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Review

Kombucha as a Sustainable Source of Metabiotics: Potential, Applications, and Future Perspectives

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Abstract

Kombucha is gaining global recognition for its potential health benefits. While traditionally made from sweetened tea, researchers are increasingly exploring local ingredients and agricultural byproducts as alternative substrates for SCOBY fermentation. As a functional beverage that embodies the concept of metabiotics—encompassing live or non-viable probiotics and their bioactive metabolites. This review highlights the holistic health benefits and sustainability aspects of kombucha. Both the fermented beverage, rich in bioactive compounds, and the cellulose-based zoogleal mat can be utilized in various applications, including medical and industrial uses. Moreover, the increasing use of local ingredients and agricultural byproducts as alternative substrates for kombucha production may further improve its sustainability and expand the range of its functional properties. Kombucha has shown promising antioxidant, anti-inflammatory, antimicrobial, anticancer, and antidiabetic properties in pre-clinical studies, positioning it as an emerging functional food. However, further clinical trials and stronger regulatory frameworks are essential to validate its health claims and ensure consumer safety.

Keywords: kombucha; postbiotics; SCOBY; fermented beverage; functional beverage

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1. Introduction

In recent years, the global demand for functional foods and beverages has surged, due to increased consumer awareness of the link between diet and health. Among these, kombucha, a fermented beverage traditionally made from sweetened tea and now increasingly produced with a variety of alternative substrates, has gained widespread popularity for its perceived health benefits, refreshing taste, and natural origin. Originated in Northeast Asia over two millennia ago, kombucha has gained renewed global interest, largely due to consumer demand for functional foods and microbiome-supportive dietary products [1,2]. The global market for kombucha is expanding rapidly, driven by rising health awareness of consumers and continuous innovation in formulation and fermentation substrates by the producers [3].

The emerging interest in fermented foods such as kombucha arises from the concept that they are natural sources of *postbiotics*, defined by the International Scientific Association of Probiotics and Prebiotics (ISAPP) as a preparation of non-viable microorganisms and/or their components that confers a health benefit on the host [1]. The definition of postbiotics

encompasses bioactive compounds generated through the metabolic processes of progenitor microorganisms; these compounds will be referred to as *metabiotics* throughout this article. Metabiotics also offer health benefits per se, for example, in short-chain fatty acids, bacteriocins, signaling molecules and other low molecular weight compounds. Postbiotics demonstrate immunomodulatory, antioxidant, anti-inflammatory, and antimicrobial activities [4], with additional potential as modulators of the gut–brain axis [2]. The non-viable cells or their components—classified as *paraprobiotics*—are also known as "ghost" or "killed" probiotics, encompassing whole inactivated microbial cells, cell lysates, or specific microbial fragments such as teichoic acids, surface proteins, peptidoglycans, chitin, pili, fimbriae, and bacterial DNA. Despite being non-viable, these components can still deliver health benefits, such as modulating the immune system and reducing inflammation [1]. Considered safer and more stable than live probiotics, postbiotics find a wider range of applications as ingredients of functional foods, pharmaceuticals, and nutraceuticals.

The kombucha fermentation process is mediated by a symbiotic consortium of bacteria and yeast (SCOBY), typically dominated by acetic acid bacteria (AAB) such as *Komagataeibacter* spp. and yeast genera including *Zygosaccharomyces* and *Saccharomyces* [5,6]. These microbes cooperatively convert sucrose into a variety of metabolites, including ethanol, carbon dioxide, vitamins, polyphenolic derivatives, and organic acids such as acetic acid (AA), gluconic acid (GA), and glucuronic acid (GlucUA). These bioactive compounds are thought to underline many of the beverage's purported health benefits, such as antioxidant, antimicrobial, and anti-inflammatory effects.

From the viewpoint of sustainability, the low-energy input process and the amenability to upcycling local agricultural byproducts make kombucha production a promising model of eco-efficient innovation. This aligns well with the principles of circular bioeconomy, thus maximizing environmental, economic, and social benefits.

This review examines the growing potential of kombucha, produced from both tea and non-tea substrates, as a sustainable source of postbiotics. It covers the microbial ecology of kombucha fermentation, the diversity of bioactive metabolites produced, and their potential as bioactives. The paper also discusses the sustainability aspects of kombucha production and highlights future directions for integrating kombucha-derived postbiotics as well as their cell-free metabiotics into functional foods, nutraceuticals, and circular bioeconomy models.

2. Connection of Kombucha to Postbiotics

In response to the limitations of using live probiotics, the study of postbiotics began in 2004 [7–9]. Like most fermented foods and beverages, kombucha is also regarded as a natural source of postbiotics. However, their roles and mechanisms have not yet been fully elucidated. Figure 1 illustrates the wide range of postbiotics that can derive from kombucha production, and their potential applications.

Freshly brewed kombucha contains a complex community of bacteria and yeasts, which are potential probiotics. However, for safety and shelf-life purposes, most commercial kombucha products undergo pasteurization, which inactivates the microorganisms. Therefore, to be precise, most commercial kombucha products are sources of postbiotics, including bioactive molecules and parabiotics. Considered a safer alternative to probiotics, particularly for vulnerable populations such as premature infants [10,11], postbiotics can be added to a wider range of foods, beverages and supplements.

What sets kombucha apart from other fermented products is the generation of a cellulose biofilm, also known as zoogleal mat, SCOBY, tea fungus and other terms [12]. Far from being a mere byproduct, this pellicle exhibits prebiotic potential and offers a range of promising applications due to its unique structural and functional properties. Notably,

it has been investigated as a bioadsorbent for heavy metals [13–15], an encapsulating agent in the food industry [16], a material for packaging films [17,18], a biomaterial for tissue regeneration [19,20], and an innovative material for the textile industry [21,22]. These applications contribute to making kombucha highly sustainable by promoting a zero-waste approach.

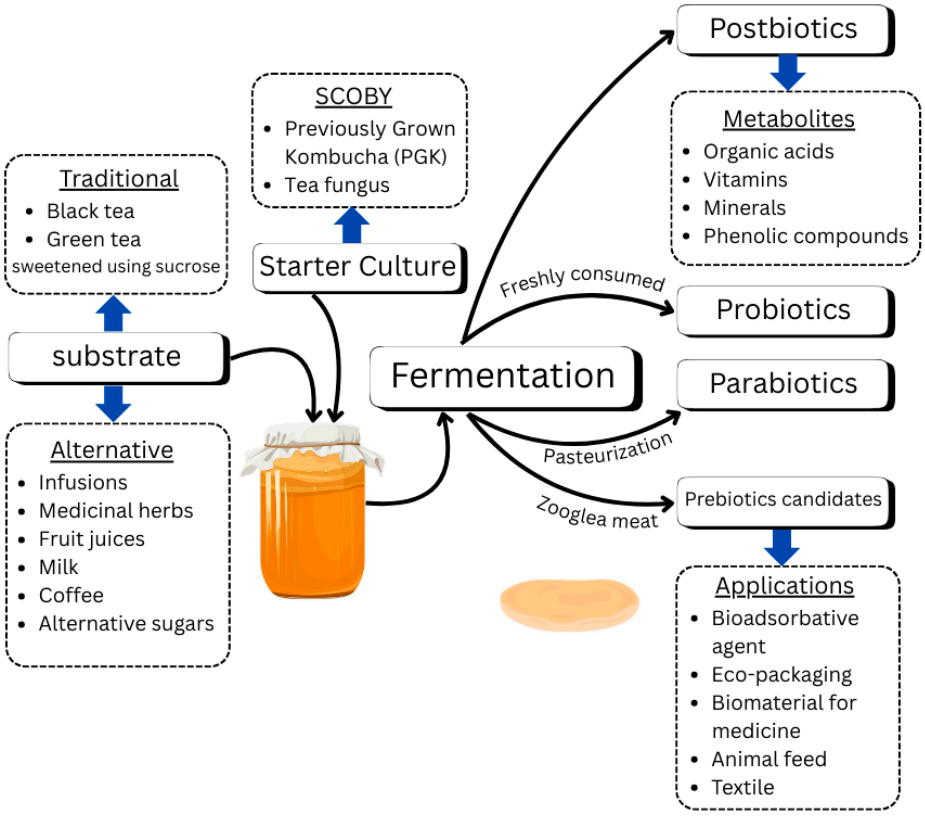


Figure 1. Overview of connections of kombucha production to postbiotics.

