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A narrative review on the role of gut microbiome, dietary strategies, and supplements in managing metabolic syndrome

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Abstract

Metabolic syndrome is a complex, multifactorial disorder, with emerging research emphasizing the significant role of gut health in its prevention and management. Recent studies suggest that dietary strategies promoting a healthy gut microbiome, including the incorporation of fiber, fermented foods, and healthy fats, are crucial for regulating metabolism. Additionally, the use of postbiotics and supplements, such as probiotics, omega-3 fatty acids, and polyphenols, provides promising avenues for enhancing metabolic health. This holistic approach to managing metabolic syndrome not only supports gut health but also offers the potential for improving long-term health outcomes. This review examines the influence of the gut microbiome on metabolism, highlighting the increasing significance of dietary strategies and supplements in managing metabolic syndrome.

Keywords

Metabolic syndrome, healthy gut microbiome, probiotics, omega-3 fatty acid, dietary strategies

Introduction

Metabolic syndrome, a cluster of risk factors for cardiovascular diseases, diabetes, and obesity, has become one of the leading global health challenges of the 21st century. Defined by a combination of abdominal obesity, hypertension, dyslipidemia, and insulin resistance, this condition affects millions worldwide and has a profound impact on healthcare systems and individuals' well-being. As a multifactorial disorder, the treatment and management of metabolic syndrome require a comprehensive, integrated approach that goes beyond traditional pharmaceutical interventions [1–3].

Recent research has highlighted the critical role of the gut microbiome in influencing metabolic health. The gut microbiome, comprising trillions of microorganisms residing in the digestive tract, plays a crucial role in the digestion of food, regulation of metabolism, immune function, and even mental health. A growing body of evidence suggests that the composition of the gut microbiome plays a pivotal role in the development and progression of metabolic syndrome. Consequently, dietary strategies that promote a healthy gut microbiome, using postbiotics, and incorporating innovative supplements are emerging as key interventions for managing and potentially reversing metabolic syndrome [4–6].

Therefore, this study aims to investigate the role of the gut microbiota (GM) in the prevention and management of metabolic syndrome. It focuses on the effects of dietary strategies and supplements, such as fiber, fermented foods, healthy fats, probiotics, postbiotics, omega-3 fatty acids, and polyphenols, on regulating metabolism and enhancing long-term metabolic health outcomes.

The role of the gut microbiome in metabolic syndrome

The regulation of metabolic syndrome, which includes insulin resistance, obesity, and dyslipidemia, is greatly influenced by the gut microbiome [7]. Increased energy extraction and changed fat storage are two effects of dysbiosis, whereas insulin resistance impacts vascular tone and insulin sensitivity. It also has an impact on bile acid synthesis and lipid metabolism, resulting in lower HDL cholesterol levels and higher LDL cholesterol levels. An unbalanced microbiome can exacerbate metabolic syndrome and inflammation by causing endotoxemia [8]. The gut-brain axis influences hormones that regulate appetite, and beneficial gut bacteria produce short-chain fatty acids (SCFAs) that modulate insulin sensitivity and glucose metabolism. A balanced immune response and better metabolic profiles are supported by a varied microbiome [9, 10]. There are various aspects of metabolic syndrome, as shown in Figure 1.

Figure 1. Various aspects of metabolic syndrome. SCFAs: short-chain fatty acids; NAFLD: non-alcoholic fatty liver disease

The gut microbiome plays a crucial role in digesting complex carbohydrates, producing SCFAs, and regulating various metabolic pathways. Studies have shown that individuals with metabolic syndrome tend to have an altered gut microbiome characterized by lower microbial diversity and an overabundance of harmful bacteria. This dysbiosis contributes to systemic inflammation, insulin resistance, and disturbances in lipid metabolism—key features of metabolic syndrome [11, 12].

A contributing factor to the rise in non-alcoholic fatty liver disease (NAFLD) worldwide is GM. By increasing permeability, dysbiosis exposes the liver to bacteria and their byproducts. Although the exact pathogenic processes of GM in NAFLD are unknown, gut dysbiosis seems to be linked to its development. The pathophysiology of NAFLD, a common chronic liver disease, is significantly influenced by dysbiosis of the GM. According to European clinical recommendations, only 40% of people can lose weight and improve their lifestyle [13]. Though further research is required to generalize these findings, new therapy techniques, such as GM modification-based medicines like probiotics synbiotics, have demonstrated encouraging benefits in animal experiments [14]. In patients with metabolic dysfunction associated with steatotic liver disease (MASLD), the study found a nonlinear association between the neutrophil percentage-to-albumin ratio, the neutrophil-to-lymphocyte ratio, and the systemic immune-inflammation index (SII) with all-cause and cardiovascular disease mortality. However, after controlling for relevant factors, there was no significant correlation between the SII and mortality [15].

