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Review Article

Garlic (*Allium Sativum*) As A Cardiometabolic Sentry: Unraveling Its Multifaceted Mechanisms

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ABSTRACT

Cardiometabolic disorders, including cardiovascular diseases, hypertension, obesity, dyslipidemia, insulin resistance, metabolic syndrome, and type 2 diabetes mellitus, represent a major global health burden due to their increasing prevalence and associated morbidity and mortality. Central pathophysiological processes driving these conditions include oxidative damage, persistent inflammatory responses, vascular endothelial impairment, and disrupted glucose and lipid homeostasis. Contemporary scientific attention has increasingly turned toward natural nutritional approaches and bioactive foods possessing broad-spectrum therapeutic capabilities. Within this context, garlic (*Allium sativum* L.) has distinguished itself as among the most thoroughly studied medicinal botanicals due to its varied pharmacological properties and abundant phytochemical profile. This plant harbors multiple bioactive components, notably organosulfur molecules including allicin, ajoene, diallyl sulfides, and S-allyl cysteine, alongside flavonoids, phenolic substances, vitamins, minerals, and saponins. These phytochemicals synergistically provide antioxidative, anti-inflammatory, lipid-lowering, blood pressure-reducing, glucose-regulating, anticoagulant, and vascular protective properties. Research demonstrates that garlic modulates various molecular signaling cascades, including NF- κ B, Nrf2, AMPK, PI3K/Akt, and MAPK networks,

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consequently diminishing oxidative damage, controlling inflammation, enhancing vascular performance, and promoting metabolic equilibrium. Furthermore, garlic affects nitric oxide and hydrogen sulfide transmission, platelet function, mitochondrial activity, and intestinal microbiome composition, thereby reinforcing its cardiovascular protective characteristics. This analysis provides a thorough examination of garlic's botanical characteristics, chemical constituents, mechanistic actions, and cardiometabolic benefits. It emphasizes existing obstacles regarding standardization, bioavailability, and clinical verification while exploring future directions for garlic-derived therapeutic approaches. In summary, garlic emerges as a valuable natural cardiometabolic guardian with considerable promise in preventive nutrition and integrative medicine.

INTRODUCTION

Cardiometabolic pathologies encompass an extensive range of interrelated disease states, including cardiovascular ailments, elevated blood pressure, excessive body weight, lipid metabolism disorders, glucose intolerance, metabolic syndrome, and diabetes mellitus type 2 [1]. These conditions collectively rank among the primary contributors to global disease burden and mortality while continuing to exert substantial pressure on healthcare infrastructure, economic resources, and patient well-being. Accelerated urban development, physical inactivity, poor nutritional habits, prolonged psychological stress, tobacco use, excessive alcohol intake, and environmental factors have markedly increased the occurrence of these pathologies across both industrialized and emerging economies [2]. The rising frequency of cardiometabolic disturbances has evolved into a critical public health challenge owing to their persistent character, advancing complications, and correlation with early mortality. Cardiovascular pathologies persist as the predominant cause of worldwide deaths, responsible for millions of fatalities each year. Concurrently, diabetes and excessive weight have become global health crises, impacting people of all ages [3-5]. These

conditions demonstrate close interconnection through shared pathophysiological processes including oxidative damage, sustained inflammation, vascular endothelial impairment, cellular energy dysfunction, altered lipid profiles, and disrupted glucose homeostasis [6]. Continuous subclinical inflammatory responses and overproduction of oxygen-derived free radicals serve as fundamental drivers in promoting vascular injury, glucose intolerance, and metabolic dysfunction, eventually resulting in serious cardiovascular sequelae [7].

The simultaneous presence of elevated blood pressure, excess adiposity, and diabetes substantially increases susceptibility to arterial plaque formation, cardiac muscle death, cerebrovascular accidents, kidney impairment, and cardiac insufficiency. Hence, there exists an immediate requirement for preventive and treatment approaches that can simultaneously address multiple disease mechanisms [8]. While established pharmaceutical treatments including blood pressure medications, cholesterol-lowering agents, glucose-controlling drugs, and blood-thinning medications have shown clinical efficacy, prolonged medication use frequently involves unwanted effects, therapeutic resistance, financial strain, and inadequate patient adherence. Additionally, synthetic pharmaceuticals commonly focus on individual pathways instead of addressing the complex, multifactorial characteristics of cardiometabolic disorders [9].

Consequently, growing research focus has shifted toward natural compounds and nutritional approaches that demonstrate broad therapeutic capabilities with relatively minimal adverse reactions. Throughout recent years, functional nutrition and botanical medicines have acquired significant recognition due to their protective, nutritional, and therapeutic characteristics. Within



this category, garlic (*Allium sativum*) has distinguished itself as among the most comprehensively studied medicinal plants demonstrating substantial cardiometabolic advantages [10]. Garlic represents a perennial bulbous species within the Amaryllidaceae family that has served dual purposes as a culinary component and medicinal remedy throughout history. This plant undergoes extensive cultivation globally and demonstrates distinctive aromatic characteristics alongside a complex phytochemical profile [11]. The bioactive profile of garlic encompasses various constituents, notably organosulfur derivatives including allicin, ajoene, diallyl sulfide, diallyl disulfide, S-allyl cysteine, and allyl methyl sulfide, which primarily account for its therapeutic properties. Moreover, garlic provides substantial quantities of flavonoids, phenolic substances, vitamins, minerals, selenium, and enzymatic compounds that enhance its antioxidative and anti-inflammatory capabilities [12]. Research findings have established that garlic demonstrates diverse biological functions encompassing antihyperlipidemic, antihypertensive, antidiabetic, antithrombotic, antioxidant, anti-inflammatory, antimicrobial, anticancer, hepatoprotective, and immunomodulatory properties. The cardiovascular protective capacity of garlic has garnered considerable research attention due to its influence on multiple fundamental processes underlying cardiovascular disease [13]. Evidence shows that garlic decreases serum cholesterol and triglyceride concentrations, prevents low-density lipoprotein oxidation, promotes endothelial function, increases nitric oxide availability, reduces platelet aggregation, and controls blood pressure. These combined actions support the prevention of atherosclerotic development and vascular impairment. Additionally, garlic-derived substances demonstrate powerful antioxidant capabilities that neutralize free radicals and

strengthen intrinsic antioxidant mechanisms including superoxide dismutase, catalase, and glutathione peroxidase [14]. Through reducing oxidative stress and inflammatory cascade activation, garlic provides protection to vascular structures and metabolic tissues against chronic deterioration.

A notable characteristic of garlic involves its antidiabetic and metabolic modulatory properties. Accumulating research suggests that garlic enhances insulin responsiveness, controls glucose processing, and decreases hyperglycemia via diverse pathways. Garlic bioactive compounds affect insulin release, regulate glucose transporter activity, inhibit hepatic gluconeogenesis, and enhance pancreatic β -cell performance. Furthermore, garlic may contribute to reducing obesity-associated complications by affecting adipogenesis, lipid processing, and energy utilization [15]. These comprehensive actions position garlic as a valuable nutraceutical option for addressing metabolic syndrome and related conditions. The contribution of oxidative stress and inflammation to cardiometabolic pathologies has emphasized the significance of antioxidant-enriched functional foods in disease prevention strategies. Functional foods are characterized as dietary products that offer health advantages beyond fundamental nutrition through the presence of biologically active substances [16]. The increasing focus on functional foods represents a transition from treatment-focused healthcare toward preventive medicine and lifestyle interventions. Consumers demonstrate growing interest in natural dietary approaches that can promote health, minimize disease susceptibility, and extend longevity. Garlic has emerged as a significant element in functional nutrition due to its broad pharmacological characteristics and extensive history of human use. In contrast to numerous synthetic pharmaceuticals,

garlic demonstrates pleiotropic effects through simultaneous influence on multiple molecular targets and signaling networks [17].

Contemporary investigations have revealed that garlic influences multiple molecular cascades involved in cardiometabolic control, encompassing nuclear factor-kappa B (NF- κ B), AMP-activated protein kinase (AMPK), phosphoinositide 3-kinase/protein kinase B (PI3K/Akt), nuclear factor erythroid 2-related factor 2 (Nrf2), and mitogen-activated protein kinase (MAPK) signaling networks [18]. By modulating these signaling cascades, garlic inhibits the synthesis of pro-inflammatory cytokines, strengthens antioxidant mechanisms, maintains endothelial function, and supports metabolic equilibrium. These comprehensive mechanistic actions establish garlic as a promising cardiometabolic guardian with the capacity to defend against various pathological challenges [19, 20].

Global burden of cardiometabolic disorders

Cardiometabolic conditions have emerged as a predominant worldwide health concern owing to their rapidly escalating incidence and related complications. Based on international health documentation, cardiac ailments represent roughly one-third of global mortality, whereas diabetes incidence continues expanding at a concerning pace [21]. Adiposity, which demonstrates strong associations with diabetes and cardiac pathology, has attained pandemic levels across numerous nations due to poor nutritional practices and diminished physical engagement. The impact proves especially pronounced in developing economies where medical resources remain constrained and lifestyle transformations occur swiftly. The escalating incidence of cardiometabolic pathologies stems from numerous determinants including overconsumption of

manufactured foods, elevated intake of saturated lipids and sugars, sedentary behavior, psychological strain, tobacco use, excessive alcohol consumption, demographic aging, and hereditary susceptibility [22]. Urban development and technological advancement have substantially modified nutritional behaviors, resulting in heightened consumption of energy-dense products and decreased intake of fruits, vegetables, and fiber-containing foods. These modifications contribute to adiposity, lipid abnormalities, elevated blood pressure, and impaired glucose metabolism, which collectively enhance cardiometabolic vulnerability. Metabolic syndrome constitutes a constellation of related metabolic disturbances encompassing central adiposity, elevated glucose levels, increased blood pressure, and lipid disorders [23-25]. Persons presenting with metabolic syndrome face considerably elevated risk for developing cardiac complications and type 2 diabetes mellitus. Persistent inflammatory processes linked to obesity further exacerbate endothelial impairment and oxidative damage, facilitating vascular harm and atherosclerotic development [26]. Therefore, cardiometabolic pathologies represent interconnected rather than independent conditions sharing similar molecular pathways. The socioeconomic consequences of cardiometabolic disorders prove equally substantial [27]. These conditions result in elevated medical costs, decreased work performance, functional impairment, and compromised life quality. Extended management frequently necessitates continuous pharmaceutical intervention and recurrent hospital admissions, creating considerable economic strain on individuals and medical institutions. Consequently, prevention approaches emphasizing nutritional modifications, exercise promotion, and natural therapeutic approaches have gained prominence in



diminishing disease occurrence and advancement [28-30].

Role of functional foods in disease prevention

Functional foods have become an essential element of preventive medicine due to their capacity to deliver physiological advantages that extend beyond fundamental nutritional needs. These food products contain bioactive constituents that can influence metabolic pathways, strengthen immune responses, diminish oxidative damage, and decrease disease susceptibility [31]. Increasing recognition of the constraints and negative consequences associated with synthetic medications has amplified focus on plant-based nutraceuticals and nutritional therapeutics. The bioactive constituents found in functional foods encompass polyphenols, flavonoids, carotenoids, alkaloids, sulfur compounds, dietary fibers, omega-3 fatty acids, probiotics, and phytosterols. These components demonstrate antioxidant, anti-inflammatory, antimicrobial, antidiabetic, antihyperlipidemic, and cardioprotective properties [32]. Consistent intake of functional foods has been linked to decreased prevalence of chronic conditions including cardiovascular diseases, cancer, obesity, and diabetes. Garlic represents one of the most significant functional foods owing to its extensive pharmacological characteristics and nutritional density. The sulfur-bearing compounds in garlic demonstrate potent free radical neutralizing capabilities and assist in controlling lipid and glucose metabolism [33]. Garlic supplementation has been demonstrated to lower blood pressure, enhance lipid parameters, reduce oxidative damage, and suppress inflammatory factors. Furthermore, garlic modifies gut microbiota composition, which serves a vital function in metabolic control and immune performance. The principle of food serving as medicine has achieved renewed

scientific importance in contemporary times [34]. Nutritional strategies addressing inflammation and oxidative damage are progressively acknowledged as efficacious methods for preventing chronic metabolic disorders. Functional foods provide a more secure and sustainable methodology for long-term health maintenance when compared to sole reliance on synthetic pharmaceuticals. Therefore, incorporating garlic into dietary and therapeutic protocols constitutes a valuable strategy for enhancing cardiometabolic wellness [35].

