

Kombucha Tea As a Next-Generation Functional Fermented Beverage: A Comprehensive Review On Antioxidant Bio-Actives, Microbial-Driven Health Benefits, Toxicological Risks, And Regulatory Challenges

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ABSTRACT

Kombucha tea is a traditional fermented beverage that has recently gained global popularity as a functional drink due to its perceived health-promoting properties. Produced through the fermentation of sweetened tea by a symbiotic culture of bacteria and yeast (SCOBY), kombucha is rich in bioactive compounds such as polyphenols, organic acids, vitamins, and microbial metabolites. This comprehensive review critically evaluates current scientific evidence on the antioxidant potential, microbial-mediated health benefits, and safety concerns associated with kombucha tea consumption. Emphasis is placed on the transformation of tea polyphenols during fermentation and their contribution to antioxidant activity, as well as the role of fermentative microbiota in modulating gut health, metabolic functions, and immune responses. Despite promising findings from in vitro and animal studies, human clinical evidence remains limited and inconsistent. Furthermore, emerging reports of toxicity, including metabolic acidosis, hepatotoxicity, microbial contamination, excessive ethanol formation, and heavy metal exposure, highlight the need for cautious consumption and stringent quality control. Regulatory challenges related to standardization, labeling, alcohol limits, and safety assessment are also discussed. This review identifies critical research gaps and proposes future directions for ensuring the safe development of kombucha as a scientifically validated functional beverage.

Keywords: Kombucha Tea; Functional Fermented Beverages; Antioxidant Bioactives; Gut Microbiota Modulation; Toxicological Risks; Food Safety and Regulation.

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1. Introduction

Fermentation is one of the oldest biotechnological processes used in food preservation and transformation, with historical roots extending back several millennia. Traditionally employed to enhance shelf life, sensory quality, and safety of foods, fermentation has recently gained renewed scientific and commercial importance due to its role in improving nutritional quality and generating health-promoting bioactive compounds. In the context of modern nutrition science, fermented foods and beverages are increasingly recognized as functional products capable of exerting physiological benefits beyond basic nutrition. This renewed interest is strongly linked to the growing understanding of the relationship between diet, gut microbiota, immune function, and chronic disease prevention (Marco et al., 2017; Tamang et al., 2020). Fermented beverages, in particular, have emerged as a major focus within the functional food sector. Their liquid form allows for rapid absorption of bioactive compounds and facilitates the delivery of live microorganisms and fermentation-derived metabolites. Among these beverages, kombucha tea has achieved remarkable global popularity and is often marketed as a natural health drink rich in antioxidants, organic acids, and probiotic microorganisms. Despite its long history of traditional consumption, kombucha has only recently become the subject of systematic scientific investigation. While numerous studies suggest potential health benefits, concerns regarding safety, standardization, and exaggerated health claims have also been raised, underscoring the need for a balanced and evidence-based evaluation.

1.1 Global Resurgence of Fermented Functional Beverages

The global resurgence of fermented functional beverages is largely driven by changing consumer perceptions of food and health. Modern dietary patterns, characterized by high intake of processed foods and reduced dietary diversity, have been associated with increased prevalence of metabolic disorders, gastrointestinal diseases, and immune dysfunction. Consequently, there is growing interest in foods that support gut health and contribute to disease prevention through natural means (Sonnenburg and Bäckhed, 2016). Fermented beverages such as kefir, kombucha, kvass, traditional vinegars, and probiotic dairy drinks are increasingly perceived as functional alternatives to sugar-sweetened beverages. These products are rich

in organic acids, vitamins, bioactive peptides, polyphenols, and, in some cases, live microorganisms that can interact with the host gut microbiota. Fermentation enhances nutrient bioavailability, reduces antinutritional factors, and promotes the synthesis or transformation of bioactive compounds with antioxidant and anti-inflammatory properties (Bell et al., 2018; Hutkins, 2019). From an industrial perspective, fermentation aligns well with the “clean-label” movement, as it relies on natural microbial processes rather than synthetic additives to achieve preservation and functional enhancement. Advances in food microbiology, metagenomics, and metabolomics have further strengthened scientific interest in fermented beverages by enabling detailed characterization of microbial communities and their metabolic outputs. These tools have revealed that fermented beverages are complex ecosystems whose functional properties depend on microbial diversity, substrate composition, and processing conditions is shown in table 1 (Derrien et al., 2017).

Table 1. Key drivers behind the global resurgence of fermented functional beverages

Driver	Description	Health and industry relevance
Gut microbiota awareness	Increased focus on diet–microbiome interactions	Digestive and immune health
Rise in lifestyle diseases	Diet-linked chronic disorders	Preventive nutrition strategies
Clean-label demand	Preference for natural processing	Reduced chemical preservatives
Advances in fermentation science	Application of omics technologies	Targeted functional formulations

Although fermented functional beverages are widely perceived as beneficial, their health effects are highly product-specific and depend on factors such as raw materials, fermentation conditions, microbial composition, and consumption patterns. Kombucha tea exemplifies this complexity, offering both promising functional attributes and potential safety challenges.

1.2 Kombucha Tea: Historical Background and Modern Commercialization

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Kombucha tea is a traditional fermented beverage prepared by fermenting sweetened tea using a symbiotic culture of bacteria and yeast (SCOBY). Historical records suggest that kombucha originated in Northeast China during the Qin Dynasty (approximately 200–300 BCE), where it was consumed for its purported medicinal and longevity-enhancing properties (Greenwalt et al., 2000). Over time, the beverage spread to Russia, Eastern Europe, and Central Asia, becoming embedded in folk medicine traditions before gaining popularity in Western countries during the late twentieth century. The fermentation process of kombucha involves a complex interplay between yeasts and acetic acid bacteria. Yeasts initially hydrolyze sucrose into glucose and fructose and convert these sugars into ethanol and carbon dioxide. Acetic acid bacteria subsequently oxidize ethanol to acetic acid and produce other organic acids such as gluconic and glucuronic acids. Simultaneously, microbial enzymes facilitate the biotransformation of tea polyphenols, potentially altering their antioxidant activity and bioaccessibility (Villarreal-Soto et al., 2018). In recent decades, kombucha has transitioned from a home-brewed beverage to a globally commercialized product. The rapid expansion of the kombucha market has been driven by its positioning as a functional and probiotic drink, along with diversification into flavored, low-sugar, and fortified formulations. Commercial production has introduced improved hygiene, controlled fermentation, and extended shelf life; however, it has also raised new challenges related to product consistency, alcohol accumulation, and microbial stability (Jayabalan et al., 2014). Regulatory classification of kombucha varies considerably across countries, with the beverage being categorized as a non-alcoholic drink, fermented food, or dietary supplement depending on national frameworks. This lack of harmonization complicates quality control, labeling, and safety assessment, particularly with respect to ethanol content and probiotic claims (Marsh et al., 2014).

