Garlic (*Allium sativum*) and Its Role in Modulating Gut Microbiota: A Comprehensive Review

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Abstract- Garlic (*Allium sativum L.*) is widely consumed as both a culinary ingredient and a medicinal plant due to its diverse bioactive compounds and therapeutic properties. Recent research highlights its role in modulating gut microbiota, which plays a critical role in human health and disease prevention. Garlic contains organosulfur compounds such as allicin, diallyl sulfides, and ajoene, as well as phenolic compounds, flavonoids, and prebiotic carbohydrates including inulin and fructooligosaccharides. These components contribute to antimicrobial, antioxidant, and anti-inflammatory activities that influence the composition and metabolic functions of intestinal microbial communities. Studies from in vitro models, animal experiments, and human clinical trials suggest that garlic consumption promotes beneficial microorganisms such as *Bifidobacterium* and *Lactobacillus* while inhibiting pathogenic bacteria. Garlic-derived prebiotics are fermented by intestinal microbiota to produce short-chain fatty acids (SCFAs) including acetate, propionate, and butyrate, which support intestinal barrier integrity, immune regulation, and metabolic homeostasis. Through microbiota-mediated mechanisms, garlic has been associated with improvements in metabolic disorders, cardiovascular diseases, gastrointestinal health, immune responses, and cancer prevention. Despite promising findings, variability in garlic preparations and limited human clinical trials remain challenges for clinical translation. Further research integrating advanced microbiome technologies and well-designed clinical studies is necessary to fully elucidate garlic's role as a functional food and nutraceutical for microbiome modulation and disease prevention.

Keywords: Garlic; *Allium sativum*; gut microbiota; microbiome; prebiotics; organosulfur compounds; SCFAs; functional foods.

I. INTRODUCTION

The human gastrointestinal tract harbors trillions of microorganisms collectively known as the gut microbiota. These microbes play essential roles in digestion, metabolism, immune regulation, and protection against pathogens. The gut microbiome contributes to the fermentation of dietary fibers and non-digestible carbohydrates, producing short-chain fatty acids (SCFAs) that regulate intestinal health and systemic metabolic processes [1,2].

Disruption of microbial balance, known as dysbiosis, has been associated with numerous diseases including obesity, diabetes, inflammatory bowel disease, cardiovascular disorders, and certain cancers [3,4]. Consequently, dietary interventions that influence gut microbial composition have gained considerable attention as potential strategies for disease prevention and health promotion [5].

Plant-derived phytochemicals have emerged as important modulators of gut microbiota. Compounds such as polyphenols, flavonoids, and organosulfur compounds can selectively stimulate beneficial microbes while inhibiting pathogenic microorganisms [6]. Garlic (*Allium sativum*), one of the most extensively studied medicinal plants, contains a wide range of bioactive compounds capable of modulating microbial communities in the gastrointestinal tract.

