or inulin). Further, fruit and vegetable waste and byproducts are rich in complex, nondigestible carbohydrates and polyphenols, which are considered prebiotic substrates. Flavonoids are one of the main classes of polyphenols, which influence the growth of the gut microbiota composition and benefit the host.[16] Naturally occurring components in fruit and vegetable wastes can enhance intestinal microbial diversity and encourage the growth of probiotics. Intestinal flora breaks prebiotics down in the large intestine to create secondary metabolites, which are then absorbed by the intestinal epithelium or transported to the liver via the portal vein. These metabolites have many positive health effects on the host, such as enhancing intestinal barrier function, lowering blood lipid levels, regulating immunity, and preventing infections (Figure 3).

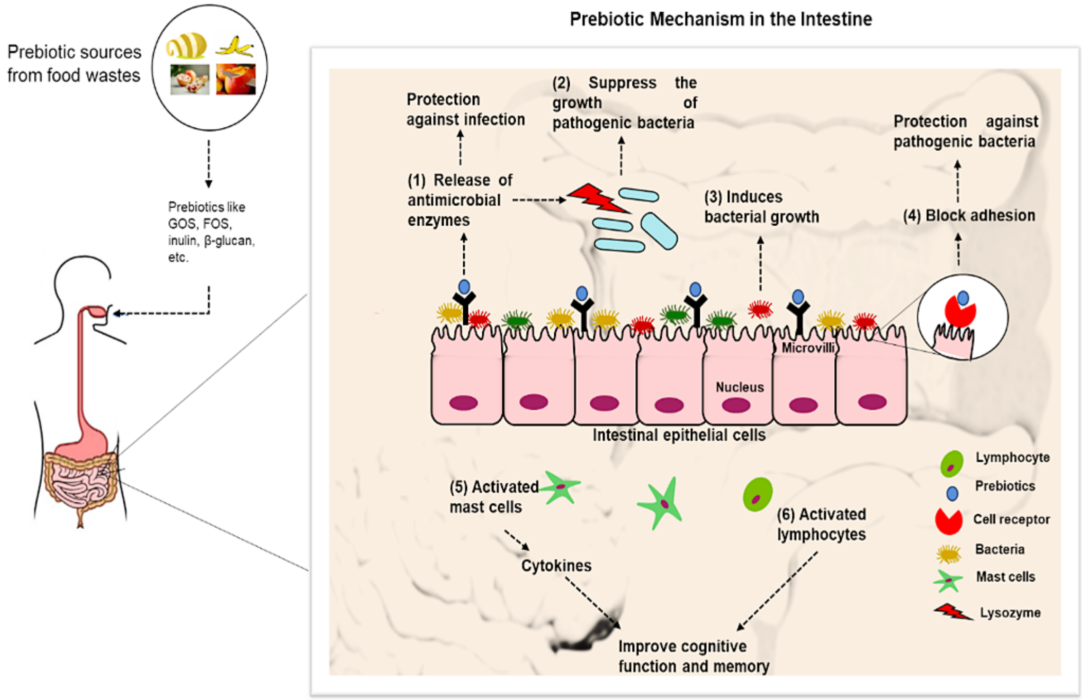

Fig. 3: Prebiotic action in the intestine (Credits: BioRender.com)

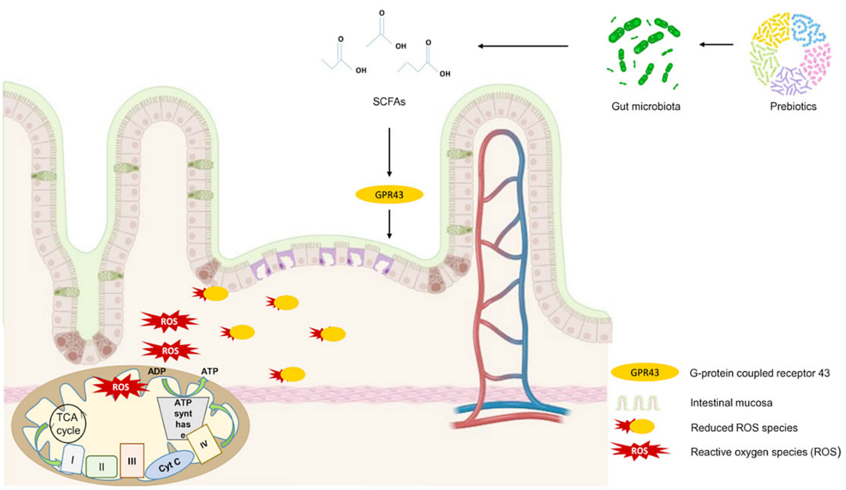

Fig. 4: Anti-inflammatory effects on the intestinal lumen by prebiotic associated SCFA activated G protein-coupled receptor (GPR43) (Credits: BioRender.com)

Oxygen and reactive oxygen species (ROS) generated by the electron transport system and TCA cycle during the oxidative phosphorylation of oxygen in mitochondria surround these microbes. Overexposure to ROS may be harmful to the probiotic population.[17] As prebiotics, fructans (fructo-oligosaccharides and inulin) have a protective impact. In addition to activating antioxidant enzymes like glutathione S-transferases (GSTs), the short-chain fatty acids (SCFAs) generated as a result of their intestinal fermentation can indirectly scavenge ROS (Figure 4). An *ex vivo* experimental model reported the contrasting effect of inulin on the oxidative stress induced by lipo-polysaccharide in human colonic mucosa.[18]

The generated galacto-oligosaccharides from the β-galactosidase transferase enzyme acting upon lactose favor *Bifidobacteria* proliferation. This was attributed to the galactose polymer-associated β-linked glucose monomer. The prebiotic effectiveness of lactulose was reported to depend on the dose given and the recipient's physiology.[19] Studies show that lactulose given at a dose of 5 g per day helps maintain an optimal balance of the members of the microbial community, comprising *Bifidobacteria*, *Lactobacilli*, and *Anaerostipes*. Such an intake also supports the generation of SCFAs. On the other hand, a high dose of 10 g per day was seen to suppress butyrate production while increasing the output of acetate, a byproduct of *Bifidobacteria* metabolism.[20] Also, xylose-oligosaccharides exhibited a more significant bifidogenic effect on *Bifidobacterium lactis* compared to fructose-oligosaccharides in an artificial colon model. Isomaltooligosaccharides (IMO) acted in synergism with green tea extract in an *in vivo* model. Studies also demonstrated beneficial impacts on visceral adipose tissue, the synthesis of pro-inflammatory cytokines, and the regulation of lipid and glycemic levels, leading to enhancements in insulin, glucagon, and leptin concentrations.[21]

Carbohydrate Components in Fruit and Vegetable Wastes with Prebiotic Properties

Cellulose

Cellulose makes up most of the cell walls of all plants and is a polysaccharide consisting of anhydro-β-D-glucopyranose units that are favored by β-1,4-glycosyl linkages. Cellobiose, cellotriose, and cellotetraose are the names of the different oligosaccharides of cellulose and are sometimes referred to as cellodextrins. These include dimers, trimers, and tetramers. Because each bundle of fibers contains hydrogen bonds, cellulose has the strength and resistance to chemical and biological hydrolysis.[22] It can absorb large volumes of water molecules, tends to swell, and is known to increase satiety and control body weight.[23]

