REVIEW

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Exploration of black garlic's functions and its applications

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Author contributions

Xu BL conceived the structure of this article and wrote the paper. Wang YY and Li FH collected data and analyzed relevant studies. Dong CM directed the drawing and critically reviewed the article. All authors read and approved the final manuscript.

Competing interests

The authors declare no conflicts of interest.

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Abbreviations

SOD, superoxide dismutase; SAC, S-allyl-L-cysteine; 5-HMF, 5-hydroxymethylfurfural; BGE, black garlic extract.

Citation

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Abstract

Black garlic is a product transformed from fresh garlic through special processing techniques, possessing a unique flavor, appearance, and enhanced bioactive components. This article provides an overview of the main processing methods, quality influencing factors, chemical composition, health benefits, and applications in the food industry of black garlic. Firstly, we explore the processing technologies including solid-state fermentation, liquid-state fermentation, and ultra-high pressure treatment, and analyze their impacts on the quality of black garlic. Secondly, we describe in detail the complex chemical changes during the processing, which significantly increase the content of bioactive substances such as polyphenols, sulfur-containing compounds, and melanoidins in black garlic. Furthermore, this article elucidates the physiological functions of black garlic in antioxidant, antitumor, immunomodulatory, antibacterial and anti-inflammatory, cardiovascular health protection, and anti-obesity aspects, and introduces its current application status in food fields such as beverages, preserves, and condiments. Black garlic is not only used as a unique food ingredient but also gradually developed into a functional food with health benefits. Lastly, we discuss the challenges faced by the black garlic industry and future development directions, emphasizing the importance of technological innovation, process optimization, and strict quality control in promoting the sustainable development of this industry. Through continuous research and development, the black garlic industry is expected to achieve greater market potential and health value in the future.

Keywords: black garlic; fermentation technology; functionality; food

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Introduction

In the realm of health foods in the 21st century, black garlic, a unique processed product of garlic, is gradually garnering extensive attention from both the scientific community and the market. First invented by Scott Kim in 1997 and refined through nearly a decade of technological optimization, black garlic officially received patent certification in 2007. This milestone marked the transition of this innovative food product from the laboratory to the market [1]. The birth of black garlic not only represents an innovation in traditional food processing techniques but also signifies a significant breakthrough in the field of natural health product research.

Black garlic is produced from fresh garlic through a long fermentation process in a strictly controlled high-temperature and high-humidity environment [2]. This unique processing not only dramatically alters the appearance of garlic, turning its outer skin into a deep black or dark brown color, but also greatly improves its taste, becoming sweet and sour, soft, and elastic, effectively eliminating the pungent and stimulating odor of fresh garlic, thereby significantly broadening consumer acceptance [3, 4]. More importantly, black garlic undergoes complex and subtle chemical changes during processing, which significantly enhance its nutritional value and the content of bioactive components, especially polyphenolic compounds [5], sulfur-containing compounds, and melanoidins [6, 7], making black garlic exhibit exceptional potential in antioxidant, anti-inflammatory, anticancer, and cardiovascular health protection [8].

With the global awakening of health awareness and the surge in demand for natural health products, black garlic, as a food rich in nutrition and possessing various potential health benefits, is gradually becoming a hot topic in the food industry and medical research [9]. Early studies have indicated that black garlic shows promise in reducing the risk of cardiovascular diseases, enhancing immune function, exhibiting antibacterial and anti-inflammatory effects, and demonstrating antitumor properties [10, 11]. However, these findings require further scientific research for validation and deepening. In particular, the bioactive components in black garlic and their potential mechanisms of impact on human health have become important topics urgently needing to be addressed in current scientific research.

Although studies have suggested that black garlic offers a wide range of health benefits, including potential antioxidant, anti-inflammatory, anti-cancer, and cardiovascular health-protecting properties, there is still limited knowledge regarding its exact mechanisms of action and long-term safety. Furthermore, evidence supporting black garlic's prevention of various diseases primarily comes from small-scale or animal experiments, lacking the support of large-scale human studies. In this context, this article aims to comprehensively and systematically review the current research status of black garlic, delving deeply into its processing methods, chemical composition, nutritional value, and health benefits. It also explores the widespread application and potential value of black garlic in food products. By integrating existing research findings, this article will reveal the unique appeal of black garlic as an emerging health food and provide a solid theoretical foundation and practical guidance for its future scientific research and practical applications. We firmly believe that with the continuous deepening of research and advancements in technology, black garlic will undoubtedly showcase broader application prospects in the health food sector, making significant contributions to human health.

Preparation and processing technology of black garlic

Researchers commonly employ heating treatment methods to induce the Maillard reaction in garlic, thereby eliminating its pungent taste and significantly enhancing its softness, elasticity, color, flavor, and aroma, ultimately producing unique black garlic products [12]. The preparation techniques for black garlic mainly include three heat treatment methods: solid-state fermentation, liquid-state fermentation, and ultra-high pressure [13, 14]. The production of black garlic primarily relies on the solid-state fermentation process. It should be noted that the term "fermentation" here does not refer to a microbial fermentation process. So-called fermented black garlic is produced under high temperature and humidity conditions without any additives, allowing the degradation of raw garlic's own tissues and triggering a series of physicochemical reactions. Compared to fresh garlic, fermented black garlic exhibits reduced pungency and irritation, and through the Maillard reaction (Figure 1), it produces a large amount of black melanoidins and other substances, forming the unique quality and appearance characteristics of black garlic [15].

