International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 18s, 2025
https://theaspd.com/index.php

Plant-Based Mucilages And Extracts As Potential Prebiotics: A Comprehensive Review

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Abstract
The human gut microbiome is a complicated ecosystem that is very important for the health of the host because it affects metabolism, immunity, and disease prevention. Prebiotics are substances that some bacteria in the host use preferentially to improve health. They are very important for changing this microbial ecology. This review looks at the growing potential of mucilages and extracts from plants as new sources of prebiotics. It goes into detail about their different chemical makeups, how they work (through selective fermentation, short-chain fatty acid production, and targeted microbial modulation), and the many health benefits they have, such as better immune function, better gastrointestinal health, better metabolic health, and better neurological health. The paper uses evidence from research on cells, animals, and people to show how different plant sources, like chia, flaxseed, okra mucilage, and polyphenol-rich extracts from chicory, garlic, and grape seed, are different from each other. The current problems, such as the necessity for standardization and strong human clinical studies, are talked about. Advanced extraction methods, tailored nutrition, and synergistic synbiotic formulations are all important areas for future research. These natural substances have the potential to change the way we think about gut health and general health.
Keywords
Prebiotic, probiotic, synbiotic, nutrition, mucilage

1. INTRODUCTION

The gut microbiota is a complex and varied group of bacteria that live in the human gastrointestinal system. This microbial ecosystem, which is often called a "superorgan" because of how important it is, is essential for human health. It helps with nutrient metabolism, vitamin synthesis, immune system development, and protection against harmful invaders.[1] To avoid a wide range of disorders, from inflammatory bowel disease and metabolic conditions like obesity and diabetes to neurological and psychological health problems, it is important to keep the delicate balance and rich diversity within this community.[2]

Because the gut microbiome is so important, there has been a lot of scientific and public interest in finding ways to change its makeup and activity in a good way. Prebiotics are one of the most important things that can be done. Prebiotics are food parts that can't be digested but selectively boost the growth and/or activity of helpful microorganisms in the gut, which is good for the host's health.[1] Their main way of working is by acting as fermentable substrates for gut microbes, which makes different helpful metabolites, especially short-chain fatty acids (SCFAs).[1]

There has been a lot of research into new sources of prebiotics since more and more people around the world want functional foods and natural ingredients that are good for their health. Mucilages and other extracts from plants are a very promising area of research. These natural substances are a long-lasting, affordable, and eco-friendly alternative to synthetic additives. This is in line with a growing preference for natural and minimally processed products.[3] Plant mucilages and extracts are rich in different polysaccharides, fibres, and bioactive compounds, which makes them great candidates for changing the gut microbiota and improving host health. This is why they need a full review of their potential as prebiotics.[3]

2. Defining Key Concepts

2.1. Evolution and Current Criteria for Prebiotics

Since they were first thought of, our understanding and definition of prebiotics have changed a lot. Glenn Gibson and Marcel Roberfroid first talked about prebiotics in 1995 as "a non-digestible food ingredient that beneficially affects the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon, and thus improves host health."[1] This basic definition emphasized the compound's inability to be digested and its selective effect on certain beneficial gut bacteria.

There are three main requirements that a substance must meet in order to be officially called a prebiotic. First, it must be able to survive the stomach's harsh acidic environment, not be broken down by mammalian digestive enzymes, and not be absorbed in the upper gastrointestinal tract.[1] This makes sure that the compound mostly stays intact until it gets to the colon. Second, the local intestinal microflora must be able to ferment it. Third, and most importantly, it must selectively boost the growth and/or activity of gut bacteria that are linked to health and overall well-being.

In 2016, the International Scientific Association for Probiotics and Prebiotics (ISAPP) made a significant change to this definition by calling prebiotics "a selectively utilized substrate by host microorganisms conferring a health benefit." This new wording shows that we have a better understanding of how gut microbes work together. The transition from "selectively stimulating one or a limited number of bacteria" to "selectively utilized substrate by host microorganisms conferring a health benefit" is more than just a change in words. It acknowledges that the beneficial effects of prebiotics often arise from complex interactions within the entire microbial community, including phenomena like cross-feeding, where the metabolic products of one bacterial group become substrates for others.[4] This broader perspective allows for the inclusion of a wider array of compounds, such as certain polyphenols, and recognizes the intricate network of microbial cooperation and competition within the gut.[4] Consequently, future research and product development can extend beyond targeting only a few well-known probiotic strains, opening doors to exploring novel plant-derived compounds that modulate a broader spectrum of beneficial microbiota or support a healthier microbial ecosystem through indirect mechanisms, such as reducing oxidative stress in the gut environment.[5] This emphasis on the health benefit as the ultimate criterion, rather than a strict adherence to a mechanism limited to specific bacterial growth, expands the potential for identifying and developing new prebiotics.

2.2. Plant Mucilages: Characteristics, Chemical Nature, and Functions

Plant mucilage is a sticky, jelly-like substance that almost all plants and some protists, like phytoplankton and green algae, secrete.[3] Mucilage easily absorbs water, forming a thick solution or gel, which is why it is classified as a hydrocolloid.[6] Mucilage is different from plant gums, which are often made when a plant is hurt or stressed. Instead, mucilage is a normal part of plant metabolism that is made inside the cell.[7] This difference shows how important it is to the plant's physiology.

Plant mucilages are chemically complex polymeric polysaccharides with a high molecular weight that are often linked to organic acids.[3] Their main building blocks are monosaccharide units like galactose, pentose, and methyl pentose, which are usually linked to uronic acid residues (six-carbon molecules with aldohexose in carboxylic acid form) through glycosidic bonds.[6] Mucilages can also contain proteins, minerals, and lipids in addition to carbohydrates.[6] Some examples of polysaccharides found in mucilages are arabinoxylan in flaxseed and psyllium, unique tetrasaccharides in chia, and acemannan in Aloe vera.[3] When dissolved in water, mucilage can have a very high water content, sometimes over 98%.[7]

Mucilages do a lot of important things for plants while they are in their natural habitat. These include storing food and water efficiently, thickening cell membranes, helping seeds germinate, improving nutrient absorption, and protecting against pathogens and environmental stressors like drought.[613] Mucilage can also improve soil structure and its ability to hold water, which is important for establishing seedlings and overall plant growth.[8]

Plant mucilages are very interesting as possible prebiotics since they are made up of a lot of polysaccharides and are naturally hard to digest. The gut microbiota can ferment their complex carbohydrate structures, which are not broken down by human digestive enzymes.[2] Their hydrocolloid properties can also change how quickly food moves through the gut and how nutrients are absorbed, which indirectly makes the gut environment healthier.[9] The wide range of chemical compositions found in plant mucilages, from complex polysaccharides like arabinoxylan and acemannan to specific uronic acids and even glycoproteins [3], suggests that this chemical diversity is what gives plants their different functional properties. When these varied structures get into the gut, they interact with the specific enzymes of different gut bacteria in distinct ways. This suggests that different mucilages are likely to help certain types of microbes grow and change the SCFA profiles, rather than having the same prebiotic effect on all of them. So, instead of just calling "mucilage" a prebiotic, research should look at the specific structural properties of mucilages from diverse plant sources and see how these connect to specific changes in the composition of gut microbiota and metabolic output. This method would make it possible to provide targeted prebiotic therapies, where certain mucilages are chosen for their ability to support certain good bacteria or make certain SCFAs that are good for certain health problems.