Hemicellulose

After cellulose, hemicelluloses are the second most common biopolymer in the kingdom of plants. They form a primary component of the cell wall and are a relatively homogeneous 1-4-β-linked polyglucan, which sets them apart from cellulose. Hemicelluloses are a class of heteropolysaccharides that have complex structures and, depending on the source, vary in proportions of glucose, xylose, mannose, galactose, arabinose, fucose, glucuronic acid, and galacturonic acid.[24]

Lignin

Lignin is a complex natural aromatic polymer made up primarily of monolignols of substituted phenylpropanoid alcohols with methoxy ($-OCH_3$) and hydroxy (-OH) groups. Its molecular weight ranges from 0.6 to 1.5 x 10^6 kg/kmol. Lignin originates from the enzymatic dehydrogenative polymerization of coniferyl alcohol, sinapyl alcohol, and p-coumaryl alcohol, the three main precursors of monolignols. The polymeric structure of lignin shows several connections between the monolignols, with the majority being alkyl- and aryl-ether linkages (β-O-4, α-O-4, 4-O-5, etc.) and less carbon-carbon and ester linkages.[25]

Pectin

Pectin is found in the cell walls of all higher plants. It is a complex polysaccharide rich in galacturonic acid (GalA). Three main pectin domains can be identified based on their structural characteristics: homogalacturonan (HG), which is the linear region of the polysaccharide, and rhamnogalacturonan-I (RG-I) and rhamnogalacturonan-II (RG-II), which are the branched domains of the polymer. HG is a homopolymer comprising a-D-GalA residues with some methyl-esterified C-6 carboxyl groups.[26] However, the RG-I family of highly branched pectic polymers has a repeating disaccharide backbone (→4)-a-D-GalA-(1→2)-aL-Rha-(1→), in which side chains primarily composed of Rhamnose residues can be replaced with galactosyl and/or arabinosyl residues. The RG-II has about nine GalA residue backbones and four hetero-oligomeric side chains with a known and constant composition and length.[27]

Resistant Starch (RS)

RS is a general term for a wide range of starch classes that can arise from different sources and are all resistant to upper gastrointestinal tract digestion. RS is primarily made up of the linear portion with α-(1-4) D-glucan units, which are primarily derived from the retrograded amylose fraction of starch and have a relatively low molecular weight (1.2×10^5 Da).[28] Additionally, the authors reported that this type of starch is one of the most prevalent dietary sources of nondigestible carbohydrates and can be found in large quantities in whole grains, seeds, legumes, cooked and chilled pasta, potatoes, rice, unripe bananas, and cooled heat-treated starchy foods. From a physiological viewpoint, RS behaves generally in a manner akin to that of soluble, fermentable fiber.

Oligosaccharides

Galacto-oligosaccharides (GOS)

GOS are lactose-derived substances that have galactose or glucose at the reducing end and β-linked galactose moieties. Leguminous plant seeds are a natural source of GOS. The GOS comprises several β-connected galactose moieties, ranging in degree of polymerization (DP) from 2 to 8, such as β-(1 → 2), β-(1 → 3), β-(1 → 4), and β-(1 → 6).[29] The most promising nondigestible oligosaccharides, GOS, have gained interest in the functional food industry because of their established health advantages and capacity to enhance the nutritional value of a wide range of meals. Because GOS are not digestible in the upper digestive system but are still fermentable by gut microorganisms, they are an excellent prebiotic. As a result, these are sometimes referred to as "nondigestible fibers" or "befidiogenic prebiotics" since they support the growth of bacterial species related to *Bifidobacterium*[30,31] Currently, GOS is also utilized as a low-calorie sweetener in a variety of food items, including yogurt, beverages, confections, and bread.[32]

Fructo-oligosaccharides (FOS)

Inulin and FOS are collectively termed 'fructans.' FOS are a type of oligosaccharides that have prebiotic potential as a functional food ingredient. FOS are composed of linear chains of fructose connected by β-2,1-links; typically, with glucose positioned at the end. Hydrolytic enzymes are unable to hydrolyse the linkage in inulin or FOSs. These substances have the distinct quality of being prebiotics.[33] They are broken down by intestinal bacteria into L-lactate, CO_2, H_2, and SCFA, among other metabolites. To improve host health, the goal of FOS is to specifically encourage the growth and/or activity of one or a few beneficial bacterial species in the colon. One glucose (G) moiety and two to sixty fructose (F) moieties, such as those found in 1-kestose (1G, 2F), nystose (1G, 3F), and fructofuranosyl nystose (1G, 4F), are connected by (2–1)/ (2–6) glycosidic linkages.[34] Typically, the sweetness of FOS decreases when DP rises. FOS lowers cholesterol, phospholipids, and fatty acid levels and improves the absorption of minerals like Ca^{2+}, K^+ and Mg^{2+} It has been discovered that two cultivated plants that are good providers of FOS are yacon and jerusalem artichokes.[35] It is reported to have at least 4 g/day but preferably 8 g/day of FOS to show significant elevation in *Bifidobacterium* spp. in the human gut.[36]

Xylose-oligosaccharides (XOS)

Nondigestible oligosaccharides, or XOS, are produced from xylan-rich compounds and are short (DP 2–10) oligosaccharides linked together by β 1,4-linkages.[37] Additionally, some researchers recommend considering compounds of xylose DP up to 20 as XOS.[29] XOS are oligomers with an arabinose unit, uronic acid, or acetyl group as a replacement for the 1,4-linked xylose backbone. The degree of polymerization, the degree of substitutions (ratio of arabinose to xylose), and the links of XOS vary greatly. The kind of substitutions, how often they occur, and the molecular weight distribution on the xylan backbone determine the physical and biological properties of XOS.[38] XOS is generated by the physical or chemical hydrolysis of lignocellulosic biomass and the enzymatic hydrolysis of plant biomass, and is used as a sweetener in food additives.[39] Because XOS resists hydrolytic enzymes and promotes the growth and stimulation of gut bacteria, primarily *Bifidobacterium* spp. it demonstrates prebiotic qualities.[40] Lignocellulosic biomass, such as agro-industrial wastes, is a sustainable source for XOS manufacture for industrial applications.[39]

Arabinoxylo-oligosaccharides (AXOS)

The AXOS are a class of oligosaccharides that can be derived from agro-processing wastes is characterized by a β-(1 → 4)- xylose backbone with arabinose residues attached to O-2 and/or O-3 positions and some arabinose esterified at O-5 with ferulic acid.[41] Arabinoxylans, upon enzymatic treatment, will yield AXOS with different average degrees of polymerization and substitution, which may exhibit different prebiotic properties.[42] AXOS has a DP of up to 20, with DP 2-6 potentially having the most prebiotic potential.[43,44]

Mannan-oligosaccharide (MOS)

The MOS class is derived from hemicellulosic polysaccharides found in plant cell walls and seeds.[45] Linear mannans and glucomannan both have manno- and glucopyranose moieties linked together with similar linkages; however, the side chains in each of these two MOS are α-1,6-linked galactopyranosyl units, and the MOS are referred to as "galactomannans" and "galactoglucomannans," respectively.[29]

Cello-oligosaccharides (COS)

