Nutritional, biological, and therapeutic properties of black garlic: a critical review

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ABSTRACT
Functional foods play a key role in human health and disease. Garlic (\textit{Allium sativum}) is an eminent plant and has been part of food since ancient times due to its high medicinal food value. The unpleasant taste and odor of raw garlic make consumers reluctant for its use. With consumer demand, the trend for black garlic is getting attention worldwide. Black garlic is obtained from fresh garlic after a controlled fermentation process at high humidity and temperature. The fermentation process causes implausible changes in its physicochemical properties. Several in vitro and in vivo studies have been conducted to elucidate the effect of this natural agent against different health disorders and it has been found that black garlic is an effective in decreasing diabetic, hypercholesterolemic atherosclerosis, hyperlipidemic hypertension, inflammation, oxidative stress, cancer, and different neuro risks. The market for black garlic is developing rapidly to its positive functionality for human health. In the present review article, we have recapitulated the nutritional, chemical, bioactivity, physiochemical modifications during processing, food, and medicinal use and current knowledge of the subject, as well as the sensory aspects, and proposed future prospects on their possible applications as a functional food product.

Introduction

The consumption of functional food is one of the best strategies to minimize the prevalence of chronic health disorders. This concept has created the awareness among consumers across the world and has forced the market growth of functional foods.\cite{1} Keeping in view the importance of functional foods, the researchers have been conducted in detail to understand the functional properties and pharmacological behavior of plant-derived compounds.\cite{2}

Garlic (\textit{Allium sativum} L.) belongs to the Alliaceae family and is a well known plant for its traditional medicinal use. The most frequently used ingredient in gastronomy is garlic (\textit{Allium sativum} L.) and is also being used as a spice for centuries. Garlic therapeutic uses include, increasing stamina, aiding digestion to prevent diarrhea, treating heart disease, fatigue, worm infestations, and arthritis, due to these biological effects they are used as traditional medicine.\cite{3} The processed products of garlic (dehydrated garlic, garlic oil, aged and garlic extract) have additional medicinal benefits and are being extensively used.

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Recently, the black garlic (BG) is being considered as one of the fastest health promoting foods in Asia.\textsuperscript{[4,5]} Many scientists have reported that the actual origin of black garlic is still questionable. The literature evidence showed that BG has been consumed since ancient times in Thailand, Japan, and Korea. The estimated market value of black garlic, as reported by Bae et al.\textsuperscript{[6]} is about 94 million the US $ which is increasing rapidly.

Black garlic (BG) is a processed garlic product prepared by heat treatment of whole garlic bulbs (\textit{Allium sativum} L.) at high temperature under high humidity for several days, resulting in black cloves with a sweet taste. Black garlic is a phenomenon vegetable with multiple biological effects. Black garlic has a sweet taste, no pungent odor, and that is why can be eaten as a fruit just after peeling off the outer coat.

Black garlic is produced by the process of fermentation of simple fresh garlic (\textit{Allium sativum} L) under-controlled conditions.\textsuperscript{[7]} In Asia, aged black garlic is popular and is known as a functional food. The major challenge in the production of black garlic is to reduce the unpleasant taste and pungent odor. The whole process is heat dependent. Heating produces aromatic products with gelatin texture and sweet taste.\textsuperscript{[8]}

The functional potential of black garlic making and its use in various products (beverages, candies, ice-cream, sausages, vinegar, tofu, white pan bread, yogurt, alcohol, and jams) throughout the Europe and America is very popular.\textsuperscript{[9,10]} The high antioxidant potential encourages its use in non-food items like shampoo, cosmetics, skin protector, facial cream, soap, etc.\textsuperscript{[11]} During the aging process, the modification, conversion, and interaction of different components (carbohydrates, amino acids, polyphenols, and volatile compounds) takes place. The aforementioned conversions and interactions increased the bioactivity of the black garlic compared to raw garlic.\textsuperscript{[12,13]}

All the changes that take place during the aging process depends on the heat treatment conditions. The degree of the reactions including, Maillard reaction (reaction that take place between amino acids, free amino groups, and peptides and carbonyl groups to reduce sugars), oxidation of phenols, and thermal degradation of organo-sulfur is heat treatment dependent.\textsuperscript{[7]} Many studies have shown a critical and key role of Maillard reaction in the production of BG. The results of the different studies revealed that during the aging process the major changes take place in carbohydrate based compounds and the development of Amadori and Heyns have also been observed.\textsuperscript{[14,15]} Keeping in view the importance of the black garlic and its bioactivity potential, we have given a comprehensive picture regarding the processing, nutritional composition, fermentation process, and different bioactive properties of the black garlic. This review paper can help understand the process and the bioactive potential of the black garlic for its use in food and non-food products.

