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Beyond Sweetness: Evaluating the Bioactivity and Safety of Chemical Sugar Substitutes and Natural Functional Polysaccharides

Zhu Wang, Siyuan Wang *, Lijun Qin, Yushan Ye

Jianghan University, Wuhan, China

ABSTRACT

With the global pandemic of obesity, type 2 diabetes mellitus (T2DM), and other metabolic syndromes, excessive sucrose intake has been widely recognized as a core modifiable risk factor for chronic non-communicable diseases. Driven by rising global health awareness, the market demand for sugar substitutes has undergone a fundamental transformation: from the initial goal of simple calorie reduction and sucrose replacement to the pursuit of additional functional health benefits while reducing sugar intake. Against this background, this paper systematically evaluates the performance, advantages, and limitations of two major categories of sugar substitutes: chemical synthetic sweeteners (CSS) and natural functional polysaccharides (NPs), with a specific focus on polysaccharides extracted from white hyacinth beans (Lablab purpureus (L.) Sweet), a classic medicinal and edible homologous plant in China. For CSS represented by aspartame, sucralose, and acesulfame potassium, their core advantages lie in ultra-high sweetness intensity (up to 600 times that of sucrose), zero or near-zero caloric value, and low production cost, which have made them dominate the global sugar substitute market for decades. However, emerging toxicological studies, clinical trials, and cohort studies in recent 5 years have gradually revealed the potential long-term risks of CSS intake, including disruption of gut microbiota homeostasis, impairment of intestinal barrier integrity, induction of glucose intolerance and insulin resistance, and even increased risk of metabolic syndrome. In contrast, NPs derived from medicinal and edible plants, especially the white hyacinth bean polysaccharides (WHBP) and white hyacinth flower polysaccharides (WHFP) focused on in this study, exhibit multiple biological activities and health benefits beyond simple sucrose replacement. In this study, we adopted a green extraction strategy combining composite enzymatic hydrolysis and low-temperature ultrasound, which achieved a polysaccharide purity of ≥65% and a biological activity retention rate of ≥90%, avoiding the activity loss caused by traditional high-temperature extraction. Furthermore, microbial fermentation modification with Bacillus subtilis or Lactobacillus casei significantly reduced the molecular weight of WHBP (from 87.7 kDa to 45.8 kDa) and WHFP (from 106.387 kDa to 36.364 kDa), exposing more active hydroxyl and carboxyl groups, thus further enhancing their biological activities. A series of in vitro and in vivo experiments confirmed that the fermented WHBP and WHFP have strong free radical scavenging capacity, significant inhibitory effect on α-amylase activity to reduce postprandial blood glucose, excellent bile salt binding capacity to regulate cholesterol metabolism, and prebiotic effects to modulate gut microbiota. This study not only systematically compares the safety and functionality of CSS and NPs through multi-dimensional evidence, but also provides theoretical support and technical reference for the development of new-generation functional sugar substitutes based on medicinal and edible plant polysaccharides, as well as the high-value utilization of white hyacinth bean resources.

KEYWORDS

Sugar substitutes; Functional polysaccharides; White hyacinth bean; Bioactivity; Food safety; Gut microbiota; Microbial fermentation

1. INTRODUCTION

The global prevalence of metabolic syndromes, including obesity, T2DM, hyperlipidemia, and non-alcoholic fatty liver disease (NAFLD), has become one of the most severe public health challenges in the 21st century. According to the World Health Organization (WHO) 2023 guideline on non-sugar sweeteners, the global prevalence of obesity has nearly tripled since 1975, with over 1 billion adults living with overweight or obesity in 2022, and this number is projected to exceed 2 billion by 2035. In China, the latest Report on Chinese Residents' Nutrition and Chronic Disease Status (2023) shows that the overweight rate of adults aged 18 and above has reached 34.3%, and the obesity rate is 16.4%, while the prevalence of diabetes among Chinese adults has risen to 11.9%, with more than 140 million diabetic patients. A large number of epidemiological studies and clinical trials have confirmed that long-term excessive intake of added sugar, especially sucrose and high-fructose corn syrup, is a key driving factor for the occurrence and development of these metabolic syndromes. Excessive sugar intake can not only lead to excessive caloric intake and weight gain, but also directly induce insulin resistance, chronic low-grade inflammation, oxidative stress, and gut microbiota disorder, further increasing the risk of T2DM, cardiovascular diseases, and even certain cancers.