2.3. Plant Extracts: Composition and Relevance to Prebiotic Activity

Plant extracts are concentrated forms of different portions of plants that include a wide range of bioactive chemicals that give them their medicinal and functional capabilities. A lot of medicinal plants and their extracts are high in polyphenols, which are plant metabolites that are active in the body and have a wide range of biological activities.[10] In addition to polyphenols, plant extracts can also have other health-promoting components like polysaccharides, dietary fibres, vitamins, and minerals.[9]

The particular way that many of their bioactive components are metabolized in the human body makes plant extracts relevant to prebiotic action. The small intestine absorbs a large part of the polyphenols that are eaten, which is thought to be less than 5–10%.[5] The rest of the compounds then go to the large intestine, where they are broken down by the gut microbiota.[516] This important interaction between polyphenols and intestinal microbes affects their activity toward the human host, which is why they are called a new group of prebiotics.[5] Similarly, polysaccharides from edible and medicinal mushrooms and other plant extracts have shown prebiotic effects similar to those of well-known functional oligosaccharides.[10]

There are many ways that polyphenols work as prebiotics. They can have two positive effects on the gut microbiota at the same time: they can stop the growth of harmful microorganisms and encourage the growth of helpful bacteria, especially those in the Lactobacillus and Bifidobacterium genera.[5] This selective pressure helps to keep the microbial balance healthy. One idea for how probiotics help plants grow is that they can break down O-glycosylated polyphenols into aglycone and glucose, which can then be used as energy and carbon sources.[5] For example, Lactiplantibacillus plantarum can break down different phenolic acids to get energy.16 Also, polyphenols in extracts may help probiotics grow by lowering oxidative stress in the growth medium, which is a common byproduct of microbial metabolic activities.[5]

The fact that the overall effect of all the parts of a plant extract can be stronger than the effect of certain isolated substances [5] shows that there are complicated interactions between them. This suggests that an extract's total prebiotic action is probably a complex combination of directly feeding microbes, selectively stopping pathogens, and changing the gut environment in a broader way, including its redox state. This shows how complicated plant extracts are as prebiotics and suggests that isolating individual chemicals may not show the entire prebiotic potential of a whole extract. In the future, researchers should focus on looking into "holistic" extract formulations and how they work together to affect the gut microbiome, rather than only looking at them in a reductionist way. This also makes it possible to create "prophybiotics," which are new combinations of probiotics and plant extracts that have both antimicrobial and prebiotic properties. In these formulations, the plant extract not only feeds good bacteria but also actively stops bad pathogens from growing, making it easier for the probiotics to thrive.

3. Plant Sources of Mucilages and Extracts with Prebiotic Potential

There are many different kinds of plants that can be used to make mucilages and extracts that have a lot of prebiotic potential. These chemicals have different chemical structures and affect the gut flora in different ways, which makes them good candidates for developing functional foods.

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3.1. Mucilage-Rich Plant Sources

A few plant species are known for having a lot of mucilage, which gives them prebiotic properties:

- Chia Seeds (Salvia hispanica): The mucilage from chia seeds has been investigated a lot, not only for its use in technology as a fat/oil replacer in baked goods, where it increases texture and shelf life [6], but also for its prebiotic properties. Chia mucilage is full of carbohydrates that your body can't digest, and it has been shown to help probiotic cultures like Bifidobacterium and Lactobacillus grow.[2] Chemically, chia mucilage is a tetrasaccharide made up of β-D-xylopyranosyl, α-D-glucopyranosyl, and 4-O-methyl-α-D-glucopyranosyluronic acid units, along with other monosaccharides like xylose, mannose, glucose, galactose, and arabinose, as well as uronic acids.8 It also has planteose, a galactosyl-sucrose oligosaccharide that is known for its prebiotic properties.[3]
- Flaxseed (Linum usitatissimum): Flaxseed mucilage (FSM) is a soluble fibre that is mostly made up of polysaccharides (about 48%) and has a molecular weight that ranges from 0.8 to 2 MDa. It also has small amounts of ash (8%), protein (4%), and fat (1%).10 Its prebiotic activity is strongly linked to the presence of arabinoxylan, which can stimulate the growth of Lactobacillus species.[7] In vitro studies have also shown that FSM can improve the survival, auto-aggregation, hydrophobicity, adhesive, and antioxidant properties of L. bulgaricus, L. fermentum, and L. plantarum.[11]
- Fenugreek, Basil, and Mustard Seeds: The mucilages extracted from these seeds are full of indigestible carbohydrates and have been shown to help beneficial probiotics like Bifidobacterium and Lactobacillus grow.[2] In vitro fecal fermentation models using these mucilages have shown that they increase the production of SCFAs and the number of beneficial fibre degraders and SCFA producers, such as Lachnospiraceae ND3007, Lachnospiraceae NK4A136, and Butyricicoccus.[2] Fenugreek and mustard seed mucilages were especially good at stopping the growth of bacteria from the Proteobacteria phylum and Escherichia–Shigella genera, which often include pro-inflammatory species.[2]
- Psyllium (Plantago ovata): Psyllium mucilage is a soluble fibre that is made up of the polysaccharide xylan, which has 1→3 and 1→4 links that contain arabinose and xylose. There are also other monosaccharide units, like rhamnose, galactose, glucose, and other uronic acids.[3] Psyllium is well-known for lowering blood lipid levels.[12]
- Okra (Abelmoschus esculentus): The thick substance in okra has polysaccharides that can help probiotics grow and change the gut microbiome, which helps reduce inflammation.20 Studies in animal models, especially in Alzheimer's disease (AD) mice, have shown that okra polysaccharides increased bacterial alpha and beta diversity, raised the levels of Lactobacillaceae and Lactobacillus, and greatly increased SCFA production, including acetate, propionate, and butyrate.[13]
- Aloe vera: Aloe vera mucilage is very high in acemannan, a polysaccharide with a backbone of β-(1→4)-D-mannose residues that are acetylated at the C-2 and C-3 positions. It also has side chains of galactose and arabinose attached to the C-6 carbon.[14] In vitro fermentation studies using human intestinal microbiota have confirmed its prebiotic potential by measuring SCFA production and seeing how it changed dynamic bacterial populations.[14]