Historical and traditional significance of Garlic

Throughout millennia, garlic has served both therapeutic and nutritional functions across diverse cultures. Multiple ancient civilizations, including Egyptian, Greek, Roman, Chinese, and Indian medical traditions, acknowledged garlic as a potent healing agent effective against various health conditions [36]. Within traditional Chinese medicine and Ayurvedic practices, garlic found widespread application in addressing respiratory conditions, gastrointestinal issues, infectious diseases, elevated blood pressure, and vascular complications. Greek medical practitioners, notably Hippocrates, recommended garlic for treating lung ailments, promoting wound recovery, and resolving digestive disorders. Roman military personnel similarly incorporated garlic consumption to enhance endurance and bolster immunity against pathogenic threats [37]. Ayurvedic literature characterizes garlic as a powerful revitalizing agent possessing heart-strengthening, digestive-enhancing, antimicrobial, and inflammation-reducing qualities. Indigenous healers additionally utilized garlic for addressing parasitic conditions, febrile states, joint inflammation, and metabolic imbalances [38]. The therapeutic significance of garlic stems primarily from sulfur-based constituents formed through



mechanical disruption of the bulb segments. The enzymatic transformation of alliin to allicin generates the distinctive aroma and biological activity characteristic of fresh garlic preparations [39]. Traditional medical systems frequently advocated unprocessed garlic or concentrated preparations for cardiovascular and metabolic wellness well before contemporary scientific substantiation emerged. Subsequently, technological progress has validated numerous historical assertions concerning garlic's healing capabilities. Current pharmacological investigations have established garlic's blood pressure-lowering, glucose-regulating, antioxidative, anti-inflammatory, antimicrobial, and heart-protective effects. This alignment between ancestral wisdom and modern research has intensified scientific interest in garlic as an evidence-based functional food [40].

Rationale and scope of the review

Although garlic has been subject to considerable investigation, the rising incidence of cardiometabolic conditions demands a thorough comprehension of its diverse therapeutic pathways. Multiple experimental and clinical investigations have examined specific impacts of garlic on cardiac wellness, lipid processing, oxidative burden, inflammatory responses, and glucose regulation. Nevertheless, an integration of these observations into a cohesive framework that emphasizes garlic's role as a multi-targeted cardiometabolic protective compound remains necessary. This review's foundation stems from the escalating requirement for natural therapeutic approaches capable of targeting the intricate and interrelated mechanisms underlying cardiometabolic pathologies. Garlic constitutes a distinctive functional food possessing diverse biological activities that simultaneously influence various molecular and metabolic pathways.

Comprehending these mechanisms could offer important perspectives for developing innovative nutraceutical and treatment approaches. This review endeavors to thoroughly examine garlic's phytochemical profile, its molecular action mechanisms, cardiac and antidiabetic characteristics, regulation of inflammatory and oxidative cascades, microbiome interactions, clinical documentation, safety profiles, and future therapeutic applications. Additionally, the review investigates garlic's function in controlling signaling networks related to endothelial performance, lipid processing, glucose balance, and vascular health. Through combining traditional medicinal wisdom with modern scientific data, this review attempts to position garlic as a significant cardiometabolic guardian with considerable preventive and treatment capabilities. The presented evidence may advance the expanding domain of functional nutrition and promote additional investigation directed toward evidence-supported application of garlic in cardiometabolic condition management.

Botanical Profile of Garlic (*Allium sativum*)

Allium sativum L., commonly known as garlic, represents one of the most extensively grown and medicinally significant plant species globally. For millennia, this species has served diverse functions spanning culinary applications, therapeutic uses, agricultural practices, and spiritual ceremonies. As a member of the *Allium* genus, garlic demonstrates taxonomic relationships with related species including onions, shallots, leeks, and chives [41]. The species is particularly distinguished by its distinctive sharp aroma, sulfur-containing bioactive compounds, and extensive pharmacological properties. Due to its remarkable medicinal capabilities, garlic has generated substantial research attention across multiple scientific disciplines, including phytochemical



analysis, pharmacological investigation, nutraceutical development, traditional medicine studies, and cardiovascular-metabolic research [42]. The therapeutic value of garlic stems predominantly from its abundant content of organosulfur molecules, flavonoid compounds, essential vitamins, enzymatic proteins, amino acid components, and mineral elements. These active constituents underlie its antioxidative, anti-inflammatory, antimicrobial, cardiac-protective, glucose-lowering, blood pressure-reducing, and immune-modulating properties [43]. Beyond its medicinal applications, garlic holds considerable economic importance as a commercially valuable spice crop grown across various temperate and subtropical territories globally [44]. Its capacity to adapt to diverse environmental conditions and soil compositions has facilitated worldwide cultivation and utilization. From a botanical perspective, garlic constitutes a herbaceous perennial species typically managed as an annual agricultural crop, harvested for its subterranean bulbous structure containing numerous cloves surrounded by papery protective sheaths [45]. Various garlic cultivars demonstrate differences in bulb dimensions, clove quantities, coloration patterns, flavor potency, and chemical profiles. Such variability results from genetic determinants, environmental factors, agricultural methodologies, and regional origins. Comprehensive understanding of garlic's botanical features, taxonomic classification, and global distribution patterns remains fundamental for accurate species identification, successful cultivation, quality assessment, and therapeutic standardization [46]. Garlic has maintained significant importance within traditional healing systems, including Ayurvedic medicine, Traditional Chinese Medicine, Unani practices, ancient Egyptian therapeutics, and Greco-Arab medical traditions [47]. Historical civilizations regarded garlic as a sacred and health-enhancing organism capable of promoting physical vigor,

immune function, and life extension [48]. Contemporary scientific investigations have substantiated numerous traditional applications and established garlic as a significant functional food possessing diverse pharmacological mechanisms. Therefore, comprehensive botanical understanding of garlic remains essential for both agricultural progress and biomedical investigation [49, 50].

Taxonomy and classification

Garlic is positioned within the kingdom Plantae and categorized within the Amaryllidaceae family, encompassing numerous bulbous flowering species of medicinal and culinary significance [51]. Previously, garlic was assigned to the Liliaceae family; nevertheless, progress in molecular phylogenetic research and taxonomic investigations resulted in its reassignment to the Amaryllidaceae family and Allioideae subfamily [52]. The *Allium* genus represents among the most extensive genera of monocotyledonous flowering species, containing over 900 species with worldwide distribution. Species within this genus are distinguished by sulfur-based volatile compounds that account for their characteristic odor and biological properties [53]. The scientific classification of garlic is as follows:

- **Kingdom:** Plantae
- **Subkingdom:** Tracheobionta
- **Division:** Magnoliophyta
- **Class:** Liliopsida (Monocotyledons)
- **Order:** Asparagales
- **Family:** Amaryllidaceae
- **Subfamily:** Allioideae



- **Genus:** *Allium*
- **Species:** *Allium sativum* L.

The taxonomic designation "sativum" originates from Latin vocabulary signifying "cultivated," reflecting its extensive historical relationship with human domestication and farming practices [54]. Garlic is thought to have emerged from Central Asian regions, specifically areas spanning from northeastern Iran through Turkmenistan and adjacent territories. Throughout millennia, this plant dispersed across Asia, Europe, Africa, and ultimately reached all populated continents via commercial pathways, population movements, and cultural interactions [55].

Two primary botanical classifications of garlic are conventionally distinguished according to reproductive features and bulb architecture: hardneck and softneck varieties. Hardneck garlic (*Allium sativum* var. *ophioscorodon*) develops a firm reproductive stalk termed a scape and typically exhibits fewer yet larger cloves positioned around a central axis. Softneck garlic (*Allium sativum* var. *sativum*) demonstrates absence of a rigid reproductive stalk and commonly displays multiple smaller cloves. Softneck cultivars receive greater commercial attention due to their extended storage capacity and tolerance to varied environmental circumstances. Garlic reproduction occurs predominantly through vegetative means via cloves rather than sexual reproduction, as fertile seed development remains constrained in numerous commercial varieties [56]. Vegetative multiplication preserves genetic consistency while simultaneously limiting genetic diversity. Nevertheless, considerable variation exists among garlic cultivars regarding morphological characteristics, bulb coloration, taste attributes, phytochemical profiles, and medicinal strength. Scientists have documented multiple ecotypes and

cultivars specialized for particular climatic and cultivation environments. Taxonomic classification of garlic serves essential purposes beyond botanical recognition, extending to pharmacognostic and pharmaceutical standardization requirements [57]. Various cultivars may demonstrate differences in allicin concentrations, sulfur constituents, antioxidant capacity, and therapeutic effectiveness. Therefore, precise classification supports researchers in identifying suitable varieties for medicinal and agricultural purposes [58]. Molecular techniques, cytogenetic analysis, and DNA profiling methods are progressively utilized for garlic genetic resource characterization, biodiversity evaluation, and improvement initiatives. The *Allium* genus possesses tremendous medicinal importance, as multiple species including onion (*Allium cepa*), leek (*Allium porrum*), and chives (*Allium schoenoprasum*) demonstrate significant pharmacological properties [59]. Nevertheless, garlic maintains prominence as one of the most bioactive species attributed to its remarkably elevated sulfur-containing compound levels. These constituents function critically in plant protection systems against pathogens and environmental challenges while concurrently providing human health advantages [60].

Morphological characteristics

Garlic represents a bulbous herbaceous perennial species typically grown on an annual basis for its subterranean bulb. This plant demonstrates distinctive morphological characteristics that enable its recognition and agricultural management. Garlic specimens commonly reach heights between 30 and 100 cm, influenced by variety selection, environmental parameters, and cultivation methods. The organism features a superficial fibrous root network, a subterranean

bulb containing cloves, extended foliage, and sometimes a reproductive stem [61].

Root Network: The plant develops a fibrous adventitious root structure originating from the basal disc positioned at the bulb's lower section. These roots remain relatively superficial and exhibit limited branching, rendering the species vulnerable to moisture deficiency and soil compaction. Proper root establishment proves crucial for nutrient uptake, bulb expansion, and overall plant performance. Root systems undergo continuous renewal throughout development and deteriorate following bulb maturity [62].

Bulb anatomy: The bulb constitutes the primary economically and therapeutically valuable component of the garlic plant. This structure consists of numerous individual units termed cloves, surrounded by delicate papery coverings. Clove quantity per bulb fluctuates based on variety, environmental influences, and hereditary traits. Individual cloves function as modified lateral buds with the capacity to generate new plants through vegetative reproduction. Garlic bulbs exhibit variation in dimensions, form, pigmentation, and clove organization across different varieties. Bulb coloration spans from white and cream tones to purple or pink hues due to anthocyanin pigment presence. External protective layers prevent moisture depletion and pathogen infiltration during storage periods. The distinctive pungent fragrance characteristic of garlic bulbs results from sulfur-based compounds generated upon tissue damage. Intact garlic cloves house the sulfur amino acid alliin and the enzyme alliinase within distinct cellular locations. Upon crushing or cutting garlic tissue, alliinase transforms alliin into allicin, a highly reactive substance responsible for garlic's typical scent and numerous biological properties [63].

Stem and basal structure: The actual stem of garlic undergoes significant reduction and compression into a basal disc positioned at the bulb's base. This basal structure functions as the attachment site for roots and cloves. In hardneck garlic types, a pseudostem created by overlapping leaf sheaths extends upward and generates a reproductive stalk termed a scape.