Against this background, sugar substitutes (also known as sweeteners) have become the core solution for the food industry to reduce added sugar content while maintaining the sweet taste of food, and their market scale has expanded rapidly in recent years. According to the 2024 market research report by Markets and Markets, the global sugar substitutes market size was valued at USD 22.3 billion in 2023, and is projected to reach USD 32.8 billion by 2028, with a compound annual growth rate (CAGR) of 8.0% during the forecast period. For a long time, chemical synthetic sweeteners (CSS) have dominated the sugar substitute market due to their outstanding advantages: ultra-high sweetness intensity (hundreds to thousands of times that of sucrose), zero or near-zero caloric value, excellent processing stability, and extremely low production cost. Typical CSS include saccharin sodium, cyclamate, aspartame, sucralose, acesulfame potassium, and neotame, which are widely used in sugar-free beverages, baked goods, confectionery, dairy products, and pharmaceutical preparations.

However, in recent years, with the deepening of toxicological and nutritional research, the long-term safety of CSS has been widely questioned. In 2023, the International Agency for Research on Cancer (IARC) under the WHO classified aspartame, the most widely used CSS in the world, into Group 2B (possibly carcinogenic to humans), which further aroused global concern about the safety of CSS. More importantly, a growing number of studies have found that long-term intake of CSS, even within the acceptable daily intake (ADI) range, may not achieve the expected weight control and blood sugar management effects, but instead induce a series of metabolic disorders. A landmark study published in Cell in 2022 confirmed that non-nutritive sweeteners can alter the composition and function of human gut microbiota in a personalized manner, and further induce glucose intolerance, which is a key precursor of T2DM. Subsequent systematic reviews and meta-analyses have also confirmed that long-term CSS intake is significantly associated with increased risk of obesity, T2DM, cardiovascular events, and all-cause mortality. These findings have revealed that the "physiological blankness" of CSS, which was once considered an advantage, has become their biggest defect: they only provide sweet taste without any nutritional value or health benefits, and may even interfere with the normal physiological functions of the human body.

Therefore, the development of natural, safe, and functional sugar substitutes has become a research hotspot in the field of food science and nutrition in recent years. Natural polysaccharides (NPs) derived from medicinal and edible homologous plants have attracted extensive attention due to their excellent safety, multiple biological activities, and great potential as sugar substitutes. Polysaccharides are natural polymer compounds formed by the connection of more than 10 monosaccharide units through glycosidic bonds, which are widely present in plants, animals, and microorganisms. As an important active ingredient of medicinal and edible plants, polysaccharides have been confirmed to have a variety of physiological activities, including antioxidant, hypoglycemic, hypolipidemic, anti-inflammatory, immunomodulatory, and prebiotic effects, with low toxicity and high safety. Unlike CSS, which only provide sweet taste, NPs used as sugar substitutes can not only reduce the caloric value of food (most NPs are low-calorie or non-calorie, as they cannot be digested and absorbed by the human upper gastrointestinal tract), but also exert a variety of health benefits through multi-target regulation of human physiological functions.

White hyacinth bean (Lablab purpureus (L.) Sweet), also known as Dolichos lablab L., is a classic medicinal and edible homologous plant included in the Catalogue of Items for Both Medicinal and Food Uses issued by the National Health Commission of China. It has a cultivation history of more than 2000 years in China, and is widely planted in most provinces of China, with abundant and easily available raw material resources. In traditional Chinese medicine, white hyacinth bean is recorded to have the effects of invigorating the spleen, resolving dampness, regulating the middle warmer, and relieving summer heat, and is commonly used for the treatment of spleen deficiency, diarrhea, nausea, and vomiting. Modern phytochemical studies have confirmed that polysaccharides are the main active ingredients of white hyacinth beans, with a variety of biological activities. However, the current research on white hyacinth bean polysaccharides (WHBP) and white hyacinth flower polysaccharides (WHFP) is still in the initial stage, especially the research on their application as functional sugar substitutes is very limited, and there is a lack of systematic comparison between WHBP and mainstream CSS in terms of safety, functionality, and application potential.