Recently, a relatively new class of nondigestible oligomers called COS has been investigated. These oligomers have D-glucose units with β-1,4 connections.[46] COS fall under the NDO category of oligosaccharides and are water-soluble and nondigestible to the human gut due to their linear chain of D-glucose coupled with a β-1,4-glycosidic bond present with a low DP (~6).[46] While the longer COS produce insoluble cellulose material, the shorter COS, or disaccharides, are water soluble and include three (cellotriose) to six (cellohexose) glucose monomer units. COS enhances the growth and development of gut microorganisms, particularly *Lactobacillus* and *Bifidobacterium* species.[47] Plant biomass contains cellulose, the most prevalent polysaccharide in nature, which serves as a natural source for the production of COS.[29] Probiotic strain growth promotion was investigated using COS, and results indicated up to 4.1-fold increase in cell density for *L. rhamnosus, L. lactis, L. paracasei,* and *Clostridium butyricum* compared to inulin, trans-galacto-oligosaccharides, and cellobiose, indicating that COS works as a helpful functional prebiotic carbohydrate. These results point to new understandings of COS commercial use and industrial production.[6]

Malto- and Iso-maltooligosaccharides

The α-1,4-bonds, which hold glucose moieties together in maltooligomers, are produced by amylolytic and pullulanase enzymes from polymeric carbohydrates like starch and glycogen. Isomaltooligosaccharides (IMO) are made up of isomaltose/triose/tetraose/pentaose, panose, nigerose, and kojibiose oligomers that contain α-1,6- and α-1,2-/1,3/1,4 bonded glucose. They are produced by starch-hydrolyzing enzymes and then transglycosylated by α-transglucosidase enzymes.[34] As a naturally occurring component of many fermented foods and sweets, including sake, soybean sauce, and honey, IMO is made up of glucose monomers connected by α-1,6 (and rarely α-1,4) glucosidic linkages.[48]

Isomaltulose is a natural component of honey and sugar cane. Isomaltulose (6-O-α-D-Glucopyranosyl-D-fructose) is a disaccharide that is especially useful as a non-cariogenic substitute for sucrose.[49] Bananas, rye, dragon fruit, onions, chicory root, garlic, asparagus, barley, wheat, tomatoes, leeks, and *Stevia rebaudiana* are among the fruits and vegetables from which this chemical is isolated.[50,51] Isomaltotriose or α-D-glucopyranosyl (1→6) (1-6)-α-D-glucopyranosyl-D-glucose encourages the development of gut-dwelling good bacteria. The glucosyltransferase enzyme displaces the D-glucosyl groups during the production of D-glucosyl oligosaccharide.[35]

Specific Fruits and Vegetable Wastes and their Prebiotic Constituents

Potential prebiotics can be found in many fruits and vegetables. This section presents commodity-specific examples, focusing mainly on fractions that are often discarded as waste. To alter functionality, future prebiotic molecules may potentially undergo structural or chemical modification using oxidation, high-pressure, acid, enzyme, and sonication treatments. Furthermore, novel benefit profiles may be created by combining distinct prebiotic combinations in optimized mixtures.[52] Figure 2 illustrates the major bioactive molecules sources of fruit and vegetable waste.

Fruits

Fruit wastes contain proteins, fibers, phytochemicals, flavor compounds, polysaccharides, etc., which are utilized in the making of high-value products such as medicines, food items, and cosmetics.

Fruit wastes and their Prebiotic Benefits

Citrus Fruits

Oranges, grapefruit, lemons, and mandarins constitute the majority of industrialized crops. Albedo, or the interior of the mesocarp, and flavedo make up the shell and refer to the white, spongy, cellulose tissue that is thought to be the primary source of dietary fiber in shells. Using HPLC-DAD, several phenolic and flavonoid chemicals, including coumaric acid, tangerine, and nobiletin, have been screened in orange peels.[53] Further, Czech *et al*.[54] found that all citrus fruits' peels contained much more phenolic components than their pulp.

Apple

Apple peel, pulp, and seeds make up 25–30% of the total fruit. These are rich sources of fiber (4.4-47.3 g/100 g pomace), and the ratio of soluble to insoluble fibers varies depending on the types of apples used to obtain pomace. Along with fermentable carbohydrates, flavonoids and other antioxidants present in these discards can influence prebiotic action. A study on three commercial probiotic strains (*L. rhamnosus, L. casei* and *B. lactis*) showed that a small percentage (2%) of powdered apple, banana, and mango peels could be effectively used as prebiotics to improve lactic acid bacteria.[55]

Berries

Blackberries, blueberries, strawberries, raspberries, red, white, and black currants, sea buckthorn, and other berries are a few of the popular berries and the berry pomace or press cake typically includes seed, stem, and skin pieces, significantly rich in dietary fiber. Dietary fiber comes in the forms of inulin, cellulose, hemicellulose, pectin, and lignin.[56] Importantly, polyphenols attached to the polysaccharides showed prebiotic activity. For example, cranberries are rich in anthocyanins, p-coumaric acid and quercetin, which may play a vital role in prebiotic mechanisms.[57]

Pomegranate

Chemical analysis of dried pomegranate peels showed about 11% crude fiber, 29% neutral detergent fiber, 19% acid detergent fiber, 15% cellulose and 10% hemicellulose.[58] Bioactive phenolic acids like punicalagin, ellagic acid glucoside and flavonoids like anthocyanins are found in pomegranate peel. Punicalagin can be metabolized by lactic acid bacteria and transformed into ellagic acid and further to urolithins, and easily uptaken by the intestine.[59] Studies have also shown that pomegranate peel extracts outperform other wastes in terms of their soluble phenolic content and antioxidant activity.[60]

Watermelon

Roughly 40% of the watermelon's mass is its rind. Insoluble fiber is the main kind of fiber present in watermelon rinds. Since watermelon has a high pectin concentration, it has a strong potential to function as a prebiotic.[61] The impact of freeze-dried watermelon peel powders (WPP) and banana peel powders (BPP) on the survival, growth kinetics, and bile salt tolerance of *L. acidophilus* and *Lactiplantibacillus plantarum* was studied, concluding with beneficial effects.[62] Similarly, the *polysaccharide* extract of yellow watermelon peel was able to significantly raise *L. rhamnosus* and *B. bifidum* counts.[63]

Kiwi

Bagasse, skin, and seeds are essentially obtained as waste from kiwi processing. The dietary fiber from the pomace leftovers of kiwis was found to be around 26%.[64] The fruit peel contains more polyphenols than its flesh: catechin, quercetin, epicatechin, epigallocatechin and p-coumaric acid are a few of them, which produce better-absorbing metabolites like hydroxyphenyl acetic acid and hydroxyphenyl propionic acids when metabolized by gut microbiota.[57,65]

Pear

Pear pomace contains 44 to 79% fiber on a dry weight basis, and is rich in polyphenols apart from organic acids and triterpenes.[66] Arbutin, chlorogenic acid, catechin, quercetin, kaempferol, various hydroxycinnamoylmalic acids and their ethyl esters, hydroxycinnamoyl malates, procyanidins and triterpenes are the few reported compounds found in the peel of the pear at levels higher than in the pulp.[67]