3. Microbial Ecology of Kombucha Fermentation

3.1. Kombucha Fermentation

Black, oolong, and green tea combined with sucrose has traditionally served as the primary substrate for kombucha fermentation. An overview of the standard stages in traditional kombucha production and the corresponding microbial communities involved, is illustrated in Figure 2 [23]. Within the SCOBY, a range of symbiotic interactions takes place. Kombucha fermentation is primarily driven by acetic acid bacteria (AAB) from the genera *Komagataeibacter*, *Acetobacter*, and *Gluconobacter*, along with yeasts such as *Zygosaccharomyces*, *Saccharomyces*, and *Brettanomyces* [24,25]. Additionally, lactic acid bacteria (LAB), including *Lactobacillus* and *Leuconostoc*, have been frequently identified in the beverage [6,24]. Initially, studies on the microbial composition of kombucha relied on culture-dependent methods [24,25]. However, the introduction of culture-independent techniques such as microbiome analysis and metabarcoding has significantly enhanced the understanding of the microbial diversity, metabolic processes, and interactions within the kombucha ecosystem [6]. Research employing high-throughput sequencing techniques has revealed that yeasts from the genera *Candida* and *Zygosaccharomyces* dominate in kombucha at the end of fermentation. Among bacteria, the most prevalent genera include *Komagataeibacter*, *Lyngbya*, *Gluconobacter*, *Lactobacilli*, and *Bifidobacteria* [26,27].

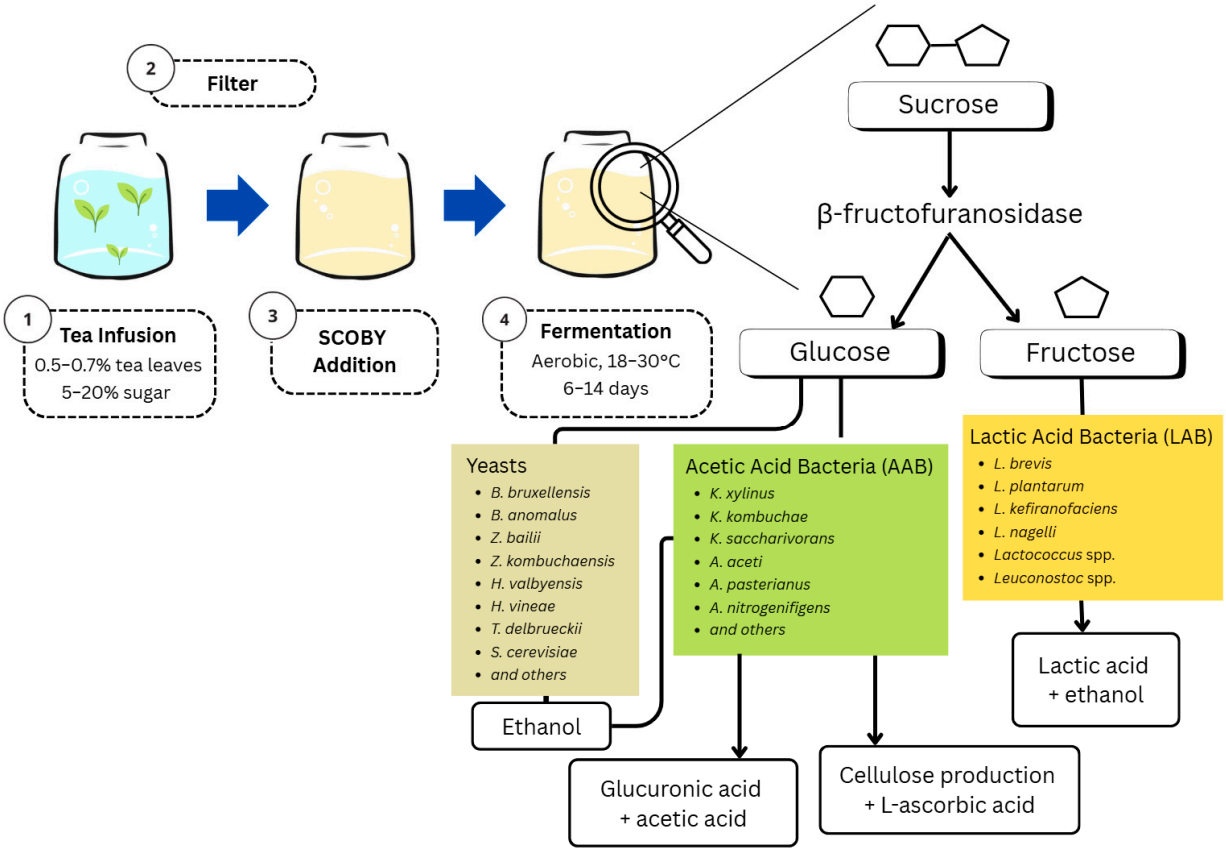


Figure 2. Typical steps of traditional kombucha production and microbial ecology involved. The different background colors represent a different group of microorganisms.

The fermentative process starts with yeasts secreting invertases (β-fructofuranosidase, EC 3.2.1.26), which break down sucrose into glucose and fructose, key substrates for subsequent metabolic activity. Then, *Saccharomyces* species metabolize glucose to produce ethanol, while *Zygosaccharomyces* species are more efficient at converting fructose into ethanol. Among the SCOBY components, yeasts are the primary producers ethanol, which is subsequently oxidized by AAB to form AA [28]. *Komagataeibacter* species, meanwhile, utilize glucose to synthesize bacterial cellulose, although ethanol, sucrose, and glycerol can also contribute to this process [29,30]. Besides AA and cellulose, AAB also produces GlucUA, which is associated with several health-promoting effects [29,31]. Furthermore, some *Gluconobacter* strains can convert D-sorbitol, derived from glucose, into vitamin C (L-ascorbic acid) [31].

Some lactic acid bacteria (LAB) species can metabolize glucose, yielding lactic acid as the primary product, while others may produce lactic acid along with ethanol and carbon dioxide through the pentose phosphate pathway. When fermenting fructose, LAB may produce AA instead of ethanol [32]. Additional compounds derived from bacterial and yeast metabolism in kombucha are discussed in Section 4 of this article.