In this context, this paper aims to systematically compare the advantages and limitations of CSS and NPs through the latest research evidence, with a focus on the structural characteristics, extraction and modification technology, biological activity, and application potential as functional sugar substitutes of WHBP and WHFP. This study not only fills the gap in the systematic comparison between chemical synthetic sweeteners and natural functional polysaccharide sugar substitutes, but also provides theoretical basis and technical support for the high-value utilization of white hyacinth bean resources and the development of new-generation functional sugar substitutes.

2. CHEMICAL SYNTHETIC SWEETENERS: APPLICATION ADVANTAGES AND POTENTIAL HEALTH RISKS

2.1. Classification and Market Application Status of CSS

Chemical synthetic sweeteners, also known as non-nutritive synthetic sweeteners, are artificially synthesized organic compounds with sweet taste, which can be divided into high-intensity sweeteners and bulk sweeteners according to their sweetness intensity and dosage. High-intensity CSS are the mainstream products in the current market, with sweetness intensity ranging from 30 to 8000 times that of sucrose, so the dosage in food is extremely low, and the caloric contribution can be almost ignored. Typical high-intensity CSS include: saccharin sodium (300-500 times the sweetness of sucrose), cyclamate (30-40 times), aspartame (180-200 times), sucralose (400-600 times), acesulfame potassium (200 times), and neotame (6000-8000 times).

The core advantages of CSS lie in their high efficiency, low cost, and excellent processing adaptability. Unlike sucrose, most CSS have stable physicochemical properties under high temperature, acid, and alkali conditions, so they can be widely used in various food processing technologies, including high-temperature baking, sterilization, and fermentation. In addition, CSS do not participate in Maillard reaction, so they will not cause browning of food during processing, which is conducive to maintaining the appearance quality of products. Due to these advantages, CSS have become the most widely used sugar substitutes in the global food industry for more than half a century, and are still the first choice for most sugar-free food products at present.

2.2. Potential Health Risks of Long-Term CSS Intake

Although CSS have been approved for use by food regulatory authorities in most countries around the world, with clear acceptable daily intake (ADI) standards, emerging research in recent years has gradually revealed the potential long-term health risks of CSS intake, which are mainly reflected in the following aspects.

2.2.1. Disruption of Gut Microbiota Homeostasis and Intestinal Barrier Function

The human gut microbiota is a complex ecosystem that plays a key role in nutrient metabolism, immune regulation, and maintenance of host health. The gut microbiota-gut-brain axis is also an important regulatory pathway for host glucose and lipid metabolism and energy balance. In recent years, a large number of in vitro, animal, and human studies have confirmed that CSS intake can significantly alter the composition, diversity, and metabolic function of gut microbiota. A 2024 systematic review published in Critical Reviews in Food Science and Nutrition summarized 42 related studies and found that long-term intake of sucralose, aspartame, and saccharin can significantly reduce the abundance of beneficial bacteria such as Bifidobacterium and Lactobacillus in the gut, while increasing the abundance of potentially pathogenic bacteria such as Escherichia coli and Salmonella, leading to a decrease in gut microbiota diversity and imbalance of the microecological structure.

More importantly, CSS can also damage the integrity of the intestinal barrier. The intestinal barrier is the first line of defense for the human body to prevent the invasion of pathogenic bacteria and endotoxins. Studies have found that CSS can reduce the expression of tight junction proteins (such as occludin and claudin) in intestinal epithelial cells, increase intestinal permeability, and lead to the translocation of lipopolysaccharide (LPS, an endotoxin produced by Gram-negative bacteria) into the blood circulation, thereby inducing chronic low-grade inflammation in the whole body. Chronic low-grade inflammation is the core pathological basis of insulin resistance, T2DM, obesity, and other metabolic syndromes, which is the key mechanism by which CSS induce metabolic disorders.

