

Exploring the Role of Yoga in Modulating Gut Microbiota in Obesity: A Narrative Review of Mechanistic Insights and Integrative Potential

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ABSTRACT

Obesity has emerged as a major global public health concern, with its prevalence rising sharply in recent decades. Increasing evidence links gut dysbiosis with obesity and its associated complications. Factors such as chronic stress, neuroendocrine dysregulation, and sedentary behavior contribute significantly to alterations in gut microbiota. Yoga, as a holistic mind-body practice, may help counter these influences by reducing stress, regulating autonomic nervous system function, and potentially modulating the gut microbiome. This review explores the potential role of Yoga in influencing gut microbiota in individuals with obesity and outlines the plausible mechanisms through which it may confer metabolic benefits. A comprehensive literature search was conducted across PubMed, Google Scholar, PsycINFO, Embase, and Web of Science, focusing on studies from the past two decades. A total of 100 peer-reviewed articles, including both human and animal studies, were selected based on their relevance to gut health, obesity, and Yoga-based interventions. While direct studies remain limited, available evidence suggests that Yoga may impact gut microbiota through stress reduction, modulation of the hypothalamic-pituitary-adrenal (HPA) axis, regulation of cytokines, and enhancement of vagal tone. These effects may collectively reduce inflammation and improve metabolic function. This review proposes a theoretical framework in which Yoga could serve as a supportive, non-pharmacological strategy to help restore gut microbial balance in obesity. Although preliminary findings are encouraging, more rigorous clinical and mechanistic research is needed to validate these effects and establish the role of Yoga in microbiome-targeted obesity interventions.

KEYWORDS: Yoga, Gut microbiota, Obesity, Gut Dysbiosis, Mind body therapy.

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INTRODUCTION

Obesity has emerged as a major global health crisis, with its prevalence rising at an alarming pace across the world over recent decades.^[1] In 2022, around 2.5 billion adults globally were classified as overweight, and approximately 890 million of them were living with obesity.^[2] Globally, the prevalence of obesity among adults has more than doubled since 1990, while the rate among adolescents has increased approximately fourfold.^[3] That same year, one in eight people across the globe were living with obesity, underscoring the widespread and growing nature of this public health challenge.^[4] Beyond its impact on physical appearance, obesity is closely linked to a range of serious metabolic disorders,^[5] including type 2 diabetes^[6], nonalcoholic fatty liver disease (NAFLD),^[7] cardiovascular disease^[8], and certain cancers.^[9] The major risk factors associated with obesity across multiple body systems are illustrated in Figure 1. The condition also played a critical role in the severity of COVID-19 outcomes, where individuals with obesity were found to have a higher risk of hospitalization, mechanical ventilation, and mortality.^[10] While excessive caloric intake and sedentary lifestyles are primary contributors to the development of obesity, growing research highlights the complexity of its underlying mechanisms.^[11] In particular, the gut microbiota—a vast and dynamic community of trillions of microorganisms residing in the human gastrointestinal tract—has drawn attention for its role in regulating metabolism, immune function, and energy homeostasis.^[12] Dysbiosis, or an imbalance in gut microbial composition, has been increasingly associated with obesity and related metabolic disturbances.^[13] It contributes to chronic low-grade inflammation, altered lipid metabolism, insulin resistance, and disruptions in appetite regulation.^[14]

Diet remains one of the most influential factors shaping gut microbiota composition, but other lifestyle elements such as stress, sleep, and physical activity also play significant roles.^[15] In recent years, Yoga has gained popularity not only as a form of physical exercise but also as a holistic therapeutic intervention that combines movement, breath regulation, and mindfulness.^[16] Emerging evidence suggests that Yoga can positively influence metabolic health through stress reduction, improved autonomic

nervous system balance, and anti-inflammatory effects-factors that are also known to impact gut microbiota.^[17] Given the limited but growing body of literature connecting Yoga practice to gut microbiome modulation, this review aims to explore the potential mechanisms through which Yoga therapy might influence gut microbiota in the context of obesity. By integrating insights from microbiology, neuroendocrinology, and integrative medicine, this paper seeks to bridge conceptual gaps and propose a framework for understanding Yoga as a possible adjunctive strategy for restoring microbial balance and addressing obesity-related metabolic dysfunctions.