1.3 Rationale and Scope of the Review

Despite its growing popularity and strong health-oriented marketing, kombucha tea remains scientifically controversial. A substantial proportion of published studies are based on *in vitro* assays and animal models, which consistently demonstrate antioxidant, antimicrobial, hepatoprotective, and metabolic effects. However, translation of these findings to humans remains limited due to the

scarcity of well-designed clinical trials and the heterogeneity of kombucha formulations used in existing studies (Kapp and Sumner, 2019). In addition to uncertainties regarding efficacy, safety concerns associated with kombucha consumption have gained increasing attention. Case reports have linked excessive or improperly produced kombucha to adverse health effects such as metabolic acidosis, hepatotoxicity, hyponatremia, microbial contamination, excessive ethanol intake, and heavy metal exposure from inappropriate fermentation vessels (Centers for Disease Control and Prevention, 1995; Srinivasan et al., 1997). These risks are particularly relevant for vulnerable populations including pregnant women, immunocompromised individuals, children, and the elderly. Therefore, a comprehensive and critical review is required to move beyond anecdotal claims and provide an evidence-based assessment of kombucha tea. The scope of this review includes:

- Evaluation of antioxidant bioactive compounds and their transformation during fermentation
- Assessment of microbial-driven health benefits, particularly gut microbiota modulation
- Critical analysis of toxicological risks and safety concerns
- Discussion of regulatory and standardization challenges affecting kombucha production and consumption

By integrating perspectives from food chemistry, microbiology, nutrition, and toxicology, this review aims to provide a balanced scientific framework for understanding kombucha tea as a next-generation functional fermented beverage and to guide future research, industry practices, and regulatory policies.

2. Kombucha Fermentation: Composition and Processing

Kombucha fermentation is a complex biochemical process governed by the interaction between raw materials and a dynamic symbiotic microbial consortium. The chemical composition, sensory characteristics, functional properties, and safety of the final beverage are strongly influenced by the type of tea used, the nature of the fermentable sugars, and the metabolic activities of bacteria and yeasts present in the SCOBY. Understanding these compositional and processing variables is critical for interpreting the variability observed in kombucha's antioxidant potential, health effects, and toxicological risks.

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2.1 Raw Materials Used in Kombucha Production

2.1.1 Tea varieties used in kombucha fermentation

Tea serves as the primary substrate providing nitrogenous compounds, minerals, caffeine, and polyphenols essential for microbial growth and bioactive compound formation. Traditionally, black and green teas derived from *Camellia sinensis* are most commonly used, although oolong and herbal teas are increasingly employed in commercial formulations. Black tea is rich in theaflavins and thearubigins formed during tea oxidation, which contribute to higher total phenolic content and robust flavor is shown in figure 1.

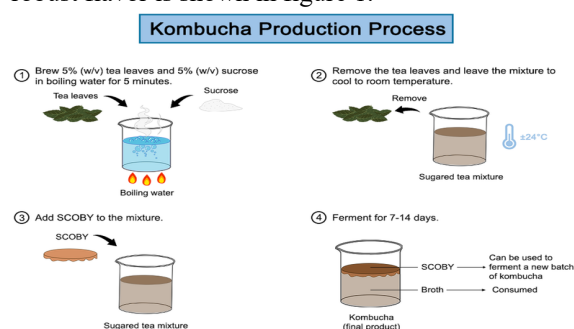


Figure 1: Kombucha Production Process

Several studies have reported that kombucha prepared with black tea exhibits stronger antioxidant activity and supports stable SCOBY growth due to its higher nitrogen and mineral availability (Jayabalan et al., 2014; Villarreal-Soto et al., 2018). Green tea, in contrast, contains higher levels of catechins such as epigallocatechin gallate (EGCG), which are potent antioxidants but may inhibit microbial growth at high concentrations. Oolong tea, being partially oxidized, offers an intermediate polyphenol profile and is reported to produce kombucha with balanced sensory attributes and moderate acidity. Herbal teas (e.g., hibiscus, rooibos, chamomile) are caffeine-free alternatives increasingly used for consumer diversification. However, the absence of caffeine and certain nitrogenous compounds in herbal infusions can negatively affect SCOBY development and fermentation consistency, often requiring supplementation or adaptation of fermentation parameters (Greenwalt et al., 2000).

2.1.2 Sugars and alternative sweeteners

Sucrose is the most widely used fermentable sugar in kombucha production due to its efficient utilization by yeasts and acetic acid bacteria. During fermentation, yeast-derived invertase hydrolyzes

sucrose into glucose and fructose, which serve as primary carbon sources for microbial metabolism (Marsh et al., 2014). Alternative sweeteners such as honey, jaggery, molasses, coconut sugar, and maple syrup have been explored to enhance mineral content and sensory complexity. While these substrates can support fermentation, their variable composition may alter microbial succession, organic acid profiles, and ethanol production. Non-caloric sweeteners (e.g., stevia, erythritol) are generally unsuitable as sole carbon sources, as they do not support microbial growth and can lead to fermentation failure (Hutkins, 2019).

2.2 Symbiotic Culture of Bacteria and Yeast (SCOBY)

The SCOBY is the defining biological component of kombucha fermentation. It forms a cellulose-based biofilm at the air-liquid interface and functions as both a microbial reservoir and a metabolic engine driving fermentation is shown in figure 2.

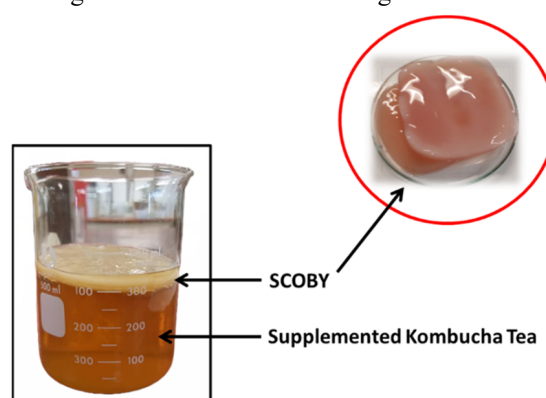


Figure 2: Symbiotic Culture of Bacteria and Yeast (SCOBY)

2.2.1 Dominant bacterial genera

Acetic acid bacteria dominate the bacterial community in kombucha fermentation. The most frequently reported genera include *Komagataeibacter* (formerly *Gluconacetobacter*), *Acetobacter*, and *Gluconobacter*. These bacteria are responsible for oxidizing ethanol into acetic acid and synthesizing bacterial cellulose, which provides structural integrity to the SCOBY (Villarreal-Soto et al., 2018). *Komagataeibacter* species are particularly important due to their high tolerance to acidic environments and their ability to produce gluconic and glucuronic acids. These organic acids contribute to the characteristic acidity of kombucha and are often associated with its purported detoxifying effects, although human evidence remains limited (Jayabalan et al., 2014).