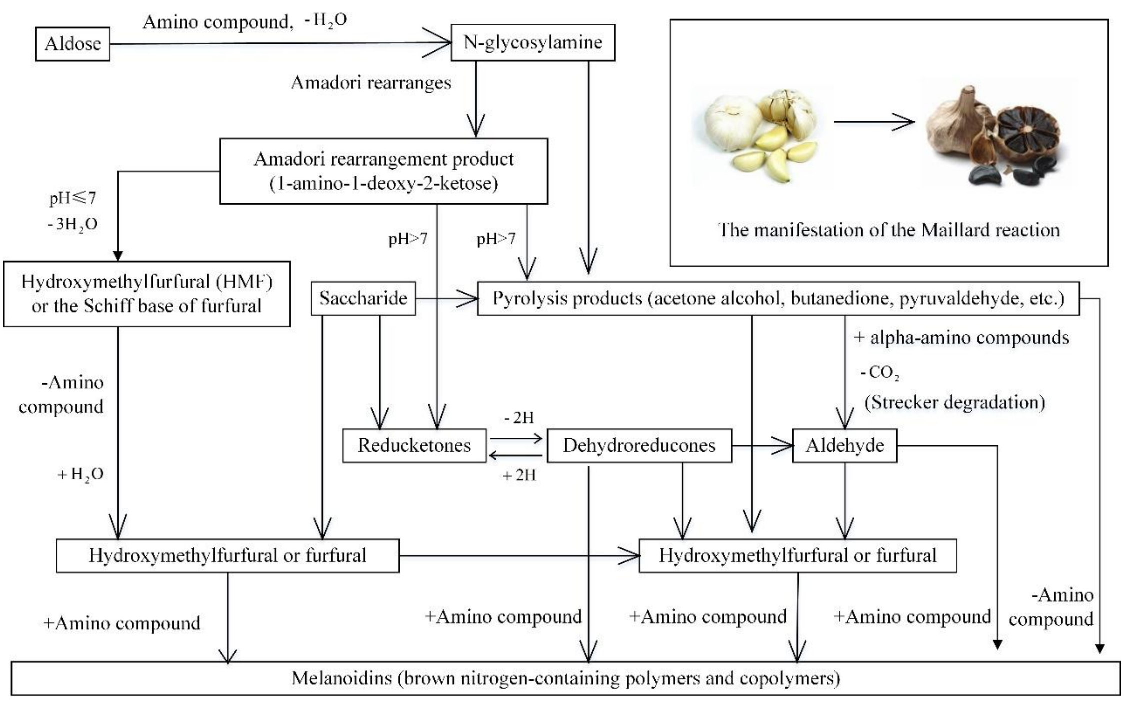

Figure 1 Schematic diagram of Maillard reaction. HMF, hydroxymethylfurfural.

The abundant amino acids and reducing sugars in garlic provide excellent conditions for the Maillard reaction. During the processing of black garlic, thermal effects promote the formation of various reaction products, which are important precursors for the unique aroma and color of black garlic [16]. In addition, the Maillard reaction significantly affects the texture characteristics of black garlic, and the degree of change in texture characteristics increases with higher reaction temperatures. At the same time, various nutritional and functional components in black garlic also undergo significant changes due to the Maillard reaction. To further enhance the quality of black garlic, optimizing the process to better regulate the progress of the Maillard reaction has become crucial. The following is a brief introduction to several main types of black garlic preparation processes:

Solid-state fermentation process for black garlic

Solid-state fermentation, as the dominant process for producing black garlic, focuses on selecting fresh and plump whole garlic bulbs and subjecting them to additive-free fermentation under specific high-temperature and humidity conditions [17, 18]. This process covers multiple stages from raw material selection, pretreatment, and fermentation, to post-processing, ensuring the quality of black garlic products. In recent years, researchers have innovated based on traditional solid-state fermentation methods, developing new production techniques aimed at shortening the fermentation cycle and further enhancing the nutritional content of black garlic. By exploring various pretreatment technologies, such as ultra-high pressure treatment, and combined application of microwave and low temperature [19, 20], the quality indicators of black garlic have been significantly improved. At the same time, precise control of high-temperature and humidity conditions plays a crucial role in the occurrence of key chemical reactions in garlic and the generation of nutritional and functional components in black garlic. However, despite the widespread use of solid-state fermentation technology in black garlic production, it still faces challenges such as high requirements for raw material quality, complex operational processes, suboptimal working environments, and difficulties in achieving automated and industrialized production.

Liquid-state fermentation process for black garlic

Liquid-state fermentation, as an innovative process for black garlic production, covers multiple key steps from raw material selection to final product output. This process begins with the selection of fresh, whole garlic bulbs. After pretreatment, the garlic cloves are broken and mixed with an appropriate amount of water to form a fermentation substrate [3]. This mixture is then packed into high-temperature-resistant polyethylene bags and vacuum-sealed to ensure the closed nature of the fermentation process and effectively block pungent odors, thereby enhancing work environment comfort and efficiency. The use of a fermentation chamber for variable-temperature fermentation helps shorten the fermentation cycle and increase the content of active substances in black garlic [21]. Under optimal process conditions, the total phenol content and superoxide dismutase (SOD) activity of black garlic are significantly increased, with ideal color and no garlic odor [22]. After fermentation, a series of treatments are performed to ultimately form the finished black garlic product. The liquid-state fermentation process is simple to operate, conducive to industrial production, aligns with the production principles of energy efficiency and high effectiveness, and demonstrates significant advantages and wide application potential.