Foliage: Garlic leaves appear elongated, slender, flattened, and linear with parallel venation typical of monocotyledonous species. Leaves emerge alternately from the basal disc and possess tubular sheaths at their base. Leaf pigmentation typically ranges from light green to bluish-green based on cultivar and environmental factors. Foliage performs an essential function in photosynthesis and nutrient storage necessary for bulb formation. Vigorous leaf development directly affects bulb dimensions and quality. Throughout maturation, older leaves progressively deteriorate and desiccate, indicating bulb preparation for harvest [64].

Reproductive structure and flowers: Specific garlic varieties, especially hardneck cultivars, develop a reproductive stalk or scape emerging from the plant's center. The scape concludes in an umbel-type inflorescence initially surrounded by a papery bract. Garlic flowers typically appear small, pinkish-white, or light purple. Nevertheless, numerous cultivated garlic varieties demonstrate sterility or diminished fertility and seldom generate viable seeds. Rather than fertile flowers, certain garlic plants develop bulbils—small aerial bulb-like formations capable of vegetative multiplication. These bulbils may serve germplasm preservation and breeding objectives. The restricted seed production in garlic has promoted its primary vegetative propagation method [65].



Considerable morphological variation characterizes garlic cultivars, manifesting through differences in bulb diameter, clove quantity and dimensions, foliar measurements, coloration patterns, scape development, and maturation periods. Hardneck types typically exhibit larger cloves accompanied by more intense flavor characteristics, while softneck types feature smaller cloves yet demonstrate enhanced storage longevity. Environmental conditions including temperature regimes, photoperiodic responses, soil nutrient status, water management, and elevation contribute significantly to morphological expression. Morphological assessment serves a critical role in garlic improvement initiatives targeting enhanced productivity, pathogen resistance, storage durability, and bioactive compound content [66].

Cultivation of Garlic

Garlic experiences widespread cultivation globally, serving dual purposes as a culinary seasoning and therapeutic herb. The plant's remarkable environmental flexibility facilitates successful production across temperate, subtropical, and semi-arid zones. Optimal growth requires cool weather during vegetative development and relatively arid conditions throughout bulb maturation phases [67]. Cultivation typically occurs during winter months in subtropical areas and spring-summer periods in temperate zones. The crop performs optimally under moderate climatic circumstances with temperature ranges of 12°C to 24°C. Lower temperatures enhance vegetative development, while elevated conditions encourage bulb formation and ripening. Extremely high temperatures may compromise bulb quality and productivity, whereas severe freezing conditions can harm foliage and impede development. Daylength substantially affects bulb initiation.

Extended daylight periods typically encourage bulb expansion in numerous garlic varieties [68]. Adequate soil hydration during vegetative phases remains crucial; nevertheless, excessive saturation may increase susceptibility to fungal pathologies and root decay. Garlic flourishes in nutrient-rich, well-draining loamy substrates abundant in organic content. Sandy loam and clay loam soils providing adequate ventilation and moderate water retention represent ideal cultivation media. Soil acidity levels between 6.0 and 7.5 typically optimize healthy development and bulb formation [69]. Dense compacted substrates may impede bulb expansion and root infiltration. Organic amendments and balanced nutrient applications substantially enhance garlic production. Nitrogen facilitates vegetative development, while phosphorus and potassium support bulb formation and quality improvement. Sufficient micronutrient provision, especially sulfur, remains vital for synthesizing sulfur-based bioactive constituents [70]. Garlic reproduction occurs primarily through vegetative propagation using cloves. Disease-free healthy cloves serve as planting stock to ensure superior crop establishment. Larger cloves typically yield more robust plants and enhanced bulb size relative to smaller propagules. Establishment usually involves manual placement in rows with appropriate spacing to accommodate bulb development and field operations [71]. Cloves are positioned in soil with the acute end oriented upward. Based on environmental conditions and variety characteristics, garlic maturation may span approximately 4–8 months following establishment. Consistent irrigation remains essential throughout initial vegetative growth phases. However, water application decreases approaching maturity to prevent bulb deterioration and promote desiccation. Weed management proves critical since garlic plants exhibit superficial root systems and limited competitive capacity against weeds [72].



Mulching frequently serves to preserve soil hydration, control weeds, and moderate soil temperature. Garlic production may encounter various pest and disease challenges including nematodes, thrips, fungal decay, rust, downy mildew, and bacterial infections. Comprehensive pest management strategies, crop rotation systems, resistant varieties, and appropriate storage protocols are essential for maintaining crop vitality and output. Garlic bulbs undergo harvest when foliage initiates yellowing and desiccation, signaling physiological maturity [73-75]. Following collection, bulbs receive curing treatment under dry ventilated environments to decrease moisture levels and improve storage longevity. Appropriate curing inhibits microbial deterioration and extends shelf duration. Softneck garlic cultivars typically demonstrate enhanced storage capabilities compared to hardneck varieties. Stored garlic bulbs require protection from excessive moisture and temperature variations to prevent sprouting and fungal deterioration [76].

Geographical distribution

Garlic cultivation occurs on a worldwide scale and represents a significant agricultural product across numerous nations. The Asian continent serves as the predominant garlic-producing area, with China maintaining its position as the foremost global producer. Additional significant garlic-producing nations encompass India, Bangladesh, South Korea, Egypt, Spain, Russia, and the United States [77]. China maintains supremacy in international garlic production and exportation through expansive cultivation territories, advantageous climate patterns, and industrial-scale farming methodologies. India similarly functions as a substantial producer, with garlic being widely grown across states including Madhya Pradesh, Gujarat, Rajasthan, Uttar Pradesh, and Punjab.

Indian garlic cultivars are recognized for their intense pungency and therapeutic properties [78]. Throughout Europe, garlic production is notable in Spain, Italy, and France, where it serves as a fundamental component of customary culinary practices and botanical medicine. Mediterranean climate patterns support the development of superior garlic bulbs characterized by enhanced flavor profiles and phytochemical concentrations [79]. Within North America, garlic production primarily occurs in California and additional areas featuring appropriate temperate environments. Garlic cultivation has successfully extended to African, Middle Eastern, and South American regions. Variations in environmental conditions, elevation, soil characteristics, and farming methodologies result in regional diversity regarding garlic structure, taste, and phytochemical composition. The extensive global presence of garlic demonstrates its exceptional adaptability and profound cultural, gastronomic, and therapeutic importance. Ongoing developments in agricultural biotechnology, selective breeding initiatives, and phytochemical investigations are anticipated to further advance garlic production and medicinal utilization internationally [80].

Phytochemical composition of Garlic (*Allium sativum*)

Allium sativum L., commonly known as garlic, stands among the most pharmaceutically significant medicinal plants due to its remarkably rich and varied phytochemical profile. The medicinal properties of garlic stem principally from its abundant bioactive components, encompassing organosulfur compounds, phenolic substances, flavonoids, saponins, enzymatic proteins, amino acids, vitamins, minerals, and trace elements [81]. These phytochemical constituents synergistically produce garlic's



extensive range of biological functions, including antioxidant, anti-inflammatory, antimicrobial, cardioprotective, antihyperlipidemic, antidiabetic, anticancer, hepatoprotective, and immunomodulatory properties. The levels and profiles of these active compounds vary according to multiple variables such as cultivar selection, growing environments, geographic location, developmental stage, storage parameters, and processing techniques including mechanical disruption, thermal treatment, dehydration, or fermentation.

Organosulfur constituents represent the most significant and biologically potent components within garlic's phytochemical arsenal. Unprocessed whole garlic bulbs predominantly harbor sulfur-containing amino acid derivatives termed cysteine sulfoxides, with alliin (S-allyl-L-cysteine sulfoxide) serving as the principal

precursor molecule [82]. Alliin maintains relative stability and remains odorless within undamaged garlic tissues due to spatial separation from the enzyme alliinase. When garlic undergoes mechanical damage through crushing, cutting, or mastication, cellular breakdown enables alliinase-alliin interaction, leading to swift allicin (diallyl thiosulfinate) generation. Allicin accounts for garlic's distinctive sharp aroma and numerous pharmacological properties associated with fresh preparations. Nevertheless, allicin demonstrates marked instability and rapidly degrades into various lipophilic sulfur derivatives including diallyl sulfide, diallyl disulfide, diallyl trisulfide, ajoene, and vinyl dithiins. These sulfur breakdown products exhibit substantial antioxidant, antimicrobial, anti-inflammatory, and cardiovascular protective characteristics [83].

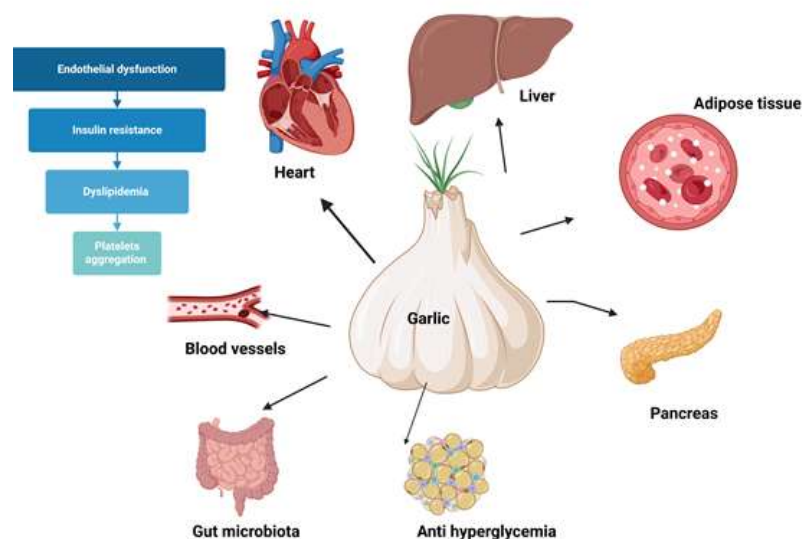


Fig: 1 The impact of Garlic on metabolic health and related organs

Alliin has garnered considerable scientific interest owing to its powerful biological functionality. It demonstrates robust antimicrobial efficacy against diverse bacterial, fungal, viral, and parasitic organisms through disruption of sulfhydryl-containing enzymes and metabolic processes. Moreover, allicin displays exceptional antioxidant capacity via reactive oxygen species

neutralization and lipid peroxidation prevention [84]. Research indicates that allicin facilitates blood pressure reduction, platelet aggregation inhibition, endothelial function enhancement, and lipid metabolism modulation, thus contributing significantly to cardiometabolic health protection. Despite its therapeutic importance, allicin's chemical instability and high reactivity restrict its

direct bioavailability within physiological systems. Therefore, numerous long-term biological benefits of garlic are mediated through its more chemically stable sulfur-containing derivatives. Diallyl sulfide, diallyl disulfide, and diallyl trisulfide constitute significant volatile sulfur metabolites produced during allicin breakdown. These lipophilic molecules demonstrate comprehensive pharmacological properties encompassing antioxidant, anti-inflammatory, anticarcinogenic, and hepatoprotective functions. Diallyl disulfide has been documented to regulate detoxification enzyme systems, suppress inflammatory mediator synthesis, and prevent oxidative stress-mediated tissue injury. Diallyl trisulfide exhibits substantial cardiovascular protection through augmentation of endogenous hydrogen sulfide signaling mechanisms, vascular relaxation, and mitigation of myocardial oxidative damage. Additionally, these compounds affect lipid homeostasis and contribute to decreased serum cholesterol and triglyceride concentrations [85].