2.2.2 Yeast diversity and functional roles

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Yeasts initiate kombucha fermentation by metabolizing sugars into ethanol and carbon dioxide. Commonly reported yeast genera include *Saccharomyces*, *Brettanomyces*, *Zygosaccharomyces*, *Candida*, and *Pichia*. Yeasts also produce enzymes such as invertase and β -glucosidase, which facilitate sugar hydrolysis and polyphenol transformation (Marsh et al., 2014). Yeast metabolism contributes to effervescence, flavor complexity, and ethanol formation. Importantly, excessive yeast activity can result in elevated ethanol levels, raising regulatory and safety concerns, particularly in commercial products intended to remain non-alcoholic is shown in table 2.

Table 2. Microbial composition of SCOBY and their functional roles

Microbial group	Dominant genera	Primary functions
Acetic acid bacteria	<i>Komagataeibacter</i> , <i>Acetobacter</i>	Ethanol oxidation, acid production, cellulose synthesis
Yeasts	<i>Saccharomyces</i> , <i>Brettanomyces</i>	Sugar metabolism, ethanol and CO ₂ production
Lactic acid bacteria (minor)	<i>Lactobacillus</i> spp.	Organic acid formation, potential probiotic effects

2.3 Fermentation Dynamics and Biochemical Transformations

2.3.1 Sugar metabolism and organic acid production

Kombucha fermentation is typically divided into early, mid, and late stages. During the early stage, yeasts dominate, rapidly hydrolyzing sucrose and producing ethanol. In the mid-stage, acetic acid bacteria increase in abundance, oxidizing ethanol into acetic acid and producing gluconic, lactic, and glucuronic acids. These reactions lead to a progressive decrease in pH, typically reaching values between 2.5 and 3.5 depending on fermentation duration (Villarreal-Soto et al., 2018). Organic acids are key contributors to kombucha's antimicrobial activity, shelf stability, and sensory attributes. However, excessive acid accumulation

due to prolonged fermentation can result in overly acidic beverages, potentially causing gastrointestinal discomfort or metabolic disturbances if consumed in large quantities (Kapp and Sumner, 2019).

2.3.2 Ethanol and carbon dioxide formation

Ethanol is an inevitable intermediate in kombucha fermentation, produced primarily by yeasts during sugar metabolism. While most ethanol is subsequently converted into organic acids by acetic acid bacteria, residual ethanol levels may vary widely depending on fermentation conditions, sugar concentration, temperature, and microbial balance.

3. Antioxidant Bioactives in Kombucha Tea

Oxidative stress, resulting from an imbalance between reactive oxygen species (ROS) production and antioxidant defense mechanisms, is implicated in the pathogenesis of numerous chronic diseases, including cardiovascular disorders, diabetes, neurodegeneration, and cancer. Dietary antioxidants play a crucial role in mitigating oxidative damage by neutralizing free radicals and modulating endogenous antioxidant systems. Kombucha tea has attracted considerable scientific interest as a fermented beverage rich in antioxidant bioactives derived from tea leaves and modified through microbial fermentation. The antioxidant potential of kombucha is widely regarded as one of its primary functional attributes, although its magnitude and physiological relevance depend strongly on raw materials, fermentation conditions, and microbial composition.

3.1 Tea-Derived Polyphenols and Flavonoids

Tea leaves from *Camellia sinensis* are a rich source of polyphenolic compounds, which form the biochemical foundation of kombucha's antioxidant activity. The major classes of tea polyphenols include flavan-3-ols (catechins), flavonols, theaflavins, and thearubigins, with their relative abundance varying according to tea type and processing. Green tea is particularly rich in catechins such as epigallocatechin gallate (EGCG), epicatechin, and epicatechin gallate, whereas black tea contains higher levels of theaflavins and thearubigins formed during enzymatic oxidation (Jayabalan et al., 2014). During kombucha preparation, a substantial proportion of these polyphenols is retained in the fermented beverage. Several studies have reported that kombucha produced from black or green tea exhibits higher total phenolic content and stronger antioxidant capacity than unfermented tea infusions, particularly

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during early to mid-fermentation stages (Villarreal-Soto et al., 2018). The presence of these compounds contributes directly to the beverage's ability to scavenge free radicals and inhibit lipid peroxidation is shown in figure 3.

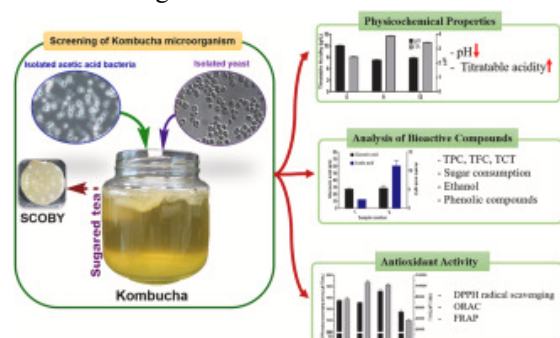


Figure 3: Analysis of Bioactive compounds

Flavonoids not only act as direct antioxidants but also exert synergistic effects with organic acids and microbial metabolites generated during fermentation is shown in table 3. However, prolonged fermentation can lead to partial degradation or polymerization of phenolic compounds, potentially reducing antioxidant activity if fermentation is not carefully controlled.

Table 3. Major tea-derived antioxidant compounds present in kombucha tea

Compound class	Representative compounds	Primary antioxidant role
Catechins	EGCG, epicatechin	Free radical scavenging
Flavonols	Quercetin, kaempferol	Metal chelation, anti-inflammatory
Theaflavins	Theaflavin-3-gallate	Lipid peroxidation inhibition
Thearubigins	Polymeric phenolics	Long-term antioxidant stability

3.2 Microbial Transformation of Phenolic Compounds During Fermentation

Microbial fermentation plays a critical role in modifying the chemical structure, bioavailability, and bioactivity of tea polyphenols in kombucha. Yeasts and bacteria within the SCOBY produce enzymes such as β -glucosidase, esterase, and oxidoreductases, which catalyze the hydrolysis of glycosylated phenolics and the conversion of complex polyphenols into simpler phenolic acids (Marsh et al., 2014). These transformations can

enhance the bioaccessibility of phenolic compounds by releasing aglycone forms that are more readily absorbed in the human gastrointestinal tract. For example, fermentation has been shown to increase levels of gallic acid, caffeic acid, and ferulic acid, which possess strong antioxidant and anti-inflammatory properties (Villarreal-Soto et al., 2018). At the same time, microbial oxidation and polymerization reactions may lead to the partial degradation of certain catechins, particularly during extended fermentation. As a result, antioxidant activity often follows a dynamic pattern, increasing during the early stages of fermentation and declining with prolonged acidification. This highlights the importance of fermentation control in maximizing antioxidant benefits.