2.2.2. Induction of Glucose Intolerance and Insulin Resistance

The original core application value of CSS is to control blood sugar and weight by reducing caloric intake. However, more and more studies have found that long-term CSS intake may not achieve the expected effect, but instead increase the risk of glucose intolerance and insulin resistance, which are the core precursors of T2DM. The 2022 Cell study conducted a randomized controlled trial in 120 healthy adults and found that 4 weeks of intake of saccharin, sucralose, aspartame, and stevioside all induced significant glucose intolerance in the subjects, and this effect was mediated by the alteration of gut microbiota. Another 10-year prospective cohort study including more than 100,000 participants also found that daily intake of CSS was significantly associated with a 34% increased risk of T2DM, independent of body mass index (BMI) and total caloric intake.

The mechanism of CSS inducing glucose metabolism disorder is not only related to gut microbiota disorder, but also related to the interference of CSS on the gut-brain axis. CSS can bind to sweet taste receptors on the tongue and intestinal tract, send false sweet signals to the brain through the gut-brain axis, and disrupt the normal coupling between sweet taste and caloric intake. This will lead to increased appetite and craving for high-sugar foods, resulting in excessive caloric intake and weight gain. In addition, CSS can also directly affect the insulin secretion of pancreatic β-cells and the insulin sensitivity of peripheral tissues, further aggravating insulin resistance.

2.2.3. Other Potential Safety Risks

In addition to metabolic disorders, CSS also have other potential safety risks. In 2023, IARC classified aspartame into Group 2B (possibly carcinogenic to humans) based on limited evidence of carcinogenicity in animals and humans. Although the WHO Joint Expert Committee on Food Additives (JECFA) still maintained the ADI of 40 mg/kg body weight for aspartame, this classification has aroused widespread concern about the long-term carcinogenic risk of CSS. In addition, studies have found that long-term high-dose intake of CSS may be associated with an increased risk of adverse neurological outcomes, including headache, dizziness, insomnia, and even epileptic seizures in susceptible populations. Some studies have also found that CSS may have potential nephrotoxicity and hepatotoxicity, which can damage the function of the kidney and liver after long-term intake.

3. NATURAL FUNCTIONAL POLYSACCHARIDES: STRUCTURAL CHARACTERISTICS, GREEN EXTRACTION, MODIFICATION, AND BIOACTIVITY

3.1. Structural Characteristics and Sugar Substitute Potential of Medicinal and Edible Plant Polysaccharides

Natural plant polysaccharides are polymer carbohydrates formed by the polymerization of aldose and ketose through glycosidic bonds, with molecular weights ranging from tens of thousands to millions of Daltons. The physicochemical properties and biological activities of polysaccharides are determined by their structural characteristics, including monosaccharide composition, molecular weight, glycosidic bond type, branching degree, chain conformation, and functional group content. Most medicinal and edible plant polysaccharides are heteropolysaccharides, which are composed of multiple monosaccharides such as glucose, galactose, mannose, arabinose, xylose, rhamnose, galacturonic acid, and glucuronic acid, with a large number of active groups such as hydroxyl, carboxyl, and amino groups in the molecular chain, which are the structural basis for their biological activities.

As sugar substitutes, medicinal and edible plant polysaccharides have unique advantages that CSS cannot match. First, in terms of sweetness and caloric value, most plant polysaccharides have low sweetness intensity, usually 20%-50% of that of sucrose, so they can be used as bulk sugar substitutes to replace sucrose in food, providing similar texture and mouthfeel to sucrose. At the same time, plant polysaccharides cannot be hydrolyzed by digestive enzymes in the human upper gastrointestinal tract, so they cannot be digested and absorbed to provide calories, and their caloric value is only 0-2 kcal/g, which is much lower than that of sucrose (4 kcal/g), belonging to low-calorie or non-calorie sugar substitutes. Second, and most importantly, plant polysaccharides have a variety of biological activities and health benefits, which can not only replace sucrose to reduce sugar intake, but also actively regulate the physiological functions of the human body, which is completely different from the "physiological blankness" of CSS.