**Production process and critical factors affecting the quality of black garlic (BG)**

BG is produced by the process of fermentation. Heat treatment of the raw garlic (RG) bulbs is carried out under specific controlled conditions. The process of fermentation is carried out at temperature range (60–90°C) and humidity (50–95%) for a period of several weeks. No, additives are used for the production of the black garlic.\textsuperscript{[7]} Methods for the production of black garlic are not standardized as the processing conditions vary broadly depending on the type, tradition and desired characteristics of the final product.\textsuperscript{[16]} In literature, the typical conditions for the production of black garlic are temperatures (40°C to 90°C) relative humidity (70% and 90% aging period and 8–69 days) have been reported.\textsuperscript{[5]} Black Garlic is a processed food that is produced under controlled conditions (Figure 1). Pretreatment of fresh garlic (FG) affects the final quality of the black garlic. Pretreatment of FG may disrupt the cell structure of garlic. The types of garlic, temperature, and humidity are the critical factors that played a significant role in the production and end quality of the black garlic. The garlic varieties differ due to their location, climate, and growth conditions. The nutritional profile of the fresh garlic has a direct impact on the quality of BG.\textsuperscript{[17]}
Pretreatments

The garlic varieties available in Asia is differed in sugar, protein, allicin, etc.\(^ {18}\) Studies conducted with different pretreatments for the production of black garlic showed that the freezing time could speed up the browning and reduction in processing time.\(^ {19}\) It has been stated that freezing pretreatment is also helpful in the hydrolysis of fructans. In another study, the use of high pressure as a pretreatment could enhance the nutritional and antioxidant potentials of the produced black garlic. The peeling process also affects antioxidant capacity, as reported in a study that peeled black garlic has more antioxidant capacity as compared to unpeeled black garlic cloves.\(^ {16}\)

Temperature

The temperature is also a critical and most variable factor that affects the final quality of the black garlic. High temperatures resulted in fast browning, loss of allicin and moisture, and an increase in total acids and phenols.\(^ {20}\) The published data showed that the temperature (70 °C) is considered as the most suitable for the production of black garlic with desired attributes. This temperature gives the most desirable sensory attributes. Bae et al.\(^ {6}\) reported that the increase in temperature caused a significant increase in the bioactive properties, particularly the antioxidant potential. Enzymatic activity, moisture level, and the physical and chemical changes are also affected by the temperature. Compositional changes take place during the processing of fresh garlic into black garlic. The compositional changes are also temperature dependent.

Relative humidity

Relative humidity has a significant effect on the enzymatic activity and physiochemical changes that take place during the aging process for the production of black garlic. The ultimate effect of the humidity has been observed on the nutritional, biological activity, and sensory characteristics of the black garlic. The physical appearance, amount of moisture, texture, and degree of browning are
directly linked with the relative humidity.\textsuperscript{[21]} Higher humidity could result in slow browning, low organic acid, and less sweet while an increase in polyphenol and reducing sugars. Sun and Wang\textsuperscript{[22]} described the most suitable level of humidity (75°C and 85%) for the production of black garlic having high antioxidant capacity. The process of hydrolysis of macromolecule, on-enzymatic browning is also affected by the level of humidity and degree of temperature. Millard reactions and relative humidity are interrelated as high levels of humidity could result in slowing the process of the reaction.

**Physicochemical modifications in bioactive components during processing of black garlic**

The typical composition of fresh garlic changes during its aging process. Fresh garlic consists of water, dietary fiber mono- and disaccharides, polyphenols, proteins, vitamins, allinase, and lipids.\textsuperscript{[4,23]} Thermal process and relative humidity cause modifications in the typical composition of the fresh garlic during the production of the black garlic. The typical compositional changes that take place during production of black garlic are shown in Table 1.

Bulbs of fresh garlic contain carbohydrates and are considered as a major constituent. The polysaccharide constituents (fructan, non-reducing water-soluble saccharides) are considered reserve for osmoregulation and protection from low-temperature injury. A significant amount of fructan exists in garlic. Judprasong et al.\textsuperscript{[31]} studied the composition of different varieties of garlic for fructan and found that significant amounts of inulin, fructo-oligosaccharides (FOS), and minor amounts of fructose, glucose, and sucrose in the aforementioned compounds have positive impact on modifying host microbiota and health impacts.\textsuperscript{[32]} During the production process, the carbohydrate content decreased in the final product. A decrease in the polysaccharide content up to 30% has been reported.\textsuperscript{[19]}