This compound prevents platelet aggregation through disruption of fibrinogen binding and thromboxane production, thus supporting garlic's cardiovascular protective properties. Furthermore, ajoene has shown inhibitory effects on tumor cell growth and microbial biofilm development. Vinyl dithiols, also produced from allicin breakdown, display antioxidant and anti-inflammatory characteristics and may enhance the therapeutic benefits of garlic formulations. Aged garlic extract encompasses water-soluble organosulfur molecules that differ substantially from those found in raw garlic. Throughout the aging procedure, volatile sulfur components transform into more stable and bioavailable substances including S-allyl cysteine and S-allyl mercaptocysteine. These molecules possess exceptional antioxidant capacity and remarkable

biological stability. S-allyl cysteine represents one of the most thoroughly investigated garlic components and demonstrates cardioprotective, neuroprotective, hepatoprotective, and antidiabetic properties [86]. This compound strengthens endogenous antioxidant mechanisms encompassing glutathione, superoxide dismutase, and catalase while concurrently diminishing oxidative stress and inflammation. Additionally, S-allyl cysteine exhibits favorable impacts on endothelial performance, blood pressure control, and lipid processing, establishing it as a significant therapeutic element in aged garlic formulations. Beyond sulfur-bearing components, garlic encompasses considerable quantities of phenolic compounds and flavonoids that substantially enhance its antioxidant capacity. Phenolic acids including caffeic acid, ferulic acid, p-coumaric acid, gallic acid, and chlorogenic acid exist in garlic at different concentrations. These phenolic substances function as free radical neutralizers and metal binding agents, thus safeguarding cellular components from oxidative harm. They additionally regulate inflammatory mechanisms and prevent low-density lipoprotein oxidation, a critical process in atherosclerosis progression. Flavonoids comprising quercetin, kaempferol, myricetin, and catechin have been detected in garlic. These molecules demonstrate potent antioxidant and anti-inflammatory actions and support vascular protection, metabolic control, and immune regulation. Quercetin specifically has shown antihypertensive, antiatherosclerotic, and antidiabetic characteristics through regulation of endothelial nitric oxide production, suppression of inflammatory mediators, and inhibition of oxidative stress mechanisms. The cooperative relationship between sulfur compounds and polyphenolic components amplifies the comprehensive therapeutic effectiveness of garlic [87].



Garlic additionally encompasses steroidal saponins, which represent glycosidic molecules with significant pharmacological characteristics. Saponins extracted from garlic demonstrate cholesterol-reducing, immunomodulatory, antimicrobial, and anticancer effects. These substances support the decrease of serum lipid concentrations by disrupting cholesterol uptake and bile acid processing. Moreover, steroidal saponins may exhibit anti-inflammatory properties and affect cellular signaling networks related to metabolic control and programmed cell death. An additional significant element of garlic phytochemistry involves the occurrence of essential amino acids, peptides, and enzymes. Garlic encompasses amino acids including arginine, cysteine, methionine, and glutamic acid that participate in protein formation and metabolic processes [88]. The enzyme alliinase holds particular importance as it facilitates the

transformation of alliin to allicin following tissue damage. Additional enzymes encompassing peroxidases, myrosinase-like enzymes, and proteases may also participate in the biochemical modifications occurring in garlic tissues. Garlic possesses an abundance of diverse vitamins that enhance both its nutritional profile and medicinal properties. These include vitamin C, vitamin B6, thiamine, riboflavin, niacin, and folic acid. Vitamin C functions as a powerful antioxidant while promoting immune system activity, collagen formation, and blood vessel health [89]. Vitamin B6 is involved in amino acid processing, neurotransmitter production, and homocysteine control, which holds significance for heart health. The simultaneous occurrence of antioxidant vitamins alongside sulfur-containing compounds amplifies garlic's ability to counteract oxidative damage and inflammatory processes [90].

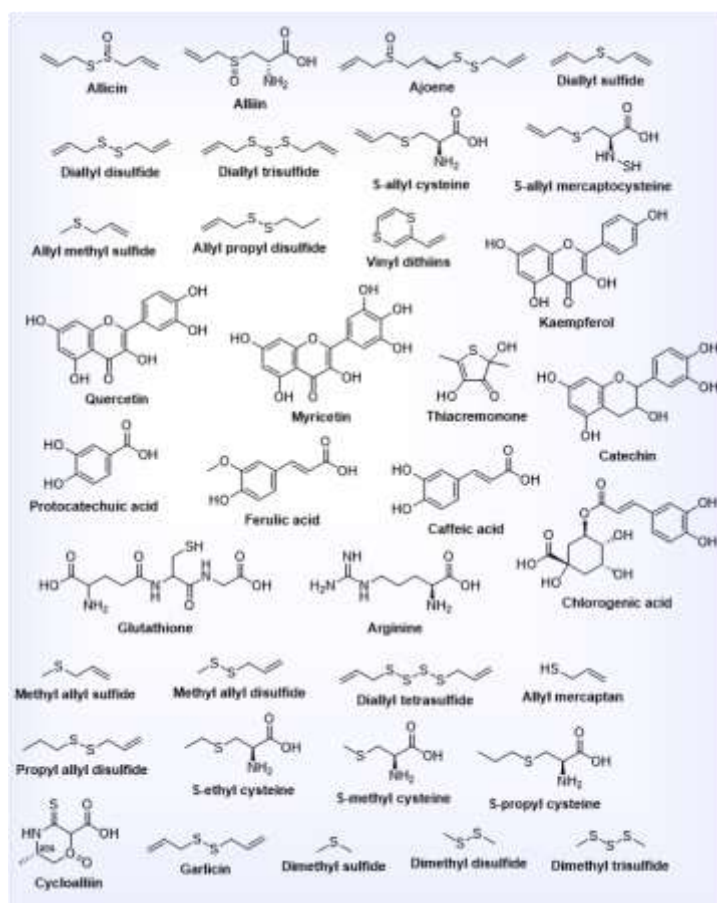


Fig.2: Phytochemistry of *Allium sativum*

Pathophysiology of cardiometabolic disorders

Cardiometabolic conditions constitute an intricate constellation of interconnected pathological states encompassing cardiovascular pathology, adiposity, elevated blood pressure, lipid abnormalities, diminished insulin sensitivity, metabolic syndrome, and type 2 diabetes mellitus [91]. These conditions exhibit shared molecular, biochemical, and physiological pathways that synergistically promote advancing vascular and metabolic impairment. The etiology of cardiometabolic conditions is multifaceted, involving complex relationships between hereditary susceptibility, environmental factors, inactive lifestyle patterns, poor nutritional practices, persistent psychological stress, hormonal dysregulation, inflammatory processes, oxidative damage, vascular endothelial impairment, and disrupted glucose and lipid homeostasis. The simultaneous presence of these abnormalities markedly elevates the likelihood of atherosclerotic disease, cardiac infarction, cerebrovascular accidents, kidney pathology, and early death [92].

A fundamental pathway underlying cardiometabolic conditions involves diminished insulin sensitivity, wherein peripheral organs including skeletal muscle, fat tissue, and hepatic cells demonstrate decreased insulin responsiveness. During typical physiological states, insulin promotes cellular glucose absorption and governs carbohydrate, fat, and protein metabolism. Nevertheless, prolonged excessive nutrition, adiposity, and lack of physical activity compromise insulin signaling mechanisms, resulting in reduced glucose utilization and compensatory elevated insulin levels. Sustained insulin resistance facilitates elevated blood glucose, hepatic glucose production, enhanced free fatty acid mobilization,

and altered lipid metabolism, thus promoting type 2 diabetes mellitus and metabolic syndrome development. Additionally, insulin resistance correlates strongly with vascular endothelial impairment, elevated blood pressure, and vessel inflammation, connecting metabolic disturbances with cardiovascular consequences [93-95].

Adiposity, especially central or intra-abdominal fat accumulation, serves a pivotal function in cardiometabolic disorder development. Fat tissue is currently understood as a metabolically active endocrine structure that produces various bioactive substances termed adipokines, such as leptin, adiponectin, resistin, tumor necrosis factor-alpha (TNF- α), and interleukins. Excessive central fat deposition causes fat cell enlargement and inflammatory immune cell infiltration, particularly macrophages, resulting in persistent mild inflammatory states [96]. Enhanced pro-inflammatory mediator synthesis interferes with insulin signaling mechanisms and intensifies oxidative damage, thus worsening metabolic dysfunction. Additionally, adiposity encourages lipid disorders characterized by increased triglycerides, elevated low-density lipoprotein cholesterol, and decreased high-density lipoprotein cholesterol, all contributing to atherosclerotic processes and cardiovascular disease advancement [97].

Oxidative stress constitutes a core pathophysiological process in cardiometabolic disease development. This phenomenon emerges from disequilibrium between the production of reactive oxygen species and the capacity of antioxidant defense mechanisms. Overproduction of free radicals causes deterioration of lipids, proteins, nucleic acids, and cellular membranes, culminating in cellular malfunction and tissue damage. Within cardiometabolic conditions, elevated glucose levels, adiposity, and sustained



inflammation trigger mitochondrial impairment and stimulation of oxidative enzymes including NADPH oxidase, resulting in enhanced reactive oxygen species generation. This oxidative burden promotes endothelial impairment, vascular inflammation, insulin resistance, and lipid peroxidation, thus accelerating atherogenesis and organ deterioration. Furthermore, oxidative stress diminishes nitric oxide availability, compromising vasodilation and fostering vascular rigidity and hypertension [98].

Sustained inflammation demonstrates complex interconnections with cardiometabolic disorder advancement. In contrast to acute inflammatory responses, cardiometabolic inflammation exhibits persistent, subclinical, and systemic characteristics. Adipose tissue-produced cytokines including TNF- α , interleukin-6, and C-reactive protein stimulate inflammatory cascades encompassing nuclear factor-kappa B (NF- κ B) and c-Jun N-terminal kinase pathways. These inflammatory substances disrupt insulin receptor signaling, compromise endothelial performance, and facilitate vascular restructuring. Inflammation additionally promotes atherosclerotic plaque development and destabilization within arterial structures, elevating thrombosis risk and cardiovascular events. Therefore, persistent inflammation serves as a crucial linking mechanism among obesity, diabetes, and cardiovascular pathology [99].

Endothelial impairment constitutes a critical milestone in cardiovascular complications linked to cardiometabolic conditions. The vascular endothelium performs vital functions in preserving vascular equilibrium through regulation of vasodilation, coagulation, inflammation, and vascular permeability. During pathological states, oxidative stress and inflammatory substances compromise endothelial nitric oxide production

while enhancing vasoconstrictor synthesis such as endothelin-1. Diminished nitric oxide accessibility results in compromised vasodilation, enhanced platelet aggregation, leukocyte adherence, and vascular inflammation. Endothelial impairment encourages arterial rigidity and facilitates atherosclerosis initiation and advancement.

Mitochondrial impairment substantially influences cardiometabolic pathophysiology. Mitochondria are crucial for cellular energy synthesis and metabolic control. Excessive nutrient consumption and oxidative stress compromise mitochondrial performance, causing reduced ATP production and elevated reactive oxygen species generation. Mitochondrial dysfunction disrupts fatty acid oxidation and glucose utilization, encouraging lipid deposition, insulin resistance, and cellular death. Within cardiac tissue, mitochondrial abnormalities compromise myocardial energy balance and contribute to heart failure and ischemic damage [100].

Hereditary and epigenetic elements additionally affect cardiometabolic disorder susceptibility. Genetic variations influencing insulin signaling, lipid processing, inflammation, and blood pressure control may increase individual vulnerability to metabolic disturbances. Epigenetic alterations including DNA methylation, histone modification, and microRNA regulation respond to environmental and lifestyle influences and may modify gene expression related to cardiometabolic risk. Moreover, aging promotes gradual metabolic deterioration through enhanced oxidative stress, chronic inflammation, hormonal changes, and diminished mitochondrial function.