Grape

The total amount of dietary fiber found in the grape pomace was 78% (d.w.), of which 9.5% was soluble and the remaining 68% was insoluble. Grape pomace is a rich source of phenolic compounds, which are available for the gut microbiome and produce 3,5-dihydroxybenzoic acid and phenylacetic acid, which can be absorbed into the body.[68] LC-MS/MS analysis showed that grape pomace is rich in phenolic compounds like resveratrol, anthocyanins (cyanidin, delphinidin, malvidin, and petunidin derivatives), flavonols (quercetin, laricitrin, syringetin, and myricetin glycosides), and flavan-3-ols (catechin/epicatechin and their procyanidin oligomers).[69]

Mango

Processing mangos to remove pulp for juice and other value-added products often results in 35–60% of waste, which contains dietary fiber.[70] Roughly 50% of the total dietary fiber content is found in mango peels and pulp. Hydrolysis with pectinase on these substances produces reducing sugars and releases phenolic compounds, which provide prebiotic properties as lactic acid bacteria are capable of conducting polyphenol hydrolysis to produce smaller molecules with antibacterial properties such as cinnamic, vanillin, ferulic, and p-coumaric acids, luteolin, and kaemferol.[71] Importantly, for every combination of probiotic and enteric strains examined, the prebiotic activity score of mango peel powder was higher than that of commercial prebiotic maltodextrin.[72]

Dragon Fruit

The unusable portion from cacti makes up 25–30% of the overall fruit mass and is rich in natural colors, phytochemicals, and dietary fiber. Pectin, cellulose, hemicellulose, and simple sugars are the main types of fiber present in the leftovers.[73] Phenolic compounds (betacyanins, flavonoids, and phenolic acids) present in dragon fruits are known to stimulate the growth of probiotic bacteria, and they may act as prebiotics.[74]

Jackfruit

The fruit of the jackfruit is made up of 25.35% rags, 18-25% seeds, 30% pulp, and 31.0% skins.[75] Jackfruit rags contain a substantial quantity of cellulose (20.5%), protein (0.3-0.6%), reducing sugar (1.7-4.50%), total sugar (1-6.8%), and pectin (1.10-1.63%), while the skin contains 8.94%-15.14% of pectin.[76] The unused parts of jackfruits are also known to be a source of β-carotene, polyphenols and chlorogenic acid, which have proven prebiotic activity.[77]

Passion Fruit

In passion fruits, the peel and seeds account for 50% of the weight of the fruit and peels from passion fruit have a good amount of cellulose, hemicellulose and pectic substances. According to Bussolo de Souza *et al*.,[78] orange bagasse and passion fruit peels have demonstrated excellent fermentation profiles that enhance bacterial diversity and SCFA production. Further, neochlorogenic acid is a phenolic acid found abundantly in passionfruit, which has a stimulatory role in the growth of gut bacteria.[79]

Date Palm

The byproducts of the date processing industries include date seed, date pomace, and discarded dates. Date seeds are a rich source of cellulose, hemicelluloses, lignin, protein and fatty acids such as oleic acid, date processing wastes contain fermentable fibers and sugars, The dietary fiber content of date seed is estimated to be 39.89% and exhibits prebiotic activity.[80] Using isolated polysaccharides (date flesh polysaccharide and date seed polysaccharide), the chemical structure, functional characteristics, prebiotic potential, and metabolite production of *L. plantarum* and *B. animalis* subsp. *lactis* were examined. On *B. animalis*, date seed polysaccharide had a significant effect on proliferation (9.32 ± 0.05 log CFU/g), and so in the case of *L. plantarum* (8.66 ± 0.06 log CFU/g); additionally, *B. animalis* generated increased levels of SCFA in date seed polysaccharide cultured cells.[81]

Others

Banana peel is a good source for polysaccharides (pectin, cellulose and hemicellulose), and the prebiotic activity of pectin and cellulose oligosaccharides from banana peel is well-known.[82] Similarly, guava wastes include peel, seed, and pulp leftovers and are rich in cellulose with proven prebiotic activity.[83] Also, in pineapples, the peel makes up around 29–40% of all waste, and is rich in ferulic acid, gallic acid, epicatechins, and catechins, all of which can be utilized as potent antioxidant components.[84] Many phenolic chemicals, including gallic acid, catechin, epicatechin, anthocyanins, kaempferol, and isoquercitrin, are present in pineapple and banana peels.[84,85] The prebiotic action of peels from bananas, oranges, and watermelons has been demonstrated, and banana peels had the highest growth boost of *L. casei*.[86]

Vegetables

Vegetable wastes include peels, pomace, rinds, cores, leaves, and scraped portions. These are rich in protein, polyphenols, polyunsaturated fatty acids, enzymes, essential oils, and other phytochemicals, which are used in biocomposites, packaging, food, and the pharmaceutical sector.

Vegetable waste and its Prebiotic Benefits

Cabbage

Around 30% of cabbages are wasted, but this fraction is rich in carbohydrates and dietary fiber, which constitute a significant component of the waste. Further, prebiotic sugars, phenolic compounds like kaempferol, quercetin, and anthocyanin (red cabbage), are present in cabbages; these compounds have proven prebiotic activity.[87]

Carrot

Carrot pomace is high in fiber, with cellulose accounting for 51.6% of the total fiber content, followed by lignin (32.2%), hemicellulose (12.3%), and pectin (3.88%).[88] Current studies have focused on the polyphenols associated with dietary fiber, exhibiting prebiotic and antioxidant activities. Interestingly, the dietary fiber was found to include 42 different polyphenolic components, including p-coumaric acids, caffeic acids, and p-hydroxybenzoic acids.[89]

Cauliflower

The amount of dietary fiber in each portion of the cauliflower varies: the florets have 40% dietary fiber, the upper stem has 48%, and the lower stem has 65% (all in d.w.). Cauliflower's upper stems and florets possess 50–60% pectic components, but the lower stem portion contains 51% cellulose and 21% hemicellulose.[90]

Onion

There are plenty of nutritional fibers in varied proportions throughout the onion's layers, and compositions are known to vary significantly with variety. It is also reported that polyphenols like rutin and quercetin present in onions may contribute to prebiotic activity.[91]

Potato

Potato wastes, primarily peel wastes, contain significant levels of bioactive substances and dietary fiber. Further, potato peels contain about 50% of the phenolic compounds in potatoes, and rutin, quercetin, and anthocyanins are of prebiotic importance.[92]

Tomato

Roughly 50% (d.w.) of dietary fibers are found in tomato pomace.[93] Dietary fiber extracted from dried tomato peels had 83% of total dietary fiber and a 10:1 ratio of soluble to insoluble dietary fibers.[94] In addition, phenolic compounds, lycopene, and carotenoids in tomatoes support prebiotic activity.