3.2. Green Extraction and Microbial Fermentation Modification of White Hyacinth Bean Polysaccharides

In this study, we focused on polysaccharides extracted from white hyacinth beans (WHBP) and white hyacinth flowers (WHFP), and adopted a green extraction technology combining composite enzymatic hydrolysis and low-temperature ultrasound to achieve efficient extraction of active polysaccharides. Traditional polysaccharide extraction methods are mainly hot water extraction, which has the disadvantages of high extraction temperature, long extraction time, low extraction rate, and serious loss of polysaccharide activity. High temperature will lead to the degradation of polysaccharide molecular chains and the destruction of active groups, thus reducing the biological activity of polysaccharides.

The composite enzymatic hydrolysis technology adopted in this study uses a compound enzyme system composed of cellulase, pectinase, and papain. The compound enzyme can specifically degrade the cellulose, pectin, and protein in the plant cell wall, break the dense cell wall structure, and fully release the intracellular polysaccharides, thus significantly improving the extraction rate of polysaccharides. On this basis, the low-temperature ultrasound-assisted extraction technology uses the cavitation effect, mechanical effect, and thermal effect of ultrasound to further destroy the plant cell wall, promote the dissolution of polysaccharides, and shorten the extraction time. More importantly, the whole extraction process is carried out at a low temperature below 40°C, which effectively avoids the degradation of polysaccharide molecular chains and the loss of active groups caused by high temperature. The results showed that this green extraction technology achieved a WHBP purity of ≥65% and a biological activity retention rate of ≥90%, which was significantly better than the traditional hot water extraction method.

In order to further improve the biological activity of WHBP and WHFP, we adopted microbial fermentation modification technology using Bacillus subtilis and Lactobacillus casei, which are both food-grade probiotics with high safety. Microbial fermentation is an efficient, green, and safe polysaccharide modification method, which has been widely used in the structural modification and activity enhancement of plant polysaccharides in recent years. During the fermentation process, the microorganisms can secrete a variety of glycosidases, which can specifically hydrolyze the glycosidic bonds in the polysaccharide molecular chain, degrade the high-molecular-weight polysaccharides into low-molecular-weight polysaccharides and oligosaccharides, reduce the molecular weight of polysaccharides, and increase the content of reducing ends. At the same time, fermentation can also change the monosaccharide composition, branching degree, and functional group content of polysaccharides, expose more active hydroxyl and carboxyl groups, thus significantly enhancing the biological activity of polysaccharides.

Our experimental results showed that after fermentation by Bacillus subtilis or Lactobacillus casei, the molecular weight of WHBP decreased from 87.7 kDa to 45.8 kDa, and the molecular weight of WHFP decreased from 106.387 kDa to 36.364 kDa. The in vitro activity test confirmed that the free radical scavenging ability, α-amylase inhibitory activity, and bile salt binding ability of the fermented WHBP and WHFP were significantly improved compared with the unfermented crude polysaccharides, which was consistent with the results of previous studies on microbial modification of plant polysaccharides.

3.3. Core Biological Activities of Fermented White Hyacinth Bean Polysaccharides

A series of in vitro and in vivo experiments confirmed that the fermented WHBP and WHFP have a variety of significant biological activities, which lay a solid foundation for their application as functional sugar substitutes.

3.3.1. Antioxidant Activity

Oxidative stress caused by the excessive production of reactive oxygen species (ROS) is the core pathological mechanism of metabolic syndromes, aging, inflammation, and other diseases. The antioxidant activity of polysaccharides is mainly derived from the active hydroxyl and carboxyl groups in their molecular chains, which can provide hydrogen atoms to quench free radicals, chelate metal ions that catalyze free radical generation, inhibit lipid peroxidation, and improve the activity of endogenous antioxidant enzymes in the body.

Our experimental results showed that the fermented WHBP and WHFP have strong scavenging ability against DPPH free radicals, ABTS free radicals, and hydroxyl free radicals, and the scavenging rate showed a significant dose-dependent relationship. Compared with unfermented polysaccharides, the free radical scavenging ability of fermented WHBP and WHFP was increased by more than 40%, which was mainly due to the decrease of molecular weight after fermentation, the exposure of more active hydroxyl groups, and the increase of reducing sugar content. In addition, in vivo experiments in diabetic mice also confirmed that WHBP can significantly increase the activity of superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH-Px) in serum and liver, reduce the content of malondialdehyde (MDA, a marker of lipid peroxidation), and effectively alleviate the oxidative stress damage caused by diabetes.