Cardioprotective mechanisms of Garlic

Allium sativum L. has achieved substantial scholarly acknowledgment as an effective cardiovascular-protective nutraceutical owing to



its diverse therapeutic characteristics and capacity to modulate multiple biochemical pathways linked to cardiac pathology [101]. Cardiac conditions, encompassing elevated blood pressure, arterial plaque formation, coronary vessel disease, heart attack, and cardiac insufficiency, continue to represent primary contributors to worldwide illness and death rates. The development of these conditions encompasses intricate processes including reactive oxygen damage, persistent inflammatory responses, vascular lining impairment, abnormal lipid profiles, blood cell clumping, vessel structural changes, and compromised nitric oxide communication. This botanical species harbors an extensive array of active plant compounds, notably sulfur-containing molecules including allicin, ajoene, diallyl sulfide, diallyl disulfide, diallyl trisulfide, and S-allyl cysteine, which synergistically produce cardiovascular benefits [102]. These substances demonstrate antioxidative, lipid-lowering, blood pressure-reducing, inflammation-suppressing, clot-preventing, vessel-relaxing, and vascular protective properties, establishing this plant as a significant natural remedy for cardiac wellness maintenance. A primary cardiovascular protection strategy involves the substantial antioxidative capacity of this herb. Oxidative damage serves as a fundamental factor in cardiac disease development through excessive production of harmful oxygen molecules that harm blood vessel structures, alter lipid composition, compromise vascular lining performance, and stimulate inflammatory processes [103]. Sulfur-containing derivatives from this plant function as efficient radical neutralizers and strengthen internal protective antioxidant mechanisms encompassing superoxide dismutase, catalase, glutathione peroxidase, and reduced glutathione. Allicin and S-allyl cysteine have shown exceptional capacity to diminish fat oxidation and shield heart muscle from oxidative damage. This plant additionally

stimulates the nuclear factor erythroid 2-related factor 2 (Nrf2) communication system, which controls antioxidant enzyme production and cellular protection proteins. By reducing oxidative damage, this botanical helps maintain blood vessel health, prevents vascular injury, and slows cardiovascular disease advancement [104].

Garlic demonstrates notable antiplatelet and antithrombotic properties that play a crucial role in averting cardiovascular complications linked to pathological blood coagulation. The processes of platelet aggregation and thrombosis are implicated in myocardial infarction, cerebrovascular accidents, and peripheral arterial disorders. Compounds derived from garlic, including ajoene, suppress platelet activation and clustering through disruption of thromboxane production, fibrinogen attachment, and intracellular calcium movement in platelets. Garlic additionally promotes fibrinolytic processes and enhances blood flow characteristics, consequently diminishing thrombotic risk. These anticoagulant mechanisms provide considerable protection against ischemic cardiac events [105].

The cardiovascular protective capacity of garlic is further associated with its influence on glucose homeostasis and insulin responsiveness. Diabetes mellitus and insulin resistance demonstrate strong correlations with cardiovascular pathology through hyperglycemia-mediated oxidative damage, endothelial impairment, and inflammatory responses. Garlic enhances insulin responsiveness, facilitates glucose uptake, and ameliorates hyperglycemic conditions via modification of insulin-related signaling cascades. Enhanced glycemic regulation indirectly supports cardiovascular health by minimizing vascular injury and metabolic burden. Furthermore, garlic decreases advanced glycation end-product accumulation and prevents hyperglycemia-related oxidative damage in vascular structures. An



additional significant cardiovascular protective mechanism of garlic encompasses the regulation of intestinal microbiota and metabolic equilibrium [106]. Garlic possesses prebiotic constituents, particularly fructooligosaccharides, which facilitate the proliferation of advantageous gut bacteria. Enhanced intestinal microbial composition leads to decreased systemic

inflammatory responses, optimized lipid processing, and improved glucose homeostasis. Given that gut microbial imbalance is increasingly acknowledged as a factor in cardiometabolic disorders, garlic-induced microbiota regulation may constitute an alternative mechanism for achieving cardiovascular protection [107].

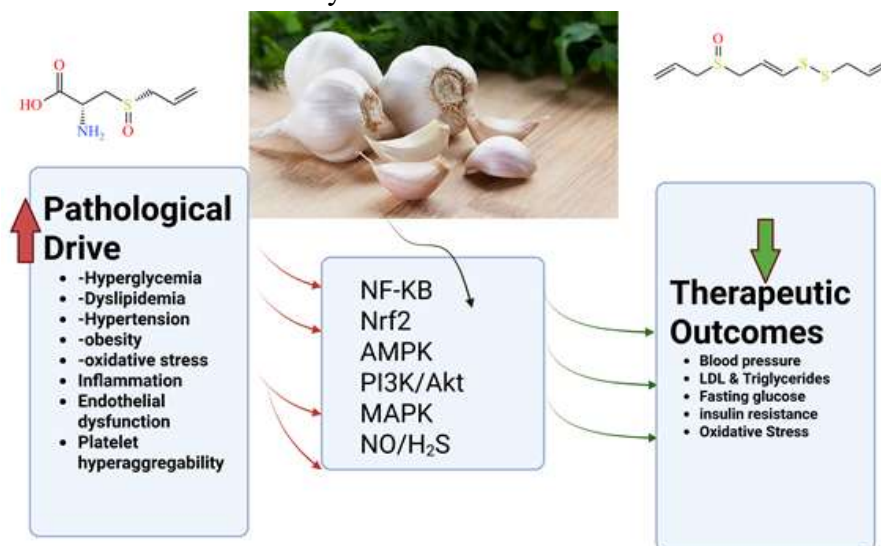


Fig: 3 Pathophysiology and therapeutic outcome of garlic bioactive compound

Molecular signaling pathways influenced by Garlic

Garlic (*Allium sativum* L.) has a wide spectrum of pharmacological and cardiometabolic protective effects that are mediated by modulation of several molecular signaling pathways related to oxidative stress, inflammation, apoptosis, endothelial dysfunction, glucose metabolism, lipid homeostasis, and cell survival [108]. Biologically active organosulfur compounds in garlic, such as allicin, diallyl sulfide, diallyl disulfide, diallyl trisulfide, ajoene and S-allyl cysteine interact with many intracellular signaling cascades and transcription factors which affect gene expression and cellular response. These molecular interactions play a major role in the antioxidant, anti-inflammatory, antihypertensive, antidiabetic and cardioprotective activities of garlic. Garlic affects one of the most critical signaling pathways,

nuclear factor-kappa B (NF-κB) pathway that is important in inflammation and immune regulation [109]. In pathogenic conditions like oxidative stress, hyperglycemia, obesity and vascular injury, NF-κB activation leads to its nuclear translocation and promotes the transcription of pro-inflammatory cytokines, adhesion molecules, cyclooxygenase-2, inducible nitric oxide synthase and other inflammatory mediators. The compounds derived from garlic have been demonstrated to inhibit activation of the NF-κB pathway by preventing both phosphorylation and degradation of inhibitor kappa B proteins [110]. This inhibition decreases the secretion of inflammatory cytokines, including tumour necrosis factor-alpha, interleukin-1 beta and interleukin-6, thus decreasing chronic inflammatory response and vascular damage in cardiometabolic diseases. Garlic also has a marked

effect on the signaling pathway involving nuclear factor erythroid 2-related factor 2 (Nrf2) that regulates the antioxidant defense mechanisms. Nrf2 is a transcription factor that regulates the expression of antioxidant and cytoprotective enzymes such as heme oxygenase-1, glutathione peroxidase, catalase, superoxide dismutase and NADPH quinone oxidoreductase-1 [111]. Garlic sulfur compounds activate the Nrf2 signaling pathway by inducing dissociation of the protein, Kelch-like ECH associated protein 1 (Keap1), from Nrf2, thus facilitating the nuclear translocation and the transcription activation of the antioxidant genes. The induction of the Nrf2 pathway increases the resistance of cells to oxidative stress, decreases lipid peroxidation, and prevents damage of vascular and myocardial tissues by free radicals. This is believed to be an important part of garlic's cardioprotective and anti-aging properties [112]. Another crucial signaling pathway regulated by garlic is the AMP-activated protein kinase (AMPK) signaling pathway, a central regulator of cellular energy metabolism. AMPK activation promotes glucose utilization, fatty acid oxidation, mitochondrial biogenesis, insulin sensitivity, and inhibits lipid synthesis and gluconeogenesis. Garlic bioactive compounds induce AMPK phosphorylation and activation, which improves metabolic homeostasis and decreases metabolic abnormalities in obesity, insulin resistance, and type 2 diabetes mellitus. AMPK activation is also associated with better endothelial function and decreased inflammatory responses, connecting metabolic regulation to heart and blood vessel protection [113].

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Garlic also affects the phosphoinositide 3-kinase/protein kinase B (PI3K/Akt) pathway, which plays a role in cell survival, glucose metabolism, nitric oxide production and vascular function. The PI3K/Akt pathway has been linked to the phosphorylation of endothelial nitric oxide synthase (eNOS) and the enhancement of nitric oxide (NO) bioavailability, resulting in vasodilation and better relaxation of the blood vessels. Akt signaling is enhanced and endothelial cells are protected from oxidative and inflammatory injury by garlic derived compounds. In addition, activation of this pathway is involved in anti-apoptosis and protection of myocardial cell viability in ischemic/oxidative stress [117]. Garlic also regulates mitogen-activated protein kinase (MAPK) signaling pathways. The MAPK pathways, such as extracellular signal-regulated kinase, c-Jun N-terminal kinase, and p38 MAPK,

control cell proliferation, inflammation, stress response and apoptosis. MAPK pathway overactivation due to oxidative stress and inflammation causes endothelial dysfunction, vascular remodeling, and cardiomyocyte injury. The compounds in garlic inhibit the activation of p38 MAPK and c-Jun N-terminal kinase signaling and modulate extracellular signal-regulated kinase activity to decrease inflammatory responses and cellular damage [118]. The regulation of the MAPK signaling pathway by garlic contributes to the integrity of the vessel wall and to cellular homeostasis. Another way garlic affects the body is by regulating nitric oxide and hydrogen sulfide signaling pathways critical for cardiovascular functions and vascular tone regulation. Sulfur compounds in garlic induce vasodilation, inhibit platelet aggregation and enhance endothelial function by enhancing the activity of endothelial nitric oxide synthase and nitric oxide production [119]. Diallyl trisulfide is a hydrogen sulfide provider that plays roles in vascular relaxation, antioxidant defense and cytoprotection. Together, increases in nitric oxide and hydrogen sulfide signaling lead to improved blood pressure control and to decreased vascular inflammation and oxidative injury [120].

Challenges and Future Perspectives

Garlic also affects the phosphoinositide 3-kinase/protein kinase B (PI3K/Akt) pathway, which plays a role in cell survival, glucose metabolism, nitric oxide production and vascular function. The PI3K/Akt pathway has been linked to the phosphorylation of endothelial nitric oxide synthase (eNOS) and the enhancement of nitric oxide (NO) bioavailability, resulting in vasodilation and better relaxation of the blood vessels. Akt signaling is enhanced and endothelial cells are protected from oxidative and inflammatory injury by garlic derived compounds.



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CONCLUSION

Garlic (*Allium sativum* L.) is a medicinal plant and a functional food that has significantly emerged as valuable due to its therapeutic potential in cardiometabolic diseases. Garlic has a wide range of phytochemicals, especially organosulfur compounds like allicin, ajoene, diallyl sulfides and

S-allyl cysteine, which imparts a variety of pharmacological activities to it like antioxidant, anti-inflammatory, antihyperlipidemic, antihypertensive, antidiabetic, antithrombotic and endothelial protective. These are multifaceted and allow garlic to act on various interrelated pathological mechanisms related to cardiovascular diseases, obesity, insulin resistance, metabolic syndrome and type 2 diabetes mellitus. There is scientific evidence from experimental, clinical and epidemiological studies showing that garlic regulates critical molecular signaling pathways including NF- κ B, Nrf2, AMPK, PI3K/Akt, and MAPK pathways, which control oxidative stress, chronic inflammation, vascular function and glucose/lipid metabolism. Garlic also helps to increase nitric oxide, inhibit platelet aggregation, and promote mitochondrial and endothelial integrity, which all help to promote cardiovascular health. Moreover, the prebiotic activity of garlic and the modulation of gut microbiota has other therapeutic implications in metabolic regulation and immune homeostasis. While these encouraging therapeutic effects exist, there are still issues with phytochemical variability, bioavailability, standardization, and the lack of long-term clinical information that needs to be addressed. Large-scale clinical trials, standardized formulations and advanced pharmaceutical technologies are crucial for proving evidence-based therapeutic uses and dose recommendations. Garlic is a potential natural multitargeted cardiometabolic protective agent with a high potential for use in preventive nutrition and complementary medicine. Continued studies targeting molecular pharmacology, nutrigenomics and novel delivery systems may further enhance the therapeutic relevance of garlic and help develop this scientifically validated strategy to improve cardiometabolic health and alleviate the global burden of chronic diseases.