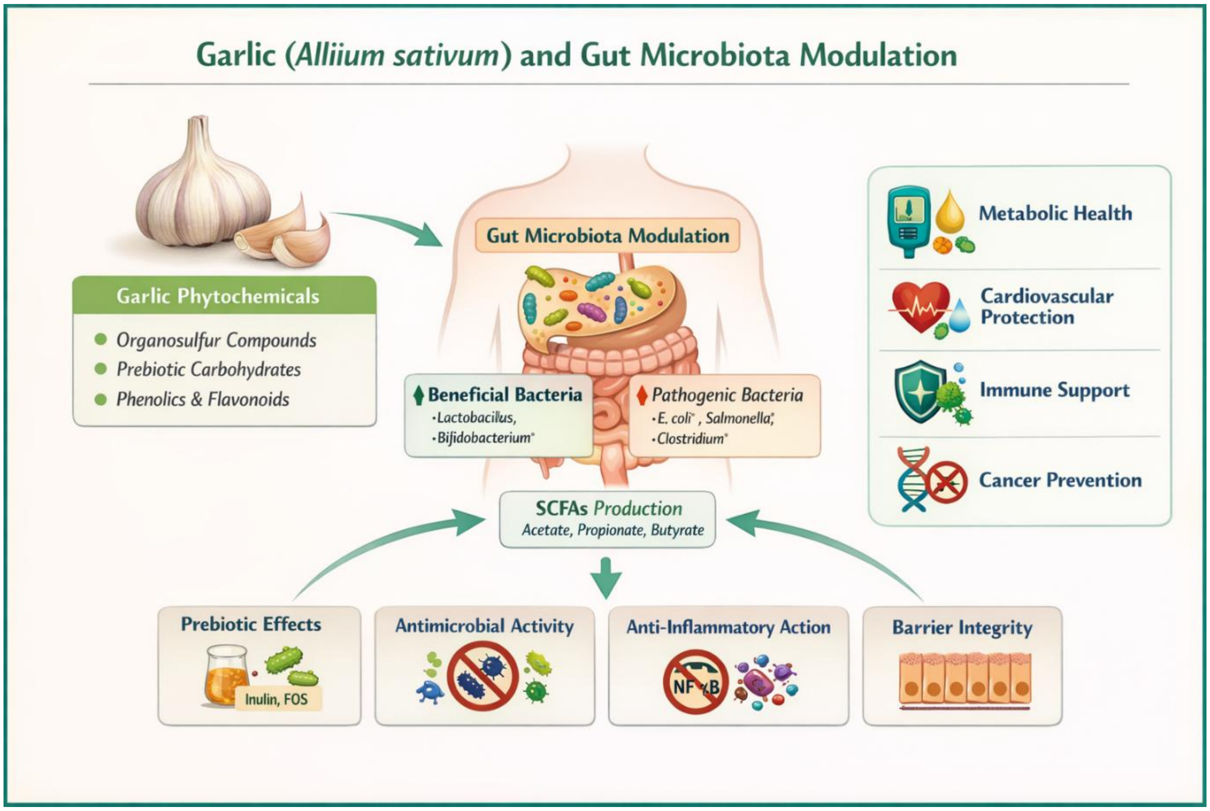

Figure 1: Graphical abstract

II. BOTANICAL AND NUTRITIONAL OVERVIEW OF GARLIC

Garlic (*Allium sativum L.*) belongs to the family Amaryllidaceae and is closely related to onion, leek, and shallot. The plant produces a bulb composed of multiple cloves enclosed in a papery sheath. Garlic has been cultivated for thousands of years and used in traditional medicine systems such as Ayurveda and Traditional Chinese Medicine for treating infections, digestive disorders, and cardiovascular conditions [7].

Garlic contains carbohydrates, proteins, dietary fiber, vitamins (C and B6), and minerals including selenium and manganese. In addition to these nutrients, garlic is rich in bioactive phytochemicals responsible for its pharmacological properties [8].

Due to its health-promoting effects, garlic is increasingly recognized as a functional food and nutraceutical ingredient used in dietary supplements and therapeutic formulations [9].

Figure 2: Garlic plant, flowering bud and bulb

Table 1: Taxonomical Classification

Rank	Classification
Kingdom	Plantae
Division	Magnoliophyta
Class	Liliopsida
Order	Asparagales
Family	Amaryllidaceae
Genus	*Allium*
Species	*Allium sativum* L.

III. PHYTOCHEMICAL CONSTITUENTS OF GARLIC

3.1 Organosulfur Compounds

The most important bioactive compounds in garlic are organosulfur compounds, including allicin, alliin, ajoene, diallyl sulfide, diallyl disulfide, and diallyl trisulfide. Crushing garlic activates the enzyme alliinase, which converts alliin into allicin, a reactive compound responsible for many biological effects such as antimicrobial and antioxidant activities [10].

Table 2: Organosulfur Compounds (Primary Bioactive Constituents)

Compound	Chemical Formula	Key Biological Activities
Allicin	$C_6H_{10}OS_2$	Antimicrobial, antioxidant, anti-inflammatory
Alliin	$C_6H_{11}NO_3S$	Precursor of allicin formed when garlic is crushed
Ajoene	$C_9H_{14}OS_3$	Antithrombotic, antimicrobial
Diallyl disulfide (DADS)	$C_6H_{10}S_2$	Anticancer, cardioprotective
Diallyl trisulfide (DATS)	$C_6H_{10}S_3$	Antioxidant, anti-inflammatory

3.2 Phenolic Compounds and Flavonoids

Garlic also contains phenolic acids and flavonoids that contribute to its antioxidant properties. These compounds neutralize reactive oxygen species and reduce oxidative stress, thereby protecting cellular components from damage [11].