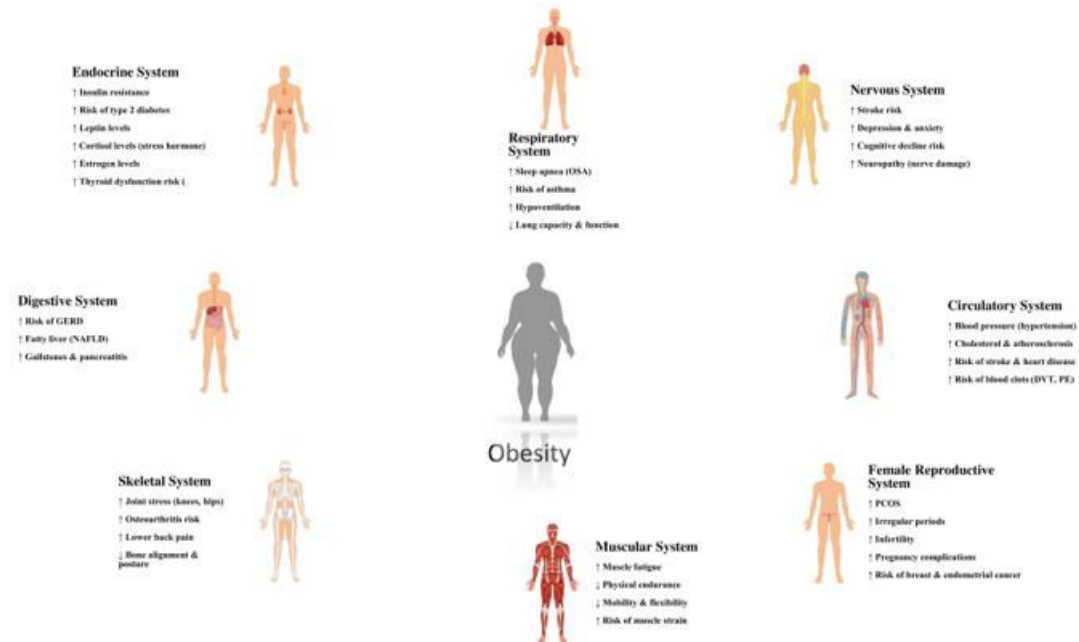


Figure 1. Major risk factors associated with obesity across multiple body systems.

METHODOLOGY

2.1. Data Sources and Search Strategy

This narrative review was informed by a structured literature search guided by elements of the PRISMA framework to ensure methodological clarity and transparency. We systematically searched five major databases-PubMed, Google Scholar, PsycINFO, Embase, and Web of Science-for studies published between 2004 and 2024. The search strategy combined keywords and MeSH terms related to “Yoga,” “obesity,” “gut microbiota,” “stress,” “inflammation,” “immune cells,” and “pro-inflammatory cytokines.” The search was designed to capture a comprehensive range of literature relevant to the effects of Yoga on gut microbial health in the context of obesity, considering both direct and indirect pathways including neuroendocrine and immune system interactions.

2.2. Eligibility Criteria and Study Selection

We included both human and animal studies that explored the relationship between Yoga and changes in gut microbiota, obesity-related metabolic parameters, stress physiology, or immune modulation. Peer-reviewed articles available in English were considered eligible. We excluded non-English publications and reports without full-text availability. Studies were first screened by title and abstract, followed by full-text review for those that met the inclusion criteria. The initial screening was performed independently by two reviewers. Discrepancies during the selection process were resolved through consensus.

2.3. Data Extraction and Synthesis

From each selected study, we extracted relevant data including the type of intervention, characteristics of study populations or models (human or animal), key findings related to gut microbial changes, inflammatory markers, and obesity-related outcomes. In total, 100 studies were included in the final synthesis. Given the narrative scope and variability in study design, populations, and outcomes, data were synthesized qualitatively rather than statistically. This integrative approach aims to construct a conceptual framework that positions Yoga as a potential adjunctive intervention for addressing obesity-related gut dysbiosis.