REFERENCES

1. Wu P, Dong T, Sun J, Chen H. Recent advances in sulfur-containing flavors of garlic (*Allium sativum* L.): formation mechanisms, controlling factors and innovative processing technologies. *Food Chemistry: X*. 2026 Apr 21;103886.
2. Huang J, Trych U, Marszałek K. Unraveling Health Benefits of Garlic (*Allium sativum* L.): Investigating the Influence of Processing Methods. *Comprehensive Reviews in Food Science and Food Safety*. 2026 Jan;25(1):e70357.
3. Binduga U, Szychowski KA. Current State of Knowledge of the Anticancer Properties of Polyphenolic Compounds from Garlic (*Allium sativum* L.). *Molecules*. 2026 Feb 27;31(5):801.
4. Ullah Z, Khan W, Shah N, Ahmad A, Mohamed HI, Ahmed AR, Elkatry HO, Ismail AM, El-Mogy MM, Elmenofy W. Synergistic role of biochar and beneficial *Aspergillus fumigatus* (P2P) in improving growth, physiological performance, and antioxidant activity of garlic (*Allium sativum* L.). *Journal of Soil Science and Plant Nutrition*. 2026 Mar 20:1-4.
5. Harper JR, Achari S, Li T, Gambley C, Harper S, Galea V. Pathogenicity and Pre-Characterised Putative Effectors of *Fusarium oxysporum* and *F. proliferatum* in Garlic (*Allium sativum*) and Other *Allium* spp. *Journal of Fungi*. 2026 Apr 6;12(4):264.
6. Shen H, Liu W, Zhao L, Guo Y, Li Y, Wu T, Han S. The complex and dynamic mitochondrial genome of garlic (*Allium sativum*): Insights from structural and evolutionary analysis. *Genomics*. 2026 Feb 18:111214.
7. Siddique S, Hossain MM, Haider MN. Antimicrobial efficacy of garlic (*Allium sativum*) extract against *Aeromonas hydrophila* isolated from diseased *Pangasius catfish*. *Veterinary Medicine and Science*. 2026 Jan;12(1):e70724.
8. Beise DC, da Silva D, de Souza Silva AK, Guterres SM, Welter LJ, Stefenon VM. From consolidation to innovation: the contribution of molecular markers in the characterization and conservation of garlic (*Allium sativum* L.) DC Beise et al. *Genetic Resources and Crop Evolution*. 2026 Mar;73(3):122.
9. Yang L, Ma Y, Wang P, Chang W, Li J, Gou G, Long H, Zhou Y, You M, Miao M, Zhong J. Comparative Genomic and Expression Analysis of the PEBP Gene Family in Three *Allium* Species with Emphasis on Garlic (*Allium sativum*). *Horticulturae*. 2026 Jan 6;12(1):69.
10. Tangahu BV, Mangkoedihardjo S, Al-Baldawi IA, Faluaburu MS. Comparative phytochemical profiling of shallot (*Allium cepa* L. var. *aggregatum*) and garlic (*Allium sativum* L.) peel decoction extracts: proximate composition, phenolic quantification, and LC-TOF-MS metabolite annotation. *Microchemical Journal*. 2026 Apr 14:118063.
11. Jassam GM, Taboor RM, Khalaf AA, Ahmed FM. Advanced multimode plasmonic refractive index sensor based on zinc nanoparticles for selective detection of garlic (*Allium sativum*). *Microsystem Technologies*. 2026 Apr;32(4):49.
12. Cava MJ, Maoirat-Abad MR, Legaspi NB, Palacio CO, Aganus CM. Alliin and Total Phenolic Content of Garlic (*Allium sativum* L.) Accessions Collected from Ilocos Norte, Philippines. *Plant Breeding and Biotechnology*. 2026 Mar 6;14:32-41.
13. Rather GA, Bhat MY, Dar MI, Sofi MA, Yadav R, Nazneen H, Abid A. Medicinal and Nutritional Importance of Garlic (*Allium sativum* L.) Human Health. In *Medicinal*



- Plants and their Bioactive Compounds in Human Health: Volume 2 2026 Jan 17 (pp. 161-181). Singapore: Springer Nature Singapore.
14. Nurulita S, Geering AD, Crew KS, Chao HY, Harper S, Thomas JE. Development of Specific Diagnostic Assays for the Eleven Main Viruses Infecting Garlic (*Allium sativum*). *Australasian Plant Pathology*. 2026 Apr;55(2):27.
 15. Salmi I, Messgo-Moumene S, Kobae Y, Rabhi ML, El Shora HM, Shahid MS. Role of Mycorrhizal Fungi in Enhancing Growth Performance and Phytochemical Profile of Garlic (*Allium sativum* L.). *Journal of Agricultural Sciences–Sri Lanka*. 2026 May 1;21(2).
 16. Getaneh M. A Review on Garlic (*Allium sativum* L.) Breeding Advances and Achievements Globally. *Turkish Journal of Agriculture-Food Science and Technology*. 2026 May 11;14(5):1426-35.
 17. Sofi MA, Yadav R, Nazneen H. Medicinal and Nutritional Importance of Garlic (*Allium sativum* L.) Human. *Medicinal Plants and their Bioactive Compounds in Human Health: Volume 2*. 2026 Feb 17;2:161.
 18. Indriyani NN, Amalia DA, Ardian MN, Ramadani D. Therapeutic Applications of Garlic (*Allium sativum* L.) Essential Oil: A Review on Different Extraction Methods and Characterization on Its Bioactive Compound. *Fabad Eczacılık Bilimler Dergisi*. 2026;51(1):305-26.
 19. Singh L, Singh SK, Thakur R. Effect of different levels of organic manures and mulch materials on garlic (*Allium sativum* L.) under Fatehgarh Sahib conditions. *Res. Jr. Agril. Sci*. 2026;17(2):181-9.
 20. Huynh HK, Nguyen NT, Vo MT, Doan DX. Effect of dietary garlic (*Allium sativum*) powder dosage on growth and hematological indices of swamp eel (*Monopterus albus* Zuiew, 1793) fry. *Israeli Journal of Aquaculture-Bamidgeh*. 2026 Feb 28;78(1):193-204.
 21. Rao GH. Cardiometabolic diseases: a global perspective. *J Cardiol Cardiovasc Ther*. 2018;12(2):555834.
 22. Danpanichkul P, Suparan K, Dutta P, Kaeosri C, Sukphutanan B, Pang Y, Kulthamrongsri N, Jaisa-Aad M, Ng CH, Teng M, Nakano M. Disparities in metabolic dysfunction-associated steatotic liver disease and cardiometabolic conditions in low and lower middle-income countries: a systematic analysis from the global burden of disease study 2019. *Metabolism*. 2024 Sep 1;158:155958.
 23. Rao GH. Cardiometabolic diseases: Risk factors and novel approaches for the management of risks. In *Cardiometabolic Diseases 2025* Jan 1 (pp. 3-26). Academic Press.
 24. Eroglu T, Capone F, Schiattarella GG. The evolving landscape of cardiometabolic diseases. *EBioMedicine*. 2024 Nov 1;109.
 25. Bahadoran Z, Mirmiran P, Azizi F. Fast food pattern and cardiometabolic disorders: a review of current studies. *Health promotion perspectives*. 2016 Jan 30;5(4):231.
 26. Miranda JJ, Barrientos-Gutierrez T, Corvalan C, Hyder AA, Lazo-Porras M, Oni T, Wells JC. Understanding the rise of cardiometabolic diseases in low-and middle-income countries. *Nature medicine*. 2019 Nov;25(11):1667-79.
 27. Giovanni A, Enrico A, Aime B, Michael B, Marianne B, Jonathan C, Josef C, Michael C, Nicole D, Sophia EB, Joaquim FS. Global burden of cardiovascular diseases and risk factors, 1990–2019: update from the GBD 2019 study. *Journal of the American College of Cardiology*. 2020 Dec 22;76(25):2982-3021.

28. Roth GA, Mensah GA, Johnson CO, Addolorato G, Ammirati E, Baddour LM, Barengo NC, Beaton AZ, Benjamin EJ, Benziger CP, Bonny A. Global burden of cardiovascular diseases and risk factors, 1990–2019: update from the GBD 2019 study. *Journal of the American college of cardiology*. 2020 Dec 22;76(25):2982-3021.
29. Chong B, Jayabaskaran J, Jauhari SM, Chan SP, Goh R, Kueh MT, Li H, Chin YH, Kong G, Anand VV, Wang JW. Global burden of cardiovascular diseases: projections from 2025 to 2050. *European journal of preventive cardiology*. 2025 Aug;32(11):1001-15.
30. Tang Y, Lin D, Xu H, Xu L, Guo S, Zheng X, Su M, Zeng K, Feng W, Ye J, Wang L. Global burden and projections of cardiometabolic diseases attributable to high alcohol use: a comparative risk assessment based on the GBD 2021 study. *Frontiers in Nutrition*. 2026 Mar 6;13:1698730.
31. Rasmi PK, Dalbhagat CG, Venugopal AP, Mishra S, Gowda N. A N, Kambhampati V. A comprehensive review of herb microgreens as emerging functional foods: insights into their nutritional potential and health benefits. *Preparative Biochemistry & Biotechnology*. 2026 Jan 2;56(1):1-3.
32. Ashoka S, Hiregoudar S, Raju CA, Patiballa M, Packialakshmi JS, Revanna ML. Personalized nutrition: Artificial intelligence-driven approaches for tailoring functional foods to individual needs. In *Artificial Intelligence in Food Science* 2026 Jan 1 (pp. 389-407). Academic Press.
33. Mafe AN, Sharifi-Rad J, Calina D, Ogunyemi AJ, Tubi AO. Postbiotics in Functional Foods: Microbial Derivatives Shaping Health, Immunity and Next-Generation Nutrition. *Food Frontiers*. 2026 Jan;7(1):e70205.
34. Balamurugan J, Adeyeye SA. Artificial Intelligence in Nutrigenomics: A Critical Review on Functional Food Insights and Personalized Nutrition Pathways. *Journal of Human Nutrition and Dietetics*. 2026 Feb;39(1):e70200.
35. Pandey S, Gupta A, Mahato DK, Paul V, Tripathi AD, Rasane P, Kumar P, Kamle M, Haque S. Lutein and zeaxanthin: source, extraction, stability, bioactivity, and functional food applications. *Current Pharmaceutical Biotechnology*. 2026 Jan;27(3):261-76.
36. Rajnani N, Hundani A, Bhojwani H, Kurup N. Garlic through the Ages: Historical Significance, Chemical Composition, and Therapeutic Potential. In *Exploration of the Medicinal Potential of Kitchen Ingredients* 2026 (pp. 14-21). CRC Press.
37. Rather GA, Bhat MY, Dar MI, Sofi MA, Yadav R, Nazneen H, Abid A. Medicinal and Nutritional Importance of Garlic (*Allium sativum* L.) Human Health. In *Medicinal Plants and their Bioactive Compounds in Human Health: Volume 2* 2026 Jan 17 (pp. 161-181). Singapore: Springer Nature Singapore.
38. Getaneh M. A Review on Garlic (*Allium sativum* L.) Breeding Advances and Achievements Globally. *Turkish Journal of Agriculture-Food Science and Technology*. 2026 May 11;14(5):1426-35.
39. Behrouz V, Zahroodi M, Clark CC, Mir E, Atashi N, Rivaz R. Effects of garlic supplementation on cardiovascular risk factors in adults: a comprehensive updated systematic review and meta-analysis of randomized controlled trials. *Nutrition reviews*. 2026 Jan;84(1):1-35.
40. Tiwari P, Srivastava R. Healing Through the Ages: Traditional Herbal Remedies. In *Harnessing Phytoconstituents for Wound Healing* 2026 (pp. 283-308). IGI Global Scientific Publishing.