SCFAs, including butyrate, acetate, and propionate, are produced by gut bacteria during the fermentation of dietary fiber. These SCFAs have numerous beneficial effects on metabolic health, including enhancing insulin sensitivity, reducing inflammation, and improving lipid profiles. Furthermore, SCFAs act as signaling molecules, influencing gene expression in the gut and other organs [7, 16]. A healthy gut microbiome, rich in fiber-fermenting bacteria, helps maintain optimal SCFA production, supporting metabolic processes crucial for preventing and managing metabolic syndrome through various mechanisms, as outlined in Table 1.

Table 1. Role of gut microbiome and their mode of action against various metabolic syndromes

Aspect of metabolic syndrome	Role of the gut microbiota (GM)	Mechanisms of action	References
Obesity	GM composition is linked to obesity risk	Dysbiosis (imbalance of GM) may lead to increased energy extraction from food and altered fat storage. Certain bacteria, such as those belonging to the Firmicutes group, are associated with a higher energy harvest from food, which contributes to weight gain.	Alou et al. [17], 2016; Amabebe et al. [18], 2020
Insulin resistance	GM affects insulin sensitivity	The altered gut microbiome can influence insulin resistance by increasing inflammation, producing metabolites such as short-chain fatty acids (SCFAs) that improve insulin function, or modifying bile acid metabolism.	Saad et al. [19], 2016; Visekruna and Luu [20], 2021
High blood pressure	GM may influence blood pressure regulation	An imbalance in GM can lead to an increased production of endotoxins, which promote inflammation and hypertension. Gut-produced SCFAs can help regulate blood pressure by affecting vascular tone and sodium balance.	Mozaffarian and Wu [21], 2018
Dyslipidemia	Microbiota affects lipid metabolism	Gut bacteria can influence lipid metabolism, bile acid synthesis, and the absorption of fat. Dysbiosis can lead to elevated levels of LDL cholesterol, triglycerides, and reduced HDL cholesterol. Beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, may help improve lipid profiles.	Schoeler and Caesar [22], 2019; Wang et al. [23], 2019; Zarezadeh et al. [24], 2023
Inflammation	Dysbiosis promotes chronic low-grade inflammation	An imbalance in GM increases gut permeability ("leaky gut"), allowing endotoxins to enter the bloodstream and trigger systemic inflammation. This inflammation contributes to metabolic dysfunction and the development of metabolic syndrome.	Candelli et al. [25], 2021
NAFLD	GM plays a role in liver health	The gut microbiome can influence liver fat accumulation and inflammation. Dysbiosis may contribute to the development of fatty liver disease by increasing intestinal permeability and triggering an inflammatory response in the liver.	Saltzman et al. [26], 2018; Yaghmaei et al. [14], 2024

Table 1. Role of gut microbiome and their mode of action against various metabolic syndromes (*continued*)

Aspect of metabolic syndrome	Role of the gut microbiota (GM)	Mechanisms of action	References
Endotoxemia	GM contributes to endotoxin production	An imbalanced gut microbiome, especially with an overgrowth of gram-negative bacteria, can lead to the production of lipopolysaccharides (LPS), which are pro-inflammatory and contribute to the development of metabolic syndrome.	Çakirlar [27], 2025
Gut-brain axis	The gut microbiome influences appetite and metabolism through the gut-brain axis	GM affects the release of appetite-regulating hormones such as ghrelin and leptin, influencing hunger and satiety signals. Altered microbiota can disrupt these signals, contributing to overeating and obesity.	Han et al. [28], 2021; Smitka et al. [29], 2021
SCFAs	SCFAs produced by GM are beneficial for metabolic health	SCFAs (e.g., acetate, propionate, butyrate) help regulate glucose metabolism, reduce inflammation, and improve insulin sensitivity. SCFAs are produced by the fermentation of dietary fibers by beneficial gut bacteria.	Koh et al. [30], 2016; Portincasa et al. [31], 2022
Bile acid metabolism	The gut microbiome plays a crucial role in regulating bile acid metabolism	Gut bacteria modify bile acids, which in turn influence fat digestion and absorption. Altered bile acid metabolism can affect lipid metabolism, insulin sensitivity, and the development of metabolic diseases.	Chávez-Talavera et al. [32], 2017; Ramirez-Pérez et al. [33], 2017
Microbial diversity	Greater microbial diversity is associated with better metabolic health	Higher microbial diversity is associated with a healthier metabolic profile, improved immune function, and reduced inflammation. Low diversity is often associated with obesity, insulin resistance, and dyslipidemia.	Aron-Wisnewsky et al. [34], 2021; Vallianou et al. [35], 2019