LITERATURE REVIEW AND MECHANISTIC INSIGHTS

3.1 Gut Microbiota and Its Role in Obesity

The human gastrointestinal (GI) tract serves as one of the most extensive interfaces between the body and the external environment, encompassing an estimated surface area of 250 to 400 square meters.^[18] Throughout a person's lifetime, the gut is exposed to nearly 60 tonnes of food, along with a continuous influx of microorganisms, antigens, and environmental compounds that challenge its structural and immune integrity.^[19] Within this complex ecosystem resides the gut microbiota-a dense community of bacteria, archaea, and eukaryotic microorganisms that has co-evolved with the human host to establish a dynamic, symbiotic relationship vital to health.^[20,21] Estimates suggest that the number of microbial cells in the human gut is roughly equivalent to the number of human cells in the body^[22], while the collective genome of these microbes, referred to as the

microbiome, contains over 100 times more genes than the human genome.^[23] Due to its extensive influence on metabolic, immune, and neurological functions, the gut microbiota is increasingly recognized as a critical “second genome” or “new organ.”^[24,25] Weighing nearly 1 kg in total, this microbial population plays a fundamental role in nutrient absorption, energy regulation, immune development, and defense against pathogens.^[26]

A growing body of research has highlighted the influence of gut microbiota composition on body weight and metabolic health shown in table 1.

3.2 Mechanisms Through Which Gut Microbiota Influence Obesity

3.2.1 Microbial Composition Shifts and Energy Harvest

Multiple studies have shown that the gut microbiota composition in obese individuals differs markedly from that of lean individuals, particularly in the relative proportions of the Firmicutes and Bacteroidetes phyla.^[27,28] Obesity is frequently associated with an increased Firmicutes-to-Bacteroidetes ratio, a pattern thought to favor enhanced energy extraction from indigestible polysaccharides, contributing to increased caloric availability and fat storage. In addition, high-fat diets have been shown to reduce the abundance of beneficial microbes such as Bacteroides^[29], Eubacterium rectale^[30], and Bifidobacterium^[31], while fostering the proliferation of microbial communities associated with inflammation and metabolic disturbances.^[32] Beyond these dominant phyla, other microbial taxa also play pivotal roles. Archaea such as Methanobrevibacter smithii have been found to enhance fermentation efficiency by consuming hydrogen, thereby promoting the breakdown of dietary substrates and increasing energy harvest.^[33] Similarly, shifts in the populations of Actinobacteria, Proteobacteria, and Verrucomicrobia may influence microbial diversity, fermentation pathways, and host metabolic regulation.^[34]

3.2.2 Energy Homeostasis Disruption

Changes in microbial composition do not merely correlate with obesity but actively contribute to it by altering host energy homeostasis. Certain microbial communities possess an enhanced ability to harvest energy from food, increasing the availability of absorbable calories to the host.^[35,36] For example, dysbiotic microbiota have been linked to an expansion of Desulfovibrio and a concurrent reduction in Clostridial species, changes that up regulate host genes such as CD36 involved in fatty acid uptake and lipid absorption.^[37] This leads to an increased deposition of energy as fat. In addition, the gut microbiota ferments dietary fibers into short-chain fatty acids (SCFAs), including acetate and butyrate. Although SCFAs generally support colonic health and host metabolism, excessive SCFA production especially in a low-diversity microbiota can paradoxically contribute to energy surplus and fat accumulation.^[38,39]

3.2.3 Central Appetite and Feeding Behavior

Gut microbiota also influence appetite regulation through the gut-brain axis. A decrease in microbial diversity has been linked to diminished secretion of satiety-related hormones, including peptide YY and glucagon-like peptide-1 (GLP-1), which play crucial roles in regulating appetite and conveying signals of fullness to the brain.^[40] Such dysregulation leads to increased food intake and poor satiety. In animal models, colonization with beneficial microbes like Lactobacillus paracasei has been shown to increase the expression of angiopoietin-like protein 4 (ANGPTL4), which inhibits lipoprotein lipase (LPL), thereby reducing fat storage and possibly influencing feeding behavior.^[41,42]

3.2.4 Lipid Synthesis and Storage

Microbial signals play a central role in lipid metabolism, including the regulation of lipid synthesis and storage. In germ-free mice colonized with microbiota derived from obese donors, there is a marked up regulation of lipogenic genes, including carbohydrate-responsive element-binding protein (ChREBP) and sterol regulatory element-binding protein-1 (SREBP-1), leading to enhanced triglyceride accumulation in both hepatic and adipose tissues.^[43,44] These effects are mediated in part by suppression of fasting-induced adipose factor (Fiaf), a protein known to regulate lipid metabolism.^[45] In parallel, gut microbiota can also influence lipid transport and secretion via direct signaling with enterocytes. For instance, commensal bacteria like Lactobacillus paracasei have been shown to modulate lipid trafficking within the intestinal epithelium.

