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Benevolent Role of Spices in Management of Metabolic Syndrome

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Abstract

Metabolic syndrome (MetS) represents a multifactorial disorder characterised by insulin resistance, central obesity, dyslipidemia, and hypertension, predisposing individuals to type 2 diabetes mellitus, cardiovascular disease, and related chronic conditions. Conventional pharmacotherapy often targets individual components of MetS, but may be limited by side effects, partial efficacy, and poor long-term adherence. Dietary interventions, particularly the use of spices rich in bioactive phytochemicals, offer a promising complementary strategy for managing MetS through multi-targeted mechanisms. Culinary spices such as cinnamon, turmeric, ginger, garlic, black pepper, fenugreek, cardamom, coriander, clove, curry leaf, chia seed, *Panax ginseng*, and black seed exhibit hypoglycemic, hypolipidemic, antihypertensive, antioxidant, and anti-inflammatory properties. Such bioactive constituents modulate key metabolic pathways, including insulin signalling, glucose uptake, lipid metabolism, adipokine regulation, and oxidative stress mitigation. Clinical and preclinical evidence supports their efficacy in improving glycemic control, lipid profile, blood pressure, endothelial function, and inflammatory status, thereby reducing cardiometabolic risk.

Major Finding: Collectively, the integration of such spices into dietary regimens represents a safe, cost-effective, and comprehensive approach for the anticipation and management of metabolic syndrome.

Keywords: Anti-Inflammatory, Antioxidant, Dyslipidemia, Insulin Resistance, Metabolic Syndrome, Spices

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1. Introduction

Metabolic syndrome (MetS) is a multifaceted, multifactorial disorder defined by a gathering of interconnected metabolic abnormalities—including insulin resistance, central obesity, dyslipidemia, and hypertension—that collectively increase the risk of type 2 diabetes mellitus (T2DM), cardiovascular disease (CVD), and other chronic conditions[1,2]. Its pathophysiology involves genetic predisposition, sedentary lifestyle, dietary habits, and hormonal imbalances, with insulin resistance considered a central driver leading to compensatory hyperinsulinemia and dysregulated glucose and lipid metabolism[3]. Diagnosis of MetS varies due to differing criteria from organisations such as WHO, NCEP ATP III, and IDF, complicating epidemiological comparisons and standardisation of interventions[4]. In the United States, prevalence ranges from 22% (ATP III) to over 30% (IDF), highlighting the influence of diagnostic thresholds[5]. Globally, MetS prevalence correlates with obesity and sedentary lifestyles, exceeding 25% in Europe and 20% in the U.S., with rapid increases in Asia due to urbanisation and dietary transitions[6,7]. Ageing, sex, race, and socioeconomic status further modulate prevalence[8,9]. Chronic inflammation,

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endothelial dysfunction, and dysregulated adipokine signalling contribute to cardiometabolic risk[10]. Given the escalating global burden of MetS, exploring preventive and therapeutic strategies—including dietary interventions rich in bioactive compounds is imperative. This review highlights the epidemiological aspects, pathophysiology, and potential management of MetS, emphasising the role of culinary spices as functional dietary components.

2. Dietary Factors and Metabolic Syndrome

Dietary patterns, particularly high intake of fructose from sweetened beverages and processed foods, contribute substantially to MetS development. Fructose induces visceral adiposity, hepatic lipid accumulation, insulin resistance, hypertriglyceridemia, and oxidative stress—hallmark features of MetS[11,12]. High-fructose-fed animal models reliably replicate these metabolic derangements, serving as robust preclinical tools for mechanistic studies and therapeutic evaluations[13]. Conventional management targets individual components of MetS using pharmacological agents for hyperglycemia, hypertension, or dyslipidemia. However, polypharmacy approaches are often limited by adverse effects, partial efficacy, and poor long-term adherence[14]. Consequently, natural dietary interventions with multi-targeted bioactive compounds are increasingly recognised as safe, cost-effective adjuncts for comprehensive management of MetS[15,16].

3. Therapeutic Role of Spices in Metabolic Syndrome

Spices are emerging as potent modulators of metabolic syndrome (MetS) owing to their rich array of bioactive constituents with antioxidant, anti-inflammatory, hypoglycemic, and lipid-lowering characteristics. Common dietary spices—including cinnamon, turmeric, ginger, garlic, black pepper, and fenugreek target multiple pathophysiological aspects of MetS, such as insulin resistance, hyperglycemia, dyslipidemia, hypertension, obesity, and chronic low-grade inflammation[16]. Cinnamaldehyde in cinnamon enhances insulin receptor signalling and GLUT-4-mediated glucose uptake[17]; gingerols in ginger improve lipid metabolism and reduce blood pressure. Sulfur compounds in garlic lower cholesterol and blood pressure[18]; piperine in black pepper enhances nutrient bioavailability and regulates lipid homeostasis[19], and saponins in fenugreek modulate glucose and lipid levels[20]. By acting on multiple metabolic pathways, these spices provide a natural, safe, and cost-effective adjunct to conventional therapies, promoting both prevention and holistic management of MetS while enhancing dietary flavour and nutritional quality.