In the advanced stages of Maillard reaction, brown color is produced, the high temperature causes the consumption of the reducing sugars and amino acids.\textsuperscript{[33]} In thermal processing, the content of fructans decreases while reducing sugars increases, this contributes toward the formation of coloring compounds.\textsuperscript{[5,7]}

The decrease in content could be due to various enzymatic and non-enzymatic changes during thermal processing of fresh garlic to black garlic. Exposure of fresh garlic to various stressful conditions like freezing might cause changes in membrane structure. These structural changes during processing of fresh garlic to black garlic bring a significant change in the composition of various nutritional contents (Table 2).\textsuperscript{[34]} In a study conducted with prestressed condition (freezing) it was indicated that fructans content reduced by 84.79% at the end, while a drastic increase was observed in fructose (508.11%).\textsuperscript{[14]}

Garlic has a high protein content 19–14% dry matter (DM), the most abundant among them is a heterogeneous glycoprotein known as lectins. It contains all essential amino acids and is of prime importance.\textsuperscript{[33,35]} Major essential amino acids include glutamic acid, arginine, aspartic acid, and tyrosine. The amino acid contents (arginine, glutamic acid, and tyrosine) decrease while the contents of phenylalanine and methionine increases.\textsuperscript{[5]} Fresh garlic is considered as a key source of sulfur and sulfur containing compounds.\textsuperscript{[4]} When garlic is heated above the subjected temperature, allinase is inactivated and allicin production decreases due to heat treatment above 60°C.\textsuperscript{[36]} Zhang et al.\textsuperscript{[20]} reported that the heating treatment (70–80°C) for the production of black garlic allicin decreased by 80% due to allicin formation. S-allylmercapto-cysteine (SAMC) and S-allyl-L-cysteine (SAC) are water soluble and considered for intestinal absorption. Diallyl sulfide (DAS), diallyl disulfide (DADS), diallyl trisulfide (DATS), and diallyl tetrasulfide are oil soluble.\textsuperscript{[26]} Different experimental studies have shown that the SAMC content increases during the production of the black garlic the results could be due to the allicin conversion.

In another study conducted by Choi et al.,\textsuperscript{[5]} reported that thermal processing of fresh garlic into black causes a decrease in the level of cysteine and tyrosine contents that could be due to antioxidant activity changes during thermal processing. Similarly, a decrease in the level of polar amino acids (threonine and serine) and nonpolar amino acids (glycine and alanine) was noted.
| Components          | Fresh garlic | Black garlic | Decrease/increase | Typical role                                                            | References |
|---------------------|--------------|--------------|-------------------|-------------------------------------------------------------------------|------------|
| Reducing sugar      | 5.9 ± 0.8 g/kg DM | 472.4 ± 46.5 g/kg DM | Increase           | Give sweet taste in black garlic                                        | [24]       |
| Lipid               | 1.8 ± 0.1 g/kg FM  | 1.7 ± 0.1 g/kg FM  | Increase           | serves as an energy source, contributes in the sensory profile          | [5,25]     |
| Protein             | 8.4% FM       | 9.1% FM       | Increase           | Participates in Millard reaction                                       | [26]       |
| Water-soluble sugar | 72.29% DM     | 85.61% DM     | Increase           | Sensory properties                                                      | [26]       |
| Water activity      | 0.98          | 0.93          | Decrease           | development of a favorable texture                                     | [16]       |
| Organic acid        | 16.68 ± 0.61 g/kg DM | 64.18 ± 7.55 g/kg DM | Increase           | Helps in absorption of nutrients, immunity and digestive health         | [20]       |
| Polyphenol          | 38.87 ± 4.53 mg GAE/g DM | 68.95 ± 1.63 mg GAE/g DM | Increase           | Have anti-oxidant properties                                            | [5]        |
| Melanoidin          | <0.1 OD FM    | 1.8 OD FM     | Increase           | Antihypertensive, antioxidant, antimicrobial, and prebiotic, effects     | [27]       |
| Mineral             | 11.74 ± 0.02 g/kg DM | 13.14 ± 0.03 g/kg DM | Increase           | vital for metabolism and physiological functions                       | [28]       |
| Vitamin             | 6.92 ± 0.02 g/kg DM | 9.26 ± 0.03 g/kg DM  | Increase           | Key role in biological activities                                       | [11]       |
| Alkaloid            | Traces        | 28.55 FM      | Increase           | pharmacological and biological properties                               | [29]       |
| Allicin             | 11.28 ± 0.22 g/kg FM  | 2.31 ± 0.07 g/kg FM  | Decrease           | Catalysis the chemical reaction                                         | [6]        |
| SAC                 | 19.61 ± 0.35 µg/g DM  | 105.07 ± 27.73 µg/g DM  | Increase           | radical scavenging properties                                           | [19]       |
| 5-HMF               | Not detected  | 0.23 ± 0.04 g/kg FM  | Increase           | Provides a range of range pharmacological and biological properties     | [30]       |
| SOD                 | 12.96 g/kg FM  | Not detected   | Decrease           | Important for radical scavenging properties                              | [30]       |
The decrease in these amino acids could also be due to the Maillard reaction (reaction between amines and carbonyl compounds) Thermal processing of fresh garlic at high-temperature cause denaturation of proteins and synthesis of free amino acids that take part in the Maillard reaction). The amino acid profile of black garlic varies in many ways from fresh garlic due to drastic changes during thermal processing.\[19,25,37\] Liang et al.\[38\] reported that the enzymatic hydrolysis (under acidic conditions) of proteins causes an increase in the amino acid due to change in pH of garlic during its processing from fresh to aged garlic.