The specific microbial composition and resulting metabolite profile of kombucha are influenced by several variables, including the type and concentration of tea and sugar used, SCOBY composition, oxygen availability, fermentation length, temperature, and storage conditions [6,12,23,33]. The typically low pH of kombucha, primarily due to elevated levels of AA, has been shown to inhibit the growth of various pathogenic microorganisms, such as *Helicobacter pylori*, *Escherichia coli*, *Salmonella typhimurium*, and *Campylobacter jejuni* [34–38]. Notably, kombucha retains antimicrobial activity even at neutral pH and following heat treatment, indicating the presence of additional antimicrobial compounds beyond AA.

Although it is originally made from sweetened tea (*Camellia sinensis*), kombucha is now being produced with alternative substrates such as fruits, fruit peels, milk, coffee, flower teas and herbal infusions [23,26,27,39–41]. Apart from increasing the diversity of flavors, metabolic profiles, and function claims of the final product, the use of alternative raw materials may also improve sustainability by encouraging the use of local produce (discussed in Section 6).

Some of the alternative base ingredients are listed in Table 1. Preparing kombucha from alternative sources often involves additional processing steps, especially when using fruits or agro-industrial byproducts. Primarily derived from fruit processing, these novel raw materials provide a diverse range of nutrients and phytochemical as substrates for SCOBY fermentation, opening new avenues for kombucha fermentation research [39–41].

Table 1. Alternative raw materials that have been studied in kombucha production.

Type of Raw Materials	Examples	References
Leaves	Oak leaves, red eucalyptus leaves, Lemonbalm, African mustard, papaya leaves	[42–47]
Flowers	Wax mallow flowers, hibiscus, malvaviscus, butterfly pea	[48–51]
Fruits	Grapes, coconut, papaya, goji berry, Acerola cherry, snake fruit, pear	[52–58]
Cereals	Wheatgrass, corn, rice, barley	[59–61]
Vegetables	Black carrot, broccoli, spinach	[62–64]
Coffee	Green and roasted beans	[65,66]
Herbs	Yerba-mate, linden, sage, mint, Rooibos, Zijuan, yarrow	[67–74]
Spices	Cardamom, cinnamon, turmeric, garlic	[75–77]
Milk	Yogurt, fermented milk, whey/cheese whey	[78–80]
Algae	Laver (*Porphrya dentata*), sea grapes	[81–83]
Sugars	Brown sugar, honey, coconut sugar molasses	[84,85]
Mixed ingredients	Infusions of more than 1 ingredient	[54,74,86,87]
Other	Soy milk, soy whey, corn silk	[88–90]

By incorporating alternative substrates in place of traditional tea, researchers have been able to investigate how fermentation unfolds and identify the key metabolites produced during the process. These investigations typically focus on sugar consumption, organic acid production, and the presence of bioactive compounds. While each substrate exhibits unique fermentation characteristics, the overall fermentation pattern tends to mirror that of traditional kombucha, marked by a decrease in pH, increased production of organic acids, and elevated levels of total phenolic compounds and antioxidant activity.

Although beverages made from non-*Camellia sinensis* sources cannot be classified as true kombucha, they are often referred to as "kombucha-like" due to the use of SCOBY as the starter culture. The complexity of these alternative substrates together with the variety of consortium in the SCOBY attract researchers to explore the fermentation results. These alternatives have also shown favorable sensory characteristics [39]. Despite the interest in diversifying kombucha substrates, relatively few studies have focused on how well SCOBYs adapt to these new environments [39–41]. Future research should therefore aim to assess the microbial dynamics, compatibility and adaptability of SCOBY cultures in fermenting alternative raw materials.

3.2. Kombucha SCOBY-Related Postbiotics

The health-promoting properties of kombucha have been primarily attributed to its probiotic content [91]. LAB and yeasts are already established as probiotics, while recent

research also suggests that AAB may also be characterized as such [92]. Emerging studies on postbiotics reinforce the potential of kombucha as a functional beverage, as it encompasses not only viable bacterial cultures but also microbial metabolites and cellular components AAB, LAB and yeasts, similar to other fermented foods [93]. However, considering that inactivation processes can extend shelf life and facilitate distribution logistics, postbiotics may represent the best form of delivering the health benefits associated with kombucha.

Nevertheless, to classify kombucha as a *postbiotic* product, it is necessary to identify the specific strains used, detail the methods of microbial inactivation, and quantify the resulting postbiotic composition [94]. Studies on the safety of kombucha consumption are also warranted, as the fermentation process may sometimes allow growth of pathogenic or toxin-producing microorganisms, especially when good manufacturing practices are not implemented or not enough optimization is done before using a novel substrate.

Although kombucha is a potential source of probiotic microorganisms, research into its postbiotic properties remains limited, offering a promising direction for future studies.

4. Metabolites Produced During Kombucha Fermentation

Bioactive metabolites are the result of microbial activity during fermentation, primarily from yeasts and bacteria. These microbial metabolites, especially organic acids, phenolic compounds, vitamins and minerals, and DSL (D-saccharic acid-1,4-lactone), are characteristic components of *postbiotics* (Figure 3). The different types of bioactive metabolites and postbiotics, along with its sources and ranges from previous studies are summarized in Table 2.

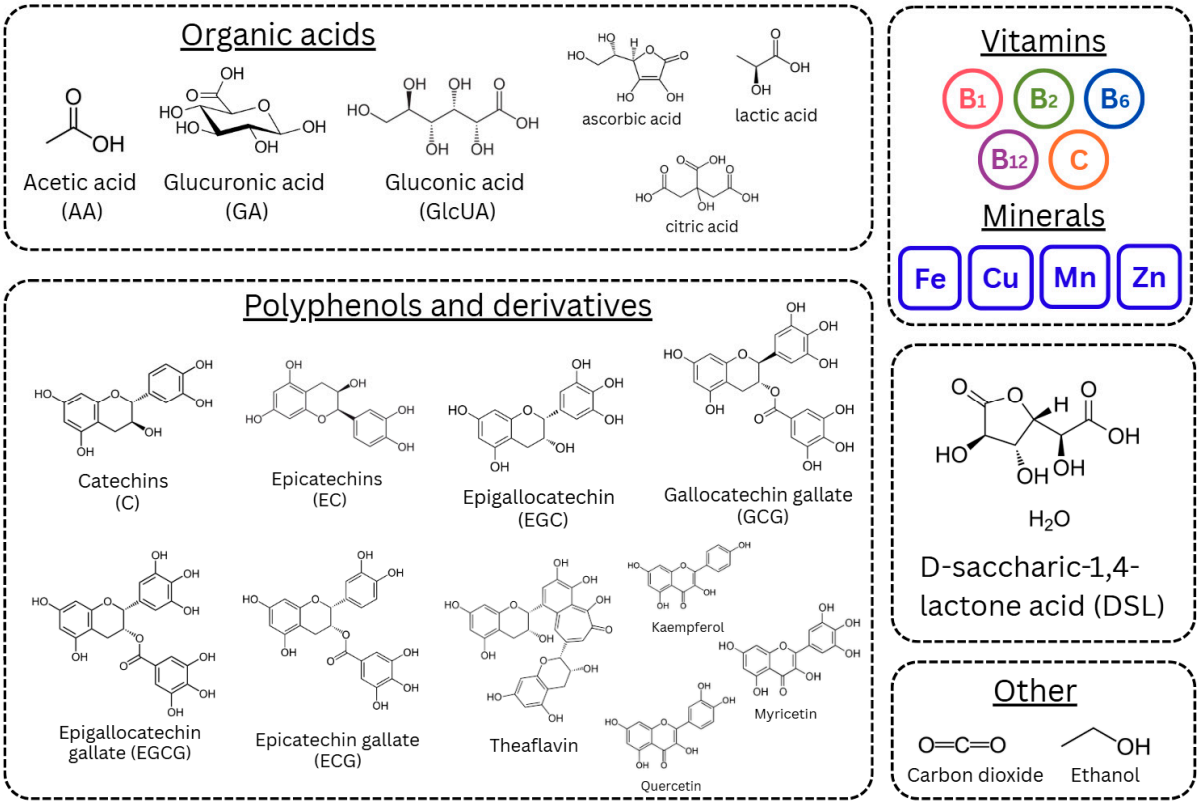


Figure 3. Bioactive metabolites and postbiotics produced during kombucha fermentation, including organic acids (e.g., AA, GA, and GlucUA), polyphenols, vitamins, and microbial-derived compounds. These components contribute to the beverage's antioxidant capacity, antimicrobial effects, and potential health-promoting properties.