3.1 Cardamom (*Elettaria cardamomum*)

Cardamom, popularly known as the "queen of spices", is a rich source of volatile oils such as cineole and α-terpinyl acetate, along with flavonoids, terpenes, and phytosterols that collectively contribute to its therapeutic potential[21]. Both preclinical and clinical studies indicate that cardamom exerts significant antihypertensive effects, primarily through endothelium-dependent vasodilation mediated by enhanced Nitric Oxide (NO) bioavailability and calcium channel blockade, leading to a decrease in both systolic and diastolic blood pressure[22]. Its polyphenolic compounds also display potent antioxidant activity, as evidenced by decreased malondialdehyde (MDA) levels and increased enzymatic defences, including superoxide dismutase (SOD) and catalase. In terms of lipid metabolism, studies indicate that cardamom intake lowers total cholesterol, LDL cholesterol, and triglycerides, and improves HDL cholesterol, thereby supporting cardiovascular health[23]. Mechanistically, cardamom modulates endothelial nitric oxide synthase (eNOS), downregulates Inflammatory signaling molecules such as TNF-α and IL-6, and increases insulin-stimulated Uptake of glucose by muscle tissue, improving insulin sensitivity and glucose homeostasis[24]. Additionally, its hepatoprotective effects, mediated by the suppression of lipid peroxidation and reinforcement of glutathione-dependent antioxidant pathways, further contribute to metabolic balance[25]. Collectively, these multifaceted actions highlight cardamom's potential as a functional spice in the dietary management of metabolic syndrome[26].

3.2 Chia Seed (*Salvia hispanica*)

Chia seeds are a nutrient-dense food, particularly abundant in α-linolenic acid (ALA), high-quality protein, soluble

and insoluble fibres, and polyphenolic compounds, all of which impart strong metabolic benefits[27]. The soluble fibre fraction produces a viscous gel in the gastrointestinal tract, slowing stomach emptying and slowing carbohydrate absorption, minimising postprandial glucose excursions and increasing satiety. This property contributes not only to improved glycemic control but also to appetite regulation and weight management[28]. The elevated content of omega-3 fatty acids, particularly ALA, activates peroxisome proliferator-activated receptors (PPAR-α and PPAR-γ), which enhance fatty acid β-oxidation, improve adipocyte metabolism, and prevent hepatic triglyceride accumulation, thereby counteracting dyslipidemia[29]. Polyphenols such as chlorogenic acid and caffeic acid exert antioxidant and vasoprotective effects, improving endothelial nitric oxide synthesis and shielding pancreatic β-cells from oxidative and inflammatory stress, which helps delay or reduce insulin resistance[30]. Clinical studies and dietary intervention trials have reported that chia seed supplementation lowers systolic blood pressure, reduces plasma triglycerides, elevates HDL cholesterol, and improves vascular compliance and arterial elasticity[31]. Furthermore, regular consumption is linked with reduced markers of systemic inflammation and improved insulin sensitivity. Collectively, chia seeds offer a multifaceted protective role in managing metabolic syndrome by targeting obesity, dyslipidemia, hypertension, and glucose intolerance[32].

3.3 Cinnamon (*Cinnamomum verum*)

Cinnamon is among the most extensively investigated spices for its therapeutic potential in metabolic syndrome and type 2 diabetes. Its principal bioactive compound, cinnamaldehyde, enhances insulin receptor autophosphorylation and promotes the translocation of glucose transporter-4 (GLUT-4) in adipocytes and skeletal muscle, thereby facilitating efficient glucose uptake and utilisation. This insulin-sensitising effect contributes to improved glycemic control and decreased insulin resistance[33,34]. In addition, procyanidins and cinnamic acid derivatives exhibit potent antioxidant and anti-inflammatory activities, primarily by suppressing NF-κB signalling, reducing reactive oxygen species (ROS) generation, and regulating cytokines that promote inflammation, like TNF-α and IL-6[35]. Cinnamate compounds also regulate lipid metabolism by decreasing hepatic triglyceride synthesis and lowering circulating LDL and total cholesterol, while enhancing HDL concentrations[36]. Furthermore, cinnamon influences adipokine secretion by increasing adiponectin levels and mitigating leptin resistance, which collectively improve insulin sensitivity and energy homeostasis[37,38]. Clinical studies corroborate these results, as multiple randomised controlled trials have reported notable decreases in fasting blood glucose, HbA1c levels, triglycerides, and systolic blood pressure among patients with type 2 diabetes and metabolic syndrome after cinnamon supplementation[39,40].