Substances containing one or more aromatic rings and hydroxyl groups are termed as polyphenols. The major polyphenols are tannins, flavonoids, and phenolic acids. The good sources for these polyphenols are the cereals, fruits, and vegetables. These polyphenols have high antioxidant potential and prevent humans from cancer and many other disorders.\[39\] The higher phenolic contents contribute toward the health promotion. Both the qualitative and quantitative contents of polyphenols are of great importance. Different factors (environmental, genomic, and agronomic) cause variation in both qualitative and quantitative content in garlic.\[40\] The heating process causes an increase in the phenolic content in free form. The results of the different studies conducted to find the effects of heat processing on the total phenolic content (TPC) shows a significant increase during the conversion of fresh garlic to black garlic.\[11,13\] The total phenolic contents are measured by using the spectrophotometer.

It has been reported that the total phenolic content of fresh garlic and black garlic differ significantly. Black garlic contains 5–8-times higher phenolic contents than that of fresh garlic owing to this black garlic has good antioxidant potentially compared to fresh garlic. activity rather than fresh garlic.\[13\] Garlic is one of the richest sources of phenolic compounds among common vegetables in human diet. The total phenolic contents in the fresh garlic ranges from 3.4 to 10.8 mg gallic acid equivalents (GAE)/gDM. The total phenolic acid content varies from 1.9 to 20.9 mg/kg DM. The most dominant acid in garlic is caffeic acid followed by ferulic, vanillic, and p-hydroxybenzoic acid.\[40\] On the other hand, the processing of the fresh garlic increased the total phenol and total acid contents in the black garlic. The results of different studies showed that an increase of 7–11-fold has been reported Martínez-Casas et al.\[24\] However, it has been reported that processing of fresh garlic at high temperatures for a long period could cause a decrease in the phenolic contents. Jeong, et al.\[27\] studied the impact of different thermal processing steps on the phenolic contents of fresh and black garlic and reported that the concentration flavonoid compounds and polyphenolic was significantly higher compared to fresh and steamed garlic.
Nutritional profile of black garlic and impact on human health

The black garlic is nutritionally rich and possesses a lot of health benefits due to its high bioactive profile. However, there has been no results regarding the direct effect of the black garlic on human health. Nutritionally, oligosaccharides and monosaccharides (water-soluble carbohydrates) are the most dominant components that are present in the black garlic. Fructose (present in BG) is a perchance metabolized via the pathways involving the liver, kidney cortex, and intestinal mucosa along with the associated enzymes.\textsuperscript{[37]} Glucose is absorbed through the gastrointestinal tract and metabolized through the glycolytic pathway.\textsuperscript{[41]} It has been reported that fructose intake has negative impacts on human health causing different problems like obesity, insulin resistance, obesity, diabetes, and liver-related diseases.

FOSs behave as prebiotic and positively boost up the microbiota. These are not digestible in the stomach or small intestine. FOS are used by the probiotics present in the colon to produce different useful end products.\textsuperscript{[42]} These useful end products like short chain fatty acids (SCFAs) prevent from different gastrointestinal issues.\textsuperscript{[43]}