3.3 Antioxidant Mechanisms of Action

The antioxidant activity of kombucha tea is mediated through multiple complementary mechanisms, involving both direct chemical interactions and indirect modulation of biological pathways.

3.3.1 Free radical scavenging

Tea polyphenols and fermentation-derived phenolic acids act as hydrogen or electron donors, directly neutralizing reactive oxygen species such as superoxide anions, hydroxyl radicals, and peroxy radicals. In vitro assays, including DPPH, ABTS, and FRAP, consistently demonstrate strong radical scavenging activity of kombucha tea, often exceeding that of unfermented tea infusions at optimal fermentation times (Jayabalan et al., 2014).

3.3.2 Metal chelation

Certain flavonoids present in kombucha possess the ability to chelate transition metals such as iron and copper, which catalyze the formation of highly reactive hydroxyl radicals through Fenton-type reactions. By binding these metals, kombucha-derived polyphenols reduce metal-induced oxidative stress and inhibit lipid and protein oxidation (Bell et al., 2018).

3.3.3 Modulation of endogenous antioxidant enzymes

Beyond direct antioxidant effects, kombucha consumption has been shown in animal models to modulate endogenous antioxidant defense systems. Studies report increased activity of superoxide dismutase (SOD), catalase, and glutathione peroxidase in liver and kidney tissues following kombucha intake, suggesting an indirect antioxidant mechanism mediated by gene expression and

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cellular signaling pathways (Bhattacharya et al., 2011).

3.4 In Vitro and In Vivo Evidence of Antioxidant Activity

A substantial body of evidence supporting the antioxidant potential of kombucha originates from in vitro studies, which consistently report high radical scavenging activity and inhibition of lipid peroxidation. These effects are influenced by fermentation duration, tea type, and microbial composition. Kombucha prepared from green or black tea generally exhibits higher antioxidant capacity than herbal tea-based variants (Jayabalan et al., 2014). In in vivo animal studies, kombucha consumption has been associated with reduced oxidative stress markers, improved antioxidant enzyme activity, and protective effects against chemically induced liver and kidney damage. For instance, kombucha administration in rodent models has been shown to decrease malondialdehyde levels while enhancing glutathione status, indicating reduced lipid peroxidation (Bhattacharya et al., 2011). However, human clinical evidence remains limited. Few small-scale studies have evaluated systemic antioxidant effects of kombucha consumption in humans, and results are inconsistent due to variability in study design, dosage, and kombucha composition. Consequently, while preclinical data are promising, the translation of antioxidant benefits to human health outcomes remains to be conclusively established (Kapp and Sumner, 2019).

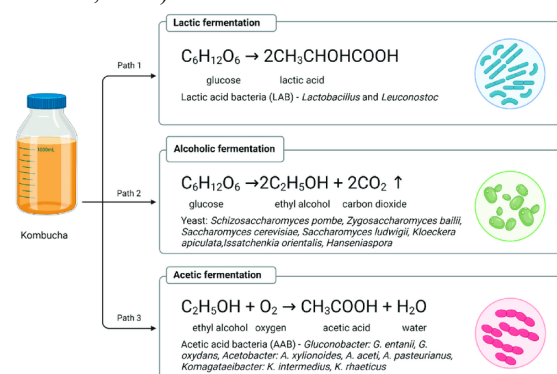


Figure 4: Primary, Secondary and Tertiary Fermentation of Kombucha

Carbon dioxide production contributes to the effervescence characteristic of kombucha. In sealed containers, secondary fermentation can significantly increase CO₂ pressure and ethanol content, posing risks of bottle explosion and regulatory non-compliance is shown in figure 4. Commercial producers often employ cold storage, pasteurization,

or controlled fermentation to limit ethanol formation and ensure product safety (Jayabalan et al., 2014).

4. Microbial-Driven Health Benefits of Kombucha Tea:

The health-promoting potential of kombucha tea is closely linked to its microbial ecology and fermentation-derived metabolites, which collectively interact with host physiological systems. Unlike conventional tea infusions, kombucha contains a complex mixture of organic acids, transformed polyphenols, microbial enzymes, and, in some cases, viable microorganisms. These components are believed to contribute to gut microbiota modulation, immune regulation, metabolic homeostasis, and protection against pathogenic microorganisms. However, the magnitude and consistency of these effects depend on kombucha composition, fermentation parameters, and host-related factors.

4.1 Modulation of Gut Microbiota and Digestive Health

The human gastrointestinal tract harbors a diverse microbial community that plays a central role in digestion, nutrient absorption, immune development, and metabolic regulation. Disruptions in gut microbiota composition, commonly referred to as dysbiosis, have been associated with gastrointestinal disorders, metabolic syndrome, and inflammatory diseases. Fermented foods and beverages are increasingly studied for their capacity to restore microbial balance and support digestive health (Marco et al., 2017). Kombucha tea may influence gut microbiota through multiple mechanisms. First, organic acids such as acetic, gluconic, and lactic acids lower gastrointestinal pH, creating an environment unfavorable to certain pathogenic bacteria while supporting acid-tolerant beneficial microbes. Second, fermentation-derived metabolites and partially transformed polyphenols may act as prebiotic-like substrates, selectively stimulating the growth of beneficial bacterial taxa (Villarreal-Soto et al., 2018). Although kombucha is often described as a probiotic beverage, it does not consistently meet the formal definition of probiotics, as microbial viability and strain identity vary widely across products. Nevertheless, animal studies suggest that kombucha consumption can increase microbial diversity and improve intestinal barrier function, as evidenced by reduced intestinal permeability and improved mucosal integrity (Bhattacharya et al., 2013). Improved digestion, reduced bloating, and enhanced bowel regularity are

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commonly reported by consumers, though such effects remain largely anecdotal in the absence of robust clinical trials.