Ultra-high pressure process for black garlic

Ultra-high pressure black garlic, as an emerging production method for black garlic products, is centered on using ultra-high pressure technology to steam garlic within a short time, thereby achieving a rapid black garlic production process. Compared with traditional solid-state and liquid-state fermentation processes for black garlic, the ultra-high pressure black garlic production process has significant advantages such as lower processing costs, shorter production cycles, and relatively simplified processing techniques [23, 24]. Furthermore, this innovative processing technology greatly enhances the nutritional value and functional activity of black garlic products, giving them higher application potential in the health food sector [19]. However, ultra-high pressure black garlic fails to meet the dark brown color standard of traditional black garlic products. At the same time, in terms of sensory indicators such as reducing sugars and acidity, it also exhibits certain gaps compared to fermented black garlic. More importantly, there are certain safety risks associated with the application of ultra-high pressure technology, which limits its widespread use in industrial production. Therefore, a crucial direction for future research will be to further optimize the ultra-high pressure black garlic production process and enhance its safety.

Factors influencing the quality of black garlic

The impact of processing pretreatment methods

In the production process of black garlic, the pretreatment of raw garlic is a crucial step. Low-temperature freezing, ultrasonic pretreatment, and microwave pretreatment are widely adopted technologies. Low-temperature freezing promotes the release and conversion of beneficial substances by disrupting the cell structure of garlic, thereby significantly enhancing the quality of black garlic products. For example, research by Li Ningyang et al. shows that after 30 h of freezing pretreatment, the reduced sugar content in garlic increases significantly, which helps improve the overall quality of black garlic, including increased levels of reducing sugar, amino nitrogen, total phenols, and 5-hydroxymethylfurfural (5-HMF) [25, 26].

Ultrasonic pretreatment, as an emerging technology, disrupts cell structures through the induction of cavitation effects, accelerating chemical reactions in food and contributing to the improvement of the flavor and nutritional value of black garlic. Pei Houbao's research reveals the impact of different pretreatment methods on the processing of black garlic and identifies optimal pretreatment conditions. The results indicate that these methods can significantly increase the content of reducing sugars, polyphenols, and 5-HMF, shorten processing time, and enhance product quality [27]. Zhao Xueqing et al. further confirm that low-temperature freezing pretreatment shortens the processing cycle while improving the quality of black garlic [26].

Microwave pretreatment, as a non-thermal physical processing method, is proven to effectively shorten the processing time of black garlic and improve its quality due to its ability to quickly penetrate materials and achieve simultaneous heating from the inside out. Research by Masztalerz K shows that microwave pretreatment at 450 W can reduce the processing time of black garlic from 21 d to 18 d. Additionally, the microwave-treated group achieves higher browning intensity and reducing sugar content early in the fermentation process and exhibits higher total phenol content throughout the fermentation process [28].

The impact of production processes

The production process has a direct impact on the quality of black garlic. Although the traditional high-temperature and high-humidity preparation method is simple, it suffers from issues such as long processing cycles and high energy consumption. Therefore, researchers have explored various process optimization techniques, such as freezing treatment, high-temperature short-time heating, ultrasonic pretreatment, and adjusting processing temperature and humidity. Among these, the segmented variable-temperature processing method has been proven to significantly shorten the processing time to around 15 d [29]. Research by An Dong shows that compared to fixed-temperature processes, segmented processing techniques can better improve the sensory quality of black garlic products and save energy [30]. However, current research on segmented processing techniques mainly focuses on some conventional indicators such as reducing sugar, amino nitrogen,

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polyphenols, total acid, texture, and browning intensity, without delving into the changes in alliin and its related sulfide content.

The impact of storage conditions

Storage conditions have a significant impact on the quality of black garlic. Research shows that lower temperatures are beneficial for maintaining the main chemical components and functional properties of black garlic. For example, Liu Tianyu et al. studied the effects of different storage temperatures on the quality of black garlic and found that low-temperature storage at 4 °C is more conducive to maintaining the total sugar content, amino acid composition, and antioxidant capacity of black garlic [31]. Zhang Lili et al. focused on the quality changes of black garlic paste during storage, including the variation patterns of indicators such as microorganisms, total acid, total sugar, soluble solids, and texture [32]. In addition, Ma Hongcheng et al. investigated the impact of different packaging materials on the antioxidant activity, solubility, color, and shelf life of black garlic powder. However, there is currently no detailed research exploring the changes in alliin and its related sulfides in black garlic under different storage conditions, which represents an important direction for future research. To more comprehensively understand the impact of storage conditions on the quality of black garlic, future research should pay closer attention to the changes of these compounds during storage, with the aim of finding the best storage strategies to maintain the quality and nutritional value of black garlic.

Chemical components in black garlic

Free amino acid

As core nutrients in food, amino acids not only determine the nutritional value of food but also profoundly influence human taste experience [33]. During the processing of black garlic, proteins undergo decomposition and transformation, ultimately generating amino acids [34]. Some of these amino acids actively participate in the Maillard reaction, giving black garlic its unique flavor and color, while others remain in a free state, providing a rich nutritional foundation for black garlic [35]. Research by Choi et al. [36] found that, except for leucine, isoleucine, methionine, and phenylalanine, the content of other amino acids generally showed a downward trend in processed black garlic, which may be related to the chemical reactions and temperature control during processing.

Saccharide

Reducing sugar is one of the key indicators for measuring the quality of black garlic, and its content directly affects the taste and blackening speed of black garlic. During the processing of black garlic, the fructan in garlic gradually decomposes into various sugars such as glucose, fructose, and sucrose under the influence of enzymatic hydrolysis and high temperature, significantly increasing the reducing sugar content of black garlic to over 60% of the dry weight of the finished product [37]. This significant increase not only enhances the sweetness of black garlic but also brings a richer taste experience.