Bioactive compounds derived from black garlic with various functional characteristics (anti-oxidant, antimicrobial, and anti-inflammatory) are of great importance for humans. These bioactive components increased during the processing of fresh garlic at a significant rate. The meticulous metabolic transit and biotransformation of the mentioned bioactive compounds is still unclear. Melanoidins could be directly absorbed or bio transformed in body using different pathways.\textsuperscript{[44]} The other polyphenols and bioactive compounds derived from black garlic with various functional characteristics are of great importance for humans that influence the human health. The metabolic pathways of the different polyphenols differ depending on their type, while most of the polyphenols are directly absorbed into the body. Few polyphenols undergo the process of transformation.\textsuperscript{[45]} Microbial interactions with polyphenols are very complex; however, different polyphenols modulate the intestinal microbiota.\textsuperscript{[46]} Five-hydroxymethylfurfural (5-HMF) is produced during the conversion of fresh garlic to black garlic. The 5-HMF is produced in large quantities and exists in various forms (methylated, acetylated, and glucuronidated) and have direct impact on the human intestinal microbiota.\textsuperscript{[47]} The metabolites produced during the Maillard reaction have a significant effect on microorganisms through their direct interaction with microbes as well as by the indirect influence of metabolites.\textsuperscript{[48]}

Bioactive properties of the black garlic (BG)

Garlic has been a traditional medicine for various functional purposes (such as antibacterial, anti-diabetic, anti-oxidant, anti-inflammatory, etc.) due to the presence of various organo-sulfur compounds.\textsuperscript{[37,49]} The production process of black garlic from fresh garlic process persuades modifications in biological activities.

Anti-Obesity properties

Obesity and overweight issues are increasing across the world due to abnormal lifestyle disorders. These factors are contributing as a great health risk among the populations.\textsuperscript{[50–52]} The consumption of over nutrients and sedentary life style is greatly contributing in being obese or overweight. Obesity and overweight leads to an increase in fatty liver and other complicated issues.\textsuperscript{[51]} Obesity and overweight also persuades other diseases like heart-related issues, liver damage, hyperlipidemia, diabetes, etc.\textsuperscript{[53]} Many researchers have reported that the garlic as a whole and the functional components are helpful in treating obesity and related issues. The whole garlic, its oil and a few important natural compounds (rutin, epigallocatechin 3-gallate, gallic acid, o-coumaric acid) are being considered very significant in the treatment of obesity. The study conducted by Seo et al.\textsuperscript{[54]} showed that the incorporation of black garlic in diet having amount (0.2%, 0.6%, or 1.2%) is very effective in controlling overweight,
peritoneal fat and epididymal fat. Functional foods play a key role in controlling obesity; however, the consumption of black garlic has a prominent role in this regard. Diet containing 1.5% black garlic can reduce epididymal fat. Black garlic plays a significant role in ameliorating the diet-induced obesity by downregulation of transcription and enzymes.

**Antioxidant properties**

Many natural substances have the potential to neutralize the harmful reactive oxygen species via endogenous enzymatic defense system. Many plant-based substances (flavonoids, phenolic acid and phenolic diterpenes) have significant antioxidant effects.\(^{[55]}\) The antioxidant potential of phenolic compounds is due to their redox effect. Phenolic compounds have a key role in absorbing/neutralizing the free radical.\(^{[56–58]}\) The composition of the black garlic indicates that it contains amino acids, particularly leucine and iso-leucine in an abundant amount as compared to the raw or fresh garlic. The presence of amino acid in garlic is involved in the breaking of neutral polysaccharide, these in reaction with sugars (fructose) from browning. Among the amino acid histidine has a key role in browning as it can inhibit the effect of all organic acids on the Maillard reaction. The studies result also indicated that histidine has high reactivity and buffering capacity.\(^{[59]}\)

Black garlic also contains cysteine, a sulfur containing amino acids.\(^{[60]}\) The aging process increases the amount of desired polyphenols in the black garlic that also increases the antioxidant potential.\(^{[61,62]}\) The aging process of garlic converts unstable and odorous compounds into S-allylcysteine which enhances the antioxidant potential of the black garlic.\(^{[9]}\) S-allylcysteine is an effective antioxidant and have the ability to dissolve in water. The experimental data have shown that the amount of S-allylcysteine increases six times as compared to the raw garlic that contains 20–30 µg/g.\(^{[6,63]}\)

The processing conditions affect the level of existence of flavonoids in the final products, the amount of phenolic acid increases in black garlic with aging process. The amount of phenolic acid content is directly proportional to the amount of the total acid present in the black garlic.\(^{[64]}\) The presence of different vitamins (B, folic acid) and antioxidant phytochemical slow down the progression of oxidative stress and atherosclerosis.\(^{[65]}\) The major enzymes (catalase, glutathione peroxide superoxide dismutase) help in playing a key role against the oxygen reactive species and decreasing the total protein carbonyl content.\(^{[66,67]}\)