4.2 Anti-Inflammatory and Immunomodulatory Effects

Chronic low-grade inflammation is a hallmark of many non-communicable diseases, including obesity, diabetes, cardiovascular disorders, and autoimmune conditions. Bioactive compounds present in kombucha, particularly polyphenols and organic acids, have been shown to exert anti-inflammatory effects through modulation of cellular signaling pathways involved in oxidative stress and immune responses (Bell et al., 2018). Fermentation enhances the bioavailability of tea polyphenols, allowing them to interact more effectively with immune cells and intestinal epithelial tissues. In animal models, kombucha consumption has been associated with reduced expression of pro-inflammatory cytokines such as tumor necrosis factor- α (TNF- α) and interleukin-6 (IL-6), alongside increased levels of anti-inflammatory mediators (Bhattacharya et al., 2011). These effects are thought to be mediated by inhibition of nuclear factor- κ B (NF- κ B) signaling and improved antioxidant status. Kombucha-derived organic acids may also contribute indirectly to immune modulation by shaping gut microbiota composition. A balanced gut microbiota is essential for immune homeostasis, and fermentation metabolites can influence the production of short-chain fatty acids and other signaling molecules involved in immune regulation. While these findings are promising, evidence from controlled human studies remains limited.

4.3 Metabolic Health Benefits

4.3.1 Glycemic control

Emerging evidence suggests that kombucha tea may exert beneficial effects on glucose metabolism. Animal studies have demonstrated that kombucha consumption can reduce fasting blood glucose levels and improve insulin sensitivity, potentially through modulation of carbohydrate-digesting enzymes and enhancement of antioxidant defenses in pancreatic tissues (Aloulou et al., 2012). Organic acids such as acetic acid may slow gastric emptying and reduce postprandial glucose spikes, while polyphenols can inhibit α -amylase and α -glucosidase activities. Preliminary human observations suggest modest improvements in glycemic response among individuals with impaired glucose tolerance; however, these findings are based on small sample sizes and short intervention durations. Variability in

sugar content across kombucha products further complicates interpretation is shown in figure 5.

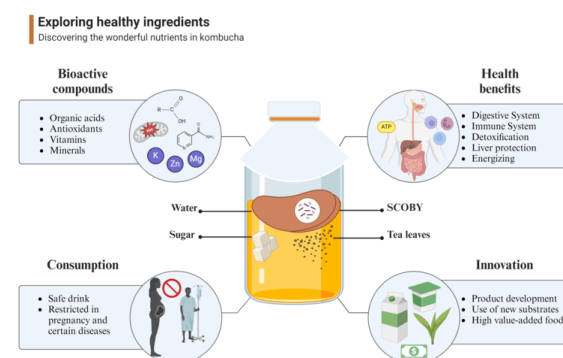


Figure 5: Metabolic Health Benefits of Kombucha

4.3.2 Lipid metabolism

Kombucha consumption has been linked to improvements in lipid metabolism in several animal models. Reported effects include reductions in total cholesterol, low-density lipoprotein (LDL) cholesterol, and triglyceride levels, along with increased high-density lipoprotein (HDL) cholesterol (Jayabalan et al., 2014). These effects may be attributed to polyphenol-mediated inhibition of lipid peroxidation and modulation of hepatic lipid metabolism enzymes.

Organic acids and antioxidant compounds may also reduce oxidative modification of lipoproteins, a key factor in atherosclerosis development. Despite encouraging preclinical data, well-designed human trials evaluating lipid outcomes are still scarce.

4.3.3 Body weight regulation

The potential role of kombucha in body weight regulation has received limited scientific attention. Animal studies suggest that kombucha consumption may reduce body weight gain and adiposity when included as part of a high-fat diet, possibly due to improved lipid metabolism and reduced inflammation (Bhattacharya et al., 2013). Acetic acid has been independently associated with appetite regulation and increased fat oxidation, which may partially explain these observations. However, kombucha products vary widely in sugar and calorie content, and excessive consumption may counteract potential weight management benefits. Human evidence supporting weight control effects remains insufficient.

4.4 Antimicrobial and Detoxifying Properties

Kombucha tea exhibits notable antimicrobial activity against a range of pathogenic microorganisms, including *Escherichia coli*, *Salmonella* spp., and *Staphylococcus aureus*. This activity is primarily attributed to the combined

effects of low pH, acetic acid, and other organic acids rather than to live microbes alone (Greenwalt et al., 2000). In addition to antimicrobial effects, kombucha has been promoted for its “detoxifying” properties, often linked to the presence of glucuronic acid. In animal models, kombucha consumption has been shown to enhance hepatic antioxidant enzyme activity and reduce toxin-induced liver damage (Bhattacharya et al., 2011). While these findings suggest hepatoprotective potential, claims regarding detoxification in humans remain largely unsubstantiated and require careful scientific validation.

4.5 Limitations of Current Human Clinical Evidence

Despite extensive preclinical research, the translation of kombucha’s microbial-driven health benefits to humans remains limited. Most available evidence is derived from in vitro assays and animal models, which do not fully replicate human physiological complexity. Human studies are often characterized by small sample sizes, short intervention periods, lack of standardized kombucha formulations, and reliance on surrogate biomarkers rather than clinical endpoints (Kapp and Sumner, 2019). Additionally, variability in fermentation conditions, sugar content, microbial composition, and alcohol levels across kombucha products poses significant challenges for reproducibility and comparison across studies. These limitations underscore the need for well-designed randomized controlled trials using standardized kombucha preparations to establish dose–response relationships, safety thresholds, and long-term health effects.

5. Toxicological Risks and Safety Concerns:

Despite its growing reputation as a health-promoting fermented beverage, kombucha tea is not without potential risks. Toxicological and safety concerns associated with kombucha consumption have been increasingly documented, particularly in relation to improper fermentation practices, microbial contamination, excessive acidification, ethanol accumulation, and inappropriate fermentation vessels. Unlike standardized fermented foods, kombucha production—especially at the household or artisanal level—often lacks consistent quality control, leading to significant variability in chemical composition and microbial safety. These concerns underscore the need for a critical evaluation of kombucha’s risk profile alongside its purported health benefits.

5.1 Reported Adverse Effects Associated with Kombucha Consumption

A number of adverse health effects have been reported in association with kombucha consumption, ranging from mild gastrointestinal discomfort to severe metabolic disturbances. Early case reports described symptoms such as nausea, dizziness, allergic reactions, and gastrointestinal upset following excessive intake of home-brewed kombucha (Greenwalt et al., 2000). More serious outcomes, including metabolic acidosis, hepatotoxicity, hyponatremia, and lactic acidosis, have also been documented, although these events remain rare (Centers for Disease Control and Prevention, 1995; Srinivasan et al., 1997). Most severe adverse events appear to be associated with prolonged fermentation, consumption of large volumes, or pre-existing medical conditions. In particular, excessive intake of highly acidic kombucha has been linked to acid–base imbalance, especially in individuals with compromised renal function. While causal relationships are difficult to establish due to confounding factors, these reports highlight the importance of moderation and proper fermentation control. Importantly, adverse effects are more frequently reported for home-brewed kombucha, where fermentation parameters, hygiene practices, and microbial composition are poorly controlled. Commercial products generally undergo quality assurance testing; however, variability in alcohol content and acidity has still been observed across brands (Jayabalan et al., 2014).