Seed mucilages have been shown to have specific effects, such as boosting Bifidobacterium and Lactobacillus [2], increasing certain SCFA producers like Butyricicoccus and Lachnospiraceae [2], and even stopping harmful genera like Escherichia–Shigella and Proteobacteria [2]. This suggests that these compounds do more than just provide fibre. Because different microbial enzymes are needed to break down different polysaccharide connections, this targeted modulation is probably due to the fact that these mucilages have diverse chemical structures. This means that the prebiotic effects of seed mucilages are not the same. Because of their unique chemical makeups, they preferentially feed or kill certain types of microbes, which leads to different health outcomes. This knowledge makes it possible to create very targeted prebiotic interventions by picking mucilages that are made to fix certain microbial imbalances or boost certain SCFA production pathways that are important for a certain health issue. Fenugreek or mustard mucilage, for instance, might be especially helpful for diseases that are linked to too many Proteobacteria.

3.2. Polyphenol-Rich Plant Extracts

Many plant extracts, especially those high in polyphenols, have strong prebiotic activity in addition to mucilages:

- Chicory Root (Cichorium intybus): This plant is a major source of inulin, a well-known prebiotic that can make up to 68% of fresh chicory and 98% of dried chicory.[15] Inulin feeds probiotic bacteria and helps control the populations of good microbes, like Bifidobacteria.[15] Chicory also has other good things in it, like minerals, vitamins, and phenolic compounds.[16]
- Dandelion greens (Taraxacum officinale) are full of oligofructans and other prebiotic fibres, such as inulin. It is known that these substances help the growth of the bacteria in the intestines and have a good effect on fat metabolism.[15]
- Jerusalem artichoke, sometimes called sunroot or sunchoke, is a plant that has a lot of inulin-containing dietary fibre. This fibre helps friendly bacteria develop in the colon and helps the body absorb important minerals.[15]
- Garlic (Allium sativum): Garlic is a prebiotic because it helps good Bifidobacteria thrive in the stomach and stops bad bacteria from spreading.[15] In vitro studies have also shown that garlic extract can have prebiotic effects on L. reuteri and P. pentosaceus.[17]
- Onions and leeks are part of the same family as garlic. They are high in inulin and fructooligosaccharides (FOS). These chemicals help break down fat and make gut flora stronger.[15]
- Asparagus is a tasty and healthy vegetable that naturally includes inulin, which helps healthy gut flora grow.[15]
- Bananas: Bananas have some inulin in them, and unripe (green) bananas have a lot of resistant starch, which is good for your gut.[15]
- Barley and oats are whole grains that contain beta-glucan, a prebiotic fibre that has been found to lower total and LDL ("bad") cholesterol and may help lower blood sugar levels.[15] Oats also have resistant starch and other phytochemicals that serve as prebiotics.[15]
- Apples have pectin, which is a type of soluble fibre that is good for your gut. Researchers have found that pectin raises the level of butyrate, a short-chain fatty acid that is important for feeding good gut bacteria and lowering the number of bad bacteria.[15]
- Konjac Root: This flour comes from the konjac root, which is also called elephant yam. It is quite high in glucomannan fibre (70–90%). This thick dietary fibre works as a prebiotic by helping good bacteria in the stomach grow.[15]
- Cocoa: Cocoa beans are a high source of polyphenols, such as flavanols, which not only fight inflammation and free radicals but also help good gut bacteria thrive while stopping bad bacteria from growing.[15]
- Burdock Root: This vegetable has a lot of inulin and FOS, which help good bacteria develop in the digestive tract. There are also different phenolic chemicals in it.[15]
- Turmeric (Curcuma longa): In vitro studies have shown that turmeric extract (at concentrations ranging from 0.06% to 0.6%) can have prebiotic effects on Pediococcus pentosaceus and Leuconostoc mesenteroides, with little effect on other lactic acid bacteria (LAB) strains at lower concentrations.[17]
- Green Tea (Camellia sinensis): Some studies suggest that it might be good for you, but in vitro tests have mostly shown that green tea extract can slow the growth of most LAB strains, especially at higher concentrations.[17] This means that when thinking about using it as a prebiotic, you need to be very careful about how much you use or which strain you choose.

- Grape Seed Proanthocyanidins (GSP): Studies on pigs and other animals have demonstrated that GSP can lower oxidative stress and boost growth by raising the number of Lactobacillus species.

This supports the idea that polyphenols can act as prebiotics.[18]

- Rosa roxburghii Polyphenol (RRTP): In experiments conducted on mice, RRTP was reported to ameliorate acute lung injury by improving SCFA production and raising the population of Akkermansia muciniphila, a bacteria closely related with gut barrier integrity.[18]
- Mulberry Leaf Polysaccharide (MLP): MLP protected chicks from cyclophosphamide-induced immunosuppression by increasing the activity of antioxidant enzymes and the production of tight junction proteins, which are important for gut barrier function.[18]
- Bamboo Shoot (BS) and Potato Peel (PP) Extracts: In vitro studies have shown that these extracts, which are high in polysaccharides, can help different types of lactic acid bacteria (LAB), like Lactobacillus paracasei and Streptococcus thermophilus, grow faster and become more tolerant of conditions that mimic the gut.[19]

Polyphenols are known as a "novel group of prebiotics" because they are not well absorbed in the upper gastrointestinal tract and then interact with gut microbes.[5] However, the data also show that some polyphenols, like those in green tea extract, can stop certain LAB strains from growing [17], while others, like those in garlic and turmeric, can help good bacteria grow and even stop bad bacteria from growing.[2] This means that polyphenols have a more complicated role, acting as both selective substrates and antimicrobial agents. This knowledge has led to the idea of "prophybiotics" [17], which are a mix of plant extracts and probiotics that use both their ability to promote growth and stop pathogens from growing. This means that choosing plant extracts for prebiotic uses needs to be done with a lot of thought about their individual bioactivities. It's not only about what they eat; it's also about what they stop doing or how they change the intestinal environment. The idea of "prophybiotics" is a big step forward. It leads to more complex synergistic formulations that can actively change the gut microbiome by promoting good species and suppressing bad ones. This has big effects on personalized nutrition and targeted therapeutic interventions.