Sulfur-containing compound

Sulfur-containing compounds are the main biologically active substances in garlic and the primary source of its unique pungent flavor. During the processing of black garlic, heat treatment disrupts garlic cells and vacuoles, releasing alliinase that cleaves cysteine sulfides to form alkyl thioalkyl sulfoxides (mainly allicin) [38]. Allicin is unstable under high-temperature conditions and converts into other sulfur-containing derivatives. These changes bring a faint and pleasant aroma to black garlic and eliminate the undesirable pungent odor and gastrointestinal irritation. Compared with fresh garlic, the content of diallyl trisulfide and allyl methyl trisulfide in black garlic is significantly reduced, while the content of dimethyl trisulfide and allyl methyl sulfide is higher. Among them, allyl methyl sulfide is the most abundant volatile compound in black garlic [39, 40].

As shown in Figure 2, the processing of black garlic involves a series of transformations of organic sulfur compounds in garlic. Initially, these organic sulfur compounds are converted into γ-L-glutamyl-S-allyl-L-cysteine by the action of γ-glutamyl peptidase. Subsequently, this product is further converted into S-allyl-L-cysteine (SAC) or γ-L-glutamyl-S-allyl-L-cysteine-S-oxide through deamidation or S-oxidation. Ultimately, through S-oxidation or deamidation reactions, S-allyl-L-cysteine sulfoxide, also known as alliin, is generated. When garlic is crushed or ground, alliinase hydrolyzes alliin to produce dehydroalanine and allyl sulfonic acid. These two allyl sulfonic acid molecules can then spontaneously condense to form allicin, which is the main source of garlic's pungent odor. However, allicin is unstable and decomposes into volatile sulfides such as diallyl sulfide, diallyl disulfide, and diallyl trisulfide. It is worth noting that during the fermentation process of black garlic, allicin can undergo transformation to produce stable and odorless S-allyl-L-cysteine (SAMC). The content of this compound in black garlic is six times higher than in garlic, which is significant for the formation of black garlic's unique flavor.

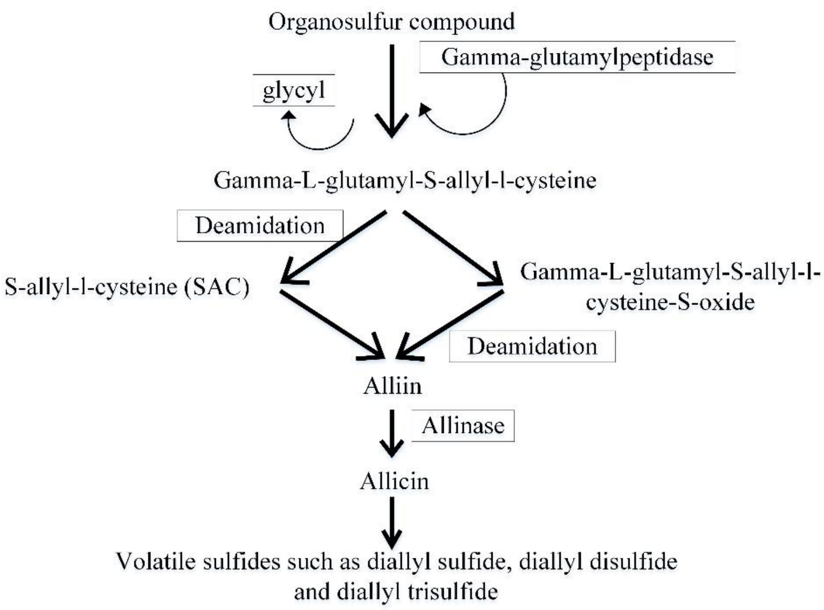

Figure 2 Changes of organic sulfur compounds during the processing of black garlic. SAC, S-allyl-L-cysteine.

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Melanoidin

Melanoidins are a type of nitrogen-containing polymers with a carbohydrate backbone, which often form naturally during food processing and preservation. During the processing of black garlic, the content of melanoidins increases significantly and is closely related to the browning phenomenon. The rate of browning reaction is closely related to heating temperature and relative humidity, and high temperature and high humidity conditions can affect the rate of browning and the formation of melanoidins [41]. Melanoidins have multiple biological activities such as antioxidant [42], antibacterial [43], regulation of intestinal flora, and antihypertensive effects [44], bringing rich health benefits to black garlic.

Polyphenols

Polyphenols are a class of substances that contain one or more aromatic rings and are widely distributed in common foods such as fruits, vegetables, and grains. Garlic is rich in phenolic compounds, including caffeic acid, ferulic acid, vanillic acid, and p-hydroxybenzoic acid. When fresh garlic is processed into black garlic at high temperatures, its content of polyphenols, total flavonoids, and total phenolic acids increases significantly, making black garlic exhibit stronger antioxidant activity [45]. Specifically, when purple-skin garlic is processed into black garlic, the total polyphenol content increases significantly, and the content of coumaric acid and epicatechin also increases significantly.

5-HMF

5-HMF is a low-molecular-weight black compound and one of the main coloring substances in black garlic. It is formed during the thermal processing of food and widely exists in various foods. During the processing of black garlic, sugars undergo thermal degradation reactions to produce 5-HMF, and its content continuously increases with time [46]. The accumulation of 5-HMF is an important reason for the blackening of black garlic and the production of bitter substances, so its content can be used as an important indicator to predict the rate of blackening. Although 5-HMF has certain toxicity, recent research has also revealed its potential value in scavenging free radicals, treating endotoxemia, and improving nerve damage [47].

SOD

SOD is a key metalloenzyme widely present in aerobic or oxygen-tolerant organisms, primarily responsible for scavenging free radicals in organisms and possessing unique physiological activity [48]. SOD levels are closely related to the aging and death processes of organisms. Research indicates that SOD can combat and block the damage caused by oxygen free radicals to cells, promptly repairing damaged cells [49]. In the food industry, SOD is highly favored for its strong antioxidant capacity, especially as the SOD activity in black garlic is significantly increased, bringing enhanced health benefits [50].