5.2 Microbial Contamination and Hygiene-Related Hazards

Microbial safety represents a major concern in kombucha production due to its reliance on mixed microbial cultures and open fermentation systems. Although the acidic environment of kombucha inhibits many pathogenic microorganisms, contamination can occur during early fermentation stages or under unsanitary conditions. Mold growth on the surface of the SCOBY is a well-recognized hazard and is indicative of improper hygiene or unfavorable fermentation conditions (Villarreal-Soto et al., 2018). Potential contaminants include opportunistic bacteria and fungi that may proliferate if acidity is insufficient or if contaminated water, utensils, or raw materials are used. Consumption of contaminated kombucha may lead to gastrointestinal infections, particularly in individuals with weakened immune defenses. Unlike industrial fermentations,

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home-brewed kombucha is rarely subjected to microbial testing, increasing

5.3 Chemical Risks

5.3.1 Excessive organic acids

Organic acids, including acetic, gluconic, lactic, and glucuronic acids, are key contributors to kombucha's sensory profile and antimicrobial properties. However, excessive accumulation of these acids due to prolonged fermentation can result in extremely low pH values (<2.5), making the beverage corrosive to dental enamel and irritating to the gastrointestinal tract (Jayabalan et al., 2014). High acid intake has been associated with metabolic acidosis in susceptible individuals, particularly when consumed in large quantities or on an empty stomach. These risks emphasize the importance of controlling fermentation duration and monitoring acidity before consumption.

5.3.2 Ethanol accumulation

Ethanol is an inevitable by-product of kombucha fermentation, produced by yeasts during sugar metabolism. While most ethanol is subsequently oxidized to organic acids by acetic acid bacteria, residual alcohol levels can vary widely. Studies have shown that ethanol concentrations in kombucha can exceed non-alcoholic beverage limits if fermentation is prolonged or secondary fermentation occurs in sealed containers (Marsh et al., 2014). Elevated ethanol levels pose risks for children, pregnant women, individuals with liver disease, and those abstaining from alcohol for medical or religious reasons. In addition, ethanol accumulation may compromise regulatory compliance and consumer trust.

5.3.3 Heavy metal leaching from fermentation vessels

One of the most serious chemical hazards associated with kombucha is heavy metal contamination, particularly lead leaching from ceramic or glazed fermentation vessels shown in table 4. The acidic nature of kombucha enhances metal solubility, increasing the risk of contamination when inappropriate containers are used (Centers for Disease Control and Prevention, 1995). Several reported cases of lead toxicity have been directly linked to kombucha fermented in lead-glazed pottery. For this reason, food-grade glass or stainless-steel containers are strongly recommended for both household and commercial production.

Table 4. Chemical hazards and their sources in kombucha production

Chemical risk	Primary source	Health concern
Organic acids	Prolonged fermentation	Acidosis, GI irritation
Ethanol	Yeast metabolism	Alcohol exposure
Heavy metals	Ceramic/glazed vessels	Neurotoxicity, systemic toxicity

5.4.1 Pregnant and lactating women

Pregnant and lactating women are often advised to avoid kombucha due to potential risks associated with alcohol content, microbial contamination, and excessive acidity. Even low levels of ethanol may pose developmental risks, while exposure to unpasteurized fermented products increases the likelihood of foodborne illness. The lack of robust safety data in this population warrants a precautionary approach (Kapp and Sumner, 2019) is shown in table 5.

5.4.2 Immunocompromised individuals

Individuals with compromised immune systems, including those undergoing chemotherapy, organ transplant recipients, or individuals with autoimmune disorders, are at increased risk of infection from live microbial products. Although kombucha is acidic, viable microorganisms may still pose risks in these populations, particularly when products are unpasteurized or home-brewed (Marco et al., 2017) is shown in table 5.

5.4.3 Children and the elderly

Children and elderly individuals may be more sensitive to kombucha's acidity and ethanol content. In children, even small amounts of alcohol and organic acids may cause adverse effects, while in older adults, reduced renal and hepatic function can exacerbate acid-base imbalance and alcohol metabolism issues. Moderation and careful product selection are therefore essential for these groups.

Table 5. Risk considerations for vulnerable populations

Population group	Primary concern	Recommendation
Pregnant/lactating women	Ethanol, contamination	Avoid consumption
Immunocompromised individuals	Live microbes	Avoid unpasteurized products
Children	Alcohol, acidity	Avoid or strictly limit

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Elderly	Acid–base balance	Consume cautiously
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6. Regulatory and Quality Control Challenges

The rapid global commercialization of kombucha tea has outpaced the development of harmonized regulatory frameworks and standardized quality control practices. Positioned at the intersection of fermented foods, functional beverages, and probiotic products, kombucha presents unique regulatory challenges due to its dynamic composition, live microbial content, variable alcohol levels, and diverse health claims. Inconsistencies in classification, labeling requirements, and safety assessment across countries complicate both consumer protection and international trade. Addressing these challenges is essential to ensure the safe and evidence-based development of kombucha as a next-generation functional beverage.

6.1 Regulatory Status of Kombucha Across Different Countries

The regulatory classification of kombucha varies widely across jurisdictions, reflecting differences in food laws, alcohol regulations, and approaches to functional food governance. In many countries, kombucha is regulated as a non-alcoholic fermented beverage, provided its ethanol content remains below a legally defined threshold. However, other regions classify kombucha as a functional food, dietary supplement, or even a low-alcohol beverage, depending on composition and labeling claims (Jayabalan et al., 2014). In the United States, kombucha is regulated as a conventional food by the Food and Drug Administration, but products containing more than 0.5% alcohol by volume (ABV) fall under the jurisdiction of alcohol regulatory authorities is shown in table 6. This dual oversight has led to enforcement actions and product recalls when alcohol levels exceeded permissible limits (Kapp and Sumner, 2019). In the European Union, kombucha is generally regulated under food safety legislation, with alcohol thresholds and labeling requirements varying among member states. Similar variability exists in Asia-Pacific regions, where kombucha may be categorized as a health beverage or traditional fermented product. The absence of a unified international definition for kombucha complicates regulatory oversight and creates uncertainty for manufacturers and consumers. Furthermore, inconsistent treatment of health and probiotic claims increases the risk of

misleading marketing and undermines consumer trust.

