

Garlic polysaccharides as promising functional food ingredients

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Abstract. Garlic (*Allium sativum* L.), originating in Central Asia, has gained global popularity for its distinctive flavour and medicinal properties. One of its key active components, garlic polysaccharides (GPs), can be extracted directly from water or recovered from garlic processing wastewater, contributing to sustainable agricultural development. GPs belong to the neokestose-based fructans family and are characterized by an inulin-type structure. They feature a (2→1)-linked β-D-Fruf backbone with (2→6)-linked β-D-Fruf side chains, and the total molecular weight is less than 10,000 Da. Research suggests that GPs exhibit antioxidant and immune-boosting effects, with enhanced efficacy reported through phosphorylation or selenylation derivatives. Notably, GPs demonstrate a remarkable oil adsorption capacity and have shown efficacy in reducing total cholesterol levels in diabetic mice, highlighting their hypolipidemic properties. Additionally, GPs have proven effective in ameliorating intestinal flora disorders, alleviating symptoms in models of alcoholic liver fibrosis and dextran sodium sulfate-induced Colitis. The process of obtaining GPs involves extraction, chromatographic purification, and spray drying, resulting in fine particle powder characterized by a white colour, odourlessness, good water solubility, and stability. These qualities make GPs promising functional food ingredients with potential health benefits.

1 Introduction

The rapid pace of modern life, coupled with a sedentary lifestyle and insufficient exercise, increasing mental pressure, unhealthy living environments, and poor dietary habits, has led to a surge in health problems. These include metabolic disorders, diabetes, obesity, hyperlipidemia, and associated chronic diseases and complications, as well as gastrointestinal issues such as gut dysbiosis and constipation. These health issues significantly impact the quality of daily life and contribute to substantial medical costs, placing a burden on both individuals and society. According to the International Diabetes Federation (IDF) data from 2021, the global prevalence of diabetes rose by 16% from 2019 to reach 537 million adults, and it is projected to increase to 783 million by 2045. The associated global direct health expenditure is expected to rise from USD 760 billion to USD 845 billion [1]. China faces a particularly severe challenge, with the number of diabetes patients reaching 116 million in 2019, making it the country with the highest number of diabetes cases globally. The prevalence of diabetes and prediabetes is alarming, with 50.5% of the population at potential risk [2]. However, awareness and treatment rates remain low. Lifestyle interventions, including dietary changes, have been shown to significantly reduce the incidence of diabetes and related complications [3]. Similarly, lifestyle factors, especially diet, contribute to obesity and dyslipidemia, leading to metabolic abnormalities and various complications, such as hypertension and cardiovascular

diseases [4]. In China, over half of adults are overweight or obese, with a 40% prevalence of dyslipidemia. Childhood obesity rates have also risen dramatically. Chronic disease prevention and control account for 80% of medical expenses and over 80% of annual deaths in China, presenting a significant challenge [5]. Gastrointestinal health problems, often overlooked, have become a critical factor affecting life quality. Intestinal issues are prevalent, affecting 90% of the population with age, and are linked to metabolic diseases [6]. Improving intestinal flora has shown promise in alleviating chronic diseases [7]. Given the increasing burden of chronic diseases worldwide, exacerbated by the COVID-19 pandemic, prevention and control have become global health priorities [8]. Natural plant active ingredients, such as polysaccharides, polyphenols, and flavonoids, are gaining attention for their potential in preventing and treating chronic diseases [9].

Garlic, a traditional remedy with a history spanning 5,000 years, is rich in active ingredients like sulfur compounds, polypeptides, and polysaccharides [10]. Garlic polysaccharides (GPs), comprising fructans linked by β-2-1 fructose glycosidic bonds, have demonstrated antioxidant, bacteriostatic, immune, and intestinal improvement effects [11]. GPs can be efficiently extracted from garlic processing wastewater, contributing to sustainable agricultural development. Considering the current prevalence of chronic diseases and the lack of dietary fibre, exploring the benefits of GPs becomes crucial. Encouraging the food industry to produce stable, affordable, and healthy diets can play a

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significant role in preventing and treating chronic diseases effectively.

2. Functional advances in garlic polysaccharides research

Although the efficacy of garlic has been studied for a long time, it is only in recent years that the active ingredients in garlic have been specially isolated and purified for efficacy study.