NAFLD: non-alcoholic fatty liver disease

Dietary strategies to enhance gut microbiome health

A well-balanced diet is essential for supporting gut health and general well-being. Increasing fiber intake from fruits, vegetables, and whole grains enhances digestion and promotes a balanced gut microbiome. Prebiotics support healthy gut flora and are found in foods such as garlic, onions, and bananas. Yogurt, kefir, and kimchi are examples of fermented foods that contain probiotics that improve intestinal health. Berries, green tea, and dark chocolate are examples of foods high in polyphenols that can help prevent inflammation and oxidative stress [36, 37]. The anti-inflammatory properties of omega-3 fatty acids, which can be found in foods such as walnuts, chia seeds, and fish, are beneficial for the heart and brain [38]. It is crucial to cut back on processed foods and added sugars to prevent affecting metabolism and gut health [39]. Eating more plant-based foods, such as legumes, nuts, and leafy greens, and limiting animal protein and fat can promote improved digestion and lower the risk of developing chronic illnesses [40]. A prebiotic and blood sugar regulator, resistant starch is found in foods such as potatoes, rice, and oats [41]. For proper digestion and nutrition absorption, it is essential to stay hydrated by drinking lots of water. Because too much alcohol can harm the gut lining and upset the microbial balance, it is crucial to moderate your intake. Ultimately, consuming a varied diet rich in plant-based foods ensures a diverse range of nutrients and fosters a well-balanced gut microbiome [42, 43]. The dietary habits that impact GM health are shown in Figure 2.

Anti-inflammatory diets, as indicated by lower dietary inflammatory index (DII) scores, may be associated with variations in the microbiome, offering potential insights into microbiota research; however, further research is required [44]. According to the study, there is a negative link between the dietary index for GM (DI-GM) and the prevalence of metabolic dysfunction-associated fatty liver disease (MAFLD), with race having a major impact on this relationship. This suggests that dietary modifications may help prevent MAFLD and highlight racial disparities in intervention efforts [45]. Using the DII to measure gut microbiome diversity, composition, and function, another study investigated the relationship between dietary inflammatory potential and these variables. The results showed that while *Akkermansia muciniphila* was more common in the group that followed the most anti-inflammatory diet, certain microbes, such as *Ruminococcus torques*, *Eubacterium nodatum*, *Acidaminococcus intestini*, and *Clostridium leptum*, were more common in the group that followed the most pro-inflammatory diet. The study suggests that more research is needed with prospective cohorts and larger sample sizes [46]. According to research, consuming a more anti-inflammatory diet can help prevent ectopic fat deposition, maintain a healthy GM, reduce