Table 1: Key Plant Sources of Mucilages and Extracts with Documented Prebiotic Potential

Plant Source	**Primary Bioactive Compound(s) (Mucilage/Extract Type)**	**Observed Prebiotic Effects**
Chia Seeds	Mucilage (tetrasaccharide, xylose, mannose, glucose, galactose, arabinose, uronic acids, planteose)	Increased *Bifidobacterium*, *Lactobacillus*; Enhanced SCFA production [2]
Flaxseed	Mucilage (arabinoxylan polysaccharide)	Increased *Lactobacillus* survival, auto-aggregation, antioxidant properties [7]
Fenugreek, Basil, Mustard Seeds	Mucilage (indigestible carbohydrates)	Enhanced *Bifidobacterium*, *Lactobacillus*; Increased SCFA production (*Butyricicoccus*, *Lachnospiraceae*); Inhibition of *Proteobacteria*, *Escherichia–Shigella* [2]
Psyllium	Mucilage (xylan, arabinose, xylose, rhamnose, galactose, glucose, uronic acids)	Lowered blood lipids; Potential for microbial modulation [7]

Okra	Polysaccharides	Increased bacterial alpha/beta diversity; Elevated *Lactobacillaceae*, *Lactobacillus*; Increased SCFA (acetate, propionate, butyrate); Inhibited inflammation [13]
Aloe vera	Mucilage (acemannan, mannose, galactose, arabinose)	Increased SCFA production; Modulated bacterial populations [14]
Chicory Root	Inulin, Oligofructans, Phenolic compounds	Nourished probiotic bacteria; Modulated *Bifidobacteria*; Positively affected lipid metabolism [15]
Dandelion Greens	Oligofructans, Inulin	Enhanced intestinal microbiota growth; Positively affected lipid metabolism [15]
Garlic	Inulin, FOS, Polyphenols	Promoted *Bifidobacteria*, *L. reuteri*, *P. pentosaceus*; Prevented pathogen growth [15]
Onions, Leeks	Inulin, FOS	Strengthened gut flora; Aided fat breakdown [15]
Apples	Pectin	Increased butyrate; Decreased harmful bacteria [15]
Cocoa	Polyphenols (flavanols)	Promoted beneficial gut bacteria; Reduced harmful bacteria [15]
Turmeric Extract	Polyphenols (curcumin)	Prebiotic effects on *Pediococcus pentosaceus*, *Leuconostoc mesenteroides* [17]
Grape Seed Extract	Proanthocyanidins (polyphenols)	Reduced oxidative stress; Increased *Lactobacillus* abundance [18]
Rosa roxburghii Extract	Polyphenol	Enhanced SCFA production; Increased *Akkermansia muciniphila*; Alleviated acute lung injury [18]
Mulberry Leaf Extract	Polysaccharide	Protected against immunosuppression; Improved antioxidant enzyme activity; Enhanced tight junction proteins [18]
Bamboo Shoot, Potato Peel Extracts	Polysaccharides, Starch, Cellulose, Hemicellulose	Enhanced growth of LAB (*Lactobacillus paracasei*, *Streptococcus thermophilus*); Improved tolerance to GI conditions [19]

4. Mechanisms of Prebiotic Action

Prebiotics have a number of positive impacts on host health that happen through a number of interrelated processes in the gastrointestinal tract. These effects are mostly caused by their interaction with the gut flora.

4.1. Selective Fermentation by Gut Microbiota

Prebiotics are special because they don't break down in the upper gastrointestinal tract, which means they mostly stay whole when they get to the large intestine.[1] When they get to the colon, these complex carbohydrates can be fermented by certain helpful gut microbes. Bacteria from the Bifidobacterium and Lactobacillus genera are some of the most important ones. They have special carbohydrate-active enzymes (CAZymes) that help break down these complex prebiotics into simpler forms.[1] This fermentation process is naturally selective, meaning that it encourages the growth and/or activity of these health-promoting bacteria, which makes their populations grow in the gut.[1]

But the way prebiotic fermentation works is more complicated than just direct feeding. The idea of "exploitative competition," where prebiotics feed certain groups of bacteria, and "cross-feeding" mechanisms show that the process is more complicated.[20] Prebiotics don't just feed one type of bacteria; their partial breakdown products can be used by other beneficial bacteria, starting a chain reaction of fermentation.[20] For example, Bifidobacterium species can make lactate and acetate, which are then eaten by other bacteria that make butyrate.[20] This means that prebiotics don't just stimulate certain bacteria; they change the whole microbial ecosystem by making new metabolic niches and encouraging cooperation between different microbial groups. This means that you might not be able to see all the health advantages of a prebiotic just by looking at the rise in a few target bacteria. Instead, to really grasp something, you need to look at the metabolic output of the whole microbial population and the complicated web of relationships. This point of view also suggests that mixing different prebiotics could create stronger and more diverse cross-feeding networks, which could lead to better and more widespread health advantages than using just one prebiotic.

4.2. Production of Short-Chain Fatty Acids (SCFAs) and Their Systemic Impact

One of the most important effects of prebiotic fermentation by gut microbiota is the production of short-chain fatty acids (SCFAs), mainly acetate, propionate, and butyrate.[1] These SCFAs are important for both local gut health and overall body function.

Butyrate is very important for the health of the colon. Butyrate is the main source of energy for colonic epithelial cells, which helps them grow and differentiate normally. It is also important for keeping the gut barrier strong. In addition to its role in cellular energetics, butyrate also has anti-inflammatory and anti-cancer properties in the colon.

Unlike butyrate, acetate and propionate can easily move from the colon into the bloodstream, where they can have effects on organs far away from the gastrointestinal tract. For example, propionate has been shown to affect T helper 2 cells in the airways and macrophages.[20] Together, SCFAs help the host get energy from dietary components that would otherwise be hard to digest.

Other fermentation products are made along with SCFAs. Bifidobacterium and Lactobacillus species make lactic acid, which lowers the pH of the intestines.[1] This more acidic environment makes it harder for many harmful bacteria to grow, which protects the body.[1] Peptidoglycan, another fermentation byproduct, has been shown to boost the body's natural immune system.[1]

The constant focus on SCFA generation as a main result of prebiotic fermentation, along with the fact that SCFAs can penetrate systemic circulation and influence organs far away [1], shows that these metabolites are not just local energy sources. Instead, they act as important signalling molecules that let the gut microbiota and the host's systemic physiology talk to each other in complicated ways. The effect of propionate on immune cells [1] and the bigger effect of SCFAs on brain processes [5] show that these microbial metabolites are part of a complex "gut-brain axis" or "gut-immune axis." This new knowledge changes the focus from only encouraging good bacteria to understanding and improving the metabolic output of the gut microbiome. It suggests that future prebiotic techniques could involve tailoring interventions to produce various SCFA profiles to target different systemic health benefits, such as immunological regulation, metabolic health, or even neurological well-being, moving towards a more precise nutrition approach.