3.2.5 Chronic Inflammation

Chronic low-grade inflammation is a characteristic feature of obesity and represents a central pathway through which the gut microbiota contributes to the progression of metabolic disorders. Dysbiosis, particularly a reduction in butyrate-producing bacteria such as Ruminococcaceae and Lachnospiraceae, weakens the intestinal barrier and promotes systemic exposure to microbial-derived endotoxins like lipopolysaccharide (LPS).^[46,47] Butyrate normally acts to enhance mitochondrial activity, tighten epithelial junctions, and suppress inflammatory gene expression.^[48-50] When these bacteria decline, circulating LPS increases, triggering inflammatory cascades that contribute to insulin resistance and adipose dysfunction. Specific genera like Veillonella, enriched in some obese individuals, can produce elevated levels of LPS, aggravating the inflammatory state.

3.2.6 Circadian Rhythm Disruption and Metabolic Dysregulation

Recent studies highlight the interplay between the gut microbiota and the host circadian system. Disruptions in microbial composition can interfere with the diurnal oscillation of bile acid metabolism, leading to misregulation of host genes responsible for lipid handling and energy storage.^[51-53] These circadian misalignments may impair the synchronization of metabolic processes, promoting weight gain and metabolic dysfunction even in the absence of excess caloric intake.

Altogether, these mechanisms show that the gut microbiota plays a powerful and active role in regulating key metabolic functions such as how we extract energy from food, control appetite, store fat, manage inflammation, and maintain our body's internal clock. This complex, ever-changing relationship between gut microbes and the body is deeply involved in the development of obesity.

Title	Year	Study Type	Result
The role of Gut Microbiota in the development of obesity and Diabetes ^[28]	2016	Review	Gut dysbiosis, an imbalance in the gut microbiome, is associated with the development of obesity and type 2 diabetes by contributing to metabolic dysfunction and chronic inflammation
Obesity alters gut microbial ecology ^[54]	2006	Experimental (Mouse Study)	The study found that obese mice had an altered gut microbiota composition, with a higher ratio of Firmicutes to Bacteroidetes. These shifts may influence obesity by altering the microbiome's role in digesting and absorbing dietary energy.
The Firmicutes/Bacteroidetes ratio of the human microbiota changes with age ^[55]	2009	Observational Study	This study observed that the ratio of Firmicutes to Bacteroidetes changes with age in humans. The ratio's fluctuation may be linked to energy balance and could contribute to an individual's risk of obesity over time.
An obesity-associated gut microbiome with increased capacity for energy harvest ^[56]	2006	Experimental (Human & Mouse)	Study have demonstrated that the gut microbiome of obese individuals possesses an elevated capacity to extract energy from food. This enhanced energy harvest from the diet contributes to increased fat accumulation. contributing to obesity.
Changes in gut microbiota control inflammation in obese mice via GLP-2 improvement of gut permeability ^[57]	2009	Experimental (Mouse Study)	The study highlighted that changes in the gut microbiota can reduce systemic inflammation and improve gut barrier function. These changes, driven by certain gut bacteria, may be beneficial in managing obesity-related inflammation and metabolic disruptions.
The gut microbiota and its relationship to diet and obesity: New insights ^[58]	2012	Review	The paper discusses how the gut microbiota is influenced by diet and how these changes can, in turn, impact metabolism. Certain dietary patterns can lead to shifts in gut bacteria that either increase or decrease the risk of obesity, suggesting that microbiota management could be a strategy for preventing obesity.