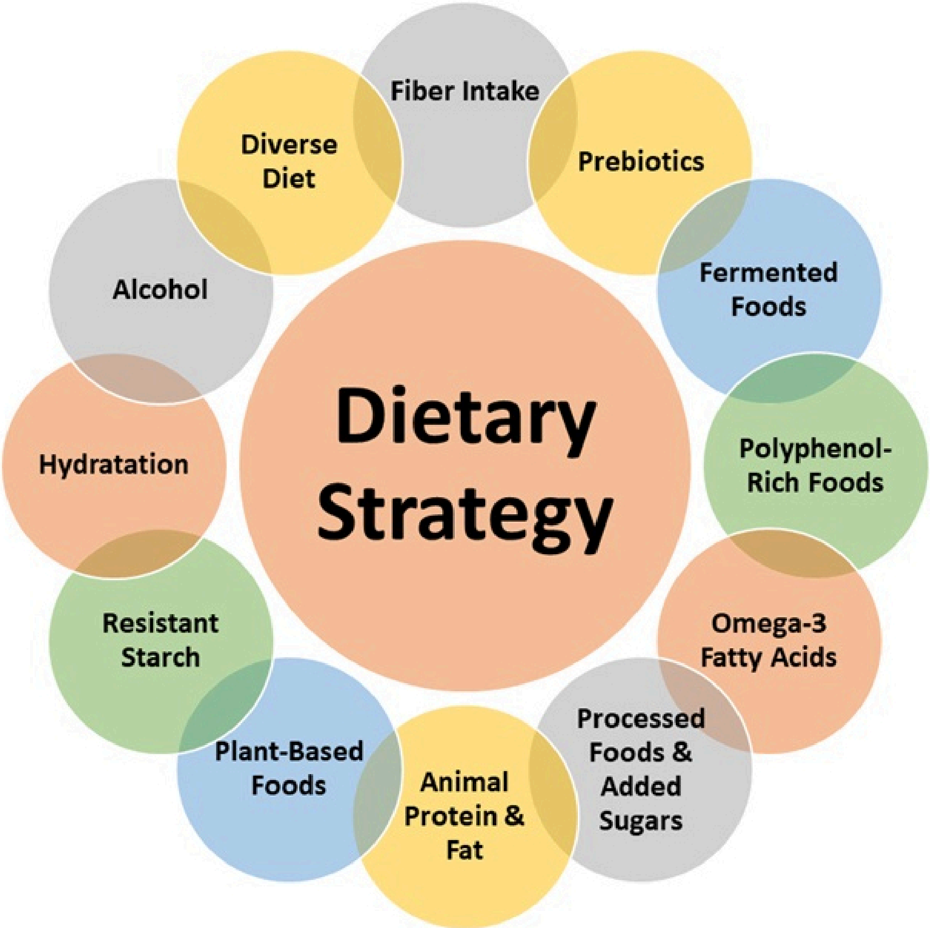

Figure 2. Dietary practices that affect the health of the gut microbiota

inflammation, and limit the accumulation of fat mass. To confirm these results, however, more extensive prospective research is required [47].

A diet that supports gut health is essential for preventing and managing metabolic syndrome. Table 2 provides several dietary strategies that can enhance the gut microbiome, improve metabolic markers, and help mitigate the risk factors associated with metabolic syndrome.

Table 2. Outlines dietary strategies to improve gut health and metabolism

Dietary strategy	Food sources	Mechanisms of action	Impact on metabolic syndrome	References
Increase fiber intake	Whole grains (e.g., oats, quinoa), legumes (e.g., beans, lentils), fruits (e.g., apples, berries), vegetables (e.g., broccoli, spinach), nuts, seeds	Fiber serves as a prebiotic, feeding beneficial gut bacteria and promoting the production of SCFAs.	It improves insulin sensitivity, supports weight management, and helps reduce inflammation—key factors in managing metabolic syndrome.	Tannock and Liu [48], 2020; Vinelli et al. [49], 2022
Incorporate prebiotics	Garlic, onions, leeks, asparagus, bananas, chicory, artichokes	Prebiotics stimulate the growth of beneficial gut bacteria, supporting microbial diversity and SCFA production.	Enhances gut health, lowers inflammation, and supports better metabolic control.	Fernández et al. [50], 2016; Peredo-Lovillo et al. [51], 2020
Consume fermented foods	Yogurt, kefir, sauerkraut, kimchi, miso, kombucha, pickles	Fermented foods contain probiotics that introduce beneficial bacteria to the gut, improving microbial balance and digestion.	Enhances GM, boosts immunity, and may help lower cholesterol and blood pressure.	Beena Divya et al. [52], 2012; Parvez et al. [53], 2006; Dimidi et al. [54], 2019; Dahiya and Nigam [55], 2022

Table 2. Outlines dietary strategies to improve gut health and metabolism (*continued*)

Dietary strategy	Food sources	Mechanisms of action	Impact on metabolic syndrome	References
Polyphenol-rich foods	Berries, apples, dark chocolate, green tea, olive oil, red wine, nuts (e.g., almonds, walnuts)	Polyphenols support the growth of beneficial bacteria and help reduce the growth of harmful bacteria, thereby promoting anti-inflammatory effects.	Reduces oxidative stress, supports heart health, and improves lipid profiles, thereby reducing the risk of metabolic syndrome.	Wang et al. [56], 2022
Consume omega-3 fatty acids	Fatty fish (e.g., salmon, mackerel), chia seeds, flaxseeds, walnuts	Omega-3s promote the growth of anti-inflammatory gut bacteria and help regulate gut function.	Reduces systemic inflammation, supports better lipid metabolism, and improves insulin sensitivity.	Barbalho et al. [57], 2016
Processed foods & added sugars	Refined sugars, sugary drinks, processed snacks, fast food	High consumption of processed foods and added sugars disrupts GM and promotes harmful bacteria, leading to inflammation and metabolic disturbances.	Reduces the risk of obesity, insulin resistance, and dyslipidemia associated with metabolic syndrome.	Garcia et al. [58], 2022; Miclotte and Van de Wiele [39], 2020
Moderate animal protein & fat	Red meat, processed meats, fatty cuts of meat	Excessive animal protein and fat intake can lead to an imbalance in GM, promoting inflammation and metabolic dysfunction.	Helps prevent weight gain, insulin resistance, and dyslipidemia by supporting a balanced gut microbiome.	Zhao et al. [59], 2019; Ma et al. [60], 2017
Increase plant-based foods	Vegetables, fruits, whole grains, legumes, nuts, seeds	Plant-based foods are rich in fiber, antioxidants, and polyphenols that nurture a diverse microbiome and enhance overall gut health.	Supports weight management, improves insulin sensitivity, and reduces inflammation, all key to preventing metabolic syndrome.	Bulsiewicz [61], 2020; Daniel et al. [62], 2023
Include resistant starch	Cooked and cooled potatoes, pasta, rice, green bananas, legumes	Resistant starch feeds beneficial gut bacteria, enhancing SCFA production and gut health.	Improves insulin sensitivity, supports healthy blood sugar levels, and aids in weight management.	Regassa and Nyachoti [63], 2018; Keenan et al. [64], 2015
Hydrate well	Water, herbal teas, soups	Proper hydration supports digestion and gut motility, maintaining GM balance.	Promotes healthy digestion, enhances nutrient absorption, and helps regulate metabolic processes.	Mach and Fuster-Botella [65], 2017; Zhang et al. [66], 2021
Avoid excessive alcohol	N/A (moderation or avoidance of alcohol)	Excessive alcohol disrupts GM and increases gut permeability, leading to inflammation and metabolic disturbances.	Reduces risk of liver disease, insulin resistance, and inflammation associated with metabolic syndrome.	Bishehsari et al. [67], 2017; Bajaj [68], 2019
Diverse diet	A variety of fruits, vegetables, whole grains, legumes, nuts, seeds, and lean proteins	A diverse diet promotes the growth of a diverse microbiome, which is linked to better overall health and metabolic function.	Enhances metabolic flexibility, reduces inflammation, and supports weight management, all crucial for managing metabolic syndrome.	Hills et al. [69], 2019; Ross et al. [70], 2024
Use bone broth	Bone broth, collagen-rich foods	Bone broth supports gut barrier integrity and reduces gut permeability, helping maintain a healthy microbiome.	Supports gut health and immune function, improving overall metabolic markers.	Cooney et al. [71], 2021; Skinner [72], 2017