In the study, the antioxidant activity of raw and black garlic was compared along with the optimized aging for the production of black garlic. The study results indicated that the maximum production of polyphenol and HMF contents achieved at optimum temperature, humidity, and storage conditions were 90°C, 95%, and 4 days, respectively. The results indicate that optimum aging resulting in polyphenol and HMF contents of 25.80 mg/g and 3.84 mg/g, respectively, were achieved using a temperature of and humidity of for 4 days. Both BGR and BR had stronger capacities to scavenge \(\alpha,\alpha\)-diphenyl-\(\beta\)-picrylhydrazyl (DPPH) than RG with half maximal inhibitory concentration (IC50) values of 0.454, 0.514, and 4.236 mg/ml, respectively. The experimental results on mice showed that there was no significant difference in antioxidant activity of black garlic and fresh garlic under *in vivo* studies. The consumption of black garlic significantly decreased malondialdehyde (MDA) levels in serum and liver.\(^{[68,69]}\)

**Anti-inflammatory properties**

A few active compounds (pyruvate, 2-linoleoylglycerol, and 5-hydroxymethylfurfural) have distinct anti-inflammatory effects. The results also indicated that Pyruvate has both anti-inflammatory as well as antioxidant activity. Commonly, anti-inflammatory activity is directly proportional to antioxidant activity, but this is not true in all cases as it is the opposite in aged black garlic.\(^{[8,70,71]}\) Garlic oil is effective in reducing the inflammation responses.\(^{[72]}\)
A comparative study was carried out to explore the anti-inflammatory and anti-oxidant activity of fresh and black garlic. Pro-oxidant (hydrogen peroxide) pro-inflammatory (lipopolysaccharide) stressor were used in the study. The results of the study indicated that the combined form of fresh garlic with sugars that are more in aged black garlic is helpful in decreasing the anti-inflammatory activity. The presence of abundant sugar could be one of the reasons for lower anti-inflammatory activity of aged black garlic as compared to fresh garlic.\textsuperscript{8,70}

**Hypolipidemic and hypocholesterolemic effect**

Hypercholesterolemia and hyperlipidaemias are the major factors that contribute to atherosclerosis. The results of different experiments conducted in order to explore the effect of garlic on hypercholesterolemia and hyperlipidemia patients indicated that garlic extract can substantially lessens the triglyceride level and serum total cholesterol. The results also revealed that the aged garlic extract and garlic powder were found to be efficient in lowering serum total cholesterol levels and garlic oil was suitable for decreasing the level of triglyceride.\textsuperscript{73} Extensive studies have been carried out to study the impact of garlic as compared to black garlic. In a double blinded trial 41 hypercholesterolemic individuals were treated with raw and black garlic. Blood profiles and antioxidants of treated individuals were examined. Raw and aged black garlic were given at the rate of 1080 mg/day. extended exposure to aged and raw garlic supplements (1080 mg daily). The blood concentration of the individuals was not affected by either raw or aged garlic over a period of thirteen weeks of supplementation. However, the treatment with aged black garlic significantly decreased hydroperoxide concentration of serum lipids, plasma and urinary F2-isoprostanes over this defined period of time. The results of the study indicated that supplementation with aged garlic reduced oxidative stress.\textsuperscript{74}

Atherosclerosis with a composite pathogenesis involves inflammation and endothelial dysfunction, along with oxidative stress. From the results, it has been observed that pathophysiology plays a key role in chronic inflammation and oxidative stress.\textsuperscript{75} The garlic play a vital role as an anti-atherosclerosis agent.\textsuperscript{76}

**Effect of garlic on hypertension**

Hypertension is commonly causing Cardiovascular problems across the world. The problem of the hypertension is increasing rapidly across the globe. The published reports showed the number of people with hypertension in developend and developing countries will be 80% and 24%, respectively.\textsuperscript{77} The study regarding the mechanism of how black garlic directly affects lipid metabolism was carried out by Ha et al.\textsuperscript{78} Higher levels of lipids in the body lead toward various health disorders. Significant differences between different biochemical parameters of groups with and without black garlic treated groups were observed. A reduction in hepatic expression and increase in lipid fecal excretion was observed. In short, regular consumption of black garlic has a key role in reducing triglyceride, total lipids, and cholesterol.