Artichokes

Around 80-85% of the material is discarded.[95] The byproducts of artichokes are stems, bracts, and leaves, and these byproducts are high in inulin, a polysaccharide that can be broken down by digestive enzymes.[96] The essential oils, sesquiterpenes, and caffeoylquinic acids present in artichokes exert a positive effect on the gut microbiota.[97]

Broccoli

The stems and leaves of broccoli are underutilized and often discarded without valuing the potential of functional ingredients present in it. Stems are rich in carbohydrates compared to leaves; more of these carbohydrates are insoluble dietary fiber. On storage, insoluble dietary fiber composition increased by 13% but soluble dietary fiber remained unaffected. More SCFAs (acetic acid, propionic acid, butyric acid, isovaleric acid, isobutyric acid, isocaproic acid, caproic acid, and valeric acid) were discovered to be formed by broccoli leaf fiber than by stems and inflorescences, showing its superior prebiotic potential.[98] Glucosinolates are a group of specialised metabolites present in vegetables of the *Brassicaceae* family, which have no biological activity, but upon fermentation by gut bacteria, bioactive isothiocyanates, nitriles, thiocyanates, epithionitriles, and oxazolidinethiones etc, are formed, which have enhanced bioactivities.[99]

Kale

The prebiotic data on leafy vegetables are scarce. The identified prebiotic carbohydrates in kale are sugar alcohol (sorbitol, mannitol), simple sugars (glucose, fructose, sucrose) and hemicellulose (arabinose, mannose, xylose).[100]

Others

Asparagus byproducts mainly contain dietary fibers (62-77%)[101] oligosaccharides can be extracted from sugar beet molasses, soybean whey, and saccharified vegetable starch derived from peas, beans, and lentils can also be utilized as prebiotics.[102] Arugula, Brussels sprouts etc., also account for fermentable fiber content.[103]

Table 1. Recent studies highlighting the potential of utilization of fruit waste fractions in different food formulations

Plant Source	Prebiotic significance	Pre-processing method	Food product	Level of incorporation (% weight basis)	Bioactivity	Key observations
Apple pomace (*Malus domestica*)	Improves polyphenolic content, viable cell count, and antioxidant activity.	Lyophili-zation	Fermented soy milk	2%	Antioxidant activity	24% pectin yield with a degree of esterification of 38% Enhances the functional properties of fermented soy milk.[104]
Apple peel (*Malus domestica*)	Enhances the growth of lactic acid bacteria	Homog-enization	Functional ingredients	-	Antioxidant activity	Used as a thickening agent due to its higher fiber content, good water-holding capacity, and as a source of natural fiber[105]
Apple peel (*Malus domestica*)	Natural source of high-quality antioxidant and bioactive compounds Increases the viable count of probiotics.	Lyophili-zation	Yogurt	4% & 5%	Antioxidant activity	No modification in texture and flavor Good functional and physical characteristics of yogurt[106]
Apple peel (*Malus domestica*)	Apple peel polyphenol extract (APPE) increases the acidity Decreases the melting rate and enhances the overrun of ice cream	Lyophili-zation	Yoghurt ice cream	5%	Antioxidant activity	The fortification with APPE increases the yogurt ice cream's hardness, rheological, and sensory

						attributes[107]
Apple pomace (*Malus domestica*)	Dietary fiber, pectin, higher phytochemicals delivery	Lyophili-zation	Yoghurt drink	1 to 3% (w/w)	Antioxidant activity	Acts as a stabilizer and reduces sedimentation of protein aggregates pH of yogurt decreases (2 and 3%) Lightness value decreases with increasing dosage (from 1 to 6%)[108]
Red pitaya peel (*Hylocereus polyrhizus*)	Dietary fiber: pectin, lignin, cellulose, hemicellulose Replacer of fat in ice cream	Grinding	Ice cream	1%	Antioxidant activity	Addition of fiber improves the overrun, rheological properties, increases nutritional properties, and higher overall acceptability of the sample[109]
Grapefruit peel (*Cabernet sauvignon*)	Nanofibrillated cellulose reduces the digestibility of fat in the human intes-tine (0.30 % (w/w))	Drying, milling, lyophili -zation	Ice cream	0.2, 0.3, 0.4%	-	Great shape retention achieved (0.2%) Increases the sensory properties (smoo-thness, chewiness, and mushiness) by 0.4 %[110]
Grape pomace (*Cabernet sauvignon*)	Dietary fiber and prebiotic compounds: lignin, cellulose, oligosaccharide Digestibility of chocolate spread is 25% to 84%	Drying, grinding	Chocolate spread	3–5%	Antioxidant activity	Bitter taste due to phenols (5%) Higher impact on the product particle size[111]
Pomegrana seeds (*Punica granatum*)	Dietary fiber: lignin, cellulose Pomegranate seed flour (PSF) increases	Drying, milling	Bread	5, 7.5 & 10%	Antioxidant activity	Wheat flour PSF bread shows good sensory and tech-nological quality (5%)

	the intake of protein and dietary fibers (5%) Maintains sensory acceptability					There are no changes observed in the water activity of bread (5% PSF) The firmness of bread increases with increasing PSF (5%, 7.5%, 10%)[112]
Pomegrana seeds (*Punica granatum*)	Improve metabolite levels in intestinal bacteria	Boiling	Value added polysac -charide	-	-	Jack fruit peel powder does not alter the molecular weight during upper gastrointestinal digestion[113]
Banana peel	Probiotic substance: oligosacc harides - enhanced growth of lactic acid bacteria	Fermen-tation	Value added polysac-charides	-	Antioxidant activity	Pectinase is used for the preparation of pectin oligosacch-arides high enzyme cost[114]
Banana peel (*Musa paradisiaca*)	Prebiotics: Pectin	Drying	Salad cream	2%	Antioxidant activity	Alternative sources of pectin and fat replacers in food products Decreases in viscosity and lightness value due to the incorpora-tion of BPP into salad cream (30 %)[115]
Mango peel powder (*Mangifera indica*)	Dietary fiber: Better prebiotic score than commercial prebiotic maltodextrin	Drying, grinding	Synbiotic products	-	Antioxidant and antipro-liferative activity	Increased total phenolic flavonoid content, antioxidant capacity, and water and oil holding capacity.[116]
Mango peel powder (*Mangifera indica*)	Dietary fiber: Cellulose, hemicellulose	Bleach ing, drying	Instant drink	2% (w/v)	Antioxidant and antipro liferative activity	Sensory characteristic decreases during storage[117]

Pineapple pomace (*Ananas comosus*)	Dietary fiber: lignin, cellulose, hemicellulose	Steaming, lyophilization, milling	Vienna sausages	-	Antioxidant and antidia -betic activity	Decrease in nitrites, moisture, shear strength, and shrinkage Increase in carotenoids, antioxidants, polyphenols[118]
Feijoa peel (*Acca sellowiana*)	Dietary fiber: lignin, cellulose, hemicellulose-alternative source of bioactive ingredients.	Steaming, drying	Flour	-	-	Flour-containing mesocarp shows a higher water-holding capacity than the flour-containing mesocarp and epicarp[119]
Melon peel, seed (*Cucumis metuliferus*)	Dietary fiber	Drying, grinding	Fermented milk	Whole fruit powder - 0.5%, Peel powder - 0.7%, Seed powder - 1% w/v	Antioxidant activity	Low pH (1%) Changes in sensory properties due to natural oxidation, dehydration, microbial activity, and enzymatic browning during storage[120]
Melon peel (*Cucumis melo* L. *inodorus*)	Dietary fiber and phenolic compound - positively impact the gut microbiota diversity	Milling, drying	Melon juice powder	2% (w/v)	Antioxidant activity	Good accessibility index of sugars (85–90%), organic acids (90–93%), phenolics (80%), and antioxidant activity (54–76%)[121]
Papaya peel powder	Dietary fiber	Drying	Yogurt	10%	Antioxidant and antidia -betic activity	Papaya peel powder acts as a functional ingredient and yields bioactive components in the Greek yogurt matrix[122]
Rambutan peel (*Nephelium lappaceum*)	Dietary fiber – breakdown leads to the production of an enzyme that metabo lizes fiber sources and	Drying, grinding	Plant-base rice milk	-	Antioxidant activity	Enhance food waste utilization Enhanced shelf-life of up to 20 days and flavor, oil-holding capacity, antioxidant activity, and the color