GM: gut microbiota; SCFAs: short-chain fatty acids

Increase fiber intake

Dietary fiber, particularly prebiotics, serves as food for beneficial gut bacteria. The microbiota ferments prebiotic fibers in fruits, vegetables, whole grains, legumes, and certain tubers to produce SCFAs. High-fiber diets promote a healthy microbiome composition and have been shown to improve insulin sensitivity, reduce inflammation, and lower blood cholesterol levels. Foods rich in soluble fiber, such as oats, barley, and legumes, are particularly effective in modulating blood sugar and cholesterol levels, key components of metabolic syndrome [73, 74].

Incorporate fermented foods

Fermented foods, such as yogurt, kefir, kimchi, sauerkraut, and miso, are rich in probiotics—live microorganisms that confer health benefits when consumed in adequate amounts. Probiotics have been shown to improve gut microbiome diversity and modulate the immune system, which can help alleviate the systemic inflammation associated with metabolic syndrome. Regular consumption of fermented foods may help restore a healthy gut microbiome, enhance SCFA production, and improve insulin sensitivity, which is crucial for preventing and managing metabolic syndrome [75–77].

Reduce intake of processed foods and sugars

Processed foods, mainly those high in refined sugars and unhealthy fats, contribute to gut dysbiosis and inflammation. High-sugar diets promote the growth of pathogenic bacteria and fungi in the gut, leading to an imbalance that exacerbates insulin resistance and metabolic dysfunction. Reducing the intake of processed foods, sugary beverages, and trans fats can help restore gut health and improve metabolic parameters. Instead, a diet rich in whole, unprocessed foods—especially plant-based—supports a more diverse and beneficial microbiome [78, 79].

Increase healthy fats

Monounsaturated and polyunsaturated fats in foods such as olive oil, avocados, fatty fish, and nuts have anti-inflammatory properties that can improve metabolic health. These healthy fats help modulate the gut microbiome, supporting beneficial bacteria growth while reducing harmful bacteria's proliferation. Omega-3 fatty acids, in particular, have been shown to improve insulin sensitivity and reduce inflammation, which are key factors in managing metabolic syndrome [80].

Postbiotics and their role in metabolic health

While probiotics are live microorganisms that confer health benefits, postbiotics are the bioactive compounds produced by probiotics during fermentation. These include SCFAs, peptides, enzymes, and other metabolites that positively impact health. Postbiotics are gaining attention for their potential therapeutic applications in managing metabolic syndrome.

Research has shown that postbiotics derived from fermented foods and probiotics can enhance insulin sensitivity, reduce inflammation, and support the gut barrier function. Butyrate, one of the most studied postbiotics, has been shown to have potent anti-inflammatory and insulin-sensitizing effects. Butyrate, produced by the fermentation of fiber, helps regulate the expression of genes involved in glucose metabolism and fatty acid oxidation. By increasing butyrate production, individuals with metabolic syndrome can potentially experience improvements in their metabolic health [81, 82].