4.3. Modulation of Gut Microbiota Composition and Activity

Prebiotics work by changing the makeup and activity of the gut microbiota in a way that is good for you. Their main job is to selectively encourage the growth of good bacteria, like Bifidobacterium and Lactobacillus species. People know a lot about how these bacteria can help gut health and a lot of other things.[1]

Prebiotics not only help good bacteria grow, but they also help keep bad bacteria from growing. There are several ways this happens. For example, beneficial bacteria outcompete pathogens for limited resources (competitive exclusion), and harmful microorganisms are directly stopped by the production of antagonistic molecules like lactic acid and bacteriocins.[1] Fermenting bacteria make SCFAs, which lower the pH of the colon. This acidic environment makes it hard for many infections to develop, but it makes it easier for acid-tolerant beneficial bacteria to grow.[1]

Some prebiotics, such okra polysaccharides, have also been demonstrated to increase the diversity of alpha and beta bacteria in the gut microbiome.[13] More diversity is usually a sign of a healthier, more resilient, and functionally strong microbial community. The gut microbiota usually has a natural "resilience," which means it can return to its original healthy state after being disturbed.[20] Prebiotics help this happen by selectively promoting good bacteria and suppressing bad ones, which helps the microbial community return to a healthy balance or stop dysbiosis from happening.[20] The ability of some mucilages, like those from fenugreek and mustard, to stop certain pro-inflammatory genera like Escherichia–Shigella [2], or for polyphenols to stop Candida yeasts [516], shows that these are targeted corrective actions that go beyond just promoting growth. This shows that prebiotics are not just good for your health in general; they can also be quite helpful for treating some types of gut dysbiosis. In the future, researchers should try to find specific prebiotic compounds or combinations that work best to restore balance in certain dysbiotic conditions, like inflammatory bowel disease, obesity, or neurological disorders, by targeting specific microbial shifts or pathogen overgrowth. This method takes us closer to a model of precision medicine for gut health.

5. Health Benefits Associated with Plant-Based Prebiotics

Eating plant-based prebiotics is good for your health in many ways, not just in your digestive system but also in your body's other systems.

5.1. Gastrointestinal Health and Barrier Integrity

Prebiotics are very important for gut health because they strengthen the intestinal barrier, which is a key defence mechanism that keeps harmful bacteria and substances from getting into the gastrointestinal (GI) tract and then into the bloodstream. They do this by promoting the growth of good bacteria like Bifidobacterium and Lactobacillus while also lowering the number of bad bacteria like Clostridium perfringens.[22]

The increased production of short-chain fatty acids (SCFAs), especially butyrate, is a major reason why these advantages happen. Butyrate is necessary for the growth and health of intestinal epithelial cells because it is their main source of energy and helps cells differentiate and multiply normally.[1] SCFAs also help control the absorption of sodium and water in the colon and improve the absorption of important minerals like calcium, magnesium, and possibly iron.[3] In addition to these cellular and absorptive functions, prebiotics can help with laxation and regular bowel movements. They have also been demonstrated to lower the number and duration of diarrhea caused by infections and antibiotics.[15] The benefits seen, including as better barrier function, more SCFA generation, and better mineral absorption, go beyond only relieving symptoms. They mean a basic restoration and improvement of the physiological processes of the stomach. The gut barrier must be strong to stop systemic inflammation and many diseases.[5] SCFAs are not just a source of energy for colonocytes; they also affect gene expression and cell differentiation.1 This means that prebiotics are not just dietary supplements; they are also substances that can fundamentally restore and maintain the healthy functioning of the intestinal "organ."[3] This deeper understanding suggests that prebiotics should be seen as essential dietary components for long-term gut health maintenance and disease prevention, possibly showing their role in stopping chronic diseases that start with a weak gut barrier.

5.2. Immune System Modulation

Prebiotics are very important in this complex interaction since they help shape the host's immune system. Prebiotics help the host's immune responses by encouraging the growth of good bacteria and increasing the production of short-chain fatty acids (SCFAs).1 Some types of dietary fibre, like beta-glucans found in barley and oats, can also directly interact with immune cells, which boosts the immune system.[15]

Prebiotics have been shown to help with inflammatory conditions, including symptoms of irritable bowel syndrome (IBS), and they can lower pro-inflammatory immune markers.[5] In addition, some fermentation products, like peptidoglycan, are known to boost the innate immune system.[1] The gut microbiota has been shown to affect "immunomodulatory molecules" [1] and play a big role in the "barrier that prevents pathogenic bacteria from invading" [15]. SCFAs can also affect immune cells like T helper 2 cells [1] and lower inflammatory markers [15]. This all points to a strong "gut-immune axis," which means that prebiotic intake can affect the immune system not only in the gut but also throughout the body. This means that plant-based prebiotics may play a big part in treating chronic inflammatory diseases and making the immune system stronger overall. More research could look into certain prebiotic structures or plant extracts that affect particular parts of the immune system more than others. This could lead to dietary strategies for autoimmune illnesses, allergies, or even better responses to vaccines.

5.3. Metabolic Regulation

Plant-based prebiotics have a big effect on a lot of the host's metabolic processes. They can affect how well you regulate your appetite and manage your weight in a number of ways. These include making you feel fuller by making you chew more, increasing saliva and stomach acid production, and making your stomach feel fuller. Some soluble and sticky fibres hold on to water, which makes the distention even worse. Also, some fibres can slow down the emptying of the stomach and the absorption of glucose, which can make insulin less responsive. This is linked to feeling full and satisfied. Prebiotics can also affect the release of hormones that make you feel full, like peptide YY (PYY). This can lead to eating less and losing weight.[15]