Alkaloid

Carboline alkaloids exhibit a variety of biological and pharmacological properties, including anti-anxiety, anti-cancer, anti-parasitic, anti-viral, and antibacterial effects. Fresh garlic contains relatively low levels of β-carboline alkaloids, but after aging or high-temperature fermentation, the content of specific β-carboline derivatives significantly increases, enhancing hydrogen peroxide scavenging activity [51]. Compared to fresh garlic, black garlic, which undergoes spontaneous fermentation at specific temperatures and humidity, shows a significant increase in the content of specific β-carboline carboxylic acids, further promoting its hydrogen peroxide scavenging activity. These biochemical changes bring unique health benefits and pharmacological effects to black garlic [52].

Organic acid

Black garlic is rich in various organic acids, which have a positive effect on human digestive system health, nutrient absorption, and immunity enhancement. Among them, citric acid is particularly abundant, followed by malic acid, lactic acid, formic acid, and fumaric acid. Studies have shown that the total acid content of black garlic increases significantly after processing fresh garlic into black garlic [53]. When comparing the types of organic acids in fresh garlic and black garlic using nuclear magnetic resonance spectroscopy, it was found that fumaric acid disappeared in black garlic, while new organic acids such as formic acid, acetic acid, and succinic acid were formed during the fermentation process. The increase in organic acid content during the preparation of black garlic not only gives it a unique sweet and sour taste but also promotes the hydrolysis of proteins and polysaccharides [54]. Furthermore, the increase in acidity of black garlic is closely related to the Maillard reaction, the degradation of alkaline groups in fresh garlic, and the production of short-chain carboxylic acids [55].

Physiological function of black garlic

Antitumor effect

In recent years, black garlic has received widespread attention due to its significant antitumor effects. Black garlic can effectively inhibit the synthesis of the carcinogen nitrosamine and suppress the growth of cancer cells. Additionally, it contains germanium, a potent anticancer trace element that can inhibit the carcinogen nitrosamine and play a role in cancer prevention and treatment [56]. Furthermore, the selenium in black garlic has strong antioxidant capacity, which can protect cell membranes from oxidative damage, enhance immune function, and inhibit carcinogenesis. Phenylalanine among amino acids has also shown potential in inhibiting tumor growth.

Further research has revealed the significant potential of black garlic extract (BGE) in antitumor effects. For example, studies by Yang Qiwei and others have shown that BGE can significantly promote apoptosis and inhibit proliferation in the human breast cancer cell line MCF-7. This effect may be related to BGE's regulation of phosphorylation activation in the PI3K/Akt/mTOR signaling pathway [57]. Research by Yang Guiqing and others has also found that the combined use of black garlic extract and 60Coγ radiation can significantly inhibit the growth of colon cancer Ht-29 transplanted tumors, which may enhance the sensitivity of tumors to radiotherapy and have a radioprotective effect [58].

It is worth noting that organic sulfides in black garlic, such as diallyl disulfide (DADS) and allicin, have also been proven to have the potential to induce apoptosis in various tumor cells. In particular, they can induce the reversal of epithelial-mesenchymal transition (EMT) in gastric cancer cells, thereby reducing the adhesion ability of tumor cells and the possibility of distant metastasis [59]. This discovery provides a stronger scientific basis for the application of black garlic in antitumor effects and may open up new avenues for its development and utilization in cancer prevention and treatment.

Antioxidation

Black garlic, as an antioxidant, has always received attention for its antioxidant activity. As shown in Figure 3, during the process of garlic being converted into black garlic, the enhancement of antioxidant activity is closely related to the increase in the quantity of some strong antioxidants and the production of new antioxidants. These antioxidants include polyphenols, SAC, SAMC, Amadori compounds, melanoidins, polysaccharides, antioxidant enzymes, and others. The antioxidant function of black garlic may be the result of the synergistic effects of its various components.

Research indicates that after fresh garlic is processed into black garlic through specific methods, its SOD activity, hydrogen peroxide scavenging ability, and polyphenol content are significantly increased [34]. Specifically, black garlic can not only effectively reduce the malondialdehyde content in blood and liver tissues but also enhance the activity of SOD and glutathione peroxidase (GSH-Px), with more pronounced effects compared to white garlic. Furthermore, during storage, black garlic undergoes post-fermentation, which further enhances its free radical scavenging ability, reaching more than 8 times that of fresh garlic. The significant increase in polyphenols and

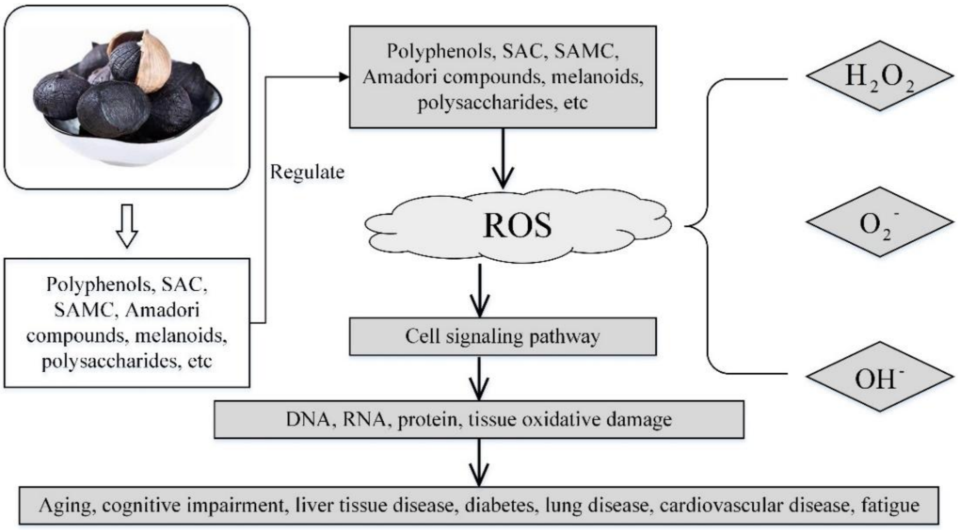

Figure 3 Antioxidant mechanism of black garlic. SAC, S-allyl-L-cysteine; ROS, reative oxygen species.