Table 3: Phenolic and Flavonoid Compounds

Compound	Chemical Class	Biological Role
Quercetin	Flavonoid	Antioxidant, anti-inflammatory
Kaempferol	Flavonoid	Cardioprotective, anticancer
Caffeic acid	Phenolic acid	Antioxidant
Ferulic acid	Phenolic acid	Anti-inflammatory

3.3 Prebiotic Carbohydrates

Garlic is a rich source of fructooligosaccharides (FOS) and inulin-type fructans. These non-digestible carbohydrates function as prebiotics by serving as substrates for beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus* [12].

Table 4: Prebiotic Carbohydrates

Compound	Type	Role in Gut Microbiota
Inulin	Fructan polysaccharide	Promotes *Bifidobacterium* growth
Fructooligosaccharides (FOS)	Oligosaccharides	Fermented to produce SCFAs
Garlic fructans	Prebiotic fiber	Support beneficial gut bacteria

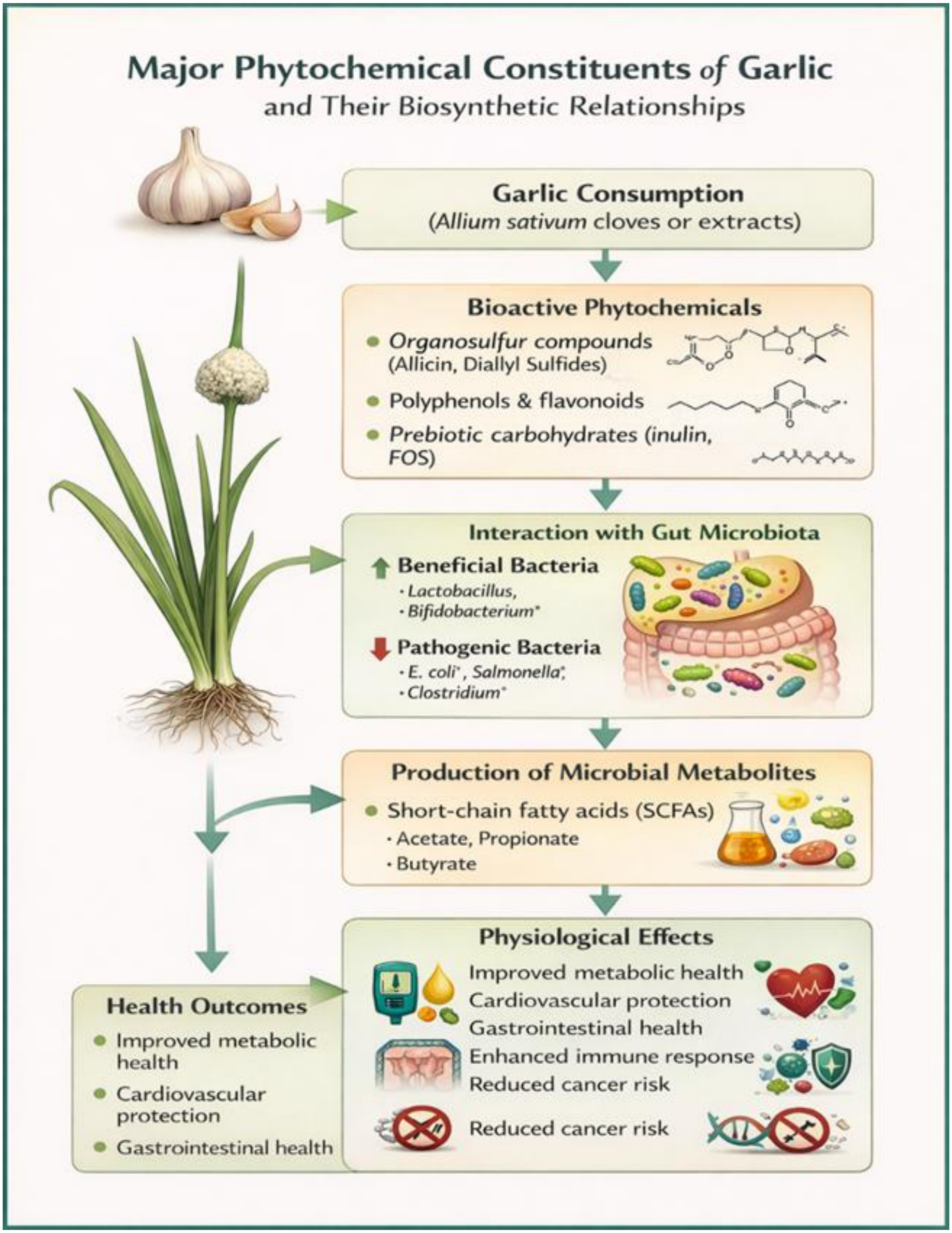

Figure 3: Major Phytoconstituents of Garlic

IV. GUT MICROBIOTA: COMPOSITION AND FUNCTIONS

The human gut microbiota consists of diverse microbial communities dominated by bacterial phyla such as Firmicutes, Bacteroidetes, Actinobacteria, Proteobacteria, and Verrucomicrobia. These microorganisms interact with host tissues through metabolic and immunological pathways that influence health and disease [13].

Gut microbes contribute to numerous physiological functions including digestion of complex carbohydrates, production of vitamins, immune system regulation, and protection against pathogenic microorganisms [14]. Additionally, microbial metabolites such as SCFAs play key roles in maintaining intestinal epithelial integrity and metabolic homeostasis.

V. MECHANISMS OF GUT MICROBIOTA MODULATION BY GARLIC

5.1 Prebiotic Effects

Garlic-derived fructans act as fermentable substrates for gut microbiota, promoting the growth of beneficial bacteria such as *Bifidobacterium* and *Lactobacillus*. Fermentation of these fibers results in the production of SCFAs, which support intestinal health and regulate metabolic processes [15].