In addition to butyrate, other postbiotics such as lactate, propionate, and acetate also play crucial roles in regulating metabolism. These metabolites help regulate the immune response, improve gut barrier integrity, and modulate lipid metabolism, all essential for managing metabolic syndrome [83].

Innovative supplements for metabolic syndrome

Probiotics, berberine, and curcumin are among the supplements that are becoming more and more well-liked due to their possible advantages in controlling metabolic health. Probiotics, such as *Bifidobacterium* and *Lactobacillus*, help balance the GM, increase insulin sensitivity, and lower inflammation, all of which contribute to weight management. AMP-activated protein kinase (AMPK) is triggered by berberine, which is obtained from Berberis species [84, 85]. This improves blood sugar and lipid profiles by enhancing glucose metabolism and lipid control. Turmeric's main ingredient, curcumin, decreases oxidative stress, has strong anti-inflammatory properties, and supports metabolic pathways related to fat metabolism and insulin resistance [86]. Omega-3 fatty acids from fish or algae oil improve lipid profiles, lower inflammation, and strengthen the heart [87]. Known for its antioxidant qualities, alpha-lipoic acid (ALA) promotes weight management, lowers oxidative stress, and improves glucose absorption. By improving glucose absorption, cinnamon extract's polyphenols reduce inflammation, lower blood sugar, and increase insulin sensitivity [88]. Chromium picolinate helps to normalize blood sugar levels and improves the action of insulin. Magnesium helps endothelial function, controls glucose metabolism, and enhances insulin sensitivity. It can be found in forms such as magnesium citrate [89, 90]. Coenzyme Q10 (CoQ10) lowers oxidative stress, increases cellular energy generation, and guards against cardiovascular disease. Due to its involvement in calcium metabolism, vitamin D enhances insulin sensitivity and boosts immunity; deficits are associated with metabolic dysfunction. In order to help with weight management, *L*-carnitine facilitates fat metabolism by delivering fatty acids into mitochondria [91, 92]. Psyllium husk and other fiber supplements help people lose weight by promoting satiety, controlling blood sugar, and enhancing intestinal health [93]. Because it contains epigallocatechin gallate (EGCG), green tea extract promotes weight loss, increases fat oxidation, and improves insulin sensitivity [94]. The antioxidant and anti-inflammatory properties of resveratrol, which is present in grapes, enhance insulin sensitivity and endothelial function [95]. Because it contains sulfur and allicin components, garlic extract helps people lose weight, improve their cholesterol, and lower their blood pressure [96]. Finally, by regulating cortisol levels, decreasing stress-induced fat storage, and improving insulin sensitivity, the adaptogen ashwagandha promotes overall metabolic health and aids in stress management [97].

The potential of *Saccharomyces boulardii* to enhance gut health and decrease inflammation—two major contributors to metabolic dysfunction—has made it a viable novel supplement in the treatment of metabolic syndrome [98]. It has been demonstrated that this probiotic yeast alters the GM, improving the ratio of good bacteria to bad bacteria and decreasing the number of harmful microorganisms. This may help mitigate some of the systemic problems linked to metabolic syndrome, including obesity and insulin resistance. In addition to improving intestinal permeability and reducing signs of chronic low-grade inflammation, a characteristic of metabolic syndrome, *S. boulardii*' anti-inflammatory qualities may also limit the transfer of toxins that could worsen metabolic abnormalities [99, 100]. Moreover, studies indicate that *S. boulardii* may contribute to liver function support, blood glucose reduction, and improved lipid profiles. Early research suggests that *S. boulardii* is a novel, supplemental supplement for those with metabolic syndrome, while additional research is needed to completely grasp its therapeutic potential [101, 102].

Alongside dietary changes and postbiotics, innovative supplements are gaining popularity as adjuncts to managing metabolic syndrome. These supplements target specific aspects of metabolism, gut health, and inflammation, as shown in Table 3.

Table 3. Innovative supplements complement dietary changes to manage metabolic syndrome effectively

Supplement	Key ingredients	Potential benefits	Mechanisms of action	References
Probiotics	*Lactobacillus*, *Bifidobacterium*, *Saccharomyces*	Improves gut microbiome health, enhances insulin sensitivity, reduces inflammation, aids weight management	Probiotics restore GM balance, enhance SCFA production, and reduce systemic inflammation, which improves metabolic markers like blood sugar and lipid profiles.	Dugoua et al. [103], 2009; Igbafe et al. [104], 2020; Yang et al. [105], 2022
Berberine	Berberine extract (from *Berberis* species)	Improves insulin sensitivity, reduces blood sugar and lipids, supports weight loss	Berberine activates AMP-activated protein kinase (AMPK), improving insulin sensitivity, glucose metabolism, and lipid regulation.	Pirillo and Catapano [106], 2015; Xu et al. [107], 2021
Curcumin	Curcumin (from turmeric)	Reduces inflammation, improves insulin sensitivity, supports liver health	Curcumin has potent anti-inflammatory effects, reduces oxidative stress, and modulates metabolic pathways linked to insulin resistance and fat metabolism.	Shao et al. [108], 2012; Navekar et al. [109], 2017
Omega-3 fatty acids	Fish oil (EPA, DHA), algal oil	Reduces inflammation, improves blood lipids, supports cardiovascular health	Omega-3 fatty acids reduce systemic inflammation, lower triglycerides, improve HDL cholesterol, and enhance insulin sensitivity.	Ellulu et al. [110], 2015; Santos et al. [111], 2020