Table: 1 Studies showing the Gut dysbiosis associated with Obesity

3.3 Yoga

Yoga, an ancient mind-body practice that integrates Asana (physical postures), Pranayama (breathing techniques) and Dhyana (meditation) has emerged as a promising non-pharmacological intervention for managing a wide range of physical and psychological conditions.^[59,60] From a yogic standpoint, obesity and metabolic disorders are seen not only as physical conditions but as manifestations of an imbalance within the body's systems^[61,62], often exacerbated by mental stress, poor digestion, and emotional turbulence.^[63] In this context, Yoga provides a comprehensive approach to restore harmony.^[64] Asanas are designed to activate and strengthen the internal organs,^[65] promote circulation, and stimulate the digestive system, thus helping to regulate metabolism and reduce excess body fat.^[66-68] Pranayama, the practice of conscious breathing, directly influences the autonomic nervous system and stress response, helping to lower cortisol levels, a hormone associated with weight gain and fat accumulation.^[69-71] By fostering mindfulness and reducing emotional eating patterns,^[72] Yoga can help to address the psychological aspects of obesity, which are often linked to stress, anxiety, and depression.^[73, 74] Moreover, meditation and mindfulness has profound effects on the gut-brain axis, a crucial link in metabolic health.^[75] Yogic practices encourage awareness of body sensations,^[76] breathing rhythms,^[77] and thoughts^[78], promoting a state of self-awareness^[79] that can influence eating habits, reduce impulsivity, and enhance overall well-being.^[80,81] In terms of metabolic regulation, certain Yogic breathing techniques, such as Ujjayi Pranayama, are believed to increase oxygen flow to the cells, thereby optimizing energy utilization and detoxification processes.^[82, 83] Through these practices, Yoga addresses the mind-body connection, offering a path toward sustainable weight management and overall metabolic balance. Overall in the context of obesity and metabolic disorders, Yoga offers a multi-dimensional therapeutic strategy that can influence stress physiology, autonomic function, systemic inflammation, and metabolic regulation-factors that are increasingly recognized as critical modulators of gut microbiota composition.

3.3.1: Yoga and Stress Regulation via the HPA Axis and Autonomic Nervous System

Chronic psychological stress is a well-established contributor to metabolic dysfunction and obesity,^[84-86] largely mediated through dysregulation of the hypothalamic–pituitary–adrenal (HPA) axis and sympathetic over activation.^[87, 88] Persistent activation of this stress-response system leads to elevated cortisol levels, disrupted circadian rhythms, increased visceral adiposity, and altered gut microbiota profiles.^[89, 90]

Multiple studies have shown that Yoga significantly reduces perceived stress and enhances stress adaptability. A randomized controlled trial demonstrated that regular Yoga practice improved heart rate variability (HRV) and reduced stress levels among mental health professionals, suggesting enhanced parasympathetic activity.^[91] Similar results were observed in other Yoga interventions that improved stress resilience and autonomic balance in distressed populations.^[92, 93]

The ability of Yoga is to activate the parasympathetic nervous system-the “rest-and-digest” branch of the autonomic nervous system-has been supported by physiological studies. These have reported increased parasympathetic tone and reductions in salivary cortisol following Yoga interventions^[94,95], while others observed improved cardiac vagal modulation in experienced Yoga practitioners. These shifts toward parasympathetic dominance not only promote relaxation but may also enhance gut motility and barrier integrity, creating a more favorable environment for microbial diversity and balance.

3.3.2: Anti-inflammatory Effects of Yoga

Low-grade chronic inflammation is a hallmark of obesity and a key driver of insulin resistance and metabolic disease.^[96] This inflammatory state is closely tied to gut dysbiosis, where microbial imbalances trigger immune activation through mechanisms such as increased lipopolysaccharide (LPS) translocation and cytokine release.^[97]

Emerging evidence suggests that Yoga can modulate inflammatory pathways. Reviews have highlighted how mind-body therapies, including Yoga, downregulate pro-inflammatory gene expression and reduce levels of cytokines like IL-6 and TNF- α . Additional studies demonstrated that Yoga interventions reduce systemic inflammation and oxidative stress in individuals with chronic stress and pain conditions.^[98-99] These effects likely involve modulation of the HPA axis, autonomic nervous system, and epigenetic changes like altered DNA methylation. By reducing inflammation, yoga may restore gut barrier integrity, lower permeability, and support beneficial microbes, helping maintain gut microbiota balance in obesity.

3.3.3: Yoga and Metabolic Health

Beyond its effects on stress and inflammation, Yoga has shown promise in improving metabolic parameters directly associated with obesity. Yoga practices have been associated with reductions in waist circumference, body mass index (BMI), blood pressure, and insulin resistance. One study observed that Yoga increased serum adiponectin-a hormone that enhances insulin sensitivity-and improved multiple components of metabolic syndrome in obese postmenopausal women^[100]. Similarly, a pilot trial found that restorative Yoga significantly improved glucose control, lipid profiles, and markers of cardiovascular risk in adults with metabolic syndrome^[101]

These changes may indirectly improve gut microbiota by reducing glucose and lipids, which limits harmful microbes and supports SCFA-producing bacteria. Higher adiponectin and lower leptin also aid energy balance and gut barrier function.