3.4 Coriander (*Coriandrum sativum*)

The medicinal efficacy of coriander seeds and leaves in metabolic syndrome is attributed to their rich profile of bioactive components, which include phenolic acids, the monoterpene linalool, and flavonoids (apigenin, quercetin)[41]. By inhibiting sterol regulatory element-binding proteins (SREBP-1c and SREBP-2), linalool suppresses de novo lipogenesis and increases fatty acid β-oxidation in hepatic tissues, resulting in hypolipidemic action[42]. One of the main flavonoids in coriander, quercetin, stimulates AMP-activated protein kinase (AMPK), which improves insulin receptor signalling and increases glucose absorption in skeletal muscle and adipose tissue[43]. Strong antioxidant properties of phenolic acids reduce oxidative stress and prevent lipid peroxidation, which tends to rise in metabolic syndrome[44].

Furthermore, coriander has been reported to stimulate peroxisome proliferator-activated receptors (PPAR-γ and PPAR-α), nuclear transcription factors essential for regulating insulin sensitivity, adipogenesis, and lipid homeostasis[45]. Preclinical studies demonstrate that coriander supplementation lowers serum triglycerides, LDL-cholesterol, and oxidative biomarkers, while elevating HDL-cholesterol. In addition to enhancing pancreatic insulin production, it also balances hepatic glucose output and peripheral use by modifying enzymes that metabolise carbohydrates, including glucokinase, glucose-6-phosphatase, and hexokinase[46,47].

3.5 Clove (*Syzygium aromaticum*)

Clove (*Syzygium aromaticum*), a spice of the *Myrtaceae* family, possesses different bioactive compounds,

mainly eugenol, gallic acid, and flavonoids, which add to its therapeutic potential against metabolic syndrome (MetS)[48]. The main component, eugenol, reduces reactive oxygen species and inhibits proinflammatory mediators like TNF-α, IL-6, and NF-κB, resulting in effective antioxidant and anti-inflammatory actions. By reducing inflammation and oxidative stress, these measures enhance vascular health and insulin sensitivity. It has been demonstrated that clove extracts improve glucose metabolism by upregulating insulin receptor signalling and activating AMP-activated protein kinase (AMPK), leading to increased glucose uptake in peripheral tissues[49]. In experimental models, clove supplementation improved mitochondrial function by elevating mitochondrial mass, membrane potential, and DNA copy number, and normalised lactate and pyruvate balance, indicating restored cellular energy homeostasis. Furthermore, clove exhibits hypolipidemic activity through downregulation of sterol regulatory element-binding proteins (SREBP-1c and SREBP-2) and activation of peroxisome proliferator-activated receptors (PPAR-α and PPAR-γ), resulting in reduced lipogenesis, enhanced fatty acid oxidation, and improved serum lipid profile[50]. The phenolic and flavonoid constituents of clove act through integrated antioxidant, anti-inflammatory, and metabolic pathways to enhance mitochondrial efficiency, lipid metabolism, and insulin sensitivity, bolstering its use as a natural medicinal agent for the therapy and prevention of metabolic syndrome[51].

3.6 Curry Leaf (*Murraya koenigii*)

Curry leaf, or *Murraya koenigii*, is an aromatic plant that is a member of the *Rutaceae* family. This family includes over 1600 species and 150 genera, native to South Asia, particularly India, Sri Lanka, and Bangladesh; it is extensively used in traditional cuisines for its distinct aroma and flavour, which persist even after drying. The characteristic fragrance is mainly attributed to volatile constituents such as pinene, sabinene, caryophyllene, cardinol, and cardinene[52,53]. Beyond its culinary significance, curry leaf has long been recognised for its medicinal value, serving as a tonic and stomachic in traditional systems of medicine[54]. Phytochemical investigations have revealed that *M. koenigii* is a rich source of bioactive constituents, including alkaloids (mahanimbine, girinimbine), terpenoids, flavonoids, phenolic acids, essential oils, tocopherol, β-carotene, and lutein. These components support a variety of pharmacological actions, including anti-inflammatory, hypoglycemic, hypolipidemic, and antioxidant properties that are important for managing and preventing metabolic syndrome (MetS)[55]. The antioxidant potential of curry leaf stems from its ability to enhance endogenous defence enzymes such as superoxide dismutase, catalase, and glutathione peroxidase, thereby decreasing lipid peroxidation and mitigating oxidative damage associated with insulin resistance and cardiovascular complications[53,56]. Experimental and epidemiological findings further suggest that curry leaf consumption may modulate metabolic and environmental risk factors contributing to MetS[57]. Notably, studies in Korean populations indicate a potential protective interaction between curry leaf consumption, serum vitamin levels, and reduced high-sensitivity C-reactive protein (hs-CRP), signifying its role in mitigating heavy metal–induced metabolic disturbances[58]. Collectively, the rich phytochemical composition and antioxidant defence-enhancing properties of *M. koenigii* support its potential as a natural dietary intervention for preventing oxidative and inflammatory perturbations underlying metabolic syndrome[59,60].