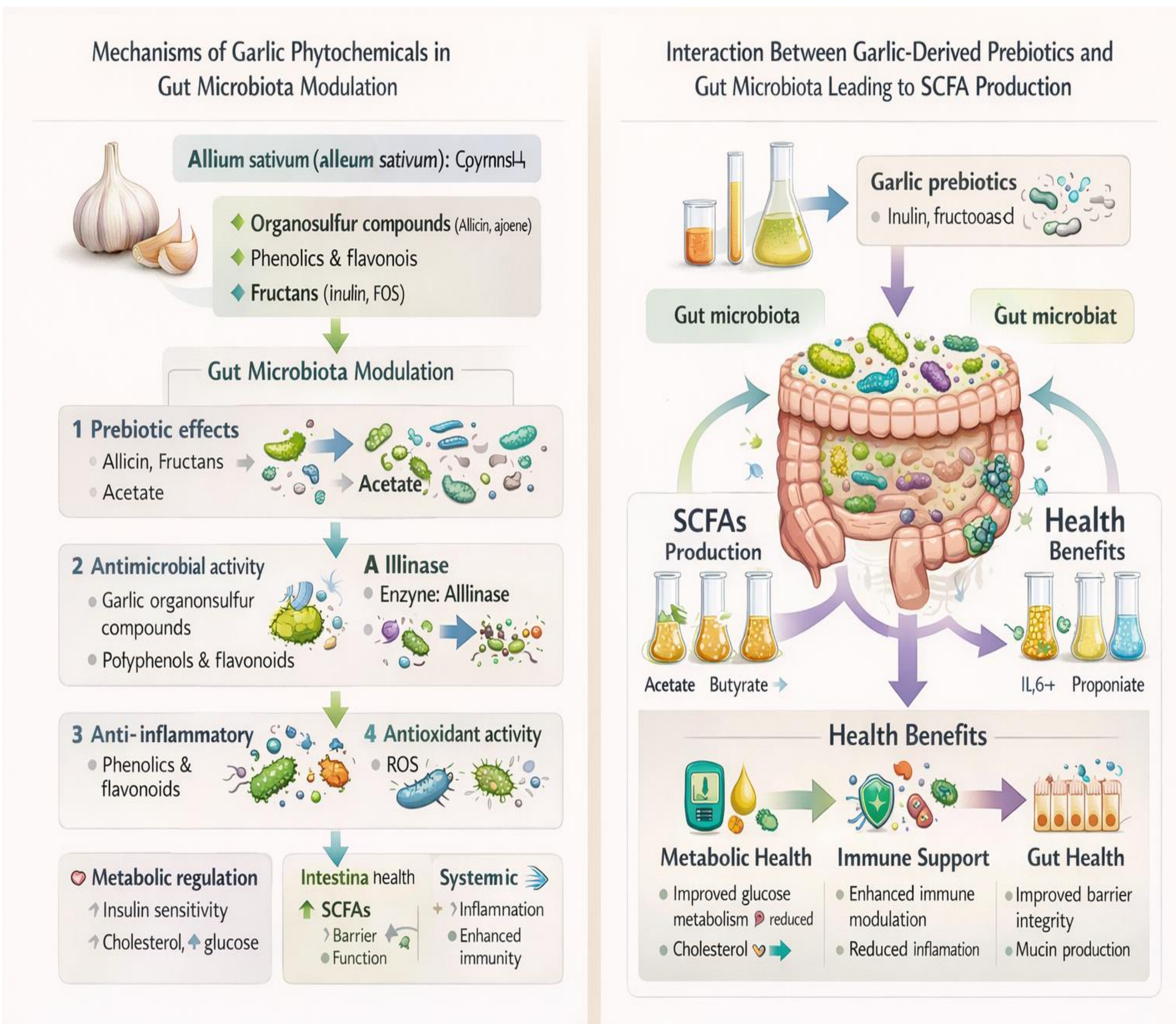

Figure 4: Mechanism of Garlic Phytochemicals and Gut Microbiota Interaction

5.2 Antimicrobial Activity

Garlic exhibits broad antimicrobial activity due to organosulfur compounds such as allicin and ajoene. These compounds disrupt microbial cell membranes, inhibit enzyme activity, and interfere with metabolic pathways in pathogenic bacteria [16].

5.3 Enhancement of Beneficial Microbes

Dietary garlic has been shown to increase the abundance of beneficial microbes including *Akkermansia*, *Lactobacillus*, and *Bifidobacterium*. These microbes contribute to improved digestion, immune modulation, and maintenance of microbial diversity [17].

5.4 Regulation of Microbial Metabolites

Garlic consumption influences microbial metabolism by enhancing the production of SCFAs such as acetate, propionate, and butyrate. These metabolites regulate intestinal barrier function, inflammation, and metabolic signaling pathways [18].

5.5 Anti-Inflammatory and Antioxidant Effects

Garlic compounds suppress inflammatory signaling pathways such as NF-κB and reduce oxidative stress, thereby creating a favorable environment for beneficial microbes [19].

5.6 Improvement of Intestinal Barrier Integrity

Garlic metabolites enhance the expression of tight junction proteins, strengthening the intestinal barrier and preventing the translocation of pathogens and toxins into systemic circulation [20].

VI. EXPERIMENTAL EVIDENCE

6.1 In Vitro Studies

In vitro fermentation studies demonstrate that garlic extracts promote beneficial microbial populations and increase SCFA production while suppressing pathogenic bacteria such as *Escherichia coli* and *Salmonella* [21].

6.2 Animal Studies

Animal studies show that garlic supplementation improves microbial diversity and increases beneficial bacteria while reducing inflammation and metabolic dysfunction in experimental models [22].

6.3 Human Clinical Studies

Clinical trials indicate that garlic supplementation may improve gut microbiota composition and metabolic health indicators such as body weight, lipid profile, and inflammatory markers [23].