2.1. Antioxidant activity

The GPs extracted and purified from garlic using a hot water extraction method demonstrated significant effects in terms of hydroxyl radical scavenging ability, superoxide anion scavenging ability, reducing power, and anti-lipid peroxidation Ability. Subsequently, derivatives of GPs were further prepared, including sulfated GPs, phosphorylated GPs, and carboxymethylated GPs. Phosphorylated GPs and carboxymethylated GPs demonstrated enhanced hydroxyl radical scavenging ability by approximately 110% and 88%, respectively, while also exhibiting increased anti-lipid peroxidation ability by around 50% and 130%, as compared to untreated GPs [12]. The study revealed that the introduction of phosphoryl and carboxymethyl groups appeared to enhance antioxidant performance, while the introduction of sulfate groups may attenuate its antioxidant properties.

2.2. Immunomodulatory effect

GPs, as a crucial component of fresh garlic, exhibit notable biological activity in immune regulation. Polysaccharides extracted from fresh garlic effectively enhance the phagocytic activity of macrophages, release nitric oxide (NO), and modulate the expression of various immune-related cytokines, thereby improving the immune function of RAW 264.7 macrophages. In contrast, fermented black garlic, due to the degradation of polysaccharides, loses its immune activity [13]. Furthermore, selenium-modified GPs demonstrated the potential for further enhancing immune activity. At concentrations ranging from 0.391 to 0.098 $\mu\text{g/mL}$, selenium-modified GPs increased lymphocyte proliferation rates by 31.33%. Correspondingly, the anti-inflammatory cytokines IL-2, IL-4, and INF- γ also exhibited significant elevation. Selenium modification promoted the secretion of anti-inflammatory cytokines by T cells, significantly augmenting immune function [14].

2.3. Hypolipidemic effect

GPs demonstrate a notable lipid-lowering effect through both *in vitro* and *in vivo* experiments. *In vitro* studies revealed their remarkable performance in cholesterol adsorption, bile acid adsorption, oil-holding capacity, and inhibition of lipase activity, suggesting its potential

role in restricting lipid absorption and digestion. Among them, GPs demonstrated outstanding lipid adsorption capability, with each gram of the sample adsorbing 315 mg of plant oil. In contrast, the control, inulin, under the same conditions, only adsorbed 51 mg [15]. *In vivo* investigations involving normal and diabetic mice indicated that GPs significantly reduced liver index, triglyceride, and low-density lipoprotein cholesterol levels. In diabetic model mice, the hepatic tissue homogenate exhibited a significant increase in total cholesterol content, reaching 14.26 mmol/kg. However, after gastric administration of GPs, the total cholesterol content markedly decreased to 11.40 mmol/kg. Although it did not reach the standard observed in normal mice (7.72 mmol/kg), this unequivocally demonstrates the advantageous impact of GPs in regulating blood lipids [15].

2.4. Hypoglycemic effect

GPs demonstrate significant hypoglycemic effects in both *in vitro* and *in vivo* experiments. *In vitro*, GPs exhibited glucose adsorption capacity and inhibitory effects on α -amylase and α -glucosidase, with a dose-dependent increase in hypoglycemic efficacy. *In vivo* experiments on diabetic mice revealed that GPs not only effectively ameliorated polyphagia and polydipsia symptoms but also significantly reduced fasting blood glucose by 42% in the high-dose group, demonstrating remarkable hypoglycemic effects. Additionally, GPs influenced serum levels of leptin, glucose, glycosylated serum protein, and insulin, indicating their potential regulatory role in metabolism. The study resulted suggest that GPs may participate in the regulation of hepatic glycogen metabolism by modulating key enzymes such as glucokinase, glycogen synthase, and phosphoenolpyruvate carboxykinase [16]. The elevation of glucokinase and glycogen synthase promotes hepatic glycogen synthesis, while the reduction of phosphoenolpyruvate carboxykinase inhibits hepatic gluconeogenesis. Consequently, during metabolic abnormalities, the increase in hepatic glycogen reserves serves to lower blood glucose levels. Overall, the findings highlight the potential hypoglycemic mechanisms of GP, involving glucose adsorption, enzyme inhibition, and metabolic regulation, both *in vitro* and *in vivo*.