41. Salmi I, Messgo-Moumene S, Kobae Y, Rabhi ML, El Shora HM, Shahid MS. Role of Mycorrhizal Fungi in Enhancing Growth Performance and Phytochemical Profile of Garlic (*Allium sativum* L.). *Journal of Agricultural Sciences–Sri Lanka*. 2026 May 1;21(2).
42. Atif MJ, Amin B, Ghani MI, Ali M, Cheng Z. Light and temperature differentially influence morphology, phytohormone profiles, and phenolic acid biosynthesis in *Allium sativum* across developmental stages. *Biologia*. 2026 May 11;81(5):132.
43. Munazir M, Kausar N, Qureshi R, Anwar T, Qureshi H, Ali S, El-Beltagi HS, Alotaibi MS, Bazarbayeva D, Alsudays IM, Alamer KH. Differential morphological, physiological, and antioxidant responses of *Allium cepa* and *Allium sativum* to untreated municipal wastewater. *Scientific Reports*. 2026 May 12.
44. Adamović B, Visković J, Tepić-Horecki A, Milić A, Šumić Z, Červenski J, Vlajić S, Jakšić S, Živanov M, Jaćimović G. Bioactive, Antioxidant, and Nutritional Responses of Garlic (*Allium sativum* L.) to Fertilization Regimes. *Molecules*. 2026 Feb 13;31(4):652.
45. Singh M, Gaurav, Gaur PK. HPTLC and LC–MS Based Metabolomics and Network Pharmacology for Garlic (*Allium sativum*) and Jamun (*Syzygium jambolanum*). *Biomedical Chromatography*. 2026 Jun;40(6):e70475.
46. Rather GA, Bhat MY, Dar MI, Sofi MA, Yadav R, Nazneen H, Abid A. Medicinal and Nutritional Importance of Garlic (*Allium sativum* L.) Human Health. In *Medicinal Plants and their Bioactive Compounds in Human Health: Volume 2* 2026 Jan 17 (pp. 161-181). Singapore: Springer Nature Singapore.
47. Harper JR, Achari S, Li T, Gambley C, Harper S, Galea V. Pathogenicity and Pre-Characterised Putative Effectors of *Fusarium oxysporum* and *F. proliferatum* in Garlic (*Allium sativum*) and Other *Allium* spp. *Journal of Fungi*. 2026 Apr 6;12(4):264.
48. Tangahu BV, Mangkoedihardjo S, Al-Baldawi IA, Faluaburu MS. Comparative phytochemical profiling of shallot (*Allium cepa* L. var. *aggregatum*) and garlic (*Allium sativum* L.) peel decoction extracts: proximate composition, phenolic quantification, and LC-TOF-MS metabolite annotation. *Microchemical Journal*. 2026 Apr 14:118063.
49. Sofi MA, Yadav R, Nazneen H. Medicinal and Nutritional Importance of Garlic (*Allium sativum* L.) Human. *Medicinal Plants and their Bioactive Compounds in Human Health: Volume 2*. 2026 Feb 17;2:161.
50. Cava MJ, Mairat-Abad MR, Legaspi NB, Palacio CO, Aganus CM. Alliin and Total Phenolic Content of Garlic (*Allium sativum* L.) Accessions Collected from Ilocos Norte, Philippines. *Plant Breeding and Biotechnology*. 2026 Mar 6;14:32-41.
51. Jo MS, Kim JE, Chu YR, Chung GY, Na CS. Morphology of Chinese Chive and Onion (*Allium*; *Amaryllidaceae*) Crop Wild Relatives: Taxonomical Relations and Implications. *Plants*. 2026 Jan 7;15(2):192.
52. Getaneh M. A Review on Garlic (*Allium sativum* L.) Breeding Advances and Achievements Globally. *Turkish Journal of Agriculture-Food Science and Technology*. 2026 May 11;14(5):1426-35.
53. Beise DC, da Silva D, de Souza Silva AK, Guterres SM, Welter LJ, Stefenon VM. From consolidation to innovation: the contribution of molecular markers in the characterization and conservation of garlic (*Allium sativum* L.) DC Beise et al. *Genetic Resources and Crop Evolution*. 2026 Mar;73(3):122.
54. Devi PB, Juneja MD, Sumitha A, Gopukumar ST. Phytochemical Profiling and Therapeutic

- Potential of Bioactive Compounds from *Allium Sativum*. *Emerging Bioactive Resources in Biotechnology and Biomedicine*. 2026 Apr:140.
55. Vidhya VG. Phytochemical Profiling of Bioactive Compounds in Ethanolic Extract of Black Garlic (*Allium sativum* L.) using GC-MS Analysis.
 56. Xian Z, Li S, Mann DA, Deng X. Geographical origin authentication of whole garlic using 16S ribosomal RNA profiling of garlic microbiota and machine learning. *Food Microbiology*. 2026 Jan 15:105039.
 57. Binduga U, Szychowski KA. Current State of Knowledge of the Anticancer Properties of Polyphenolic Compounds from Garlic (*Allium sativum* L.). *Molecules*. 2026 Feb 27;31(5):801.
 58. Qian J, Peng D, Guo F, Yang W. The variation of allicin and volatile organic compounds in stored garlic (*Allium sativum* L.) as influenced by cultivar, nitrogen fertilization, and storage temperature. *Applied Food Research*. 2026 May 6:102105.
 59. Suratno S, Alam LP, Aurum FS, Anggraeni AS, Murtiningsih RR, Aswani N, Nugroho K, Karjadi AK, Sudarmonowati E, Satyawan D, Terryana RT. Metabolomic profiling of five garlic (*Allium sativum* L.) varieties using high performance liquid chromatography-Orbitrap-high resolution mass spectrometry combined with chemometrics. *Biochemical Systematics and Ecology*. 2026 Aug 1;127:105265.
 60. Hadi SM, Hussien YA. Comparative Antibacterial Activity of Aqueous Garlic (*Allium sativum*) Extract Against Selected Pathogenic Bacteria Using CLSI Standard Methods. *Journal of Health and Biology*. 2026;2(1):41-9.
 61. Jo MS, Kim JE, Chu YR, Chung GY, Na CS. Morphology of Chinese Chive and Onion (*Allium; Amaryllidaceae*) Crop Wild Relatives: Taxonomical Relations and Implications. *Plants*. 2026 Jan 7;15(2):192.
 62. Munazir M, Kausar N, Qureshi R, Anwar T, Qureshi H, Ali S, El-Beltagi HS, Alotaibi MS, Bazarbayeva D, Alsudays IM, Alamer KH. Differential morphological, physiological, and antioxidant responses of *Allium cepa* and *Allium sativum* to untreated municipal wastewater. *Scientific Reports*. 2026 May 12.
 63. Beise DC, da Silva D, de Souza Silva AK, Guterres SM, Welter LJ, Stefenon VM. From consolidation to innovation: the contribution of molecular markers in the characterization and conservation of garlic (*Allium sativum* L.) DC Beise et al. *Genetic Resources and Crop Evolution*. 2026 Mar;73(3):122.
 64. Ullah Z, Khan W, Shah N, Ahmad A, Mohamed HI, Ahmed AR, Elkhatry HO, Ismail AM, El-Mogy MM, Elmenofy W. Synergistic role of biochar and beneficial *Aspergillus fumigatus* (P2P) in improving growth, physiological performance, and antioxidant activity of garlic (*Allium sativum* L.). *Journal of Soil Science and Plant Nutrition*. 2026 Mar 20:1-4.
 65. Getaneh M. A Review on Garlic (*Allium sativum* L.) Breeding Advances and Achievements Globally. *Turkish Journal of Agriculture-Food Science and Technology*. 2026 May 11;14(5):1426-35.
 66. Matai Z, Zhantasov S, Ibragimova G. Optimization of In vitro Sterilization and Initial Cultivation Methods for Local Garlic (*Allium sativum* L.) Varieties. *Fundamental and Experimental Biology*. 2026 Mar 30;12131(1):54-62.
 67. Getaneh M. A Review on Garlic (*Allium sativum* L.) Breeding Advances and Achievements Globally. *Turkish Journal of Agriculture-Food Science and Technology*. 2026 May 11;14(5):1426-35.



68. Wu P, Dong T, Sun J, Chen H. Recent advances in sulfur-containing flavors of garlic (*Allium sativum* L.): formation mechanisms, controlling factors and innovative processing technologies. *Food Chemistry: X*. 2026 Apr 21:103886.
69. Santos AP, Oliveira RC, Oliveira RC, Luz JM. Sucrose and hyperhydricity in the micropropagation of garlic seeds in vitro. *Revista Ciência Agronômica*. 2026 Mar 16;57:e202493270.
70. Nugraha DR, Sukmasari MD, Prasetyo TF, Andayani SA, Yusuf MN. Peningkatan Kapasitas Petani Melalui Pelatihan Smart Farming Berbasis Iot Untuk Budidaya Bawang Putih Di Dataran Rendah Kabupaten Majalengka: Increasing The Capacity of Farmers Through Iot-Based Smart Farming Training for Garlic Cultivation in The Lowlands of Majalengka Regency. *Jurnal Pengabdian dan Pengembangan Masyarakat Indonesia*. 2026 May 1;5(1):245-54.
71. Arifuddin A, Al Fatikhana A, Afifatul'Ulya HU. Analyze thermal behaviour and design performance of a passive vernalization-vertical farming system for tropical garlic production. *Journal of Agrosociology and Sustainability*. 2026 Jan 30;3(2):131-51.
72. Suryani T, Agustina L, Aryani I, Darnoto S, Sari SK. Evaluation of Rejected Soybean Milk-Based Liquid Organic Fertilizer with Garlic and Turmeric Additives in Hydroponic Cultivation. *Bioscientist: Jurnal Ilmiah Biologi*. 2026 May 1;14(2):508-18.
73. Chu Y, Meng S, Qiu L, Xu H, Li D, Song C, Fang L, Fan L. Cold-tolerant garlic hydroponics reshapes bacterial community for enhanced aquaculture wastewater remediation: Mechanisms and applications. *Aquaculture*. 2026 Mar 16:743898.
74. Li Y, Zhang J, Liu C, Liu X. Design and analysis of an intelligent, integrated garlic harvester. In *Fifth International Conference on Mechatronics and Intelligent Control (MIC 2025)* 2026 Apr 20 (Vol. 14186, pp. 724-731). SPIE.
75. Wang R, He S, Lv L, Li L, Fang D, Wang T, Shi W, Gao Z, Li X. Rhizosphere microbial community stability and phosphorus availability drive phenotypic differences in garlic growth. *Annals of Microbiology*. 2026 Dec;76(1):10.
76. Singh L, Singh SK, Thakur R. Effect of different levels of organic manures and mulch materials on garlic (*Allium sativum* L.) under Fatehgarh Sahib conditions. *Res. Jr. Agril. Sci*. 2026;17(2):181-9.
77. Marek-Spartz M, Becker R, Heimpel GE, Katovich E, Ramirez I, Cortat G. Degree-day model for establishment of the garlic mustard biological control agent, *Ceutorhynchus scrobicollis* (Coleoptera: Curculionidae) in North America. *Biocontrol Science and Technology*. 2026 Mar 13:1-25.
78. Wang Y, Lu X. Fusing Optical Remote Sensing and SAR Garlic Planting Structure Extraction Method. *Academic Journal of Applied Sciences*. 2026 Mar 30;1(1):72-8.
79. Priyadarshini S, Sahoo AK, Bharati KA, Sahu SC. Diversity, Geographical Distribution and Ethnobotanical Significance of Zingiberaceae in Odisha, India. *Tropical Conservation Science*. 2026 May;19:19400829261450179.
80. Breen C, Smith T, Diamantopoulos N, McAuley J. Inhibition of influenza virus infection by garlic oil and juice in cell culture. *JSFA Reports*. 2026 May 1.
81. Tangahu BV, Mangkoedihardjo S, Al-Baldawi IA, Faluaburu MS. Comparative phytochemical profiling of shallot (*Allium cepa* L. var. *aggregatum*) and garlic (*Allium sativum* L.) peel decoction extracts: proximate composition, phenolic quantification, and LC-