During hypertension, blood pressure continuously rises and this is a major factor in heart failure.\textsuperscript{79} Different studies conducted have shown a linkage between garlic consumption and cardiovascular diseases. The aged garlic has a protective effect on different types of cardiovascular disorders including hypertension. In another study, the results indicated that the aged garlic is effective in reducing the high blood pressure in hypersensitive patients.\textsuperscript{80,81} Garlic has the ability to reduce blood pressure, and organic polysulfide components cause vaso-rexlation.\textsuperscript{82} The allin present in garlic is changed to allicin in the occurrence of alliinase.\textsuperscript{83} this compound has vasodilation effect and reticence of angiotensin II.\textsuperscript{82} In vascular diseases the blood vessels become narrow and has direct impact on the heart function. Diseases such as atherosclerosis, obesity, and hypertension are the major contributing factors in cardiovascular problems.\textsuperscript{84} The biological effect of aged black garlic has the potential to reduce this associated risk.\textsuperscript{85} The normal intake of the garlic is helpful in reducing the high blood pressure as depicted by clinical studies.\textsuperscript{86}
Anti-cancer properties of black garlic

Designer food has listed the garlic food under the category of anti-cancer agent. The six basic characteristics (metastasis, resisted cell death, dodged growth suppressors, proliferation signaling, induced angiogenesis, activated invasion, and enabled replicative mortality) undergoes during the development of human tumors. This multistep development is choked by the functional components present in garlic. Black garlic has good chemo preventive effects in both in-vitro and in-vivo conditions. In a study conducted on human gastric cancer cells, black garlic dose inhibited the cell proliferation and induced apoptosis in aforementioned cells. In another study, conducted on Kunming mice that were inoculated with murine fore-gastric carcinoma cell lines. The results indicated that BG inhibited the growth of inoculated tumors. Dong and coauthors reported that black garlic has anticancer and antitumor properties. The results were obtained from a study conducted on colon and gastric cells with the use of black garlic. Different studies conducted in China showed a direct linkage between the consumption of garlic, onion, and cancer. The results indicated the consumption of garlic and onion greatly reduced the chances of cancer. In another study stomach cancer, risk chances were directly related to the consumption of functional foods like garlic and onion.

In a study carried out to elucidate the effect of aged black garlic on the inhibition of cell proliferation and initiation of apoptosis in human gastric cancer cells. Additionally, in vivo trials were also carried out by inoculating the murine foregastric carcinoma cell line in Kunming mice. The mice were treated using different doses of aged black garlic for a period of 2 weeks. Anti-tumor effect of black garlic was noted in tumor bearing mice.

Anti-diabetic activity

Black garlic has protective effects on obesity and diabetes. Garlic produced through the microbial fermentation reduce insulin resistance, cause a decrease in total cholesterol and triglyceride levels. Black garlic is rich in organosulfur compounds (produced during processing of fresh garlic into black garlic) that stimulate beta cells to enhance insulin secretion. The results of the study indicated that diet supplemented with black garlic up to just 1.5% significantly helpful for blood glucose homeostasis. Insulin resistance is a crucial factor in type 2 diabetes that can be controlled by enhancing plasma insulin.

On the other hand, it causes an increase in high-density lipoprotein (HDL) cholesterol via antioxidant potential. Another study conducted by Kim et al. on mice showed that black garlic juice has anti-diabetic effects in mice that was streptozotocin-induced insulin deficient. Different experimental studies showed a very distinct hypoglycemic effect of garlic; however, the effect of garlic on human blood glucose is still tarnished. The literature published showed that garlic has the potential to reduce blood glucose levels in diabetic animals.

Garlic unusually reduced LDL cholesterol and serum total cholesterol and impartially elevated HDL cholesterol as compared with placebo in diabetic patients. In a study reported by Yang et al., we found that bioactive components (S-allyl cysteine) imitative from garlic, has direct impact on the restoration of erectile function in diabetic rats. The function is performed by preventing reactive oxygen species formation via modulation of nicotinamide adenine dinucleotide phosphate hydrogen (NADPH).

Anti-allergic action

The demand for the functional food having anti-allergic effect is increasing across the world due to various environmental and genetic factors. In this connection, throughout the globe the research is being carried out to explore the anti-allergic potential of various bioactive compounds. In a study, experiments were conducted by Kim et al. that demonstrated that extracts obtained by 70% ethanol
from FG and BG bulbs exhibited anti-allergic properties. The comparative effect indicated that the extract obtained from the black garlic has more anti-allergic effects compared to the extract obtained from the fresh garlic.

**Antimicrobial activities of BG**

Antimicrobial potential of fresh and black garlic has been explored by many researchers. In a study conducted by Kang et al.[28] who studied the antimicrobial activity of black garlic pomace extract against gram positive and negative bacteria. It was found that extract of black garlic was more effective against gram-positive bacteria (Staphylococcus aureus and Listeria) as compared to gram-negative bacteria (Escherichia coli and Salmonella). In short, the extract of black garlic was found to be useful against the food-borne pathogens and improving the shelf life and quality characteristics of spinach during storage.