flavonoids in black garlic is also an important reason for its enhanced antioxidant capacity. It is noteworthy that 5-HMF, a new substance produced during the processing of black garlic, exhibits obvious antioxidant damage effects [60]. Additionally, the significant increase in β-carboline alkaloids in black garlic also confers it with strong hydrogen peroxide scavenging ability [61].

Liver function protection

The liver, as a crucial detoxifying organ in the human body, can accumulate toxins when it is constantly working under overload, leading to a series of health issues. Research has shown that different dosages of black garlic can significantly reduce malondialdehyde content in both blood and liver tissues, while simultaneously enhancing the activity of SOD and GSH-Px. This mechanism of action helps to strengthen the liver's detoxifying function [62]. In addition, the amino acids abundant in black garlic, such as alanine and asparagine, have been proven to significantly enhance liver function, playing an important role in protecting the liver [63]. Further research has also found that black garlic can significantly decrease the levels of plasma markers indicating liver function and injury, such as aspartate aminotransferase and alanine aminotransferase, and can increase the expression and activity of enzymes related to drug metabolism, thereby helping to restore glutathione levels and the activity of various antioxidant enzymes in the liver [64].

Antibacterial and anti-inflammatory effects

Black garlic exhibits significant biological activity due to its effective components such as allicin and allyl sulfide. These compounds interact with sulfhydryl enzymes through their sulfur-containing groups, leading to enzyme inactivation and exerting a powerful bactericidal effect [65]. Moreover, black garlic can effectively inhibit the growth of various pathogenic microorganisms, including Salmonella typhi, influenza virus, and Japanese encephalitis virus. It is noteworthy that black garlic also exhibits excellent antifungal ability, even surpassing traditional preservatives [66]. Furthermore, research by Kim et al. has further elucidated the anti-inflammatory mechanism of 5-HMF in black garlic. They found that 5-HMF significantly reduces inflammatory responses by inhibiting the expression of Vascular Cell Adhesion Molecule-1 (VCAM-1) and the activity of nuclear factor-kappa B (NF-κB) [67].

Immunomodulation

The immune system, as a vital defense line for the human body against pathogen invasion, possesses the crucial ability to recognize and eliminate foreign substances, as well as clear senescent or damaged cells within the body. In recent years, black garlic has garnered significant research attention due to its rich bioactive components. Among them, allicin and other fat-soluble volatile oils have demonstrated remarkable effects in enhancing immune function [68]. Multiple studies have revealed that the fat-soluble volatile oils in black garlic can effectively prevent the apoptosis of peritoneal macrophages under hypoxic conditions, thereby enhancing their phagocytic ability and strengthening the systemic immunity of the body [69]. Further research has also found that black garlic extracts have a stimulatory effect on cellular immune responses in mice, specifically manifesting as low doses primarily enhancing Th1-type cellular immune responses, while high doses are more beneficial for Th2-type responses. Innate killer (NK) cells are an important component of the innate immune response in the body [70]. Studies have shown that black garlic extracts can significantly enhance the killing activity of NK cells, improving their surveillance and clearance function of abnormal cells in the body. Additionally, components such as amino acids, vitamin C, and trace element zinc in black garlic also play a positive role in improving human immune function [71].

Protect cardiovascular health

Research indicates that black garlic extract has the potential to serve as an effective adjunctive therapy for existing antihypertensive drugs [72]. A study conducted on hypertensive patients who had received treatment but still had uncontrolled blood pressure demonstrated that black garlic extract exhibited good tolerability and extremely high acceptability, with an acceptability level reaching up to 140%. The study further pointed out that in terms of reducing systolic blood pressure, the effect of black garlic extract was similar to that of first-line antihypertensive drugs, indicating its significant adjunctive effect in lowering blood pressure [73, 74]. Besides, black garlic extract has also shown positive effects in a high-fat diet rat model. It can regulate lipid and cholesterol metabolism by inhibiting the mRNA expression of Sterol Regulatory Element Binding Protein-1C (SREBP-1C), thereby effectively reducing total lipids, triglycerides, and cholesterol levels in the blood [75].

Anti-obesity effect

Black garlic has demonstrated significant effects in improving insulin sensitivity, reducing fat absorption efficiency, and ameliorating obesity induced by a high-fat diet, while also enhancing the weight loss effects of exercise training [76]. At the cellular level, it has been found that black garlic extract at a concentration of 1.0 mg/mL can effectively stimulate the expression of uncoupling protein-1 in adipose stem cells, thereby promoting the browning of white adipocytes and increasing the body's energy expenditure [77]. Further research hasalso revealed that black garlic, especially its methanol extract, can

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significantly inhibit the proliferation and differentiation of preadipocytes in vitro experiments and promote the breakdown of mature adipocytes, indicating its potential in the prevention and treatment of obesity [78]. When exploring its active material basis, reports by HAAW et al. [79] indicated that the SAC and SAMC components in black garlic may play important roles in anti-adipogenesis. On the other hand, Wu J et al. [80] believed that melanoidins are the key anti-obesity substances in black garlic, which can improve glucose tolerance in obese mice and significantly reduce their body weight and white adipose tissue mass by regulating their circadian rhythm and intestinal flora. However, it is noteworthy that most current research remains at the stage of in vitro or in vivo animal experiments, lacking support from human clinical trial data. Therefore, more human clinical trials are needed in the future to further verify the effects of black garlic in anti-obesity.