Table 2. Bioactive metabolites that have been studied in kombucha production.

Type of Bioactive Metabolites and Postbiotics	Sources of Raw Materials	Ranges	References
Organic acids			
AA	Black tea	1.91 g/L	[87]
	Green tea	5.56 g/L	[95]
GA	Black tea	39 g/L	[96]
	Zijuan tea	2.3 g/L	[71]
GlcUA	Several sources	0.016–1.71 g/L	[97–99]
Succinic, citric, quinic, and malic acids	Several sources	below 1 g/L	[71]
Polyphenols and derivatives			
EGC	Pu-erh tea	0.031 mg/mL at 0 d to 0.041 mg/mL at the end-fermentation stage	[100]
EGCG		0.307 mg/mL at 0 d to 0.135 mg/mL at the end-fermentation stage	
GCG		0.153 mg/mL at 0 d to 0.075 mg/mL at the end-fermentation stage	
ECG		0.079 mg/mL at 0 d to 0.040 mg/mL at the end-fermentation stage	
TPC	Guava juice kombucha	360 mg GAE equivalent/g DW	[101]
Vitamins and minerals			
B_1	Black tea and green tea	0.46 to 0.74 mg/L	[102]
B_6		0.29 to 0.52 mg/L	
B_{12}		0.36 to 0.84 mg/L	
C		0.71 to 1.51 mg/L	
Co		0.004 µg/mL	
Mg		0.462 µg/mL	
F	Variety of tea	0.42 to 0.93 mg/L	[103]
DSL (D-saccharic acid-1,4-lactone)			
	Black tea	0.48–2.24 g/L	[24]
	Thai black tea	5.23 g/L	[104]
	Thai green tea	3.44 g/L	
	Chinese kombucha	0.057–0.132 g/L	[105]
Other metabolic compounds			
levans	Variety of tea	33 to 562 mg/L	[106]
d-phenyllactic acid	Kombucha tea	52 mg/L	[107]
5-methyltetrahydrofolate (5-MTHF)	Green tea kombucha	50.87 µg/mL in the liquid and 54.88 µg/mL in the biofilm	[108]

4.1. Organic Acids

Organic acids play a significant role in influencing the sensory qualities, chemical composition, and microbiological stability of food and beverages [73]. As fermentation advances, the levels of organic acids in the beverage gradually rise, leading to a reduction in pH. This acidification contributes to preservation and limits the growth of unwanted bacteria and fungi within the SCOBY [82,103,104]. Among the various organic acids present in kombucha, AA, GA, and GlucA are the most prominent, with AA being the most abundant [109]. On the other hand, high concentration of AA imparts a vinegar-like taste to kombucha, often having a negative impact on its flavor appeal.

AA is produced by AAB from ethanol via alcohol and aldehyde dehydrogenase. Its concentration during fermentation varies depending on factors such as temperature, type of SCOBY, and raw materials used. For example, a study reported 1.91 g/L AA after 13 days of

fermentation in black tea kombucha [87] and 5.56 g/L after 7 days of fermentation at 22 °C using green tea as substrate [95]. The amount of sucrose also influences yeast and lactic acid bacteria activity, and consequently ethanol and AA production. Lower sucrose levels result in lower alcohol and AA content. Over extended fermentation periods, AAB may begin oxidizing AA, leading to a gradual reduction in its concentration. Consumption of AA is considered beneficial due to its ability to suppress the activity of disaccharidase enzymes, slowing down gastric emptying and postprandial blood glucose levels. Additionally, AA may enhance glucose uptake in the liver and muscles by promoting glycogen synthesis in Streptozotocin induced diabetic rats [110], therefore being a potential functional compound in the prevention/management of type II diabetes.

GA is a naturally occurring compound known for enhancing the sensory qualities of products such as wine, vinegar, and honey by adding a mildly bitter yet refreshing flavor [111]. It is formed through the oxidation of D-glucose, primarily by AAB like *Gluconobacter oxydans* and *Komagataeibacter xylinus* [112]. Fermentation is generally believed to begin with the conversion of glucose into GA by *K. xylinus* [113]. GA has a wide range of applications as food additive and preservative, as well as in pharmaceutical products for treating anemia, hypocalcemia, and hypomagnesemia [112]. In a 60-day tea fermentation study by Chen and Liu [96], GA reached a concentration of 39 g/L, although its production was not observed during the initial days of fermentation [96]. Another study on kombucha made from Zijuan tea GA peaked at 2.3 g/L on the 14th day of fermentation [71]. GA seems to be a key flavor compound in kombucha, imparting a mild, smooth, and refreshing taste to the beverage [114]. Additional research is required to determine which substrates and fermentation conditions result in the production of GA and other compounds that improve the flavor profile.

GlcUA is produced by the oxidation of glucose by AAB belonging to the *Komagataeibacter* genus and is of particular interest among the organic acids produced during fermentation [113]. First, this compound plays a crucial role in the body's detoxification process due to its ability to bind to endobiotics (compounds produced within the body, such as bilirubin), as well as xenobiotics promoting their metabolic clearance. Additionally, it also plays a key role in maintaining hormone balance by enhancing the solubility and excretion of steroid hormones when necessary [92,115,116]. Studies have shown wide variation in GlucUA levels in kombucha. For example, Nguyen et al. [97] observed 0.03 g/L on the fifth day of fermentation using a SCOBY without lactic acid bacteria, Jayabalan et al. [98] found 1.71 g/L after 18 days, and Lončar et al. [99] reported 0.016 g/L after 21 days of fermentation. By the end of the kombucha fermentation process, GlucUA acid levels ranged from 0.839 to 1.158 g/L, whereas no detectable amount was present at the start of fermentation [76].

In all varieties of kombucha beverages, minor organic acids such as succinic, citric, quinic, and malic acids were also found at concentrations below 1 g/L [71].

4.2. Polyphenols and Derivatives

Traditional kombucha prepared from green, oolong, and black teas contains significant levels of phenolic compounds, which contribute to its health-promoting properties. These compounds are known for their antioxidant activity, and are associated with a reduced risk of degenerative conditions, cardiovascular issues, neurodegenerative disorders, and certain cancers [117]. The main phenolic compounds in kombucha include catechins, predominantly found in green tea, as well as theaflavins and thearubigins, which are more abundant in black tea [109]. Generally, green and yellow tea contain higher levels of total catechins compared to oolong, white, or black tea. Quercetin and myricetin are also found in higher amounts in green tea, while black tea provides a richer source of

kaempferol [118]. Utilizing different types of tea leaves for kombucha fermentation, thus, shows improved in vitro antioxidant properties, including superoxide radical scavenging activity and reducing power [119].