	produces lactic acid, which maintains the intestinal health					pigments of flavonoids and carotenoids[123]
Mangosteen peel (*Nephelium lappaceum*)	Increased dietary fiber (58%)	Drying, grinding, blending	Rice sausage	17% - outer pericarp, 48% - inner pericarp	-	The cardamon oil-treated mangosteen peel was added as a supplement in fermented rice sa usage to extend shelf life up to 21 days[124]
Grapes, pomegra-nate seeds (*Punica granatum* L), rosehips	Dietary fiber – Increases antioxidant activity	Grinding, sifting	Eriste (Turkish noodle)	10%	Antioxidant activity	Sample with pomegranate seed powder obtained the highest appreciation from a sensory point of view[125]

Table 2: Recent studies highlighting the potential of utilization of vegetable waste fractions in different food formulations

Plant Source	Prebiotic significance	Pre-pro-cessing method	Food product	Level of incorpo-ration (% weight basis)	Bioa ctivity	Key observations
Carrot baggase (*Daucus carota*)	Fructo-oligosac-charide	Fermentation	Natural functional beverages	-	-	High nutritional value contributes to improving human health[126]
Carrot pomace (*Daucus carota*)	Dietary fiber: pectin, lignin, cellulose, hemicellulose	Lyophilization	Agitated yogurt	1 & 2%	Antioxidant activity	Strawberry flavor was added to improve the color and smell of the sample Increases the water-holding capacity of yogurt and has high consumer accep tance (1%) Decreases in apparent viscosity

						(2%)[127]
Carrot pomace (*Daucus carota*)	Dietary fiber: pectin, lignin, cellulose, hemicellulose	Drying, grinding, sifting	Donut	6.45%	Antioxidant activity	A low-fat donut with acceptable physical, image, and sensorial properties (6.45 %)[128]
Sweet potato peel (*Ipomoea batatas* L.)	Dietary fiber – Promotes bowel movement, prevention of constipation	Milling, sieving	Bread	10%	-	Orange-flushed sweet potato peel powder of 10% and haricot bean flour of 20% show better consumer accepta-bility The protein content of composite flour increased (11.25 to 17.4 g/100g)[129]
Sweet potato root powder (*Ipomoea batatas* L.)	Resistance starch, nystose, ketose Sweet potato flour (SPRF) of 20 g/l had an average positive pre-biotic activity score (0.11 –0.55)	Blanching, drying, grinding	Ingredients for functional foods or dietary supplements	-	-	The factors affecting the outcome of host health are diet composition, types of microorganisms forming the gut microbiota, and individual host response[130]
Potato peel (*Solanum tuberosum*)	Dietary fiber, inulin or fructooligosa -ccharides 20- 30% prebiotics resulted in a considerable increase in the colon content of *Lactobacillus* sp. and *Bifido -bacteria* sp.	Drying, grinding, sieving	Cupcake	5, 10, 15, 20%	Antioxidant activity	Increase in the hardness of cup cakes Better sensory attributes (15 %)[131]

Table 3: Recent studies on utilization of fruit waste fractions in different food formulations along with the addition of probiotics

Source and part used	Food product into which it was incorporated	Level of incorporation of prebiotic source (% weight basis)	Probiotic culture added and level	Key observations	Probiotic viability and functionality
Rosehip seed powder (*Rosa canina* L.)	Probiotic yoghurt	1%, 2%, and 3% RSP	Yoghurt starters (2.5 mL/kg milk)- *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus* Probiotic bacteria (0.1% w/w) -*L. acidophilus* LA-5 and *B. animalis* subsp. *lactis* BB-12	Improved syneresis, firmness and adhesiveness and reduced parameters like aftertaste, taste, consistency and appearance Improved antioxidant activity and total phenolic content	Bacterial counts > 6 log CFU/mL were present in all yogurt samples[132]
Red dragon fruit peel (*Hylocereus polyrhizus*)	Yogurt	0%, 2%, 5%, and 7% (w/v)	Yogurt starter (0.02% w/v) - *Lactobacillus bulgaricus* and *Streptococcus thermophilus*	Incorporation of 7% RD peel powder gave the most noticeable antioxidant activity in yogurt The highest sensory scores were obtained with 2% RD peel powder	Total viable counts in all treatments ranged from 56.64×10^4 to 64.23×10^4 (CFU/mL). The yogurts' bacteriological status fell within the permissible range ($<10^6$ CFU/mL) for goods milk [133]
Sour orange peel (*Citrus aurantium*)	Yogurt	0.5%, 1.0%, and 2.0%	*L. acidophilus, S. thermophilus,* and *Bifidobacterial sp.* (1.5×10^8 CFU/mL)	Addition of CPP led to an increased acidity and decreased the moisture of the yogurt during cold storage (14 and 28 days) Improved antioxidant and antibacterial activities of yogurt	Viable counts (log CFU/g) of *L. acidophilus, S. thermophilus,* and *Bifidobacteria* sp. decreased from 8.25 to 6.10, 8.35 to 6.70 and 8.20 to 6.80 on 28th day [134]

Pineapple crown powder (*Ananas comusus*)	White finger millet vegan beverage	1–3% w/v	*Lactobacillus rhamnosus* GG (LGG) NCDC 347 (6.5 log CFU/mL)	Increase in viscosity of sample beverages on increasing PCP incorporation due to the presence of 8.71% soluble dietary fibers in the powder	After 6 h of incubation, the viable cell count increased from 6.5 to 9 log CFU/mL in pineapple crown powder-added beverages [135]
Pink Guava seed and pulp (*Psidium guajava* L.) Variety- *Sungkai* and *Semenyih*	Yogurt	1:100 (w/v) of UHT-treated milk	Probiotic strains (1g of starter culture) *Lactobacillus rhamnosus* ATCC 9595, *Lactobacillus plantarum* ATCC 14917 *Lactobacillus brevis* KCTC 3102 Enteric strain- *Escherichia coli* ATCC 25922	Cellulase and xylanase-treated seed and pulp increased the yogurt's texture by 22.28–28.05% for hardness and 67.6–68.6% for stickiness Adhesiveness ranged from 84.11 to 86.44%. Enzymatically treated byproducts of processed guava caused the growth of *Lactobacillus* species	Enzymatic treatment on yogurt increased the probiotic activity of *Lactobacillus spp.* up to 8.05 log CFU/mL [136]
Mango peel powder (*Mangifera indica*)	Freeze -dried yogurt	2% (w/v)	Mixed starter culture (2%)- *Lacticaseibacillus casei* (431®), *Lacticaseibacillus rhamnosus* (LGG®) and *Bifidobacterium* subsp. *lactis* (Bb-12®)	Inoculated yogurts had decreased brightness and increased redness values Samples enriched with MPP demonstrated 12% more sugar content than non-fortified yogurts TPC and antioxidant activity increased significantly Increased fat, ash, and protein contents	The net count of probiotics in yogurt fortified with MPP increased by at least 1 log CFU/g after 4 weeks of refrigerated storage [137]