3.7 Fenugreek (*Trigonella foenum-graecum*)

Fenugreek (*Trigonella foenum-graecum*), a leguminous plant belonging to the *Fabaceae* family, is commonly cultivated in Mediterranean regions and Asia and has long been utilised in traditional medicinal systems, particularly in India and Iran[61]. Both its seeds and leaves serve culinary and therapeutic purposes due to their rich nutritional composition and diverse phytoconstituents. Fenugreek seeds primarily contain carbohydrates (47.4%), proteins (28.4%), crude fibre (9.3%), fats (7.1%), moisture (6.87%), and ash (3.28%), along with bioactive constituents including alkaloids (trigonelline), flavonoids, saponins (diosgenin), salicylates, and nicotinic acid[62,63]. These components influence a variety of pharmacological actions, including hypoglycemic, hypolipidemic, antioxidant, anti-inflammatory, and chemoprotective actions[64]. Experimental evidence from high-fat diet and obesity models demonstrates that fenugreek supplementation improves lipid and glucose metabolism by lowering

serum cholesterol, triglycerides, and fatty acid-binding protein 4 (FABP4), while enhancing adiponectin expression and reducing fat accumulation[65,66]. Mechanistically, its soluble fibre (galactomannan) delays carbohydrate absorption and improves insulin sensitivity, whereas the amino acid 4-hydroxyisoleucine promotes insulin secretion and glucose utilization[67]. Saponins such as diosgenin further reduce intestinal cholesterol absorption and stimulate bile acid excretion, thereby ameliorating dyslipidemia[68]. Clinical studies corroborate these findings, showing that fenugreek seeds and leaves significantly decrease postprandial blood glucose levels in healthy individuals and regulate glycemic control, lipid profile, and HbA1c levels in diabetic patients[69]. The combined effects of improved glucose tolerance, lipid regulation, and antioxidant defence highlight fenugreek's potential as a functional food and a promising dietary intervention for the prevention and management of metabolic syndrome[70].

3.8 Garlic (*Allium sativum* L.)

Allium sativum L. (garlic), commonly known as "*lahsun*", is one of the most extensively used culinary spices and traditional medicinal herbs, valued for its therapeutic potential in cardiovascular and metabolic disorders[71]. Belonging to the family *Amaryllidaceae*, garlic has been widely recognised for its ability to modulate multiple components of metabolic syndrome, including hyperglycemia, dyslipidemia, hypertension, and inflammation[72]. Its bioactive constituents—such as allicin, S-allyl cysteine, diallyl disulfide, and ajoene—are primarily responsible for its diverse pharmacological actions. Preclinical and clinical studies have consistently demonstrated that garlic supplementation can lower serum total cholesterol, triglycerides, low-density lipoprotein cholesterol (LDL-C), and very-low-density lipoprotein cholesterol (VLDL-C), while elevating high-density lipoprotein cholesterol (HDL-C) and suppressing hepatic cholesterol synthesis[73]. Moreover, garlic exhibits hypoglycemic, antihypertensive, antioxidant, and anti-inflammatory activities, collectively contributing to improved endothelial function, reduced oxidative stress, and enhanced insulin sensitivity[72,74,75]. Through these multifaceted mechanisms, garlic effectively mitigates the progression of atherosclerosis and type 2 diabetes, key manifestations of metabolic syndrome. Although earlier studies strongly supported its lipid- and glucose-lowering efficacy, recent trials using standardised or enteric-coated formulations have produced variable results, highlighting the influence of preparation methods on bioavailability and clinical outcomes. Nonetheless, the cumulative evidence underscores garlic's potential as a functional food and a complementary therapeutic agent in the management of metabolic syndrome[76].