Table 3. Innovative supplements complement dietary changes to manage metabolic syndrome effectively (*continued*)

Supplement	Key ingredients	Potential benefits	Mechanisms of action	References
Alpha-lipoic acid (ALA)	ALA	Improves insulin sensitivity, reduces oxidative stress, supports weight management	ALA acts as an antioxidant, reduces oxidative damage, enhances glucose uptake, and improves lipid metabolism, helping to reduce risk factors of metabolic syndrome.	Najafi et al. [112], 2022
Cinnamon extract	Cinnamon polyphenols (*Cinnamomum cassia*)	Lowers blood sugar, improves insulin sensitivity, reduces inflammation	Cinnamon increases insulin receptor sensitivity and enhances glucose uptake in cells, contributing to better blood sugar control.	Tangvarasittichai et al. [113], 2015; Mollazadeh and Hosseinzadeh [114], 2016; Shang et al. [115], 2021
Chromium picolinate	Chromium (elemental form)	Improves blood glucose regulation, enhances insulin sensitivity	Chromium plays a role in enhancing insulin action, improving glucose uptake, and stabilizing blood sugar levels.	Zhao et al. [116], 2022
Magnesium	Magnesium citrate, magnesium glycinate	Improves insulin sensitivity, supports blood pressure regulation, aids sleep	Magnesium helps regulate glucose metabolism, supports endothelial function, and improves insulin sensitivity, which is crucial for metabolic syndrome management.	Cloyd [117], 2023; Fatima et al. [118], 2024
Coenzyme Q10 (CoQ10)	CoQ10 (ubiquinone)	Supports mitochondrial function, reduces oxidative stress, improves heart health	CoQ10 boosts cellular energy production, reduces inflammation, and protects against oxidative damage, improving overall metabolic function and cardiovascular health.	Gutierrez-Mariscal et al. [119], 2020; Ochoa et al. [120], 2005
Vitamin D	Vitamin D3 (cholecalciferol)	Improves insulin sensitivity, supports immune function, regulates blood pressure	Vitamin D plays a role in calcium metabolism, insulin sensitivity, and immune function, while deficiencies are linked to metabolic dysfunction and increased risk of diabetes.	Garbossa and Folli [121], 2017; Szymczak-Pajor et al. [122], 2020
L-Carnitine	*L*-Carnitine (from animal or plant sources)	Supports fat metabolism, improves exercise performance, aids in weight loss	*L*-Carnitine transports fatty acids into mitochondria for energy production, aiding fat oxidation and helping with weight management.	Prakash et al. [123], 2023
Fiber supplements	Psyllium husk, inulin, glucomannan	Reduces blood sugar, improves gut health, supports weight loss	Fiber supplements improve gut motility, help regulate blood sugar levels, and promote satiety, which aids in weight loss and reduces risk factors for metabolic syndrome.	Pokushalov et al. [124], 2024; Gamage et al. [125], 2018
Green tea extract	EGCG	Increases fat oxidation, improves insulin sensitivity, supports weight loss	EGCG in green tea enhances thermogenesis and fat oxidation while also increasing insulin sensitivity, which aids in reducing body fat and improving metabolic health.	Most et al. [126], 2016; Kapoor et al. [127], 2017
Resveratrol	Resveratrol (from grapes, red wine)	Reduces inflammation, improves insulin sensitivity, supports cardiovascular health	Resveratrol acts as an antioxidant and anti-inflammatory, improving endothelial function, reducing oxidative stress, and enhancing insulin sensitivity.	Castaldo et al. [128], 2019; Barber et al. [129], 2022
Garlic extract	Allicin, sulfur compounds	Reduces blood pressure, improves cholesterol levels, supports weight loss	Garlic extract possesses anti-inflammatory properties, reduces blood pressure, and enhances lipid profiles, thereby contributing to improved metabolic health.	Salehi et al. [130], 2019; Piragine et al. [131], 2022
Ashwagandha	Withanolides (from *Withania somnifera*)	Reduces stress, improves insulin sensitivity, supports	Ashwagandha modulates cortisol levels, reducing stress-related fat accumulation and	Quinones et al. [132], 2025; Rakha et al. [133], 2023

Table 3. Innovative supplements complement dietary changes to manage metabolic syndrome effectively (*continued*)

Supplement	Key ingredients	Potential benefits	Mechanisms of action	References
		weight management	inflammation while improving glucose metabolism and insulin sensitivity.	