3.3.2. Hypoglycemic and Insulin Sensitizing Activity

Postprandial hyperglycemia is the earliest clinical manifestation of T2DM, and also an important risk factor for diabetic complications. α-amylase and α-glucosidase are the key enzymes in the process of carbohydrate digestion and absorption in the human body. Inhibiting the activity of these two enzymes can delay the hydrolysis and absorption of starch and other carbohydrates, reduce the postprandial blood glucose peak, and improve glucose tolerance.

Our in vitro experiments confirmed that fermented WHBP and WHFP can significantly inhibit the activity of α-amylase, and the inhibitory rate increased with the increase of polysaccharide concentration. Compared with acarbose, a clinical α-glucosidase inhibitor, WHBP has a milder inhibitory effect, which will not cause serious gastrointestinal side effects such as abdominal distension and diarrhea, and has higher safety. In addition, in vivo experiments in type 2 diabetic mice showed that intragastric administration of WHBP for 4 weeks can significantly reduce fasting blood glucose, improve oral glucose tolerance and insulin tolerance, and increase the insulin sensitivity index of mice. The hypoglycemic mechanism of WHBP is not only related to the inhibition of carbohydrate digestive enzyme activity, but also related to the regulation of gut microbiota, promotion of short-chain fatty acid (SCFA) production, activation of AMP-activated protein kinase (AMPK) signaling pathway, promotion of hepatic glycogen synthesis, and inhibition of hepatic gluconeogenesis.

3.3.3. Hypolipidemic and Cardiovascular Protective Activity

Hyperlipidemia, characterized by elevated serum total cholesterol (TC), triglyceride (TG), and low-density lipoprotein cholesterol (LDL-C) levels, and decreased high-density lipoprotein cholesterol (HDL-C) level, is the core risk factor for atherosclerosis and cardiovascular diseases. Bile salts are the main metabolites of cholesterol in the liver, and the binding of polysaccharides to bile salts can promote the excretion of bile salts from feces, thereby accelerating the conversion of cholesterol in the liver to bile salts, and reducing the serum cholesterol level.

Our experimental results showed that fermented WHBP and WHFP have strong binding capacity to a variety of bile salts, including sodium glycodeoxycholate, sodium taurocholate, and sodium cholate, and the binding capacity was significantly higher than that of unfermented polysaccharides. In vivo experiments in hyperlipidemic mice confirmed that WHBP can significantly reduce serum TC, TG, and LDL-C levels, increase HDL-C level, and reduce lipid deposition in the liver, effectively improving hyperlipidemia and hepatic steatosis. In addition, WHBP can also inhibit the expression of genes related to lipid synthesis in the liver, and promote the expression of genes related to lipid catabolism, further regulating lipid metabolism.

3.3.4. Prebiotic Effect and Intestinal Barrier Protection Activity

As mentioned above, the core defect of CSS is the disruption of gut microbiota homeostasis, while the core advantage of NPs as sugar substitutes is their excellent prebiotic effect and intestinal barrier protection activity. WHBP cannot be digested and absorbed by the human upper gastrointestinal tract, and can completely reach the colon, where it is selectively fermented and utilized by beneficial bacteria in the gut, promoting the proliferation of beneficial bacteria and inhibiting the growth of harmful bacteria, thus regulating the structure of gut microbiota.

Previous studies have confirmed that WHBP can significantly promote the proliferation of Bifidobacterium and Lactobacillus in the gut, increase the abundance of beneficial bacteria, reduce the abundance of harmful bacteria such as Escherichia coli and Enterococcus, and improve the diversity of gut microbiota. The beneficial bacteria ferment WHBP to produce a large amount of SCFAs, mainly including acetic acid, propionic acid, and butyric acid. SCFAs are not only the main energy source of intestinal epithelial cells, but also important signaling molecules that can regulate a variety of physiological functions of the host. Butyric acid can repair the intestinal barrier, increase the expression of tight junction proteins in intestinal epithelial cells, reduce intestinal permeability, and inhibit the translocation of endotoxin into the blood, thereby alleviating chronic low-grade inflammation. In addition, SCFAs can also regulate glucose and lipid metabolism through the gut-brain axis and gut-liver axis, improve insulin sensitivity, and exert systemic health benefits.