2.5. Hepatoprotective effect

GPs has demonstrated significant hepatoprotective effects in experimental studies. The research revealed that the GPs-treated group exhibits a comprehensive range of protective mechanisms in mice with alcohol-induced liver fibrosis. These mechanisms included reducing liver function indicators such as alanine aminotransferase and aspartate aminotransferase levels, alleviating oxidative stress and inflammatory responses, modulating inflammatory signaling pathways, promoting the expression of the anti-fibrotic protein decorin, and finally improving the morphological structure of liver

tissues. Following gastric administration of GPs, malondialdehyde levels in alcoholic liver fibrosis model mice decreased by 37.5%. Concurrently, superoxide dismutase, glutathione peroxidase, and glutathione levels increased by 33.3%, 48.5%, and 57.1%, respectively. Simultaneously, the expression of the pro-inflammatory cytokines transforming growth factor β 1 and tumor necrosis factor α decreased by 60% and 25%, respectively [17].

2.6. Gastrointestinal regulation

Through gavage feeding, GPs reduced the ratio of Firmicutes to Bacteroidetes and increased the abundance of the probiotic *Akkermansia* in the cecal contents of normal mice [15]. In the intestines of mice with dextran sulfate sodium-induced colitis, GPs effectively decreased the abundance of microbiota associated with colitis, including *Muribaculaceae*, *Lachnospiraceae*, *Lachnospiraceae_NK4A136_group*, *Mucispirillum*, *Helicobacter*, *Ruminococcus_1*, and *Ruminiclostridium_5* [18]. This indicates its potential as a prebiotic in regulating intestinal microbiota.

3. Prospects of application

The preliminary research indicates that GPs are branched oligosaccharides with relatively low molecular weight. Comparing their structural features, similarities were observed between GPs and inulin as well as polydextrose. Drawing insights from the current applications of inulin and polydextrose in the food industry, this study explores the potential applications and prospects of GPs. The examination of structural characteristics reveals promising opportunities for the utilization of GPs in various food applications.

3.1. Prebiotic & probiotic

Fructans have been reported to exhibit excellent prebiotic effects. Inulin, for instance, enhances intestinal health by increasing tight junction protein content, modulating the gut microbiota, and elevating short-chain fatty acid levels. GPs can be processed into powder form, for example, through spray drying, and directly consumed as a prebiotic supplement. Additionally, considering the previously reported role of GPs in promoting the growth of probiotics, there is potential for developing a symbiotic product by encapsulating them with probiotics such as *bifidobacteria* and *Akkermansia*. This synergistic approach aims to collectively support and maintain gut health.

3.2. Dietary fibre supplement

The recommended daily intake of dietary fibre for the average adult is around 25-30 grams, with a potential improvement in health conditions such as diabetes, obesity, and high cholesterol seen at intake levels exceeding 35 grams under certain disease conditions [19]. However, statistics reveal a significant decline in

the dietary fibre intake among Chinese adults, plummeting from 13.3 grams to 9.9 grams, marking a substantial 26% reduction. These findings underscore a concerning trend, suggesting that the already low intake of dietary fibre is further diminishing, posing a potential risk in a society grappling with a high prevalence of chronic diseases. To effectively prevent and address the aforementioned chronic health issues, it becomes imperative to enhance daily dietary fibre consumption [20]. GPs, characterized by a β -type configuration in the linking pattern of fructans, remain indigestible and absorbable by the human body. Consequently, they prove to be an excellent choice as a dietary fibre supplement, seamlessly integrating into daily diets. A general recommendation for the average individual is to supplement 10-15 grams of GPs daily, while those afflicted with chronic diseases or experiencing inadequate dietary fibre intake may consider a higher supplement dosage, around 30 grams per day.

3.2. Functional beverage

There are currently three main categories of functional beverages in the market, each serving distinct purposes. First, there are energy drinks designed to replenish energy and alleviate fatigue. Second, there are peptide-based or vitamin-enriched beverages aimed at boosting immunity. Lastly, there are fibre-rich beverages targeting the supplementation of dietary fibre. Polydextrose, chosen for its high water solubility and stability, has become the preferred ingredient for fibre-rich beverages. The growing awareness of health consciousness in recent years has led to an increasing market demand for such beverages [21]. GPs, characterized by high water solubility and lack of distinct taste, present an opportunity to emulate polydextrose and develop fibre-rich functional beverages. This innovative approach opens avenues for creating beverages that not only provide the benefits of dietary fibre but also leverage the unique characteristics of GPs. As consumer preferences continue to evolve towards healthier choices, the development and preparation of fibre-rich functional beverages, incorporating GPs, may witness a surge in market acceptance and sales.