Dietary fibre, which includes prebiotics, is always connected to a lower risk of coronary heart disease (CHD) and cardiovascular disease (CVD). This benefit comes mostly from lowering levels of low-density lipoprotein (LDL) cholesterol.[15] Soluble and viscous fibres, like beta-glucan, psyllium, and pectin, are especially good at changing biomarkers of CVD in a good way.[15] Prebiotics may also help slow down the absorption of glucose, stop weight gain, and increase the intake of good nutrients and antioxidants, which could help prevent type II diabetes.[5] Animal studies using plant extracts like Porphyra umbilicalis and Melissa officinalis L. have shown changes in lipid metabolism, such as lower plasma triacylglycerols and higher free fatty acids, and changes in liver and adipose tissue gene expression, but these changes don't always lead to changes in glucose tolerance or body weight.[23] The effects of prebiotics on metabolism go beyond just fibre effects or calorie restriction. They affect how full you feel and how well you manage your weight, although their role in lipid and glucose metabolism is complicated. The fact that some fibres lower LDL cholesterol [15] and affect gene expression relevant to metabolism in animal models [23] suggests that prebiotics are active metabolic regulators. This shows that plant-based prebiotics could be very helpful for managing metabolic disorders like obesity, type II diabetes, and dyslipidemia through diet. Future studies should focus on figuring out the exact molecular pathways by which certain prebiotics affect the metabolism of the host. This could lead to new treatment targets or individualized dietary recommendations for metabolic health.

5.4. Potential Systemic Benefits (e.g., neurological and psychological conditions)

New research shows that prebiotics may have effects on neurological and psychological health, in addition to their effects on metabolism and the immune system. This shows how important the gut-brain axis is. Prebiotics can affect mental health by making metabolites that change how the brain works and how people act.[5] For example, SCFAs made during fermentation can get through the blood-brain barrier and change the levels of neurotransmitters like serotonin and dopamine precursors in the brain.[5]

Early research in humans has given us some information on these impacts. For example, drinks with inulin and polydextrose have been related to better attention, flexibility, and executive skills in older people. This may be because they change the way Bifidobacterium spp. work. and a decrease in indicators of inflammation.[24] Eating veggies, fermented foods, and prebiotics has also been linked to lower levels of perceived stress.[24]

Also, prebiotics may help with complicated neurodevelopmental and neurodegenerative disorders. Beta-galactooligosaccharides (B-GOS) have been shown to have positive effects on behavioural stereotyping, sociality, and lethargy in people with autism spectrum disorders (ASD). They also improve the composition of gut microbiota, specifically by increasing Bifidobacteria and Faecalibacterium prausnitzii.[24] There is also some evidence that prebiotics may help with Parkinson's disease, where inulin, resistant starch, and resistant maltodextrin have been linked to lower inflammatory markers, higher SCFA production, and better motor and non-motor symptoms.[24] The evidence for prebiotics affecting neurological and psychological conditions, including stress, cognitive function, and complex disorders like ASD and Parkinson's [5], is very strong. The "gut-brain axis" is a strong link between the process, which involves SCFAs crossing the blood-brain barrier and affecting neurotransmitter production [5]. This is because dietary components can directly affect brain function and mental health through their interaction with the gut bacteria. This makes prebiotics more than just good for gut health; they also have an effect on the central nervous system as a whole. This opens up a huge and exciting area for future research and the development of new treatments. Plant-based prebiotics could become a non-drug way to help mental health, boost cognitive function, or even be used as additional treatments for neurodegenerative and neurodevelopmental disorders. Finding specific prebiotics or plant extracts that change the gut-brain axis in a way that helps with specific neurobehavioral outcomes will be an important step in the future.

6. Current Research Landscape: Evidence from In Vitro, Animal, and Human Studies

Different research models have been used to study plant-based mucilages and extracts as prebiotics, and each one has given us new information about their possible uses.

6.1. In Vitro Assessments of Prebiotic Potential

In vitro investigations are an important first step in testing the prebiotic potential of different substances. Researchers use controlled fermentation models with human feces to see how some probiotic organisms, including Bifidobacterium and Lactobacillus, grow and to measure how much short-chain fatty acids (SCFAs) they make.[2]

For example, in vitro fermentation of Aloe vera mucilage with human intestinal microbiota has shown its prebiotic potential by producing measurable SCFAs and changing the populations of bacteria that are present.[14] Similarly, seed mucilages from chia, fenugreek, basil, mustard, and flaxseed have shown prebiotic properties through amylase degradation assays and increased growth of Bifidobacterium and Lactobacillus.[2] Batch fermentation studies using human fecal slurry have also shown that these mucilages can raise butyrate levels and encourage the growth of probiotics.[2]

Screening extracts from edible wild plants has also shown that they have good in vitro prebiotic potential. Some extracts, like Rorippa nudiuscula, Chenopodium album, Urtica dioica, and Tragopogon porrifolius, have made B.'s growth a lot faster. animalis, L. rhamnosus and L. acidophilus, in some cases even more effectively than inulin, a recognized prebiotic benchmark.[25] Polysaccharides from edible fungi, specifically Lepista sordida, have been shown to promote the proliferation of Lactobacillus casei and increase its acid production capacity, while also improving its tolerance to bile salts.[26] Extracts from bamboo shoots and potato peels have demonstrated the ability to enhance the growth of lactic acid bacteria (LAB), including Lactobacillus paracasei and Streptococcus thermophilus, and improve their tolerance to simulated gastrointestinal conditions.[19] In vitro investigations into turmeric, green tea, and garlic extracts have indicated that turmeric and garlic extracts possess prebiotic effects on certain LAB strains, whereas green tea extract generally exhibited inhibitory effects, underscoring the importance of careful selection and concentration in their application.[17]

In vitro research can be used for more than just simple tests of microbial growth. These models are becoming more and more useful for predicting certain bioactivities and functional outcomes. They can be used to measure SCFA production, changes in certain bacterial populations (like Butyricicoccus and Lachnospiraceae), and even how well they can handle conditions that mimic those in the gut.[2] The fact that plant extracts are compared to well-known prebiotics like inulin [2523] makes them even more useful as benchmarks. This means that well-designed in vitro studies can make it much easier to find and develop new plant-based prebiotics by giving us early information about how they might work and how well they might work. This cuts down on the need for long and expensive animal or human trials in the beginning. They make it easier to evaluate a lot of different plant materials quickly and find interesting candidates with specific effects.

6.2. Insights from Animal Model Investigations

Animal models are an important link between early in vitro data and complicated human applications. They let researchers look at complicated interactions between hosts and microbiota and how they affect the whole entire biological system.