3.3.4: Hypothetical Model of Yoga Therapy in the Prevention of Gut Microbial Dysbiosis and Obesity

Based on the existing literature, we propose an integrative model that illustrates how Yoga therapy may act through neuroendocrine, microbial, and immune mechanisms to prevent or mitigate obesity and gut dysbiosis. Central to this model is the recognition that chronic stress plays a pivotal role in the development and persistence of obesity, primarily through dysregulation

of the hypothalamic-pituitary-adrenal (HPA) axis. Prolonged activation of this axis leads to elevated cortisol levels, which in turn promote visceral adiposity, insulin resistance, and widespread metabolic dysfunction.^[102] These elevated glucocorticoids also disrupt appetite regulation by interfering with leptin and ghrelin signaling pathways, thereby encouraging hyperphagia and weight gain. Importantly, these stress-induced hormonal changes extend beyond metabolic consequences, exerting profound effects on the gut-brain axis. Increased intestinal permeability and alterations in gut microbial composition hallmarks of gut dysbiosis are strongly linked to this neuroendocrine disturbance.

Numerous studies have demonstrated that obesity is associated with distinct alterations in the composition and diversity of gut microbiota, particularly a higher Firmicutes/Bacteroidetes ratio, reduced short-chain fatty acid (SCFA)-producing bacteria, and increased endotoxin-producing strains.^[103,104] These microbial shifts contribute to low-grade systemic inflammation via lipopolysaccharide (LPS) leakage into circulation- a process termed metabolic endotoxemia- which promotes insulin resistance and fat storage.^[105] Moreover, dysbiosis alters bile acid metabolism, energy harvest, and immune function, thereby reinforcing the obesogenic state.

Yoga, as a mind-body intervention, offers a non-pharmacological approach to preventing and managing obesity by simultaneously targeting neuroendocrine, immune, and microbial pathways. Through the reduction of psychological stress and improved autonomic balance, Yoga attenuates HPA axis overactivity, as evidenced by decreased salivary cortisol levels and enhanced vagal tone.^[106] This neurophysiological shift contributes to improved regulation of gut barrier function and reduced intestinal inflammation, which are critical for maintaining microbial homeostasis. The proposed mechanisms through which Yoga may influence gut dysbiosis in the context of obesity are illustrated in Figure 2. Recent studies have demonstrated the positive impact of Yoga and meditation practices on gut microbiota composition. For example, long-term practitioners of Yoga and meditation exhibited higher abundances of beneficial microbial genera such as *Faecalibacterium*, *Bifidobacterium*, and *Akkermansia*, all of which are associated with anti-inflammatory and anti-obesogenic effects.^[107-109] These microbial changes are hypothesized to result from vagus nerve stimulation, improved mood and behavior, and reduced sympathetic nervous system activity. Meditation retreats have also shown rapid shifts in the gut microbiome toward an anti-inflammatory profile, suggesting that intensive Yoga-based interventions can modulate microbial communities within short periods.^[110,111]