3.3. Fermented dairy products

Fermented dairy products are produced by using raw cow (or sheep) milk or milk powder as raw materials, which are sterilized and fermented to achieve a lowered pH value. This category includes acidophilus milk, flavored fermented milk, and flavored acidophilus milk. Fermented dairy products are highly favored by consumers due to their elevated nutritional value and distinctive flavors. To expedite the fermentation process of probiotics and enhance the physicochemical properties of fermented dairy products, consumers have adopted the practice of incorporating prebiotics into these products. This not only accelerates the growth of beneficial bacteria but also contributes to the enrichment of the flavor characteristics of fermented dairy products.

[22]. The addition of prebiotics has become a popular strategy to further improve the overall quality and health-promoting aspects of fermented dairy items.

3.4. Fermented sausages

Fermented sausages are meat products created by combining minced meat, animal fat, seasoning, fermenting agents, and spices, which are then stuffed into casings and undergo microbial fermentation, resulting in stable microbial characteristics and a distinctive fermented flavor. In traditional fermented sausage production, the addition of animal fat is a common method to enhance quality. However, with the increasing demand for healthy diets, the excessive intake of fats can impact overall health, potentially leading to chronic diseases such as obesity. To address health concerns related to fat intake, an effective strategy involves increasing the addition of polydextrose during the fermentation process. This not only reduces the amount of added fat but also introduces prebiotics, which shorten the fermentation time, generate more small peptides, and enhance the production of enticing flavour compounds [23]. This innovative approach not only meets health-conscious dietary requirements but also results in fermented sausages with a more appealing sensory profile.

3.5. Baked products

Bakery products, similarly, have a high demand for dietary fibre. By increasing the dietary fibre content, the water-holding capacity of bread can be enhanced, effectively preventing bread from becoming stale. Combining dietary fibre with water to create fat substitutes allows for the partial replacement of vegetable oils, reducing the overall fat content in cookies. This not only lowers the calorie content of the product but also maintains sensory quality. As a result, baking products become healthier, aligning with consumer preferences for healthier choices. This innovative approach caters to the increasing consumer demand for healthier baked goods without compromising on taste and texture.

3.6. Cosmetics

Moisturizing and anti-aging skincare products typically require the addition of moisturizing agents and antioxidants to enhance their cosmetic and skincare benefits. GPs, characterized by high water solubility, can be further tested for their hygroscopic and water-retention properties. Concurrently, comparisons with the commercial moisturizer glycerin can be made to explore potential moisturizing skincare effects. Additionally, considering the confirmed antioxidant properties of GPs, there is potential for further development of skincare products with anti-oxidative and anti-aging effects.

3.7. Pharmaceuticals

Based on existing literature research, it is evident that GPs exhibit diverse physiological activities, such as antioxidant, hypoglycemic, lipid-lowering, immune modulation, and gastrointestinal regulation. Consequently, there is potential for further in-depth exploration of their mechanisms of action, leading to the development of Pharmaceuticals with specific therapeutic effects. However, this necessitates rigorous and comprehensive experimental validation, including detailed toxicology studies, animal experiments, and clinical trials.

4. Conclusion

To sum up, further research on the effects of GPs is essential for elucidating its potential and expanding its application fields, thus maximizing its value. This in-depth exploration can significantly contribute to the comprehensive utilization of garlic by-products, promoting green agriculture and sustainable development. Given the current research status, GPs are recognized as a soluble dietary fiber characterized by excellent water solubility, colorlessness, and tastelessness. It exhibits a wide range of processing adaptability, making it suitable for use in the market as dietary fiber supplements, prebiotics, or food additives. Considering the prevalent occurrence of chronic diseases and their complications resulting from lifestyle factors, particularly poor dietary habits, dietary fiber supplementation has emerged as a crucial strategy for countries aiming to prevent and manage conditions such as diabetes and hyperlipidemia. The cost-effective and readily available water-soluble dietary fiber, such as GPs, has the potential to meet public demand in terms of yield and can play a pivotal role in encouraging dietary structure changes. Moreover, optimizing the extraction process of GPs to enhance its yield is an important aspect that requires attention. Investigating efficient extraction methods will contribute not only to the economic feasibility of GPs but also to the scalability of its production. Furthermore, exploring the compatibility of GPs with other ingredients can contribute to the development of novel foods or enhance the efficacy of products for health promotion. Understanding the synergistic effects of GPs when combined with other components can pave the way for innovative formulations with enhanced health benefits. This avenue of research holds promise for the creation of functional foods and dietary supplements that leverage the complementary properties of different bioactive compounds, offering new possibilities for preventive healthcare and improved well-being.

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