3.9 Ginseng (*Panax ginseng*)

Panax ginseng (family *Araliaceae*), extensively cultivated in East Asia, is a highly valued medicinal herb that has been used for many years in traditional Chinese medicine. Its therapeutic efficacy is primarily attributed to ginsenosides, a group of triterpene saponins renowned for their antioxidant, anti-inflammatory, antidiabetic, and metabolic-regulatory activities[77,78]. More than 150 ginsenosides have been identified, approximately 40 of which are specific to *P. ginseng*. Red ginseng, produced through a steaming and drying process, has demonstrated enhanced pharmacological potency, particularly in lowering blood glucose levels and improving metabolic function[79]. Phytochemically, ginseng comprises a diverse range of bioactive constituents including saponins, polysaccharides, polyacetylenes, phenolics, along with alkaloids. Among these, ginsenosides—such as Rb1, Rg1, Rg3, and Re—are recognised as the principal mediators of its pharmacological actions[80]. These compounds modulate several signalling pathways associated with glucose and lipid homeostasis, including AMPK, PI3K/Akt, and PPARγ, thereby improving insulin sensitivity, enhancing glucose uptake, and regulating adipogenesis[81]. Experimental and clinical studies consistently report that *P. ginseng* supplementation reduces hyperglycemia, hyperlipidemia, and oxidative stress while exerting antihypertensive, hepatoprotective, anxiolytic, and immunomodulatory effects[82]. By restoring redox balance, suppressing inflammation, and optimising energy metabolism, ginseng offers protection against the pathophysiological components of metabolic syndrome[83]. Although the exact molecular mechanisms are still under investigation, accumulating evidence supports *P. ginseng* and its ginsenosides as potent natural interventions for the anticipation and management of metabolic syndrome and associated metabolic disorders[84].

3.10 Black Seed (*Nigella sativa*)

Nigella sativa (black seed), belonging to the family *Ranunculaceae*, is a nutrient-dense medicinal plant traditionally used in Middle Eastern and South Asian medicine. The seeds are rich in proteins, fats, carbohydrates, fibres, and essential minerals, with thymoquinone (TQ) recognised as the principal bioactive constituent responsible for most of its pharmacological effects[85]. *N. sativa* has gained substantial scientific attention for its role in ameliorating various components of metabolic syndrome through its potent antioxidant, anti-inflammatory, and antihyperglycemic actions[86]. Preclinical and clinical studies have verified that black seed utilisation significantly improves glycemic control by reducing fasting blood glucose (FBG) and glycated haemoglobin (HbA1c) levels, while increasing insulin sensitivity and pancreatic β-cell function[87]. Its hypolipidemic activity is evident from reductions in total cholesterol, LDL, and triglycerides, accompanied by a rise in HDL levels[88,89]. Moreover, *N. sativa* exhibits antihypertensive effects, reducing blood pressure in a dose-dependent manner, both systolic and diastolic. In obesity-related parameters, black seed supplementation has been shown to reduce waist circumference and body mass index (BMI), although findings on direct body weight reduction remain variable[90]. These beneficial outcomes are largely attributed to the ability of thymoquinone and other seed constituents to modulate oxidative stress pathways, suppress pro-inflammatory cytokines, and enhance insulin signalling and lipid metabolism. Collectively, current evidence supports *N. sativa* as an important dietary component for the prevention and management of metabolic syndrome and its associated cardiometabolic complications [91].

3.11 Ginger (*Zingiber officinale*)

Medicinal plants, rich in bioactive phytochemicals, have long played a vital function in maintaining health and managing chronic diseases. Among these, *Zingiber officinale* (ginger), a rhizomatous plant belonging to the family *Zingiberaceae*, is widely appreciated not only as a culinary spice but also as a potent medicinal agent[92]. Considering the adverse impacts and limited accessibility of conventional drugs, particularly in low-resource regions, natural remedies such as ginger offer promising, affordable, and safe alternatives for disease management[93]. The many medicinal properties of ginger are mainly due to its pharmacologically active ingredients, which include [6]-gingerol, [8]-gingerol, [10]-gingerol, and [6]-shogaol. These substances have strong anti-inflammatory and antioxidant properties, antihypertensive, hypoglycemic, anti-obesity, and lipid-modulating activities[94]. Experimental and clinical evidence indicates that ginger supplementation ameliorates multiple metabolic syndrome (MetS) components by improving insulin sensitivity, reducing fasting blood glucose and triglyceride levels, lowering blood pressure, and enhancing antioxidant defense[95]. Moreover, ginger modulates key molecular pathways involved in glucose and lipid metabolism, such as AMPK and PPARγ signalling, contributing to improved metabolic homeostasis[96,97]. Collectively, these findings establish *Z. officinale* as a valuable functional food and a natural therapeutic agent for mitigating oxidative stress, dyslipidemia, inflammation, and insulin resistance associated with metabolic syndrome[95].