VI. HEALTH BENEFITS ASSOCIATED WITH GARLIC-INDUCED MICROBIOTA MODULATION

7.1 Metabolic Disorders

Garlic consumption improves insulin sensitivity and glucose metabolism through microbiota-mediated mechanisms that increase SCFA production and reduce inflammation [24].

7.2 Cardiovascular Diseases

Garlic reduces blood pressure and modulates microbial metabolism involved in the production of trimethylamine-N-oxide (TMAO), a metabolite associated with cardiovascular risk [25].

7.3 Gastrointestinal Disorders

Garlic exhibits antimicrobial and prebiotic properties that help restore microbial balance and reduce inflammation in gastrointestinal disorders such as inflammatory bowel disease [26].

7.4 Immune System Modulation

Garlic compounds stimulate immune responses by enhancing beneficial microbial populations and regulating cytokine production [27].

7.5 Cancer Prevention

Garlic-derived compounds and SCFAs produced by gut microbes may inhibit tumor development by regulating cell proliferation, apoptosis, and inflammatory pathways [28].

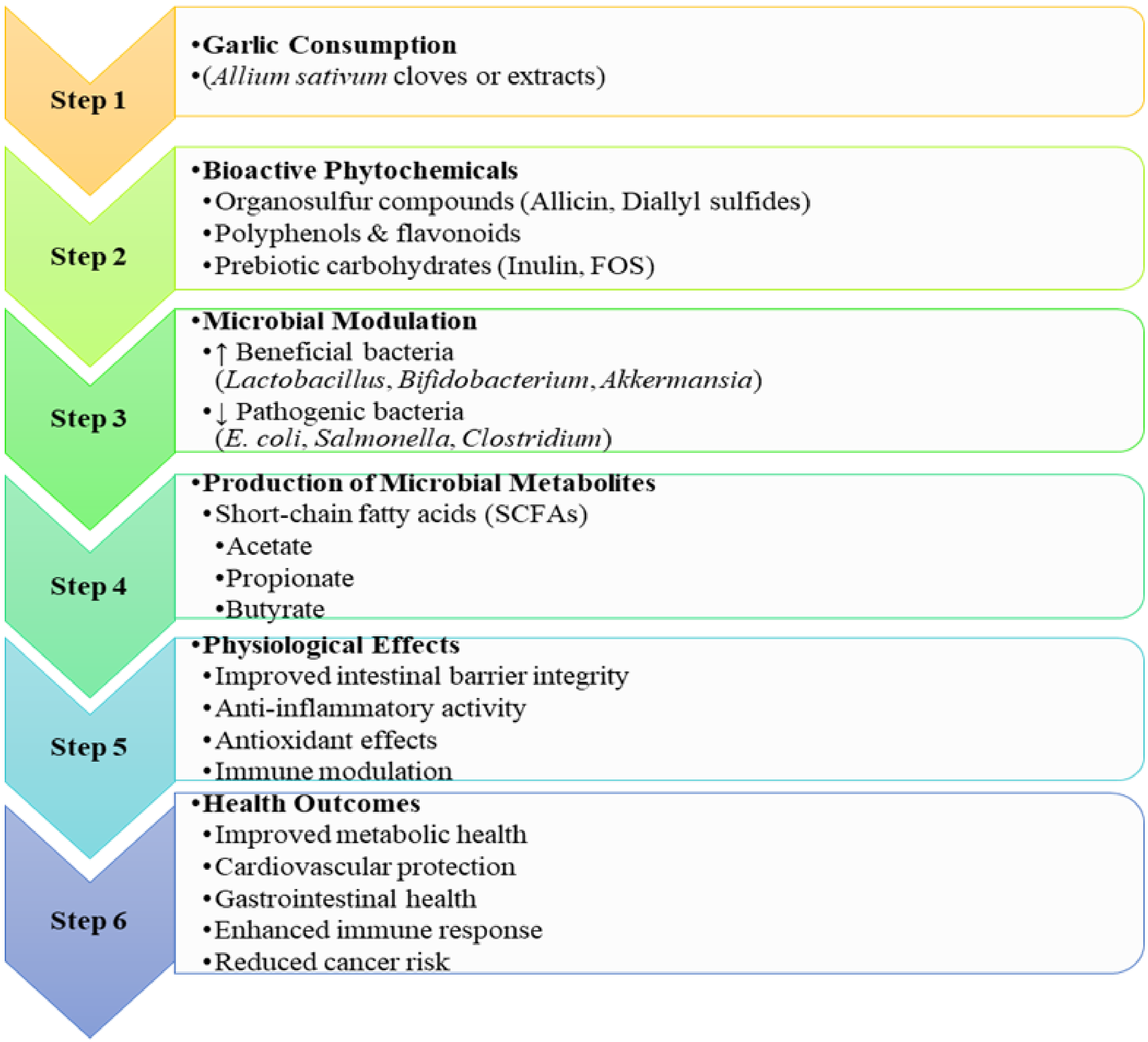

Figure 5: Health Effects of Garlic-Mediated Gut Microbiota Modulation

VIII. GARLIC-BASED FUNCTIONAL FOODS AND NUTRACEUTICALS

Garlic is widely used in the development of functional foods and nutraceutical products such as garlic powder, garlic oil, aged garlic extract, and fermented garlic products. These formulations enhance the stability and bioavailability of garlic bioactive compounds [29].

Aged garlic extract contains stable compounds such as S-allyl cysteine and has demonstrated antioxidant, anti-inflammatory, and cardioprotective effects [30].

Fermentation can also improve the digestibility and bioavailability of garlic bioactive compounds. Some studies have shown that fermentation with probiotic bacteria, such as Lactobacillus species, can enhance the functional properties of garlic extracts and increase their antioxidant and antimicrobial activities [31].

Black garlic and other fermented garlic products are increasingly used in functional foods due to their improved flavor, reduced pungency, and enhanced health benefits.

Synbiotic formulations combine probiotics (beneficial microorganisms) with prebiotics (substrates that support microbial growth) to enhance the survival and activity of probiotic bacteria in the gastrointestinal tract. Garlic-derived fructans have been investigated as potential prebiotic ingredients in synbiotic food products, including fermented dairy products and probiotic beverages.