The processing conditions (temperature, humidity, and fermentation) of raw garlic into black garlic is an effective strategy to enhance the antibacterial potential. Fermentation causes changes in the bioactive properties of the raw garlic. A number of researches and review papers have indicated the high antibacterial properties of the black garlic as compared to the fresh garlic,[8] and the trials were carried out against different human origin pathogens.

The thermal processing and fermentation of raw garlic into black garlic cue degradation of polysaccharide. The level of fructan during fermentation decreased as it decomposed while the level of galactan remained intact. However, the acid hydrolysis of galactan produces galacturonic acid.[7,96]

In a study conducted by Botas et al.,[47] it was explored that the antimicrobial potential of BG against gram positive (E. faecalis and L. monocytogenes) and gram negative (E. coli, P. aeruginosa, A. baumannii, K. pneumonia) pathogenic bacteria. Trials were carried out to evaluate the minimum inhibitory concentrations against the potential pathogens. The study results revealed that garlic showed antibacterial activity against all potential pathogens. The best results were shown against the E. coli, and P. aeruginosa. The findings of the study indicated that BG has a great antimicrobial potential and could be used effectively against different pathogens. Garlic is also effective against both gram positive as well as gram-negative bacteria.[97-99]

**Processing of black garlic and sensory properties**

The processing of fresh garlic for the production of black garlic brings many visible changes in its color, appearance, taste, and other sensory properties. The garlic develops black color and attains sweet and soft textures.[6] Little data are available on the organoleptic properties of the black garlic. In a study carried out by Rios-Ríos et al.[15] compared the different properties of the raw and processed garlic. The results of the study showed that almost 40% of the initial weight of raw garlic was lost as water during the processing. The experimental conditions did not damage the cell wall at great level, this can be compensated by the rehydration process in the obtained BG. In another study, it was conducted that under drastic conditions (freezing and high temperature) causes more cell damage and changes BG with soft tissues and gummy structure. The study results revealed that optimum conditions do not cause significant changes in cells and polysaccharide structure of the black garlic,[38] resulting in a softer tissue structure gum-like texture of the BG. The decrease in the moisture content of the BG makes it dry and poorly elastic. The literature showed that the moisture contents between 40% and 50% are suitable for softer products. The moisture contents below 35% make the BG unsuitable for consumption because it becomes too dry at this level.[20]

The actual purpose of increasing the temperature during processing of BG is to reduce the aging time. The increase in temperature greatly affects the organoleptic properties of the final product. It has been observed that the processing temperature above 80°C brings undesirable off flavors because of the conversion of reducing sugars level. The relative humidity is also another crucial factor to be considered for desirable organoleptic properties of the BG.[4] Similarly, low temperature, i.e., below
60°C is also not effective for the development of suitable color and acid contents.\textsuperscript{[98]} The BG cannot acquire sour flavor at low temperature because of the low level of total acid contents. In short, the aging of the BG at 70°C is more suitable to acquire the desired color, flavor, suitable texture, taste, quality, and general acceptability.\textsuperscript{[20]}

The sweetness level of BG depends on the fructose contents and on the hydrolysis.\textsuperscript{[14]} Temperature has a direct impact on the pungency characteristics of the raw garlic.\textsuperscript{[100]} The increase in temperature causes the inactivation of allicinase and decrease in production of allicin, which leads to distinct decrease in pungency in black garlic.

**Conclusions and future remarks**

This review focuses on processing, factors affecting the quality of black garlic, and physicochemical modifications, paying special attention to bioactive potential of the black garlic. The present review also provides the up-to-date knowledge of the subject regarding the advantages of using black garlic over the fresh garlic. There have been many benefits of the black garlic as has been described in various published papers. The unique edge of using the black garlic over the fresh garlic is its nutritional and bioactive potential. There is an emerging interest across the world on black garlic consumption due to its different bioactive properties (anti-obesity, anti-inflammatory, anti-allergic, hepatoprotective, cardioprotective and anti-cancer) and organoleptic characteristics. Results from various studies revealed that thermal processing brings the various changes in the nutritional and phytochemical profile of the fresh garlic. Important factors that are crucial to be considered in the production of black garlic are temperature and relative humidity. Organic sulfur compounds are key components that enhance the antioxidant and antimicrobial potentials of the back garlic. The work should be done to produce the black garlic under optimized or standardized conditions at an industrial scale in order to develop a safe (eliminating undesirable substances), nutritious product for the promotion of human health. There is dire to conduct in-depth research on the reactions that take place during the production of black garlic and the development, and augmentation of the bioactive components in black garlic.

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