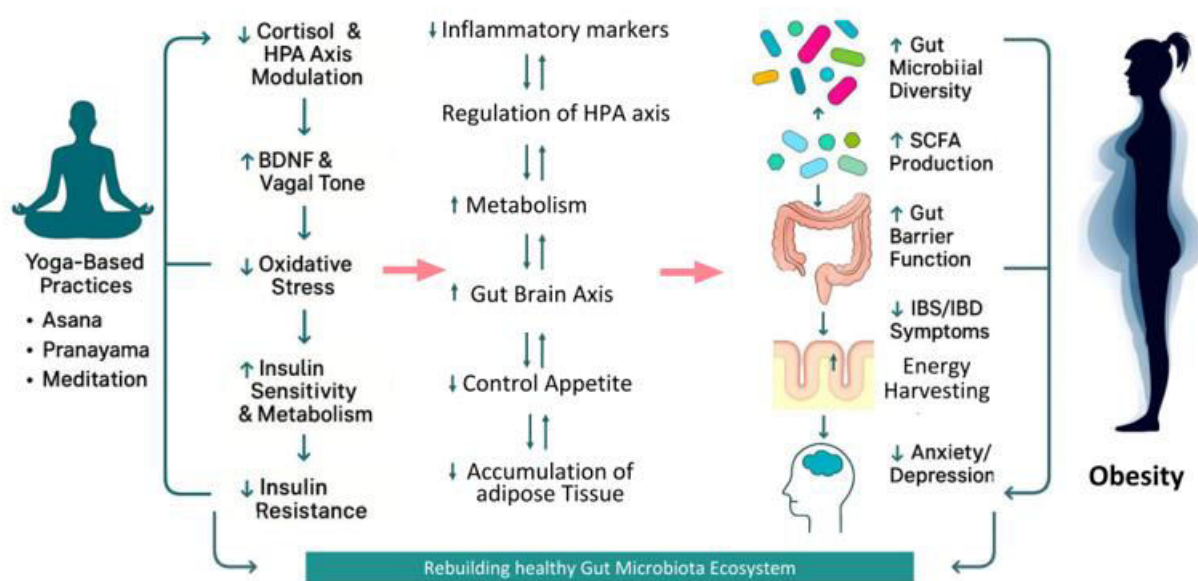


Figure 2. Proposed mechanisms through which Yoga may influence gut dysbiosis in the context of obesity.

Yoga play a major role to improve immune function adds another layer of protection against dysbiosis and obesity. Several studies and meta-analyses have reported increases in key immunological markers such as secretory IgA, CD4+, and NK cell activity in Yoga practitioners.^[112-114] These immune factors are known to influence gut microbial structure by supporting mucosal immunity and restricting the overgrowth of pathogenic bacteria. Furthermore, by lowering systemic inflammatory markers such as CRP, IL-6, and TNF- α , Yoga may interrupt the feedback loop between inflammation, microbiota imbalance, and metabolic dysfunction.^[115]

In addition to stress and immune regulation, Yoga affects the gut-brain axis through behavioral and hormonal pathways. Practices such as cyclic meditation, pranayama, and mindful movement have been associated with improved cognitive control, reduced emotional eating, and better mood regulation-all of which are crucial for sustainable obesity management.^[116] Improved vagal tone via Yoga may also enhance gut motility, serotonin release, and nutrient sensing, all of which influence appetite and energy balance. Collectively, these findings support a hypothetical model in which Yoga therapy exerts multi-level benefits to prevent obesity by restoring gut microbial balance, reducing HPA axis activity, enhancing immune surveillance, and modulating gut-

brain communication.^[117] This integrative approach aligns with the current understanding of obesity as a multifactorial condition involving endocrine, neural, microbial, and psychological dimensions.

DISCUSSION

The growing literature on the gut microbiota–obesity relationship highlights a complex interaction between host metabolism and microbial ecology. Obesity is consistently associated with dysbiosis, marked by a higher Firmicutes/Bacteroidetes ratio and reduced microbial diversity. These changes promote caloric overextraction, chronic inflammation, and weakened gut barrier function—factors that worsen metabolic dysfunction. This review synthesized the mechanisms linking gut microbiota to obesity and explored how Yoga, as a mind-body practice, may influence these pathways.

Mechanistically, microbiota-mediated effects such as SCFA production, immune modulation, and gut-brain axis signaling impact metabolic health. Concurrently, psychophysiological studies show that Yoga improves stress responses and autonomic function, which also affect gut microbial balance. However, most evidence comes from small, observational studies with variable Yoga protocols, limiting causal conclusions and generalizability.

Despite these challenges, the overlap between stress-induced metabolic disturbances and gut dysbiosis supports further study of Yoga's therapeutic potential. Yoga may indirectly promote microbial homeostasis via neuroendocrine and immune pathways, making it a promising tool in integrative metabolic care. Future research should focus on rigorous trials incorporating microbiome analysis, endocrine measures, and clinical outcomes. Personalizing approaches based on individual microbiota profiles may further enhance effectiveness.

CONCLUSION

With obesity as a persistent global health challenge, integrative strategies are urgently needed. This review presents Yoga as a potential multifaceted intervention targeting stress, autonomic regulation, and inflammation—key factors influencing gut microbiota and metabolic health. While current evidence is preliminary, it suggests Yoga could serve as a holistic tool to support microbial balance and metabolic function. Continued interdisciplinary research is vital to validate these connections, uncover mechanisms, and develop effective clinical applications.

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Conflicts of interest

There are no conflicts of interest

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