Research suggests that synbiotic formulations containing garlic-derived prebiotics may enhance gut microbial diversity, improve intestinal barrier function, and increase production of beneficial microbial metabolites such as short-chain fatty acids

IX. SAFETY, DOSAGE, AND ADVERSE EFFECTS

Garlic is generally safe when consumed in dietary amounts. Recommended intake for adults is approximately 1–2 cloves (3–5 g) per day. Higher doses used in supplements may cause mild gastrointestinal discomfort, heartburn, or allergic reactions [32].

For therapeutic purposes, garlic is often administered in different standardized forms such as garlic powder, aged garlic extract, garlic oil, or garlic supplements. Clinical studies have reported safe dosage ranges such as:

Garlic powder: approximately 300–1000 mg per day

Aged garlic extract: approximately 600–1200 mg per day

Fresh garlic: about 2–5 g per day

These doses have been used in clinical trials investigating cardiovascular health, metabolic disorders, and immune function.

Garlic may interact with certain medications, particularly anticoagulants and antiplatelet drugs, due to its effects on platelet aggregation and drug metabolism pathways [33].

Garlic has been reported to interact with several classes of drugs, including:

- Anticoagulants and antiplatelet drugs (e.g., warfarin, aspirin)
- Antihypertensive medications
- Antidiabetic drugs
- Antiretroviral medications
- Certain chemotherapeutic agents

X. CONCLUSION

Garlic (*Allium sativum*) is a promising functional food with significant potential to modulate gut microbiota and promote human health. Its bioactive compounds influence microbial composition, enhance beneficial bacteria, inhibit pathogens, and stimulate the production of beneficial microbial metabolites such as SCFAs. These microbiota-mediated effects contribute to improvements in metabolic health, cardiovascular protection, immune regulation, and cancer prevention. Although current evidence supports the health benefits of garlic, further clinical studies are required to establish optimal dosage, standardized formulations, and long-term safety. Future research integrating microbiome analysis and multi-omics technologies will provide deeper insights into the therapeutic potential of garlic in microbiota-related diseases.

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