- TOF-MS metabolite annotation. *Microchemical Journal*. 2026 Apr 14;118063.
82. Salmi I, Messgo-Moumene S, Kobae Y, Rabhi ML, El Shora HM, Shahid MS. Role of Mycorrhizal Fungi in Enhancing Growth Performance and Phytochemical Profile of Garlic (*Allium sativum* L.). *Journal of Agricultural Sciences–Sri Lanka*. 2026 May 1;21(2).
83. Munazir M, Kausar N, Qureshi R, Anwar T, Qureshi H, Ali S, El-Beltagi HS, Alotaibi MS, Bazarbayeva D, Alsudays IM, Alamer KH. Differential morphological, physiological, and antioxidant responses of *Allium cepa* and *Allium sativum* to untreated municipal wastewater. *Scientific Reports*. 2026 May 12.
84. Bandyopadhyay R, Pattnaik S. A Comparative Review of Phytochemical Composition, Bioactivity, and Health Implications of Single-and Multiple-Clove Garlic. *ACS omega*. 2026 Apr 7.
85. Jassam GM, Taboor RM, Khalaf AA, Ahmed FM. Advanced multimode plasmonic refractive index sensor based on zinc nanoparticles for selective detection of garlic (*Allium sativum*). *Microsystem Technologies*. 2026 Apr;32(4):49.
86. Ullah Z, Khan W, Shah N, Ahmad A, Mohamed HI, Ahmed AR, Elkatry HO, Ismail AM, El-Mogy MM, Elmenofy W. Synergistic role of biochar and beneficial *Aspergillus fumigatus* (P2P) in improving growth, physiological performance, and antioxidant activity of garlic (*Allium sativum* L.). *Journal of Soil Science and Plant Nutrition*. 2026 Mar 20:1-4.
87. Vidhya VG. Phytochemical Profiling of Bioactive Compounds in Ethanolic Extract of Black Garlic (*Allium sativum* L.) using GC-MS Analysis.
88. Shamsudden R, Oluwasanmi AI, Ahmad KB, Abubakar MY, Hyelalibiya A, Anani OF. Unveiling the Bioactive Architecture of Garlic (*Allium sativum*): Optimized Extraction, Molecular Profiling, and Broad-Spectrum Antimicrobial Potency. *Chemical Technology and Engineering Applications*. 2026 Feb 11;1(1):13-22.
89. Indriyani NN, Amalia DA, Ardian MN, Ramadani D. Therapeutic Applications of Garlic (*Allium sativum* L.) Essential Oil: A Review on Different Extraction Methods and Characterization on Its Bioactive Compound. *Fabad Eczacılık Bilimler Dergisi*. 2026;51(1):305-26.
90. Gupta AJ, Aribenchi KV, Volaguthala S, Sanjay DP, Mahajan V. Biochemical properties of garlic (*Allium sativum* L.) and their impact on human health.
91. Fernandez-Mendoza J. Mechanisms linking insomnia and cardiometabolic disease risk. Arteriosclerosis, thrombosis, and vascular biology. 2026 Mar;46(3):e322880.
92. Lazzeroni M, Lentini M, Maruca A, Capaccio P, Lechien JR, Pecorino B, Chiofalo B, Scibilia G, Maira S, Scollo P, Maniaci A. The Global Burden of Obstructive Sleep Apnea on Fertility: Pathophysiology, Clinical Evidence, and Therapeutic Perspectives. *Reproductive Medicine*. 2026 Jan 12;7(1):4.
93. Randerath WJ, Fanfulla F, Pépin JL. Nocturnal hypercapnia in obstructive sleep apnoea and obesity hypoventilation: from pathophysiology to measurement and treatment. *European Respiratory Review*. 2026 Apr;35(180):250260.
94. Ruiz-Saavedra A, Vidal-Ostos De Lara F, Martínez JA. Cardiometabolic Syndromes and Associated Cardiovascular Risks: A Narrative Review. *Journal of Vascular Research*. 2026 Feb 12.
95. Vacca A, Brosolo G, Marcante S, Della Mora S, Bulfone L, Da Porto A, Pagano C, Catena C, Sechi LA. Gut Microbiota and Short-Chain



- Fatty Acids in Cardiometabolic HFpEF: Mechanistic Pathways and Nutritional Therapeutic Perspectives. *Nutrients*. 2026 Jan 20;18(2):321.
96. Kaldirimitzian C, Kampanella L, Chouliara KM, Kavvadia EM, Tsinopoulou VR, Tsamis KI, Boutzios G, Peppas M, Paschou SA. New insights into sexual dimorphism in cardiometabolic health. *Hormones*. 2026 Mar;25(1):11-28.
97. Wang R, Chen YM, Wang L, Lei Q. Risks of cardiometabolic diseases in women with history of adverse pregnancy outcomes. *Journal of Human Hypertension*. 2026 Feb;40(2):71-9.
98. Cacciapuoti F. Epicardial Adipose Tissue as a Cardiometabolic Target in Atrial Fibrillation: Implications for Ablation Strategies and Emerging Metabolic Therapies. *Medical Sciences*. 2026 Mar 9;14(1):127.
99. Geraci C, Geraci G, Buonauro A, Morello V, La Rocca F, Esposito R. Gaps in Current Cardiometabolic Risk Assessment: A Review Supporting the Development of the CORE Indicator Model. *Journal of Clinical Medicine*. 2026 Jan 12;15(2):617.
100. Tanasescu MD, Rosu AM, Minca A, Rosu AL, Grigorie MM, Timofte D, Ionescu D. Metabolic Dysfunction at the Core: Revisiting the Overlap of Cardiovascular, Renal, Hepatic, and Endocrine Disorders. *Life*. 2026 Jan 20;16(1):172.
101. Morariu-Briciu DM, Jijie AR, Bolintineanu SL, Pah AM, Chiriac SD, Chevereșan A, Dumitrașcu V, Prodan Bărbulescu C, Jipa R. Medicinal Plants and Phytochemicals in Cardioprotection—Mechanistic Pathways and Translational Roadmap. *Life*. 2026 Jan 21;16(1):175.
102. Rakhmawati R, Niruri R. The Effects of Garlic (*Allium sativum* L.) and Allicin on Heart Rate: A Systematic Review and Meta-Analysis of Experimental and Clinical Studies. *Fabad Eczacılık Bilimler Dergisi*. 2026 Mar 3;51(1):223-38.
103. Bandyopadhyay R, Pattnaik S. A Comparative Review of Phytochemical Composition, Bioactivity, and Health Implications of Single-and Multiple-Clove Garlic. *ACS omega*. 2026 Apr 7.
104. Moummou H, Britel I, Hanbali A, Zniber MN, Youne OA, Youne MA, Bendahmane S, Chatoui H. Fermented Black Garlic and Probiotics Synergy: Toward an Integrated Nutritional Approach for Cardiovascular Disease Prevention.
105. Mandge HM, Rehal J, Goswami D, Choudhary A, Kaur P. Unraveling phytochemistry and biofunctionality of black garlic: a systematic review: HM Mandge et al. *Food Science and Biotechnology*. 2026 Feb;35(3):443-61.
106. Renu, Richa. Biomedical Applications of Plant Extracts for Cardiovascular Disease Prevention. *Therapeutics and Molecular Nutrition*. 2026 Mar 11:89-115.
107. Dembitsky VM, Terent'ev AO. QSAR Insights into Antidiabetic Activity of Natural Sulfur-Containing Compounds. *Diabetology*. 2026 Apr 20;7(4):81.
108. Uddin MN, Rashid MM. Unveiling the Molecular Impact: Garlic-Supplemented Diet Regulating the Gene Expressions and Signaling Pathways in Mouse Liver-A Bioinformatics Approach. *In Silico Research in Biomedicine*. 2026 Apr 6:100316.
109. Huang J, Trych U, Marszałek K. Unraveling Health Benefits of Garlic (*Allium sativum* L.): Investigating the Influence of Processing Methods. *Comprehensive Reviews in Food Science and Food Safety*. 2026 Jan;25(1):e70357.
110. Zheng H, Tang D, An S, Fang L, Li J, Zhang Q, Kong J, Lu W, Fan Z. Allicin protects

- against inflammation via suppression of PI3K/AKT/NF- κ B signaling pathway in the model of acute cutaneous injury mouse and LPS-induced keratinocyte. *International Immunopharmacology*. 2026 Apr 1;174:116331.
- 111.Hou R, Zhang X, Zhang J, Zhang W. Liposomes as carriers for garlic oil delivery to increase anti-inflammatory and antioxidant activities in mice with ALI. *Experimental Biology and Medicine*. 2026 Jan 21;251:10800.
- 112.Mony T, Jackson M, Zuckerman A, Yu W, Nguyen TT, Balderrama A, Li R, Sun GY, Cui J, Gu Z. Supplementation of aged garlic extract attenuates age-associated memory impairment and cognitive decline: Involvement of molecular pathways in the cortex and hippocampus. *Biomedical Reports*. 2026 Jan 1;24(1):1-3.
- 113.Wang Y, Wang X, Xie M, Xu H, Liu J, Su A, Pei F, Yang W. Impact of processing on sulfur compounds in garlic. *European Food Research and Technology*. 2026 Feb;252(2):93.
- 114.Bandyopadhyay R, Pattnaik S. A Comparative Review of Phytochemical Composition, Bioactivity, and Health Implications of Single-and Multiple-Clove Garlic. *ACS omega*. 2026 Apr 7.
- 115.Binduga U, Szychowski KA. Current State of Knowledge of the Anticancer Properties of Polyphenolic Compounds from Garlic (*Allium sativum* L.). *Molecules*. 2026 Feb 27;31(5):801.
- 116.Li P, Gao X, Mu Y, Gao H, Qu Q, Liu J, Yang F, Li D, Tan X. Alterations in the structural properties of polysaccharides in garlic yellow seeds before and after germination and their mechanism for alleviating colitis. *International Journal of Biological Macromolecules*. 2026 Apr 20:152129.
- 117.Masoumeh A, Mozafar K, Tayebbeh ST, Leila R. Therapeutic potential of garlic-derived exosome like nanovesicles: challenge and opportunity. *Journal of Traditional Chinese Medicine*. 2026 Apr 4;46(2):509.
- 118.Atif MJ, Amin B, Ghani MI, Ali M, Cheng Z. Light and temperature differentially influence morphology, phytohormone profiles, and phenolic acid biosynthesis in *Allium sativum* across developmental stages. *Biologia*. 2026 May 11;81(5):132.
- 119.Indriyani NN, Amalia DA, Ardian MN, Ramadani D. Therapeutic Applications of Garlic (*Allium sativum* L.) Essential Oil: A Review on Different Extraction Methods and Characterization on Its Bioactive Compound. *Fabad Eczacılık Bilimler Dergisi*. 2026;51(1):305-26.
- 120.Wang S, Wang H, Lv H, Nie R, Li P. Regulation of the Notch signaling pathway by functional foods for intestinal homeostasis: from mechanistic insights to targeted therapies. *Food Science and Human Wellness*. 2026 Mar 2.

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