Other role

Apart from the aforementioned effects, black garlic also exhibits a variety of other pharmacological activities. It has been reported that black garlic possesses certain anti-allergic effects, with mechanisms involving the inhibition of tyrosine kinase, phospholipase, arachidonate 5-lipoxygenase, and cyclooxygenase-2 (COX-2). Additionally, black garlic extract can significantly reduce blood glucose and glycated hemoglobin levels, increase serum insulin content, and improve glycemic biomarkers in diabetic rats, which may be related to enhancing the activity of aspartate aminotransferase (AST), alanine aminotransferase (ALT), and gamma-glutamyl transferase [81]. At the same time, black garlic can regulate gastrointestinal motility, promote bowel movements, and has potential applications in protecting against fluoride-induced neurotoxicity. After administering black garlic extract to constipation model mice through gavage, Lu Xiaoming et al. [82] found that it significantly increased the propulsion rate of small intestinal contents, shortened the time for the first black stool excretion, increased the number of black stools excreted within 6 h, and improved stool water content, indicating that black garlic has certain effects in moistening the intestines and facilitating bowel movements [83].

Researchers such as Du Juan [84] successfully established a mouse model of exercise-induced fatigue and divided the experimental mice into a swimming training group, a quiet control group, and low, medium, and high-dose black garlic groups. The experimental results showed that the serum urea nitrogen levels in the black garlic groups were significantly reduced, indicating that black garlic can regulate body metabolism and promote the excretion of metabolites. At the same time, the blood glucose levels in the black garlic groups increased, liver and muscle glycogen contents recovered, and lactate dehydrogenase decreased, suggesting that black garlic can promote blood glucose and glycogen recovery, alleviate fatigue, and enhance exercise endurance. Sun Yan's [85] research found that black garlic extract significantly reduced the escape latency of mice (in the place navigation test), significantly increased the number of platform crossings and the time ratio spent in the platform quadrant (in the spatial search test), greatly improving the learning and memory abilities of mice with Alzheimer's disease induced by sodium nitrite and aluminum chloride.

The application of black garlic in food

Black garlic beverage related products

In recent years, with the increasing consumer demand for health and functional beverages, products rich in special physiologically active ingredients have gained increasing market favor. Given that black garlic contains abundant nutrients and high total phenol content, it has shown great potential in enhancing the antioxidant activity of beverages. Currently, a variety of black garlic compound beverages have emerged in the market.

The black ginseng and black garlic beverage developed by Guo Jinting and his team is a typical example. They optimized the ratio of auxiliary ingredients such as citric acid, fructooligosaccharide, and white sugar to achieve the best flavor and stability of the beverage. The optimal process parameters for this beverage are: a ratio of black garlic to black ginseng of 4:1, a compound liquid addition of 15%, a mixed sugar addition of 8%, and a citric acid addition of 0.11%. This unique formula gives the product a distinctive aroma and taste [86]. At the same time, Dong Yan and her team successfully crafted a black garlic vinegar. Through careful adjustment of the formula ratio, they achieved the ideal flavor and taste. The optimal process formula is: adding 40 mL of black garlic vinegar extract, 2 g of rock sugar, and 1 g of white sugar per liter [87]. This black garlic vinegar not only has a unique taste but also incorporates multiple health benefits of black garlic. Liu Jing developed a black garlic and chicken mushroom compound beverage, which has strong antioxidant capacity and provides a new option for health-conscious consumers [88].

In the market, although black garlic-flavored alcoholic beverages such as black garlic beer and black garlic wine have not been widely promoted, they have significant development potential due to their unique taste and nutritional value. Su Chengyong and his team developed a black garlic and red date wine. By optimizing the ratio of raw materials and processing conditions, they produced a beverage with high health value. The optimal extraction process for the raw materials is: a ratio of black garlic to red dates of 1:2.5, adding 0.20% pectinase, and extracting at 45 °C for 2 h. The optimal process conditions are: a yeast addition of 0.9%, an initial sugar content of 22%, and a fermentation temperature of 22 °C [89]. This black garlic and red date wine not only has a unique taste but also incorporates multiple health functions of black garlic and red dates. Yuan Lei and his team also developed a black garlic-flavored beer. By carefully selecting yeast and adding an appropriate amount of black garlic during the main fermentation stage, they successfully achieved the best beer flavor [90]. This beer not only retains the taste and flavor of traditional beer but also incorporates the unique aroma and nutrients of black garlic.

Furthermore, Feng Sisi and her team prepared a black garlic effervescent tablet. They determined the optimal formula through dry granulation and tablet pressing methods and verified its health benefits in moistening the intestines and facilitating bowel movements [91]. This effervescent tablet is not only convenient to carry and take but also provides a new option for consumers seeking intestinal health. In summary, the application of black garlic in beverages and alcoholic drinks has shown great potential and market prospects. With the continuously growing consumer demand for health and functional products, it is believed that more innovative black garlic products will emerge in the future.