Studies have shown that kombucha contains higher levels of total polyphenols and flavonoids compared to sweetened black tea [24,120–123], likely due to the breakdown of complex compounds into smaller/simpler phenolics during fermentation. While overall catechin content declines during fermentation, concentrations of specific catechins like epigallocatechin (EGC) and epicatechin (EC) tend to increase [100]. Research also indicates that kombucha made from guava juice extract contains significant amounts of phenolic compounds such as gallic acid, catechin (C), guaiacol, and coumaric acid [101]. Furthermore, ester-type catechins like EGCG, ECG, and GCG decrease over time, whereas non-ester types including EC, C, and EGC show slight increases. Understanding the interactions between phenolic compounds and microbial activity is essential for optimizing SCOBY development and enhancing kombucha's functional properties.

4.3. Vitamins and Minerals

Kombucha contains a diverse range of water-soluble vitamins derived from green and black tea, including vitamin C and B-complex vitamins such as thiamine (B_1), riboflavin (B_2), niacin (B_3), pantothenic acid (B_5), B_6, biotin, folate (B_9), and cobalamin (B_{12}) [124]. These vitamins play essential roles in numerous physiological and biochemical processes but cannot be produced by the human body, making dietary intake necessary to maintain adequate levels [125]. Vitamins may also be produced or metabolized by microorganisms, and some interesting reports have determined the concentration of hydrosolubilic vitamins content that shown an increase in vitamin C levels during kombucha fermentation, from 0.71 to 1.51 mg/L by the fifteenth day. Moreover, the levels of B vitamins also rose, with vitamin B_1, B_6, and B_{12}, initially at 0.46, 0.29, and 0.36 to reaching concentrations of 0.74, 0.52, and 0.84 g/L, respectively [102]. LAB and yeasts can produce B-complex vitamins, which may account for the increase in their concentrations during kombucha fermentation. Strains like *Lactiplantibacillus plantarum*, *Limosilactobacillus fermentum*, and *Lactococcus lactis* synthesize vitamins B_1, B_2, and B_9. Yeasts like *Saccharomyces cerevisiae* and *Zygosaccharomyces bailii* also synthesize B-complex vitamins (B_1–B_{12}) and ergosterol, a precursor of vitamin D_2 [28].

Kombucha contains various minerals derived primarily from the tea used in its preparation. Green and black tea–based kombucha includes essential minerals like potassium (K^+), cobalt (Co^{2+}), manganese (Mn^{4+}), copper (Cu^{2+}), iron (Fe^{2+}), magnesium (Mg^{2+}), and fluoride (F^-). Bauer-Petrovska and Petrushevska-Tozi [102] measured trace amounts of these and other elements, reporting concentrations from 0.004 µg/mL for cobalt to 0.462 µg/mL for magnesium [102]. Toxic metals like lead (0.005 µg/mL which acceptable limit should not exceed 70–100 µg/mL in adults) [126] and chromium (0.001 µg/mL which the maximum concentration of 0.05 mg/L (50 ppb) is allowed in drinking water) [127] were also present, while cadmium was undetected. Unlike vitamins that can be syntesized by the microbial consortium, minerals are not. Fermentation has been shown to increase levels of some minerals (Cu, Fe, Mn, Ni, Zn), but not cobalt [102] which could be from SCOBY or additives from fermentation.

A concern over fluorine content in kombucha has been discussed. Fluoride supports hard tissue mineralization, but excessive intake can be harmful. Kombucha contains fluorine, primarily derived from the tea used in its production. Most dietary fluorine comes from food and beverages like tea, while a smaller portion comes from water and dental products. Jakubcyk et al. [103] found that fluorine levels in kombucha vary by tea type, ranging from 0.42 to 0.93 mg/L, lowest in white tea and highest in green tea. Since

municipal water may also add fluorine, the total content in kombucha can vary. A single glass of kombucha can meaningfully contribute to an adult's recommended daily fluorine intake [103].

4.4. DSL (D-Saccharic Acid-1,4-Lactone)

DSL is regarded as one of the most beneficial compounds in kombucha. Absent in unfermented tea [24], DSL is produced during fermentation through the activity of bacteria from the *Gluconacetobacter* genus. In particular, the *Gluconacetobacter* sp. A4 strain, when paired with lactic acid bacteria, has been shown to enhance DSL production [128]. DSL acts as a glucuronidase inhibitor, an enzyme linked to cancer development, exhibits strong antioxidant activity, and helps protect pancreatic β-cells from apoptotic damage. DSL is also linked to antioxidant activity, hepatoprotective effects, and reducing hyperglycemia, as well as preserving key compounds like GlucUA acid and glycosaminoglycans [105]. The concentration of DSL in the final kombucha product depends on both the type of tea infusion and the specific SCOBY used for fermentation. DSL concentration falls typically within the range of 0.48–2.24 g/L during a 21 d fermentation of black tea kombucha [24], while higher amounts have been reported in Thai kombucha: 5.23 g/L (black tea) and 3.44 g/L (green tea) after a 15 d fermentation [104]. Lower levels (0.057–0.132 g/L) were reported in Chinese kombucha, likely due to differing raw material and SCOBY compositions [105].

4.5. Emerging Trend for Metabiotics Studies in Kombucha

Beyond traditional components, new research highlights the presence of emerging metabolites such as exopolysaccharides (EPS), bioactive peptides, and various small molecules identified through advanced metabolomics. These compounds contribute to the functional properties of kombucha, including antioxidant, antimicrobial, and immunomodulatory effects [106–108,129–131]. As metabolomic tools continue to evolve, the identification and characterization of these emerging metabolites reveal new opportunities for understanding kombucha's health-promoting potential and expanding its use in functional food and nutraceutical applications.

A research group from Germany investigated the presence and structural characteristics of water-soluble EPS in kombucha fermented with green or black tea using SCOBYs from various sources [106]. After isolation, enzymatic hydrolysis, and structural analysis by NMR spectroscopy, levans (fructose-based polysaccharides) were identified as the predominant EPS in all kombucha samples, with minimal amounts of glucans detected. The levans exhibited low molecular weight and a variable degree of branching at position O1 (4.3–7.9%), and their concentration ranged from 33 to 562 mg/L depending on the SCOBY and tea type used [106]. This work provides the first detailed characterization of kombucha-derived levans and highlights the influence of fermentation conditions on their structural diversity.

Peng et al. (2023) explored the fermentation of soy milk with kombucha and fructo-oligosaccharides (FOS) to improve its stability, flavor, and functional properties [129]. In their study, FOS induced the growth of beneficial microbes, increased antioxidant activity, and boosted the production of health-related compounds like β-glucosidase and genistein. The optimal fermentation time was 84 h, during which the soy milk showed improved taste, reduced off-flavors, and higher levels of favorable compounds like citric acid and linalool. This symbiotic fermentation approach shows potential for the improvement of organoleptic characteristics of plant-based dairy alternatives [129].

In 2024, Larini et al. presented the first genomic and functional analysis of *Liquorilactobacillus nagelii* VUCC-R001, a strain isolated from kombucha tea. The nearly complete,

high-quality genome reported no genes linked to antibiotic resistance, virulence, or biogenic amine production, confirming its safety. Notably, the strain was capable of producing high levels of d-phenyllactic acid (52 mg/L) and dextran, highlighting its potential for use in food and biomedical applications. These findings offer new insights into the biotechnological potential of *L. nagelii* and its role in fermented foods [107].