Important results have come from studies using okra polysaccharides in animal models of Alzheimer's disease (AD). Giving okra polysaccharides, both with and without Lactiplantibacillus plantarum encapsulation, increased the diversity of bacterial alpha and beta, increased the number of Lactobacillaceae and Lactobacillus, and significantly raised the levels of SCFA (acetate, propionate, and butyrate) in feces.[13] These results suggest that okra polysaccharides may play a role in regulating the intestines and possibly in preventing or managing AD.[13]

Studies of plant extracts, like those from Porphyra umbilicalis and Melissa officinalis L., in obese (ob/ob) mice have shown that a two-week treatment period changed the composition of the dysbiotic gut microbiota, changed the caecum metabolome (for example, it raised levels of propionate, acetate, and butyrate), and changed markers of lipid metabolism (for example, it lowered plasma triacylglycerols).[23] These extracts also changed gene expression in white adipose tissue and liver.[23]

When pigs were given Grape Seed Proanthocyanidins (GSP), it reduced oxidative stress and helped them grow by increasing the number of Lactobacillus species.[18] Similarly, Rosa roxburghii Polyphenol (RRTP) helped mice recover from acute lung injury by increasing SCFA production and the number of Akkermansia muciniphila, a bacterium that helps keep the gut barrier intact.[18] Mulberry Leaf Polysaccharide (MLP) protected chicks from cyclophosphamide-induced immunosuppression by boosting antioxidant enzyme activity and tight junction protein expression.[18]

Also, a cocktail of probiotics, prebiotics, and plant extracts studied in a zebrafish model made hangover symptoms caused by alcohol much better. This mix of fructooligosaccharide and plant extracts from Hovenia dulcis, kudzu root, curcumin, and rice bran improved the total distance moved and boosted the activities of alcohol dehydrogenase (ADH) and aldehyde dehydrogenase (ALDH). It worked better than plant extracts alone at breaking down acetaldehyde.[27]

Animal models are very useful for studying how plant-based prebiotics could help treat complicated physiological and pathological conditions. These studies go beyond just changing the gut to show systemic effects, like lowering oxidative stress, changing liver and fat tissue gene expression, and healing lung damage.[13] Most importantly, using disease-specific models like AD mice, immunosuppressed chicks, and zebrafish with hangovers caused by alcohol [13] directly links prebiotic treatments to better health conditions. This shows how useful animal research can be for finding specific plant-based prebiotics that can be used for specific health purposes, such as protecting the brain, supporting the immune system, or managing metabolic disorders. These studies also show how complicated these interventions are, since the effects can change depending on the animal model, the type of plant utilized, and the combination of substances used. This gives us a good reason to move on to human clinical trials for certain health outcomes.

6.3. Findings from Human Clinical Trials

The last step in proving that prebiotic therapies work and are safe is human clinical studies. The information given doesn't have much direct data on human trials of new plant mucilages, but it does provide more general information about prebiotics and plant extracts.

Studies on humans show that prebiotics can greatly raise the number of Bifidobacterium and Lactobacillus in feces at low levels of ingestion, usually between 5 and 8 grams per day.[22]

Getting enough dietary fibre, which includes prebiotics, is always linked to a lower risk of cardiovascular disease (CVD) and coronary heart disease (CHD). This is true when looking at both CVD and metabolic health. This is mostly because levels of low-density lipoprotein (LDL) cholesterol have gone down.[5] Soluble fibres like beta-glucan, psyllium, and pectin have been shown to be especially good at this.[15] Prebiotics also show promise in slowing down the absorption of glucose and possibly stopping type II diabetes.[5] Fructans have been shown to improve the absorption of minerals like calcium and magnesium, which makes bones denser in teenagers.[15]

Human clinical research reveal that prebiotics may have an effect on neurological and psychiatric problems. For instance, drinks that include inulin and polydextrose have been related to better cognitive abilities in older people, such as attention, flexibility, and executive functioning. It's possible that these changes are linked to the regulation of Bifidobacterium spp. and a decrease in inflammatory markers.[30] Eating vegetables, fermented foods, and prebiotics has also been linked to feeling less stressed.[2430] In children with autism spectrum disorders (ASD), beta-galactooligosaccharides (B-GOS) have improved behavioural stereotyping, socialization, and lethargy, while also changing the gut microbiota by increasing Bifidobacteria and Faecalibacterium prausnitzii.[30] Preliminary data also suggest that prebiotics may help with Parkinson's disease, where inulin, resistant starch, and resistant maltodextrin have been linked to lower inflammatory markers, higher SCFA production, and better motor and non-motor symptoms.[30]

There is a lot of strong evidence from in vitro and animal research that different plant mucilages and extracts can serve as prebiotics [2], but there is a big lack of strong human clinical trial data on new plant mucilages. Most human data are about general groups like "dietary fibre" or well-known prebiotics like inulin and FOS.[15] This shows a major research gap: the promising preclinical results on certain plant mucilages and new extracts need to be fully tested in well-designed, randomized controlled human trials to make sure they work and are safe for people of all backgrounds. This confirmation will be very important for their use in functional foods and medical treatments to become more common.

7. Challenges, Limitations, and Research Gaps

Plant-based mucilages and extracts have a lot of potential as prebiotics, but there are still a lot of problems, limits, and research gaps that need to be fixed before they can reach their full potential.

One big problem is uniformity and characterisation. Depending on the plant species, where it comes from, the extraction methods used, and the conditions of the processing that follow, the chemical makeup and functional properties of plant mucilages and extracts can be very different.[38] This natural variability makes it hard to standardize products and makes it harder to compare studies from different research groups.[28]

Another problem has to deal with the link between dose and response. It is often not obvious what the best doses are for getting certain prebiotic benefits in people. Taking the wrong amount of a drug can cause adverse effects like bloating and gas, especially at large doses, because fermentation makes too much gas.[22]

There aren't enough strong human clinical trials that look at new plant mucilages and extracts, which is a big problem in research. While preclinical results from in vitro and animal studies are very promising, there aren't many long-term human clinical trials that look at the same things.5 This is especially important for confirming specific health claims and figuring out how these substances affect people over time.[29]

We also need to know more about how things work. We know a lot about the general pathways, but we still need to figure out exactly how certain plant-based prebiotics affect digestive enzymes, oxidative stress, and antioxidant defence systems.[29] Another problem is that different species respond differently to prebiotics. The gut microbiota is made up of different types of bacteria in different people and at different periods of life.[2] This makes it hard to predict how everyone will respond to prebiotic therapies and shows how important it is to use tailored approaches.[3]

Also, more research is needed on how live microbes might interact with pharmaceutical drugs.[30] More research is also needed on how to ensure the safety of live microbes, especially in synbiotic formulations, and how to understand how changes in microbiomes caused by probiotics might affect health.[30] The bioavailability and stability of bioactive compounds in plant extracts during processing, storage, and passage through the gastrointestinal tract is still a big problem because they can lose their effectiveness when they break down.[9] Finally, while promising, most research on new extraction technologies for plant mucilages is still at the laboratory scale, so industrial-scale trials are needed to see if they can be used practically and economically.[31] The fact that there are consistently "limited human clinical trials" [5] even if there is a lot of evidence from in vitro and animal studies [2] shows that there is a big gap in translation. This gap is made worse by problems with standardization, understanding dose-response relationships, and taking into account differences between people.[20] Showing an effect in a petri dish or a mouse is not enough; the biggest challenge is showing that the effects are consistent, safe, and helpful in different groups of people. This means that everyone in the profession needs to work together to advance from discovery to strict clinical validation. It is very important to invest in large-scale, well-controlled human studies, create consistent methods for characterisation and efficacy testing, and learn more about how people respond differently to treatments. If this gap in translation isn't fixed, the huge potential of plant-based prebiotics will stay mostly theoretical, making it harder for them to be widely accepted and used in functional foods and clinical practice.