Cavendish banana peel powder (*Musa acuminta*)	Freeze-dried yogurt	2% (w/v)	Mixed starter culture (2%) - *Lacticaseibacillus casei* (431®), Lacticaseibacillus rhamnosus (LGG®) and *Bifidobacterium* subsp. *lactis* (Bb-12®)	Samples enriched with BPP demonstrated 12% more sugar contents than non-fortified yogurts	The net count of probiotics in yogurt fortified with BPP increased by at least 1 log CFU/g after 4 weeks of refrigerated storage [137]
				TPC and antioxidant activity increased significantly	
				Increased fat, ash, and protein contents in inoculated samples	
Cranberry pomace powder (*Vaccinium oxycoccus*)	Yogurt	2%, 3%, and 4.5% (w/v)	Starter culture (5 mL/100 mL) -*Streptococcus thermophilus* and *Lactobacillus bulgaricus*	Higher total solids content (13.84%to 17.92%) with the increase in CPP	Viable counts of probiotic *Lactobacillus* spp. in yogurt was >9 log CFU/g [138]
				Protein content increased from 5.83% to 6.01%	
				The dietary fiber level rose by around 1.45% with 2% CPP incorporation	
				High dietary fiber content and better water holding capacity at 4.5% CPP incorporation	
Cornelian Cherry peel powder (*Cornus mas* L.)	Probiotic Icecream	3, 6, and 9%	*Bifidobacterium lactis* (Bl-04) 1% v/v of 109 CFU/mL of bacteria cells	The highest viscosity of ice-cream samples was obtained at 9% incorporation of peel powder	
				Water absorption ability in peel powder enhanced the melting resistance and viscosity of ice cream	Increment of 6% and 9% peel powder in ice cream increased the viability of *B. lactis* during 120-day storage and after

					gastrointestinal simulation Polyphenol compounds increase the survival of *B. lactis* [139]
Yellow watermelon peel (*Citrullus lanatus*)	Peel extract	1% w/v	*Lactobacillus rhamnosus* and *Bifidobacterium bifidum*. (1 mL of starter culture)	Higher amount of indigestible non-starch polysaccharides with WPP incorporation WPP can withstand the artificial acidic conditions of gastric juice in the stomach and digestion by α-amylase in the small intestine	WPP stimulated the growth of *L. rhamnosus* from 8.66 to 9.74 (log CFU/g dry extract) within 48 h *B. bifidum* growth increased from 9.00 to 9.90 (log CFU/g dry extract) within 48 h [140]
Honeydew peel (*Cucumis melo*)	Peel extract	1% w/v	*Lactobacillus rhamnosus* and *Bifidobacterium bifidum.* (1ml of starter culture)	Honeydew peel extract showed the least resistance to artificial human gastric juice and α-amylase digestion at 13.80% and 13.68% of the polysaccharides are being hydrolyzed,	Peel extract stimulated the growth of *L. rhamnosus* from 8.65 to 9.82 (log CFU/g dry extract) within 48 h [140]
Guava seed powder (*Psidium guajava* L.)	Yogurt	1, 2 and 3% (w/v)	ABT-5 culture (0.025%) *Streptococcus thermophilus, Lactobacillus acidophilus,* and *Bifidobacterium* BB-12	Increase in GSP showed an increase in crude fiber, acidity, viscosity, total phenolic content, and antioxidant activity A decrease in yogurt syneresis was also noted	Viable counts of probiotic *Streptococcus thermophilus, Lactobacillus acidophilus and Bifidobacterium* BB-12 reduced from 8.92 to 8.13, 8.87 to 7.99, 8.76 to 8.00 (log of CFU/g) [141]
Apple peel	Yogurt	1%, 2%, 3%,	Starter culture-*Lactobacillus*	High levels of total solid contents	

(*Malus domestica*) Variety- Red Delicious, Golden Delicious, Royal Gala, Amri, and Gacha		4% and 5% (w/v)	*delbrueckii* subsp. *bulgaricus* and *Streptococcus salivarius* subsp. *thermophilus* and Probiotics strains- *Bifidobacterium lactis* BB-12 and *Lactobacillus acidophilus* La-5	were observed in yogurt samples due to APP incorporation Yogurts incorporated with APP at 4 and 5% (w/v) had higher viscosity and water-holding capacity Increased antioxidant activity	Loss of viability in yogurts incorporated with 1%, 2%, 3%, 4% and 5% (w/v) of apple peel powder were 1.67, 1.48, 1,24, 0.79 and 0.47 log cycles, respectively, after 21 days [142]
Pomegranate peel (*Punica granatum*)	Yogurt	0.5% w/v	*L.acidophilus* and *Bifidobac terium bifidum*	A slight reduction in the pH of PPP-inoculated yogurt samples was noted Protein content was higher in samples supplemented with PPP The addition of PPP extract increased the anti-oxidative attributes of yogurt	Tannin-free PPP enhanced the viability of probiotic culture under gastrointestinal conditions All probiotic cultures were maintained at counts around 8 log CFU /g in stirred yogurt supplemented with pomegra -nate peels after 21 days [143]
Pineapple peel and pomace (*Ananas comusus*)	Yogurt	1% w/v	*Streptococcus thermophilus* ASCC 1275 and *L. delbrueckii* spp. *bulgaricus* Lb1466 1 % (v/v) *L.acidophilus, L. case*i and *L. paracasei* mono-cultures at 1 % (v/v)	Increased antioxidant and antimutagenic activities were noted in inoculated yogurts compared to the non-supple mented ones	Enhanced growth of *L.acidophilus* (8.13–8.71 log CFU/g) and *L. casei, L. paracasei* (8.12–8.72 log CFU/g) Probiotic and proteolytic activity of starter cultures increased on the incorporation of pineapple waste powder [144]

Table 4: Recent studies on utilization of vegetable waste fractions in different food formulations, along with the addition of probiotics

Source and part used	Prebiotic significance	Food product into which it was incorporated	Level of incor -poration of prebiotic source (% weight basis)	Probiotic culture added and level	Key observations	Probiotic viability and functionality
Pumpkin peel powder (*Cucurbita maxima*)	Peel powder	Yogurt	2%, 4% (w/v)	*Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus*, (50 U culture per 250 L of milk)	The springiness and adhesiveness of the yogurt decreased with the increase in the pumpkin peel powder levels Increased antioxidant activity was observed in supplemented samples [145]	-
Broccoli leaves (*Brassica oleracea* L. var *Italica*, cv. *Parthenon*)	Leaves	Antidiabetic beverage	1% w/v	*Lactiplantibacillus plantarum* (CECT 749) (6 log CFU/mL)	HHP (200 MPa, 10 min) preserved the highest concentration of sulforaphane (4.38–8.82 mg/L) High stability of antidiabetic potential after refrigeration	Levels of LAB in the broccoli leaves increased to 8.37 log CFU/g at the end of fermentation[146]
White potato powder (*Solanum tuberosum*)	Peel powder	Yogurt	2% potato peel flour in 1 L of rehydrated skim milk (10% w/v).	*Streptococcus thermophilus* and *Lactobacillus delbrue-ckii* subsp. *bulgaricus*	Yogurt syneresis was significantly less with the incorporation of potato peel powder	Prebiotic activity score (0.74) was significantly higher Higher consumption of