Khan et al. [108] investigated the nutritional and microbial dynamics of green tea kombucha during fermentation, focusing on 5-methyltetrahydrofolate (5-MTHF), a vital folate derivative. Molecular analysis identified *Microbacterium* as the dominant genus, though species-level identification remained inconclusive. 5-MTHF levels increased over time, reaching up to 50.87 µg/mL in the liquid and 54.88 µg/mL in the biofilm by day 21. While total phenolic content rose during fermentation, flavonoids and carotenoids decreased. Notably, this is the first report of 5-MTHF in kombucha, highlighting its nutritional potential, especially for prenatal health. Fermentation between days 7–14 was optimal for maximizing bioactive compounds [108].

The potential effects of cell-free metabolites from *Gluconobacter oxydans* strains isolated from kombucha, focusing on their safety, antimicrobial activity, and anticancer properties were evaluated [130]. Using gastric (AGS), colorectal (HT-29), and healthy (HUVEC) human cell lines, the results confirmed the safety of the tested strains and demonstrated notable anticancer activity, particularly against gastric adenoma cells. Among the strains, KNS30 showed the strongest potential. These findings suggest that kombucha-derived AAB may serve as a source of safe and effective postbiotics for cancer prevention or complementary therapy.

Verdier et al. [131] investigated nitrogenous nutrient dynamics during kombucha fermentation, focusing on protein and free amino nitrogen (FAN) levels over 12 days. By comparing monocultures, cocultures, and original kombucha, researchers found that microbial interactions influenced FAN consumption and supported more stable nutrient use and microbial growth. Electrophoresis revealed a common 15 kDa protein and a unique 21 kDa protein linked to *Acetobacter indonesiensis*, along with moonlighting proteins and extracellular vesicles from this bacterium. These findings highlight the complex role of microbial consortia in nutrient management and suggest new functions for bacterial vesicles in kombucha fermentation [131].

5. Health Benefits and Functional Properties of Kombucha-Derived Postbiotics

As mentioned in Section 4, the combined activity of the diverse microbes in the SCOBY, produce a broad range of metabiotics. These metabolites have been shown to offer various health benefits, including anti-inflammatory, antioxidant, antibacterial, antidiabetic, and anticancer activities, primarily in pre-clinical studies. Additional effects include cholesterol reduction, enhanced liver metabolism, strengthening of the immune function, and improved gastrointestinal health, usually when consumed as whole foods, i.e., containing both the whole range of probiotics and postbiotics [132]. A notable trend in the development of functional foods is the resurgence of traditional fermentation techniques utilizing wild starters, rather than single-organism starters. Sourdough bread, sauerkraut, keffir, and amazake are all examples of traditional foods and beverages that are experiencing a revival, mainly due to an increased awareness of gut health. New probiotic, symbiotic, or postbiotic products usually involve formulations with microbial consortia, particularly combinations of lactic acid bacteria (e.g., *Lactobacillus* spp.) and yeasts (e.g., *Saccharomyces* spp.), to better regulate metabolite production and interspecies interactions [133–135] and meet the demands of health-conscious consumers.

5.1. Antioxidant Activity

The antioxidant activity of kombucha is primarily attributed to the production of metabiotics by its diverse microbial consortium, with flavanols being the main compounds responsible for these effects. During microbial fermentation, flavanols undergo structural modifications that lead to the conjugation of aromatic rings and the presence of free 3-OH groups. This biotransformation enhances the antioxidant potential of flavanols, as well as other flavonoids in kombucha, when assessed through metal ion chelation, scavenging of prooxidant enzymes, and inhibition of molecular oxidative processes [136–138].

5.2. Antimicrobial Activity

The antibacterial properties of kombucha are primarily attributed to its organic acids, polyphenols, and lactic acid bacteria [139]. The kombucha SCOBY microbiome produces various *metabiotics*, primarily organic acids (notably AA), phenolic compounds, bacteriocins from LAB, alcohols, and aldehydes, as well as, *paraprobiotics* like moonlight proteins (Table 3). These postbiotics act synergistically to inhibit a broad spectrum of pathogenic bacteria and fungi, including common foodborne and human pathogens. The antimicrobial potency depends on the fermentation conditions, microbial composition, and substrate type. This complex microbial interaction enhances kombucha's potential as a natural antimicrobial and food preservative agent. Kombucha postbiotics exhibit broad-spectrum antimicrobial activity against a variety of pathogenic microorganisms. Among bacteria, strains shown to be inhibited include *Staphylococcus aureus*, *Escherichia coli*, *Helicobacter pylori*, *Campylobacter jejuni*, *Yersinia enterocolitica*, *Agrobacterium tumefaciens*, *Shigella sonnei*, *Salmonella enteritidis*, *Salmonella Typhimurium*, *Listeria monocytogenes*, *Bacillus cereus*, *Proteus hauseri*, *Shigella dysenteriae*, *Salmonella Typhi*, *Vibrio cholerae*, and multiple *Alicyclobacillus* species such as *A. acidoterrestris*, *A. herbarius*, *A. acidophilus*, *A. acycloheptanicus*, and *A. hesperidum*. In terms of antifungal activity, kombucha-derived compounds have been shown to inhibit *Candida albicans* and several human-pathogenic fungi, including *Alternaria* species, *Aspergillus flavus*, *Fusarium oxysporum*, and *Trichoderma* species [35,73,101,140].

Table 3. Summary of Antimicrobial Mechanisms in Kombucha.

Metabiotics from Kombucha	Description	Target/Effect
Acetic Acid	Major antimicrobial agent; lipophilic properties allow penetration of both Gram-positive and Gram-negative bacteria	Broad-spectrum antibacterial activity
Polyphenols	Destabilize microbial cell surfaces and cytoplasmic membranes	Enhanced inhibition of enteric pathogenic bacteria
Lactic Acid Bacteria (LAB) Metabolites	-Production of bacteriocins (ribosomal peptides) with antimicrobial activity against bacteria and fungi -Proteolytic enzymes releasing antimicrobial peptides and amino acids	Antibacterial and antifungal effects
Alcohols and Aldehydes	Contribute to the antimicrobial spectrum	Additional antibacterial and antifungal activity
Extracellular Vesicles and Moonlighting proteins	Produced by bacteria such as *Acetobacter indonesiensis*; potentially involved in antimicrobial activity	May enhance bacterial inhibition mechanisms

5.3. Anicarcinogenic Activity

Kombucha contains various bioactive compounds that contribute to its anticancer potential. These include GlucUA, GA, DSL, AA, ascorbic acid, succinic acid, dimethyl 2-(2-hydroxy-2-methoxypropylidene) malonate, and vitexin. These compounds are known to interact with key cancer-related protein targets such as HIF-1α, VEGF, IL-8, COX-2, as well as apoptotic regulators including caspases-3, -8, and -9, PARP, Bax, Bcl-2, p53, p21, MMP-2, MMP-9, and β-actin [141]. The anti-carcinogenic potential of kombucha is partly attributed to GlucUA, a key metabiotic produced during fermentation. This compound

supports the body's detoxification system by conjugating carcinogens and other toxins to form glucuronides, water-soluble molecules that are efficiently excreted in urine. This process reduces the overall toxic load in the body and, consequently, the risk of cancer. Additionally, GlucUA helps sustain this detoxified state by inhibiting β-glucuronidase, an enzyme that can reverse the detoxification process by releasing free carcinogens from glucuronides [116]. Other fermentation by-products in kombucha, including GA and DSL, also demonstrate synergistic anticancer effects, further highlighting kombucha's potential as a functional beverage for cancer risk reduction [141,142].