Black garlic candied products

Preserved fruits, a type of processed food made from fruits and vegetables preserved in sugar or honey, are widely loved for their unique flavor and taste. Black garlic, with its soft and sweet texture and high sugar content, has become an ideal choice for making preserved fruit products. Zhang Liming and his team innovatively prepared black garlic-infused ejiao paste by boiling powdered ejiao and skillfully adding auxiliary ingredients such as Chinese wolfberry, sesame, walnut, and red date, creating a black garlic ejiao cake rich in antioxidant components. The optimal processing conditions for this product are: 30% black garlic, 4% rock sugar, 10% ejiao, 6% sesame, 10% Chinese wolfberry, 15.8% walnut, 13% dried red date, 7.5% maltodextrin, 0.3% carrageenan, and 8% rice wine. This unique formula endows the product with rich nutritional value and excellent taste [92].

Another study conducted by Zhang Guizhi and her team focused on using black garlic concentrate, compound edible gums, and sugars as the main raw materials, and carefully determined the optimal processing technology for black garlic soft candy through orthogonal experiments. They found that using a ratio of 1:1 for granulated sugar and glucose syrup, a sugar addition of 70%, a ratio of 6:1 for gelatin and high-ester pectin, a gum addition of 7%, a black garlic concentrate addition of 4%, and a citric acid addition of 0.1%, they could produce a black garlic soft candy with black garlic aroma, smooth surface, good chewability, and elasticity. This product not only has a unique taste but also fully retains the various health benefits of black garlic [93].

Black garlic seasoning

As an indispensable part of daily diet, condiments are constantly evolving, and black garlic, with its unique flavor and rich nutritional value, is gradually becoming a new favorite in the condiment industry. By skillfully combining black garlic with other ingredients, condiments with novel taste and health-promoting functions can be developed. Jia Qingchao and his team adopted the traditional sauce-frying process, using black garlic, silver strips, chicken mushroom, or tea tree mushroom as the main raw materials, and adding star anise, pepper, cumin, onion, ginger, sugar, salt, and other auxiliary materials. Through single-factor experiments and response surface methodology experiments for further optimization, they determined the optimal formula for black garlic sauce and successfully developed black garlic silver strip sauce, black garlic chicken mushroom sauce, and black garlic tea tree mushroom sauce. These products not only have unique tastes but also possess various health-promoting functions of black garlic [94].

Ma Rongkun and his team used black garlic as the main ingredient to create a fat-free black garlic salad sauce. Their research found that the addition amounts of water, monoglyceride, and carboxymethyl cellulose sodium (CMC) had a significant impact on the sensory quality of the black garlic salad sauce. After careful formulation, they arrived at the optimal recipe for the black garlic salad sauce: 100 g of black garlic, 80 mL of water, 0.2 g of monoglyceride, and 0.3 g of CMC. This salad sauce not only has a unique taste but also fully retains the rich nutrition and health-promoting functions of black garlic, providing a new choice for consumers pursuing healthy diets [95].

Discussion

Black garlic, as a modern processed product of garlic, has emerged in the field of health preservation and wellness with its unique processing technology and significantly enhanced physiological functions, becoming an emerging research and consumption hotspot. Its market potential is huge, not only deeply loved by Chinese consumers but also widely recognized in countries such as Japan, Singapore, and Malaysia. However, despite its numerous advantages, the development of the black garlic industry still faces a series of challenges, and it is urgent for us to explore deeply and seek effective solutions [96]. Black garlic is rich and diverse in nutrients, containing various compounds beneficial to the human body, such as amino acids, sugars, vitamins, and minerals. These components are optimized and transformed during the processing of black garlic, making its nutritional value significantly higher compared to regular garlic [97]. At the same time, black garlic also exhibits superior sensory and nutritional qualities compared to regular garlic, laying a solid foundation for its application in the health food market. In terms of physiological functions, black garlic also performs exceptionally well. It not only has protective effects on memory and the nervous system [98] but also helps prevent cancer, obesity, diabetes, and various cardiovascular diseases [99, 100]. These unique physiological functions make black garlic a new type of healthy snack or functional food and are widely used in disease prevention and treatment [101, 102].

However, despite its many advantages, the development of the black garlic industry still faces many challenges. Currently, there is no unified quality standard for black garlic production, and production enterprises are relatively small, with low public awareness of black garlic. These issues severely restrict the further development of the black garlic industry. To promote the sustainable development of the black garlic industry, we need to take a series of measures. Firstly, improving the technological level and technical content of black garlic products is key. Through technological innovation and industrial upgrading, we can develop new black garlic products with greater market competitiveness to meet the diverse needs of consumers. Secondly, developing a big data platform for black garlic technology sharing is also an important measure. This will help promote industry-university-research cooperation, drive technological innovation and achievement transformation in the black garlic industry, and provide strong technical support for the development of the black garlic industry. At the same time, we also need to improve the black garlic processing technology and expand the black garlic industry chain to expand market demand and economic value. By continuously optimizing the processing technology and improving production efficiency, we can reduce production costs, improve product quality, and further expand the market space for black garlic. Looking ahead, with the gradual recognition of the nutritional value and physiological functions of black garlic by the public, the black garlic industry will usher in broad development prospects. To achieve this goal, we need to further strengthen industry-university-research cooperation, deeply explore the key effective substances in black garlic and the potential synergistic effects between characteristic components. This will help us understand the health benefits of black garlic more comprehensively and provide stronger theoretical support for its application in food, medicine, and other fields. At the same time, conducting more human clinical trials is also essential. Through the verification of clinical trials, we can more accurately assess the health benefits of black garlic and provide a scientific basis for its application in a broader range of fields. This will further enhance consumer confidence and recognition of black garlic and promote the sustained development of the black garlic industry.

In summary, black garlic, as a health food with rich nutritional components and unique physiological functions, has broad development prospects. Through the implementation of a series of measures such as technological innovation, industrial upgrading, and market expansion, we are confident in overcoming current challenges, promoting the sustainable development of the black garlic industry, and making greater contributions to human health.

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