					Yogurt viscosity and water retention capacity increased with storage time significantly	prebiotic source by the lactic acid bacteria, indicated better prebiotic capacity [147]
Beetroot pomace (*Beta vulgaris*)	Beetroot pomace (BP)	Natural Colorants	-	*Levilactobacillus brevis* KKP 804, *Limosilactobacillus fermentum* KKP 811, *Lactiplantibacillus plantarum* ATCC 4080 (1×10^9 CFU/mL)	Dry matter indicated storage properties of dried substances and ranged from 2.9–12.1 for beetroot pomace No changes in the red /violet pigment content of pomace	Concentration of *Levilactobacillus brevis, Limosilactobacillus fermentum* and *Lactiplantibacillus plantarum* in fermented beetroot pomace was 2.93, 2.46, 2.82 log CFU/g [148]

Residue of fruit and vegetable wastes with rich nutritional profiles can be incorporated into food formulations at different levels (Tables 1 and 2). Additionally, the rich content of prebiotic ingredients in fruits and vegetable wastes can be used in developing novel functional food supplements by incorporating probiotics in novel food compositions (Tables 3 and 4).

Critical Considerations in Technology Adoption

The existence of beneficial components in fruit and vegetable waste has been recognized for some time, but their potential for prebiotic uses has only recently attracted interest. Notwithstanding this advancement, numerous facets of employing these substances remain unexamined. A comprehensive investigation and understanding are essential for the complete development and implementation of this approach. For instance, limited research has evaluated the long-term impacts of consuming such fractions. The information about the synergistic or antagonistic effects of dietary habits with these substances is likewise scarce. For example, particular bioactive chemicals or their combinations may be inappropriate for certain chronic illnesses, age groups, or demographics, hence increasing potential dangers for consumers.

A primary worry is the prevalent application of herbicides, insecticides, fungicides, and fertilizers in the cultivation of fruits and vegetables. These chemicals and their residues may be present in higher levels in such waste fractions. Typically, fruits and vegetables suffer lengthy handling and supply chain operations, sometimes leading to quality deterioration such as rotting, shriveling, over-ripening, and weight loss. To mitigate these effects, the fruit and vegetable sector predominantly uses synthetic chemicals such as chlorine dioxide, nitric oxide, 1-methylcyclopropane, and salicylic acid. These compounds and their residues may come along with waste fractions and then present heightened dangers to human health, especially for at-risk populations. Similarly, waste fractions may contain anti-nutritional components, including saponins, alkaloids, tannins, phytates, oxalates, and heavy metals (e.g., lead, chromium, cadmium), which can negatively impact human metabolism. Prevalent anti-nutrients comprise alkaloids, cyanogenic glycosides, tannins, phytates, and inhibitory enzymes. Furthermore, natural toxins such as mycotoxins, aflatoxins, and fumonisins can build up in byproducts and pose a risk to human health if ingested. This is of particular concern when such waste fractions reach processing facilities after a significant time delay since their occurrence. Apart from biological and chemical hazards, waste fractions may also come along with physical hazards that require attention.

Consumer acceptance is another significant element, as the concept of utilizing waste or byproducts for prebiotic compounds may encounter reluctance. Sensory concerns, including alterations in color, flavor, aroma, texture, and mouthfeel, may further dissuade consumers. Preserving the sensory attributes of fortified or enhanced goods is crucial for the optimal integration of prebiotic chemicals sourced from waste.

Future Directions

The future of turning fruit and vegetable processing wastes into prebiotics depends on increasing market potential, enhancing customer awareness, ensuring safety assurance, promoting technological acceptance, and fostering creative product development. To ensure broad adoption, the future direction of utilizing fruit and vegetable processing wastes as prebiotics heavily emphasizes the use of scalable and reasonably priced technologies. Through enhanced extraction and biotechnological methods, including fermentation and enzymatic treatment, prebiotic fibers derived from these wastes will exhibit improved yield, purity, and functional characteristics. To guarantee consumer trust and compliance, safety and legal requirements will be crucial. Consumer safety is still crucial, and strict guidelines are necessary to ensure the efficacy and safety of these prebiotic substances.

Market acceptability will be driven by increasing consumer awareness of sustainability, health benefits, and ethical food production practices. Additionally, by combining innovation, safety, and consumer involvement, prebiotics made from fruit and vegetable waste will be positioned as essential components of circular economy and sustainable nutrition models, which in turn increases the profitability of agricultural supply chains and creates employment. It is anticipated that functional foods, drinks, and supplements utilizing prebiotic-rich recycled ingredients would be included in new product formulations. The worldwide prebiotics market's explosive growth and sustainability factors are driving its potential, which encompasses prospects in both developed and developing nations.

Significance in the Context of the Circular Food Economy

In line with the United Nations' Sustainable Development Goals (SDGs), the circular economy model provides a sustainable way to handle produce waste by turning it into valuable products like prebiotics. Prebiotics can be made from the bioactive components found in fruit and vegetable waste, which is typically thrown out after harvesting, processing, or consumption. This waste is rich in fibers, polyphenols, and oligosaccharides. By utilizing techniques like enzymatic hydrolysis and microbial fermentation, this transformation produces functional components for use in food and nutraceuticals and helps decrease food waste. This method contributes to numerous SDGs by improving food systems and advocating for inexpensive, nutrient-rich meals, aligning with SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being) by promoting gut health and decreasing the likelihood of chronic diseases. In addition, reducing landfill methane emissions and maximizing resource efficiency helps achieve SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Reducing the likelihood of trash accumulation helps achieve SDG 15 (Life on Land). It is necessary to overcome problems such as increasing production scale, obtaining regulatory permissions, and gaining market acceptability. A resilient and sustainable bioeconomy that benefits public health, the environment, and global food systems can be achieved by repurposing fruit and vegetable waste into prebiotics, with the help of correct legislation, technical innovation, and stakeholder participation. In addition to the directly linked SDGs listed above, several other SDGs are indirectly associated.

Conclusion

It is evident that a lot of waste has been generated and thrown away from fruit and vegetable processing and contains valuable bioactive and fiber materials. Considering the circularity of resources and the thrust on sustainability, generated wastes can effectively be used for different food applications. By practicing this, a tremendous amount of waste can be converted to valuable materials and the impact on the environment can also be minimized. It is interesting to note that the inedible portions of fruits and vegetables can promote gut health, given their prebiotic capabilities. Overall, the approach of valorizing fruit and vegetable discards closely associates with several prominent global mandates: 'zero discards', 'resource recovery', 'waste-to-wealth', 'upcycling', 'biorefinery', 'waste management' and 'sustainable food processing'. Challenges exist, but these can certainly be overcome, strengthening the focus towards effective valorization of such horticultural discards.

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Conflict of Interest

The author(s) do not have any conflict of interest.

Data Availability Statement

This is a review article. All relevant information has been included in the manuscript itself.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration

This research does not involve any clinical trials.

Permission to reproduce material from other sources

Not Applicable.

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