3.3.5. Immunomodulatory Activity

In addition to the above activities, WHBP also has significant immunomodulatory activity, which is another important advantage that CSS cannot match. The immune system is the body's defense system against pathogen infection and tumor occurrence, and immunomodulatory activity is one of the most classic biological activities of plant polysaccharides. Studies have confirmed that WHBP can activate macrophages, T lymphocytes, B lymphocytes, and natural killer (NK) cells, promote the secretion of cytokines such as interleukin-2 (IL-2), interleukin-6 (IL-6), and tumor necrosis factor-α (TNF-α), and enhance the non-specific and specific immune functions of the body. As a sugar substitute, WHBP can not only reduce sugar intake, but also improve the body's immunity, which is in line with the current consumer demand for healthy food.

4. COMPREHENSIVE COMPARISON AND APPLICATION PROSPECT ANALYSIS

4.1. Multi-dimensional Comprehensive Comparison Between CSS and NPs

In order to systematically clarify the advantages and limitations of CSS and NPs as sugar substitutes, we conducted a multi-dimensional comprehensive comparison based on the latest research data at home and abroad, as shown in Table 1.

Table 1. Comprehensive Comparison of Chemical Synthetic Sweeteners and Natural Functional Polysaccharides

Feature	Chemical Synthetic Sweeteners (CSS)	Natural Functional Polysaccharides (NPs, represented by WHBP)
Caloric Value	Zero or near-zero	Low to Moderate (0-2 kcal/g, non-digestible in upper gut)
Sweetness Intensity	Ultra-high (30-8000 times that of sucrose, high efficiency)	Low (20%-50% of sucrose, bulk sugar substitute potential)
Processing Stability	Excellent (stable under high temperature, acid and alkali)	Moderate (sensitive to excessive high temperature, suitable for mild processing)
Production Cost	Extremely low	Moderate to high (related to extraction and modification technology)
Metabolic Impact	Potential disruption of gut microbiota, induction of glucose intolerance and insulin resistance	Prebiotic effect, regulation of gut microbiota, improvement of insulin sensitivity and glucose metabolism
Bioactivity	None	Antioxidant, hypoglycemic, hypolipidemic, anti-inflammatory, immunomodulatory, intestinal barrier protection
Production Process	Chemical synthesis, high pollution and waste emission	Green extraction, low emission and environmental protection
Long-term Safety	Controversial potential risks of metabolic disorders and carcinogenicity	High safety, approved as medicinal and edible ingredient, no obvious toxic and side effects
Consumer Acceptance	Declining due to safety concerns	Rising rapidly, in line with the demand for natural and healthy food

From the comparison, it can be seen that CSS have obvious advantages in sweetness intensity, processing stability, and production cost, which are still irreplaceable in some application scenarios that require high sweetness and low dosage. However, their potential long-term health risks and lack of functional benefits have become the biggest limitations for their development, and the consumer acceptance of CSS is gradually declining with the deepening of safety research. In contrast, NPs represented by WHBP have outstanding advantages in safety, biological activity, and health benefits, which are in line with the development trend of the food industry and consumer demand for healthy food. Although NPs have limitations such as low sweetness intensity and relatively high production cost, these problems can be solved through formula compounding and technological upgrading.

4.2. Application Prospect of WHBP as a New-Generation Functional Sugar Substitute

With the transformation of consumer demand from "sugar reduction" to "healthy sugar reduction", the sugar substitute market is undergoing a structural upgrade, and natural functional sugar substitutes have become the mainstream development direction in the future. WHBP, as a functional polysaccharide derived from classic medicinal and edible homologous plants, has broad application prospects in the food and health product industry.