Table 6. Regulatory classification of kombucha in selected regions

Region	Regulatory category	Key regulatory considerations
United States	Conventional food / alcoholic beverage (if >0.5% ABV)	Alcohol limits, labeling compliance
European Union	Fermented beverage / food	National alcohol thresholds
Asia-Pacific	Health beverage / traditional fermented food	Functional claims oversight
Australia/New Zealand	Non-alcoholic beverage	Food Standards Code compliance

6.2 Alcohol Content Labeling and Compliance Issues

Alcohol content represents one of the most contentious regulatory issues associated with kombucha. Ethanol is an inherent by-product of fermentation, produced by yeast metabolism of sugars. Although acetic acid bacteria subsequently oxidize much of this ethanol, residual alcohol levels may fluctuate throughout the product’s shelf life due to ongoing fermentation, particularly in unpasteurized or inadequately refrigerated products (Marsh et al., 2014). Numerous studies have demonstrated that ethanol levels in kombucha can increase during storage, occasionally exceeding legal thresholds for non-alcoholic beverages. This poses significant compliance challenges for manufacturers, particularly those distributing products across multiple jurisdictions with differing alcohol limits. Inaccurate labeling of alcohol content may expose vulnerable populations, such as children, pregnant women, and individuals avoiding alcohol, to unintended risks. To address these challenges, commercial producers increasingly employ strategies such as cold-chain distribution, filtration, pasteurization, or microbial stabilization. However, these interventions may reduce microbial viability and alter the functional attributes of the

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beverage, highlighting a trade-off between safety and perceived health benefits.

6.3 Standardization of Fermentation and Product Quality

One of the most significant barriers to scientific validation and regulatory oversight of kombucha is the lack of standardized fermentation protocols. Kombucha composition is influenced by multiple variables, including tea type, sugar concentration, SCOBY composition, fermentation time, temperature, and storage conditions. As a result, products marketed under the same name may differ substantially in chemical composition, microbial profile, acidity, and alcohol content (Villarreal-Soto et al., 2018). From a quality control perspective, this variability complicates reproducibility of research findings and undermines consumer confidence. Standardization efforts are needed to define acceptable ranges for key quality parameters such as pH, total acidity, residual sugar, ethanol content, and microbial load. The adoption of good manufacturing practices (GMP) and hazard analysis and critical control point (HACCP) systems is increasingly recommended for both large-scale and artisanal producers. Standardized analytical methods for monitoring these parameters are essential to ensure consistent product quality and facilitate regulatory compliance.

6.4 Safety Assessment and Risk Management Strategies

Effective safety assessment and risk management are central to the responsible commercialization of kombucha. Traditional food safety frameworks are not always directly applicable to fermented beverages with live microbial cultures and dynamic chemical profiles. Therefore, a risk-based approach that accounts for product variability, consumer demographics, and consumption patterns is required. Risk management strategies include careful selection and characterization of starter cultures, control of fermentation conditions, routine monitoring of acidity and alcohol content, and the use of food-grade fermentation vessels is shown in table 7. Clear labeling regarding storage conditions, shelf life, and consumption recommendations is also essential for consumer safety (Greenwalt et al., 2000). From a regulatory perspective, greater collaboration between scientists, industry stakeholders, and policymakers is needed to develop evidence-based guidelines for kombucha production and labeling. Establishing internationally harmonized standards would not only enhance

consumer protection but also facilitate global trade and innovation within the functional beverage sector.

Table 7. Risk management strategies for safe kombucha production

Risk factor	Mitigation strategy	Outcome
Excess fermentation	Time and temperature control	Reduced acidity and ethanol
Microbial contamination	GMP and sanitation	Improved safety
Alcohol variability	Regular testing	Label accuracy
Consumer misuse	Clear labeling	Reduced adverse events

7. Research Gaps and Future Perspectives

Despite the rapid expansion of scientific literature on kombucha tea, significant gaps remain in the understanding of its functional efficacy, safety, and regulatory compliance. Much of the current evidence is derived from in vitro experiments and animal models, while human data are sparse and heterogeneous. In addition, the absence of standardized production methods and analytical frameworks limits reproducibility and comparability across studies. Addressing these gaps is essential for the transition of kombucha from a traditionally fermented beverage to a scientifically validated, next-generation functional food.

7.1 Need for Standardized Production and Analytical Protocols

One of the most critical challenges in kombucha research is the lack of standardized production protocols. Kombucha composition varies widely depending on tea type, sugar concentration, SCOBY composition, fermentation temperature, duration, and storage conditions is shown in table 8. As a result, kombucha samples used in different studies are often chemically and microbiologically incomparable, leading to inconsistent findings regarding antioxidant capacity, microbial viability, and health effects (Villarreal-Soto et al., 2018). Standardization is required at multiple levels, including raw material selection, fermentation parameters, and post-fermentation handling. Establishing reference kombucha formulations with defined pH ranges, organic acid profiles, ethanol limits, and microbial counts would significantly enhance reproducibility in experimental studies. Similarly, standardized analytical protocols for measuring phenolic compounds, antioxidant

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activity, microbial composition, and alcohol content are needed to ensure data reliability (Jayabalan et al., 2014). From an industry perspective, harmonized standards would facilitate quality assurance, regulatory compliance, and consumer trust. Adoption of validated analytical techniques, such as high-performance liquid chromatography for phenolic profiling and next-generation sequencing for microbial characterization, should be encouraged across both academic and industrial settings.

Table 8. Key areas requiring standardization in kombucha research

Aspect	Current limitation	Recommended future approach
Fermentation parameters	High variability	Defined time-temperature ranges
SCOBY composition	Poor characterization	Genomic and phenotypic profiling
Chemical analysis	Inconsistent methods	Validated, harmonized protocols
Reporting standards	Limited transparency	Detailed methodological disclosure

7.2 Well-Designed Human Clinical Trials

While preclinical studies provide valuable mechanistic insights, human clinical trials are essential to substantiate health claims associated with kombucha consumption. At present, available human studies are limited by small sample sizes, short intervention durations, lack of appropriate controls, and variability in kombucha formulations (Kapp and Sumner, 2019). Future clinical research should prioritize randomized, placebo-controlled trials with clearly defined endpoints related to oxidative stress, inflammation, metabolic health, and gut microbiota composition. Dose-response relationships and long-term consumption effects should also be evaluated to establish safe and effective intake levels. Importantly, clinical trials should use chemically and microbiologically characterized kombucha products to ensure reproducibility and relevance. In addition to efficacy, safety outcomes must be systematically assessed, particularly with respect to alcohol exposure, acid-base balance, and gastrointestinal tolerance. Inclusion of diverse population groups will be critical to identify potential differential responses and risks.