5.4. Gut–Brain Axis

An increasing amount of research supports the interconnected relationship between the brain and the gut microbiota. This connection, known as the gut–brain axis, is a bidirectional communication network that influences both physiological and psychological functions. The gut microbiota can affect brain activity through metabolites and signaling molecules that travel via the bloodstream. Conversely, the brain can alter the composition and activity of gut microbes through neuronal and hormonal mechanisms. This complex interaction is primarily mediated by three key pathways: the autonomic nervous system (including the enteric nervous system and the vagus nerve), the immune system, and the neuroendocrine system [143].

Kombucha is well known for its rich content of probiotics and parabiotics. Probiotics, in particular, have been scientifically proven to support the gut–brain axis, playing a beneficial role in both digestive and mental health. However, as stated by Batista et al. [143], scientific evidence on the effects of kombucha on mental health and the gut–brain axis is currently limited, with only a few inconclusive studies available. While kombucha may potentially offer indirect neuroprotective benefits due to its antioxidant, anti-inflammatory effects, there is a lack of data from clinical trials to confirm these effects. The effects from kombucha metabiotics such as glutamate and GABA, which are involved in mood regulation and cognitive function, also await corroboration from interventional studies. Rigorous pre-clinical studies and the establishment of standardized production guidelines are urgently needed prior to evaluating the safety, efficacy, and potential role of kombucha in mental health support [143].

5.5. Antidiabetic Effect

Although the antidiabetic effects of kombucha tea have been investigated in vitro, further clinical trials are necessary to confirm its efficacy in reducing glucose absorption into the bloodstream. Several studies have demonstrated that kombucha exhibits inhibitory activity against α-amylase and α-glucosidase, key enzymes involved in carbohydrate hydrolysis, thereby mitigating postprandial hyperglycemia by delaying glucose uptake [144–146]. Another aspect of its antidiabetic effect is attributed to its antioxidant capacity, a key contributor to diabetes pathogenesis [147]. As discussed in Section 5.5, antioxidant activity increases with extended fermentation due to the accumulation of flavonoid metabolites. In the recent study by Mouguech et al. [148], they explored the sustainable conversion of date palm (*Phoenix dactylifera*) leaf waste from southern Tunisia into value-added products through kombucha fermentation, using two local varieties, Deglet Nour and Alig. Fermentation significantly enhanced the total phenolic content and bioactivity, particularly in the ethyl acetate extract of Alig, which showed strong antioxidant (82.76% DPPH inhibition) and antidiabetic activity (IC_{50} = 20 μg/mL) [148]. Collectively, these findings support the potential of Kombucha as a functional beverage with relevance in diabetes management, but robust, high-quality clinical studies are essential to validate

the therapeutic potential of these products and to determine the most effective strategies for their use in managing glycemic control in individuals with diabetes.

6. Sustainability Aspects of Kombucha Production

The global food and beverage industry has raised its concern about sustainability, including climate change, waste management, and resource depletion [149]. Not only are consumers seeking sustainable or green products, but producers also want to create products that minimize environmental impact, support circular economies, and use resources efficiently. Kombucha is famous for its health benefits; however, with growing concern about sustainability, its production should align with sustainable approaches [150,151].

6.1. Low-Impact Production Process

Kombucha production is simple, involving a fermentation process. The main ingredients are water, tea, sugar, and SCOBY [23]. The fermentation is carried out between 20 and 30 °C, so there is no need for energy-intensive temperature control systems [152]. Its process ranges from 7 to 14 days, depending on the desired acidity and flavor profiles [152,153]. The short production time contributes to a short turnover, which reduces the need for prolonged storage. It means that the process will not require high energy.

Decentralized production is also one practice that provides another sustainability advantage. Kombucha can be produced at home or by small-scale local businesses, which reduces long-distance transportation from large-scale centralized operations [154]. This localized approach contributes to lower greenhouse gas emissions and energy consumption resulting from transportation. However, fermented foods can harbor spoilage bacteria and toxin-producing fungi. Thus, proper microbiological and toxicological monitoring remains a challenge for small producers.

6.2. Utilization of Alternative By-Products for Kombucha Production

The sustainability of kombucha production can be enhanced by incorporating food and agricultural waste, promoting both waste reduction and efficient resource use. Defective fruits and herbs that cannot be sold as fresh produce can be used as substrates in kombucha production [155–157]. This practice reduces the environmental impact of food waste, while presenting opportunities to improve the flavor profile of kombucha [155]. Another promising approach is the use of cocoa bean shells as raw materials in kombucha-like beverage [158]. It can reduce waste generated from cocoa production, decrease environmental impact, and increase resource efficiency. Kombucha production can also be produced using olive leaves, which are rich in polyphenols [157]. The total phenolic content of tea kombucha and kombucha produced with olive leaves is similar [157]. This substitution can replace traditional tea, lowering both costs and waste.

Alternative sugar sources and agricultural by-products, such as molasses, fruit peels or their extracts, and coffee by-products, have been explored as sustainable alternatives to refined cane sugar [155,159,160]. Molasses is considered a good ingredient for fermentation because it is cheap and contains nutrients for bacteria and yeast [153]. Cheap by-products, including tea dust and molasses, can be used as nitrogen and carbon sources for kombucha production [153]. Angela et al. [161] also focused on using molasses instead of table sugar to produce bacterial cellulose through the kombucha fermentation process. These materials are by-products of food processing chains. Utilizing these resources offers cost-effective and environmentally friendly options for kombucha production.

The use of cherry, persimmon, and pomegranate instead of tea leaves showed that the fruit-derived kombucha reaches the target pH faster than traditional kombucha produced with tea leaves [162]. The shorter fermentation time contributes to a reduced

processing period. This means that the total operating cost can be lowered, providing economic benefits.

Apart from its ingredients, kombucha production generates solid waste, such as spent tea leaves or fruit residues, which are biodegradable and can be composted or repurposed. Some producers have utilized these by-products in composting or animal feed, promoting zero-waste principle. Utilizing waste materials can lower production costs while promoting environmental sustainability by reducing landfill contributions [163,164]. Using local by-products as alternative ingredients in kombucha production can also support the local economy and reduce waste. This offers benefits in all areas of sustainability, including economic, environmental, and social aspects.

6.3. Kombucha in the Circular Bioeconomy

With the kombucha market projected to grow by USD 7.97 billion from 2024 to 2029 at a Compound Annual Growth Rate of 23.5% [165], this growth supports kombucha's role in the circular bioeconomy. Circular economy supports sustainability by transforming traditional linear supply chains into circular supply chains through reducing, reusing, recycling, and repurposing [166]. Kombucha promotes a circular bioeconomy by transforming biological resources and by-products into high-value materials [167,168]. A circular economy between the food and beverages segment and other industries can be applied [169].