3.12 Saffron (*Crocus sativus* L.)

Saffron (*Crocus sativus* L.), belonging to the family *Iridaceae*, is recognised as one of the most precious and economically significant spices worldwide. Approximately 90% of global saffron production originates from Iran, followed by India, Greece, and Spain[98]. Traditionally, saffron has been utilised not only as a culinary flavouring and natural dye but also for its diverse pharmacological properties. It has been used in the management of menstrual disorders, asthma, depression, hepatic dysfunctions, pain, and neoplastic conditions[99,100]. Saffron also influences vascular function by improving endothelial nitric oxide bioavailability and reducing lipid peroxidation, thereby contributing to cardiovascular protection[101]. Experimental models demonstrate that crocin and crocetin can modulate AMPK and PPAR signalling pathways, which are central to energy homeostasis, lipid metabolism, and insulin sensitivity. These constituents exhibit potent antioxidant, anti-inflammatory, anticarcinogenic, neuroprotective, and cardioprotective activities. Crocin and crocetin, in particular, have been shown to modulate oxidative stress and lipid peroxidation, enhance insulin sensitivity, and improve endothelial function[102,103]. Recent pharmacological and clinical investigations suggest that saffron exerts beneficial effects in metabolic

syndrome (MetS), a complex pathological condition involving hyperglycemia, dyslipidemia, central obesity, and hypertension[104]. The mechanistic basis of its action is attributed to the downregulation of inflammatory mediators (such as TNF-α, IL-6, and CRP), inhibition of lipid accumulation, and improvement in glucose homeostasis through modulation of AMPK and PPAR signalling pathways. Additionally, its antioxidant constituents mitigate oxidative damage associated with cardiovascular and metabolic complications[105,106]. Collectively, these findings indicate that saffron represents a promising nutraceutical and functional food component for the prevention and adjunct management of metabolic syndrome and its type 2 diabetes mellitus and other related co-morbidities, atherosclerosis, and cardiovascular diseases.

3.13 Turmeric (*Curcuma longa* L.)

Widely grown throughout South Asia, *Curcuma longa* L. is a rhizomatous plant belonging to the *Zingiberaceae* family that has long been used as a medicinal herb and a spice in cooking. Its primary bioactive constituent, curcumin, typically represents 60–70% of the crude extract, along with minor curcuminoids such as demethoxycurcumin and bisdemethoxycurcumin[107]. These compounds exhibit diverse pharmacological activities, including antioxidant, anti-inflammatory, antidiabetic, lipid-modulating, and antimicrobial effects. Mechanistic studies indicate that curcuminoids mitigate metabolic dysfunction through multiple pathways. Curcumin lowers the risk of oxidative damage by scavenging free radicals and boosting endogenous antioxidant defences, suppresses pro-inflammatory cytokines such as TNF-α and IL-6, and improves insulin sensitivity by modulating signalling pathways including AMPK, PI3K/Akt, and PPARγ[108]. These molecular actions translate into improvements in glycemic control, lipid metabolism, and vascular function. Clinical trials on people with prediabetes or metabolic syndrome have revealed that curcumin administration dramatically lowers fasting blood glucose and triglyceride levels, increases HDL cholesterol, and reduces diastolic blood

Table 1. Overview of selected spices, their principal bioactive compounds, underlying mechanisms of action, and therapeutic effects against metabolic syndrome

Name of Spice	Chemical Constituent(s)	Mechanism of Action	Pharmacological Activity
Cardamom (*Elettaria cardamomum*)	Cineol (1,8-cineole)	Modulates inflammatory pathways; improves vascular function	Anti-Inflammatory, Cardioprotective
	Limonene	Enhances antioxidant defence; regulates lipid metabolism	Antioxidant, Hypolipidemic
	Geraniol and Geranyl acetate	Improves glucose uptake; inhibits oxidative stress	Antidiabetic, Antioxidant
	Terpinene, α/β-pinene, Myrcene	Modulate gut microbiota; reduce oxidative stress	Antioxidant, Antimicrobial
	Stigmasterol and β-sitosterol	Inhibit cholesterol absorption/synthesis	Hypolipidemic, Cardioprotective
	Borneol and Linalool	Support digestive and hepatic function	Gastroprotective, Hepatoprotective
Chia Seed (*Salvia hispanica*)	Dietary fiber	Slows glucose absorption, increases stool bulk, modulates gut microbiota	Antidiabetic, Gastrointestinal
	Omega-3 fatty acids (α-linolenic acid)	Reduces inflammation, improves lipid metabolism, lowers platelet aggregation	Cardioprotective, Anti-Inflammatory
	Polyphenols	Neutralise free radicals, protect pancreatic β-cells, prevent oxidative damage.	Antioxidant, Nticancer
	Peptides and proteins	Modulate metabolic enzymes and blood pressure	Hypotensive, Cardioprotective
	Vitamins and minerals	Support enzymatic functions, reduce oxidative stress	Antioxidant, Metabolic Regulation

Table 1. Continued...