8. Future Directions and Novel Technologies

Plant-based prebiotics are about to make big strides in the future because to new technologies and an increasing focus on individualized health solutions.

8.1. Advanced Extraction and Modification Technologies for Enhanced Prebiotic Properties

More and more study will be done in the future on non-thermal methods for getting plant mucilages and extracts. Ultrasonication, cold plasma, microwave-assisted extraction, and pulsed electric field are some of the newer methods that work better than traditional thermal processing.[31] These advanced methods are important for keeping delicate flavours, nutrients, and heat-sensitive bioactive compounds like anthocyanins, antioxidants, flavonoids, and β-carotene from breaking down at high temperatures.[31]

By optimizing the extraction conditions, we can unlock even more of the full potential of these non-thermal technologies. Changing things like temperature, solvent, and extraction time can greatly improve the yield and functional properties of mucilages and extracts, making them more powerful and less expensive.[31] Structural modification of mucilages and other polysaccharides is another promising area. Researchers are looking at how to change their digestive patterns and functional qualities through chemical or enzymatic changes. This could lead to new prebiotics that have very precise impacts on certain bacteria groups or metabolic pathways.

Encapsulation technologies are also becoming more popular. Plant mucilages are great encapsulating agents since they are biopolymeric. This keeps sensitive antioxidant and antimicrobial compounds safe and makes sure that probiotic bacteria stay alive as they move through the digestive system, so they can be released at the right time.[9] This is an important step in making synbiotic products that work well and last. The focus on new extraction methods and structural changes [31] is a step toward precision engineering of prebiotic characteristics. Using non-thermal approaches keeps delicate molecules intact and bioactive.[31] Changing the structure could change how easily they ferment and target certain bacteria groups or metabolic pathways. This suggests a move away from just using a "natural source" to making a "optimized natural ingredient." This means that in the future, plant-based prebiotics will not only be eaten as whole foods or crude extracts, but also as highly refined and engineered ingredients made for specific functional outcomes. This will lead to a new generation of highly potent and targeted prebiotics with predictable effects for personalized dietary interventions and advanced functional food formulations.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 18s, 2025
https://theaspd.com/index.php

8.2. Personalized Nutrition Approaches and Synbiotic Formulations

Because everyone's gut flora is different and reacts differently to prebiotics [3], we need to move toward individualized nutrition. Future studies will probably focus on customizing prebiotic treatments to fit each person's particular microbiota makeup, genetic predispositions, and health needs. This would mean making diagnostic tools to figure out what kind of gut microbiome a person has and then suggesting specific plant-based prebiotics or combinations that are most likely to help.

The new idea of synbiotics, which combine prebiotics and probiotics, offers a way to improve gut health that works better than either one alone.[32] Future research will be important for finding the best pairs of prebiotics and probiotics that work well together, making sure that the prebiotic part feeds the probiotic strain that is also given.[17] An interesting extension of this is the "prophybiotic" idea, which combines plant extracts that have both antimicrobial and prebiotic properties with probiotics. This method tries to improve the intestinal environment by encouraging good bacteria and keeping bad bacteria from growing at the same time.[17]

More research will also look into how to combine plant-based prebiotics with other plant-based bioactive compounds, like polyphenols and antioxidants, to make multi-functional ingredients that have more health benefits than just changing the gut.[5] Finally, more long-term studies are needed to find out how well and safely plant-based prebiotics work in different populations, moving beyond short-term interventions to learn how they can help manage chronic health conditions.[29] The recognition of differences in gut microbiota [20] and the call for personalized nutrition show that there has been a big shift in thinking. Along with the creation of advanced synbiotic and "prophybiotic" formulations [17], the future of gut health interventions is going toward more precise solutions. This suggests that instead of using a "one-size-fits-all" approach to dietary supplements, we should start using highly personalized solutions that take into account a person's unique microbiota and health status. This will change the functional food and nutraceutical businesses forever. It will also increase the need for new diagnostic techniques, like microbiome sequencing, to help make individualized recommendations. It also requires a better understanding of how different prebiotic structures interact with certain groups of microbes in a person, which will allow for very targeted and effective treatments for a wide range of health problems.

9. CONCLUSION

Plant-based mucilages and extracts are a very promising new area of research into new prebiotics. They offer a natural, long-lasting, and flexible way to change the gut microbiome for better health. The changing definition of prebiotics shows that we are learning more about how the gut ecosystem works as a whole, not just focusing on specific bacterial strains but also on the bigger effects of microbial metabolism. Plant mucilages, which have different polysaccharide structures, and polyphenol-rich extracts, which can act as both selective substrates and antimicrobial agents, show a lot of promise for selectively feeding good bacteria, increasing SCFA production, and keeping pathogens in check.

Studies on cells in a lab, animals, and even people that are just starting to show up all show that these plant-based substances can improve gut health, change how the immune system works, control metabolic parameters, and even affect mental and neurological health. Certain sources, such as chia, flaxseed, okra, chicory, garlic, and grape seed extracts, have been demonstrated to be very good at promoting the growth of good microbes, raising SCFA levels, and improving overall health.

However, the area has some big problems, especially the need for more standards in characterisation and, most importantly, the need to turn promising preclinical results into strong, large-scale human clinical trials. Finding the best doses and figuring out how to deal with the differences in how people's gut flora respond are important stages for widespread use. Future study will focus on using advanced non-thermal extraction methods to keep and improve the bioactivity of these chemicals, as well as on creating tailored nutrition plans and complex synbiotic/probiotic formulations. Plant-based mucilages and extracts could change the way we think about functional meals and medical treatments by getting around these problems. This would open the door to precise gut health solutions and make a big difference in people's health in general.

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