The SCOBY, which plays a key role in fermentation, can be repurposed after its primary use in kombucha production. It is reported that there is an active international trade of SCOBY, reflecting its growing commercial value and applications in functional food and beverage industries [170,171]. Mat Zin Boestami et al. [172] studied the use of pumpkin peel to produce kombucha SCOBY cellulose and found that the physicochemical properties of the cellulose are similar to the kombucha SCOBY cellulose produced from tea. From this aspect, it promotes a circular bioeconomy in which by-products from other industries are utilized.

The spent SCOBY biomass can be utilized as a biodegradable polymer with a wide range of applications because it is also a source of bacterial cellulose [173]. This cellulose can be processed into bio-leather for use in textiles, footwear, or packaging, serving as sustainable alternatives to animal-derived leathers or petroleum-based plastics [169,174–178]. In some cases, they have shown potential for use in pharmaceutical products due to their bioactive properties and pharmacological effects [40,170]. Other applications include the potential use of SCOBY as a biosorbent [5] and a living filtration membrane for water treatment [179].

Circularity can be achieved by integrating kombucha production with local agriculture. Kombucha producers can utilize fruit residues or herb waste from local farms while returning composted residues or SCOBY biomass as organic soil amendments. These synergistic models support nutrient cycling, reduce waste transport, and promote social collaboration among stakeholders in the supply chain [180,181].

7. Food Safety Aspects of Kombucha

While kombucha gains recognition as a potential functional beverage, it is important to acknowledge that inherent risks may be associated with the consumption of 'novel' foods, even when there is an established history of their use within certain countries, regions, or communities.

Safety issues may arise in cases of kombucha overconsumption or associated with alcohol intake, or intake by individuals with underlying health conditions [182]. There has been a reported case of severe liver necrosis in a 42-year-old woman following daily consumption of 940 mL (32 ounces) of kombucha, in conjunction with wine, over a three-

month period [183]. Usnic acid, a compound previously associated with liver cell necrosis in animal studies, was discussed as a potential cause in this case [183]. CDC has also reported two cases of severe acidosis by kombucha, including one fatality [5]. However, FDA analysis did not detect pathogens or toxins in the tea, and other 115 persons who drank kombucha made with SCOBY from the same source did not experience any adverse effect [5]. A 22 year-old male with HIV, presented fever, and shortness of breath within twelve hours of Kombucha ingestion [4]. Other reported adverse effects probably linked to kombucha consumption are: jaundice (55 year-old woman with alcoholic liver disease) [182]; nausea, vomiting, and head and neck pain (51 year-old woman, taking thyroid hormone and estrogen replacements) [182]; allergic reactions (two patients) [184]; autoimmune inflammatory muscle disease in a 53 year-old Asian man with predisposition factors [185]; and a rare sinus infection by *Salmonella enterica* serovar Enteritidis in a 77 year-old woman with sinus carcinoma [186]. Two cases of lead intoxication through kombucha, and one case related to kefir consumption. [187,188] In all cases, lead-glazed ceramic pots have been used for fermentation, suggesting that acids produced during fermentation eluted lead from the glaze. Lead is also known to be eluted from crystal decanters to wine and spirits contained in it, thus emphasizing the importance of standardizing manufacturing practices to avoid such pitfalls.

The potential risks of kombucha consumption have been reviewed by Jalayaban et al. [5], and de Miranda et al. [189]. The adverse effects documented in these publications, which are separated by eight years, showed little difference, indicating no widespread safety issues associated with kombucha consumption in moderate quantities (less than 120 mL per day). However, there is still lack of data indicating what would be the upper limit for safe consumption. In addition, the varying alcohol content suggests that kombucha should be avoided by expecting women and children [189].

Similarly to other fermented foods, kombucha relies on a rapid pH drop to avoid growth of spoilage and pathogenic bacteria. Although necessary as a carbon source, the addition of sucrose to tea creates a nutrient-rich environment conducive to the proliferation of opportunistic bacteria or fungi that may be introduced during the brewing process, particularly under suboptimal hygiene conditions and inadequate temperature control during preparation and fermentation, as well as from the source of SCOBY. Hence, fermented foods are by nature prone to microbiological safety concerns. To illustrate, yogurt and other fermented dairy products were responsible for 15 outbreaks between 2005 and 2022 in the USA, Canada and Europe, mainly caused by pathogenic bacteria (Salmonella spp., *Listeria monocytogenes*, *E. coli*) and molds, as well as their toxins [190]. Major product recalls of dairy products are still fairly common, even in developed countries. Nevertheless, this represents a major progress from the 1940s when raw milk and associated products were responsible for 25% of all foodborne and waterborne disease outbreaks [191].

As the consumption of kombucha extends beyond its traditional context, it is crucial to address the accompanying safety concerns with appropriate scrutiny. The wider distribution and increased popularity kombucha may heighten the risk profile and potential issue. This highlights the necessity of implementing good manufacturing practices (GMP) and good hygiene practices (GHP) to ensure that the final product remains both functional and safe for consumers. Establishing regulatory frameworks is also an important step to ensure the safety of kombucha products. Brazil (Normative Instruction No. 41, 17 September 2019, from the Ministry of Agriculture, Livestock and Supply, MAPA, [192]), and Canada (Safety of fermented foods, BC Centre for Disease Control (BCCD) [190] have already implemented such measures aiming at standardizing manufacturing and hygiene practices, and setting guidelines to protect the consumer, especially those who may be more vulnerable to adverse effects.

8. Conclusions and Future Perspectives

Kombucha represents a promising functional beverage with potential health-promoting properties, arising from its content of probiotics and postbiotics (including metabiotics and paraprobiotics) that emerge during fermentation. This review emphasizes the relevance of these metabiotic components and their interplay in the context of kombucha fermentation. Despite its growing popularity mainly supported by anecdotal evidences, significant challenges remain in establishing kombucha as a scientifically validated functional beverage. There is a critical need for rigorous, controlled clinical trials in humans to substantiate its health claims and elucidate its mechanisms of action. The development of standardized kombucha models for experimental reproducibility is also essential, given the wide variability in composition due to fermentation conditions, microbial consortia, and substrate choice.

Kombucha, as a source of metabiotics, holds promise for various health benefits and represents a sustainable, health-promoting beverage. However, more interventional studies and evidence-based research is needed for promoting kombucha consumption as part of a health-supportive diet. Conversely, kombucha demonstrates potential for use as a sustainable adsorbent and in the development of novel materials, highlighting its versatility not only as a bioactive beverage but also as a source of environmentally friendly, cellulose-like material.

Recent advances in precision fermentation and microbial bioengineering may improve the targeted production of bioactive metabolites in kombucha, improving its consistency, functional potential, and safety. Robust safety assessments and regulatory frameworks are also paramount to ensure product quality and consumer safety.

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Abbreviations

The following abbreviations are used in this manuscript:

SCOBY	Symbiotic Consortium Of Bacteria and Yeast
AAB	Acetic Acid Bacteria
LAB	Lactic Acid Bacteria
AA	Acetic Acid
GA	Gluconic Acid
GlcUA	Glucuronic Acid
DSL	D-saccharic acid-1,4-lactone
EGCG	Epigallocatechin gallate
EGC	Epigallocatechin
EC	Epicatechin
ECG	Epicatechin gallate
GCG	Gallocatechin gallate

GC	Gallocatechin
C	Catechin
TPC	Total Phenolic Content
EPS	Exopolysaccharides
FOS	Fructo-oligosaccharides
5-MTHF	5-methyltetrahydrofolate
FAN	Free Amino Nitrogen
GABA	Gamma-Aminobutyric acid

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