Cinnamon (*Cinnamomum verum*)	Cinnamaldehyde	Enhances insulin sensitivity, reduces hyperglycemia, inhibits ROS-producing enzymes, reduces oxidative stress to control inflammation. Improves lipid profile, lowers blood pressure.	Anti-Diabetic, Antioxidant, Anti-Inflammatory , Cardioprotective Activity
	Cinnamic acid	Regulates glucose metabolism, improves insulin resistance, reduces inflammation	Ant Diabetic, Antioxidant, Anti-Inflammatory
	Cinnamate	Lowers triglycerides, improves HDL, modulates lipid metabolism	Anti-Inflammatory, Anti-Hyperlipidaemia Activity
	Trans-cinnamaldehyde	Reduces oxidative stress and inflammation in cardiovascular tissues; prevents cardiac hypertrophy	Anti-Inflammatory, Antimicrobial, Antioxidant, Cardioprotective Activity
	Cinnamyl acetate	Inhibits lipid peroxidation in cell membranes. Improves glucose and lipid metabolism	Antioxidant, Anti-Inflammatory Antihyperglycemic
	Eugenol	Reduces systemic inflammation, improves insulin sensitivity	Anti-Inflammatory, Antioxidant, Antimicrobial
Coriander (*Coriandrum sativum*)	Linalool (monoterpene alcohol)	Reduces oxidative stress and inflammation; lowers cholesterol and triglycerides, modulates lipid metabolism, inhibits NF-κB pathway.	Antioxidant, Anti-Inflammatory, Antihyperlipidemic Activity
	Quercetin (flavonoid)	Inhibits adipogenesis, enhances GLUT-4-mediated glucose uptake, suppresses pro-inflammatory cytokines.	Antidiabetic, Anti-Inflammatory, Hypoglycemic Activities.
	Apigenin (flavonoid)	Regulates lipid metabolism, reduces adipocyte hypertrophy, prevents obesity-related complications. Activates PPAR pathways, downregulates COX-2 and TNF-α.	Antioxidant, Anti-Inflammatory, Hypolipidemic, Anti-Obesity, Metabolic Protective Activities.
	Rutin (flavonoid glycoside)	Scavenges free radicals, inhibits LDL oxidation, enhances endothelial function. Protects against dyslipidemia and cardiovascular risk.	Cardioprotective Activity, Antioxidant Activity, Antidyslipidemic Activity
	Chlorogenic acid (phenolic acid)	Inhibits glucose-6-phosphatase, reduces intestinal glucose absorption, modulates adipocyte metabolism, lowers postprandial glucose, improves insulin resistance, reduces fat accumulation	Antidiabetic and Anti-Obesity Activity
	Caffeic acid (phenolic acid)	Inhibits adipogenesis, improves mitochondrial function. Prevents obesity-linked oxidative stress and insulin resistance.	Antioxidant, Anti-obesity, Metabolic Protective Activity
	Ferulic acid (phenolic acid)	Inhibits lipid peroxidation, improves endothelial nitric oxide (NO) availability. Protects against hypertension and vascular dysfunction in metabolic syndrome.	Antihypertensive, Cardioprotective Activity
Clove (*Syzygium aromaticum*)	Mmahanimbine, girinimbine, murrayacine)	Improve insulin sensitivity, regulate glucose metabolism	Antidiabetic, Antihyperglycemic
	Pinene, Sabinene, Caryophyllene)	Antioxidant and anti-inflammatory effects, regulate lipid metabolism	Cardioprotective, Hypolipidemic
	Quercetin, Catechin, Rutin	Scavenge free radicals, reduce oxidative stress, protect β-cells	Antioxidant, Pancreatic Protection

Table 1. Continued...