EGCG: epigallocatechin gallate; GM: gut microbiota; SCFA: short-chain fatty acid

Probiotic and prebiotic supplements

Supplements can be a valuable tool for individuals who cannot obtain sufficient probiotics and prebiotics from their diet. Probiotic supplements containing specific strains of beneficial bacteria have been shown to improve gut microbiome diversity, reduce inflammation, and enhance insulin sensitivity. Prebiotic supplements containing fibers like inulin and fructooligosaccharides can help promote the growth of beneficial bacteria and support the production of SCFAs. When combined, probiotics and prebiotics—often called synbiotics—offer synergistic benefits for metabolic health [83, 134].

Omega-3 fatty acids

Omega-3 supplements, derived from fish oil or algae, have been extensively studied for their anti-inflammatory and metabolic benefits. Omega-3 fatty acids have been shown to improve insulin sensitivity, lower triglyceride levels, and reduce inflammation—key factors in managing metabolic syndrome. Regular supplementation with omega-3 fatty acids can help restore balance to the gut microbiome and support overall metabolic health [135].

Polyphenols and antioxidants

Polyphenols, found in foods such as berries, green tea, and dark chocolate, are potent antioxidants that can help reduce oxidative stress and inflammation. Recent studies suggest that polyphenols may also have prebiotic-like effects, promoting the growth of beneficial gut bacteria. Supplements containing polyphenol-rich extracts, such as resveratrol and curcumin, may help improve insulin sensitivity and reduce the risk of developing metabolic syndrome [136].

Berberine

Berberine, a plant-derived compound, has garnered attention for its ability to improve insulin sensitivity, regulate blood sugar levels, and reduce cholesterol levels. Several studies have demonstrated its potential to combat metabolic syndrome by modulating gut microbiome composition and improving systemic inflammation. As a supplement, berberine has shown promise as a natural adjunct to conventional treatments for metabolic syndrome [137, 138].

Gaps and future directions

Despite the growing interest in the gut microbiome's role in health, several limitations hinder progress, including the heterogeneity in microbiome studies and the reliance on animal models, which often fail to translate to human health outcomes directly. To overcome these challenges, future research should focus on human-based studies, greater standardization in methodologies, and the exploration of personalized nutrition that tailors dietary recommendations based on individual microbiome profiles. Additionally, long-term randomized controlled trials (RCTs) on the efficacy of postbiotics and other microbiome-targeted therapies, such as fecal microbiota transplantation, are needed to establish their lasting impact on health. While microbiome-related interventions, including dietary strategies and supplements, hold significant promise, it is essential to acknowledge the gaps in current evidence and avoid overstatements about their potential. Future clinical applications must be guided by robust clinical trials that address individual variation and assess long-term safety and effectiveness, ultimately leading to personalized therapies that integrate dietary strategies, supplements, and microbiome modulation to enhance health outcomes.

Conclusions

Metabolic syndrome is a complex and multifactorial disorder, but emerging research highlights the critical role of gut health in its prevention and management. Dietary strategies, postbiotics, and supplements may support metabolic health, though evidence gaps remain. By adopting a diet rich in fiber, fermented foods, and healthy fats, individuals can support a diverse and beneficial gut microbiome that is pivotal in regulating metabolism. Coupled with the use of postbiotics and supplements, such as probiotics, omega-3 fatty acids, and polyphenols, these dietary strategies offer a comprehensive approach to managing metabolic syndrome and enhancing long-term health outcomes. As we continue to uncover the intricate connections between the gut microbiome and metabolic health, these innovative interventions will become increasingly important in combating metabolic syndrome. Finally, clinical trials should guide personalized therapies, integrating diet, supplements, and microbiomes.

Abbreviations

ALA: alpha-lipoic acid

CoQ10: coenzyme Q10

EGCG: epigallocatechin gallate

GM: gut microbiota

NAFLD: non-alcoholic fatty liver disease

SCFAs: short-chain fatty acids

Declarations

Author contributions

SC: Conceptualization, Writing—original draft, Writing—review & editing, Supervision. VD: Conceptualization, Writing—original draft, Writing—review & editing, Investigation. AS: Conceptualization, Writing—original draft, Writing—review & editing, Investigation. RPP: Conceptualization, Writing—original draft, Writing—review & editing, Validation, Supervision.

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The authors declare that they have no conflicts of interest.

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