7.3 Application of Omics Approaches in Kombucha Research

The application of omics technologies offers unprecedented opportunities to advance kombucha research by providing comprehensive insights into microbial dynamics, metabolic pathways, and host interactions is shown in table 9. Metagenomic and metatranscriptomic analyses can elucidate the functional roles of bacterial and yeast communities within the SCOBY, while metabolomics can identify bioactive compounds generated during fermentation (Marsh et al., 2014). Integration of multi-omics datasets through systems biology approaches can help link fermentation conditions to specific metabolic outputs and functional properties. For example, correlating microbial gene expression with phenolic transformation and antioxidant activity could enable targeted optimization of fermentation processes. Proteomics may further reveal enzyme systems involved in sugar metabolism, organic acid production, and polyphenol biotransformation. Beyond product characterization, omics tools can be applied to human intervention studies to assess changes in gut microbiota composition, metabolite profiles, and host gene expression following kombucha consumption. Such integrative approaches are essential for moving from descriptive studies toward mechanistic understanding.

Table 9. Potential applications of omics technologies in kombucha research

Omics approach	Application	Expected outcome
Metagenomics	SCOBY microbial profiling	Improved culture selection
Metabolomics	Bioactive compound identification	Functional validation
Proteomics	Enzyme pathway mapping	Process optimization
Multi-omics integration	Systems-level understanding	Precision fermentation

7.4 Development of Safer and Functional Kombucha Formulations

Future innovation in kombucha production should focus on developing safer, more consistent, and evidence-based functional formulations. This includes controlled fermentation strategies to minimize excessive acidity and ethanol accumulation while preserving bioactive

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compounds. The use of defined starter cultures, rather than undefined SCOBY consortia, may enhance predictability and safety (Hutkins, 2019). Functional enhancement strategies may involve fortification with prebiotics, plant extracts, or micronutrients with established health benefits. However, such modifications must be supported by rigorous safety and efficacy testing to avoid compounding risks. Advances in fermentation technology, including controlled bioreactors and real-time monitoring systems, could further improve product consistency and scalability. From a regulatory standpoint, future formulations should align with evolving food safety standards and consumer expectations for transparency. Clear labeling, evidence-based health claims, and adherence to alcohol and acidity limits will be essential for sustainable market growth.

8. Conclusions

Kombucha tea has emerged as one of the most prominent fermented functional beverages in contemporary food systems, driven by consumer interest in natural health products, gut microbiota modulation, and antioxidant-rich diets. Scientific investigation over the past two decades has significantly expanded understanding of kombucha's chemical composition, microbial ecology, and biological activity. Nevertheless, the evidence base remains uneven, with strong preclinical support for antioxidant and metabolic effects contrasted by limited and inconsistent human data. This concluding section synthesizes the current state of evidence, discusses implications for research and industry, and outlines pathways toward safe, evidence-based kombucha consumption.

8.1 Summary of Antioxidant, Health, and Safety Evidence

A substantial body of research confirms that kombucha tea is a rich source of antioxidant bioactives, primarily derived from tea polyphenols and fermentation-generated metabolites. *In vitro* studies consistently demonstrate strong free radical scavenging capacity, metal chelation ability, and inhibition of lipid peroxidation, particularly in kombucha prepared from black or green tea and fermented under controlled conditions (Jayabalan et al., 2014; Villarreal-Soto et al., 2018). Animal studies further suggest that kombucha consumption can enhance endogenous antioxidant defense systems, including superoxide dismutase, catalase, and glutathione peroxidase, thereby reducing oxidative stress in hepatic and renal tissues

(Bhattacharya et al., 2011). Beyond antioxidant activity, kombucha's microbial-driven health benefits include potential modulation of gut microbiota, anti-inflammatory effects, and improvements in metabolic parameters such as glycemic control and lipid metabolism. These effects are attributed to a synergistic interplay between organic acids, transformed polyphenols, and microbial metabolites. However, most supporting evidence originates from preclinical models, and translation to human health outcomes remains preliminary (Marco et al., 2017; Kapp and Sumner, 2019). In parallel with these promising findings, safety concerns have been well documented. Adverse effects associated with kombucha consumption include gastrointestinal discomfort, metabolic acidosis, hepatotoxicity, microbial contamination, excessive ethanol exposure, and heavy metal leaching from inappropriate fermentation vessels (Centers for Disease Control and Prevention, 1995; Greenwalt et al., 2000). While such events are relatively rare, they underscore the importance of controlled fermentation, hygienic practices, and regulatory oversight.

8.2 Implications for Functional Beverage Research and Industry

The growing popularity of kombucha has significant implications for both functional beverage research and the food and beverage industry. From a scientific perspective, kombucha represents a valuable model system for studying mixed-culture fermentation, polyphenol biotransformation, and diet-microbiota interactions. The complexity of its microbial ecosystem highlights the need for interdisciplinary research integrating food chemistry, microbiology, nutrition, and systems biology. For industry stakeholders, kombucha presents both opportunities and challenges. Consumer demand for fermented functional beverages continues to rise, creating strong market potential. However, variability in product composition, alcohol content, and microbial stability poses challenges for quality assurance and regulatory compliance. Manufacturers must balance the preservation of functional attributes with the need for safety, consistency, and accurate labeling (Jayabalan et al., 2014).

Investment in standardized fermentation technologies, defined starter cultures, and real-time quality monitoring systems is likely to play a key role in the sustainable growth of the kombucha sector. Moreover, evidence-based communication of

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health benefits, rather than exaggerated claims, will be essential to maintain consumer trust and regulatory acceptance.

8.3 Pathways Toward Safe and Evidence-Based Kombucha Consumption

Moving forward, the safe and effective integration of kombucha into human diets requires a science-driven, risk-aware approach. First, standardized production protocols and analytical frameworks should be established to define acceptable ranges for pH, organic acid concentration, ethanol content, and microbial load. Such standards would improve reproducibility in research and consistency in commercial products (Villarreal-Soto et al., 2018). Second, well-designed human clinical trials are essential to validate health claims and establish evidence-based consumption guidelines. These trials should employ chemically and microbiologically characterized kombucha formulations and assess both efficacy and safety outcomes over extended periods. Particular attention should be given to vulnerable populations, including pregnant women, immunocompromised individuals, children, and the elderly. Third, consumer education plays a critical role in risk mitigation. Clear labeling regarding alcohol content, storage conditions, and recommended intake levels can reduce misuse and adverse events. From a regulatory standpoint, harmonization of kombucha classification and labeling requirements across regions would facilitate global trade and consumer protection. In conclusion, kombucha tea occupies a unique position at the intersection of traditional fermentation and modern functional nutrition. While its antioxidant richness and microbial complexity offer promising health-related potential, these benefits must be weighed against documented safety risks and current gaps in human evidence. A balanced, evidence-based approach—supported by rigorous research, standardized production, and responsible regulation—will be essential for realizing kombucha's role as a safe and credible next-generation functional beverage.

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