	Carotenoids (β-carotene, lutein	Improve lipid metabolism, reduce adipogenesis, enhance antioxidant defence	Anti-obesity, Hypolipidemic
	Tocopherol	Enhance enzymatic antioxidant activity, protect vascular endothelium	Cardioprotective, Anti-Inflammatory
Garlic (*Allium sativum*)	Allicin	Inhibits HMG-CoA reductase, modulates lipid metabolism, enhances insulin sensitivity, and suppresses pro-inflammatory cytokines	Hypolipidemic, Antidiabetic, Anti-inflammatory
	S-allyl cysteine (SAC)	Antioxidant, reduces oxidative stress, improves endothelial function	Cardioprotective, Antioxidant
	Diallyldisulfide / Diallyltrisulfide	Modulates platelet aggregation, reduces cholesterol synthesis, and inhibits inflammatory pathways.	Antithrombotic, Hyperlipidemic, Anti-Inflammatory
	Ajoene	Inhibits platelet aggregation and reduces proinflammatory mediators	Antithrombotic, Anti-Inflammatory
Ginseng (*Panax ginseng*)	Ginsenosides (Rb1, Rg1, Rg3, Re)	Increased insulin sensitivity, Promote glucose uptake in muscle/adipose tissue, modulate pancreatic β-cell function, regulate lipid metabolism, antioxidant and anti-inflammatory effects.	Antidiabetic, Hypolipidemic, Anti-obesity, Antihypertensive
	Polysaccharides	Improve insulin secretion, modulate gut microbiota, enhance antioxidant defence.	Glucose Regulation, Immune-modulatory, Anti-Inflammatory
	Polyacetylenes	Inhibit lipid peroxidation, protect β-cells	Antioxidant, Hypolipidemic
	Phenolic compounds	Scavenge free radicals, reduce oxidative stress	Antioxidant, Cardioprotective
	Alkaloids	Support glucose and lipid homeostasis	Neuroprotective, Metabolic Modulation
Ginger (*Zingiber officinale*)	[6]-Gingerol[3]	Activates AMPK, inhibits NF-κB, reduces oxidative stress and enhances insulin sensitivity.	Antihypertensive, Antihyperglycemic, and Anti-Inflammatory Activity
	[8]-Gingerol[4]	Enhances insulin sensitivity, improves lipid profile	Antidiabetic Antihyperlipidemic
	[10]-Gingerol[5]	Modulates lipid metabolism, lowers triglycerides, and reduces obesity-related inflammation.	Anti-inflammatory, Antihyperlipidemic Activity
	[6]-Shogaol[6]	Suppresses adipogenesis, enhances glucose uptake	Anti-obesity, Antidiabetic Activity
	[6]-Paradol [7]	Stimulates glucose consumption in adipocytes and myotubes, lowers blood glucose.	Antihyperglycemic
Black Seed (*Nigella sativa*)	Thymoquinone (TQ)	Reduces oxidative stress; preserves pancreatic β-cell integrity and improves insulin sensitivity; lowers FBG and HbA1c	Antioxidant, Anti-inflammatory, and Anti-Diabetic Activity
	Essential Oils (volatile compounds)	Regulate vascular tone, improve endothelial function, reduce systolic and diastolic blood pressure.	Vasoprotective, Andantihypertensive Activity
	Linoleic, oleic acids	Improve hepatic lipid clearance and Lower total cholesterol, LDL, TG, and increase HDL.	Hepatoprotective , Hypolipidemic Activity
	Minerals (Zn, Fe, Cu, P)	Support enzymatic antioxidant defences and contribute to overall improvement of cardiometabolic parameters.	Antioxidant, Cardioprotective Activity

Table 1. Continued...

Saffron (*Crocus sativus*)	Crocin	Enhances insulin sensitivity, regulates glucose metabolism, antioxidant, anti-inflammatory.	Antidiabetic, Antioxidant, Anti-inflammatory
	Crocetin	Reduces oxidative stress, improves lipid profile, modulates blood pressure	Hypolipidemic, Cardioprotective, Antihypertensive
	Picrocrocin	Modulates metabolic enzymes, reduces oxidative damage	Antioxidant, Metabolic Regulator
	Safranal	Inhibits inflammation, protects vascular and pancreatic cells	Anti-inflammatory, Cardioprotective, Antidiabetic
Turmeric (*Curcuma longa*)	Curcumin	Modulates inflammatory pathways (NF-κB), enhances antioxidant defence, improves insulin signalling, regulates lipid metabolism.	Anti-inflammatory, Antioxidant, Antidiabetic, Improves Lipid Profile.
	Demethoxycurcumin	Inhibits pro-inflammatory cytokines and oxidative stress	Anti-inflammatory, Antioxidant
	Bisdemethoxycurcumin	Suppresses oxidative stress and inflammation	Antioxidant, Anti-inflammatory

pressure, although effects on waist circumference and systolic blood pressure show variability depending on dose, formulation, and duration of treatment[109]. Collectively, these findings underscore turmeric and its curcuminoids as promising natural therapeutic agents with multi-targeted efficacy for the prevention and management of metabolic syndrome, highlighting their potential as functional dietary interventions alongside conventional pharmacotherapy. A summary of spices, bioactive constituents, mechanisms of action, and pharmacological activities in metabolic syndrome is listed in Table 1.

4. Conclusion

Spices offer a multifaceted and natural therapeutic strategy for the management of metabolic syndrome, acting on multiple pathophysiological mechanisms simultaneously. Their bioactive constituents such as cinnamaldehyde, gingerols, allicin, thymoquinone, saponins, and polyphenols improve insulin sensitivity, regulate lipid metabolism, reduce oxidative stress, lower blood pressure, and attenuate chronic inflammation. Evidence from experimental models and clinical trials indicates that regular inclusion of spices like cinnamon, ginger, garlic, fenugreek, cardamom, clove, curry leaf, chia seed, ginseng, coriander, and black seed can mitigate metabolic disturbances, enhance cardiovascular health, and support glucose homeostasis. Thus, these functional dietary components provide a practical, safe, and complementary approach to conventional therapies, emphasising the role of nutrition-based interventions in the comprehensive management and anticipation of metabolic syndrome.

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Author Contribution

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