First, in the field of functional sugar-free food, WHBP can be used as a bulk sugar substitute to replace sucrose in baked goods, dairy products, jam, cereal products, and other foods. It can not only reduce the sugar content and caloric value of the product, but also improve the nutritional value and functional properties of the product. At the same time, WHBP can be compounded with high-intensity natural sweeteners such as steviol glycosides and mogroside, which can not only make up for the lack of sweetness intensity of WHBP, but also improve the taste quality of high-intensity sweeteners, reduce the bitter aftertaste, and form a compound functional sugar substitute formula with both good taste and health benefits, which can be widely used in sugar-free beverages and other fields.

Second, in the field of health food and special medical food, WHBP can be developed into a variety of functional health products with hypoglycemic, hypolipidemic, intestinal conditioning, and immunomodulatory effects, such as polysaccharide granules, oral liquid, and probiotic compound preparations. For special populations such as diabetic patients, obese people, and people with intestinal flora disorders, WHBP can not only meet their demand for sweet taste, but also assist in the regulation of blood glucose, blood lipid, and intestinal health, which has important application value.

In addition, the raw material of WHBP is white hyacinth bean, which is widely planted in China, with abundant resources and low price. The green extraction and fermentation modification technology adopted in this study has the advantages of high efficiency, low energy consumption, and environmental protection, which is suitable for industrial scale-up production. The development of WHBP functional sugar substitute can not only promote the high-value utilization of white hyacinth bean resources, but also drive the development of the characteristic agricultural industry, which has good economic and social benefits.

5. SUMMARY AND PROSPECTS

With the global pandemic of metabolic syndromes and the continuous improvement of public health awareness, the demand for sugar substitutes has undergone a fundamental transformation from simple calorie reduction to functional health benefits. This paper systematically evaluates the advantages and limitations of chemical synthetic sweeteners (CSS) and natural functional polysaccharides (NPs) through the latest research evidence, with a specific focus on the extraction, modification, biological activity, and application potential of white hyacinth bean polysaccharides (WHBP) and white hyacinth flower polysaccharides (WHFP).

The results show that CSS represented by aspartame and sucralose have the advantages of ultra-high sweetness intensity, zero caloric value, low production cost, and excellent processing stability, which have dominated the sugar substitute market for decades. However, emerging studies have confirmed that long-term intake of CSS, even within the ADI range, may disrupt the homeostasis of gut microbiota, damage the intestinal barrier, induce glucose intolerance and insulin resistance, and increase the risk of metabolic syndromes, with potential long-term safety risks. In contrast, NPs derived from medicinal and edible plants, especially the fermented WHBP and WHFP focused on in this study, have excellent safety and a variety of significant biological activities, including antioxidant, hypoglycemic, hypolipidemic, prebiotic, intestinal barrier protection, and immunomodulatory effects. The green extraction technology combining composite enzymatic hydrolysis and low-temperature ultrasound can achieve efficient extraction of WHBP with high purity and high activity retention, and microbial fermentation modification can further reduce the molecular weight of polysaccharides and significantly enhance their biological activity. As a new-generation functional sugar substitute, WHBP can not only replace sucrose to reduce sugar intake and caloric value, but also exert multi-target health regulation effects, which is in line with the development trend of the food industry and consumer demand for healthy food.

For future research and industrial application, we put forward the following prospects: First, further optimize the green extraction and microbial fermentation modification technology of WHBP, improve the extraction rate and activity of polysaccharides, reduce the production cost, and realize the large-scale industrial production of WHBP. Second, carry out large-sample, long-term randomized controlled clinical trials to clarify the dose-effect relationship, long-term safety, and health benefits of WHBP in the human body, and provide more sufficient clinical evidence for its application. Third, develop compound functional sugar substitute formulas based on WHBP, optimize the taste and processing adaptability of the products, and expand their application in different food fields. Fourth, further explore the molecular mechanism of the biological activity of WHBP, clarify its specific action targets and signal pathways, and lay a theoretical foundation for its wider application in the fields of functional food and medicine.

In conclusion, natural functional polysaccharides represented by white hyacinth bean polysaccharides have become the development direction of the new generation of functional sugar substitutes. Compared with traditional chemical synthetic sweeteners, they can not only meet the demand for sweet taste, but also bring comprehensive health benefits to consumers, which has broad market prospects and important research value.

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