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Antimicrobial potential of kombucha against foodborne pathogens: a review

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REVIEW ARTICLE

Abstract

The survival of foodborne pathogens under stressful food processing conditions and in host's gastrointestinal tract has been widely reported to cause the outbreak of human diseases. Generally, antibiotics have been used to eliminate the microbial flora of foodborne pathogens. However, the overuse of antibiotics has contributed to the emergence and spread of multi-drug-resistant foodborne pathogens. Kombucha is a beverage prepared by fermenting sugared tea or other substrates with a symbiotic culture of yeasts and bacteria, and has been proved to fight foodborne pathogens and affect gastrointestinal microbial flora to prevent foodborne illnesses. In this context, this review primarily focused on microbiological and chemical compositions of kombucha obtained by fermenting different substrates. It further discussed the antimicrobial activity of kombucha, as well as potential antimicrobial agents found in kombucha, and the limitations of kombucha in the food industry. In addition, the need for developing antimicrobial agents from kombucha has been discussed for potential applications. The information provided in this review indicates that kombucha could serve as an alternative approach to control pathogens in place of using antibiotics.

Keywords: kombucha; foodborne pathogens; antimicrobial activity; food safety

Introduction

Foodborne pathogens have gained much attention because of frequent outbreaks of serious safety issues. In general, foodborne illnesses are characterized by acute conditions such as hemorrhagic colitis and hemolytic uremic syndrome (caused by *Escherichia coli* O157:H7), listeriotic and abnormalities (caused by *Listeria monocytogenes*), bacterial gastroenteritis (caused by *Campylobacter*, *Salmonella*, and *Vibrio parahaemolyticus*), chronic arthritis (caused by *Shigella* and *Salmonella*), and even colon cancer (caused by *Salmonella*) (Buchanan *et al.*, 2017; Li *et al.*, 2019; Luo *et al.*, 2018; Ssemanda *et al.*, 2018). The World Health Organization (WHO) has reported around 600 million cases of foodborne diseases and 420,000 related deaths occurring annually due to pathogens (Shan *et al.*, 2019).

Conventional physical treatment may efficiently deactivate foodborne pathogens but influence the functional and sensory properties of foods. Chemical agents, including antibiotics, also have been used widely to reduce microbiological contamination done by foodborne pathogens. However, misuse of antibiotics has contributed to the large spread of foodborne pathogens that have become resistant to multiple antibiotics (Caniça *et al.*, 2019; Liao *et al.*, 2020; Yuan *et al.*, 2020). Consumption of contaminated food products could transfer resistant genes from antibiotic-resistant microorganisms to the human body through mobile genetic elements, leading to foodborne diseases, and hence enormous pressure on medical system (Das *et al.*, 2017). This led researchers to develop novel methods to fight foodborne pathogens.

Recently, in order to reduce the heavy burden of foodborne diseases, natural antiseptic strategies have been increasingly developed to control foodborne pathogens (Ghazy *et al.*, 2021; Kim *et al.*, 2021; Savas *et al.*, 2020; Zhu *et al.*, 2021). Kombucha is known as anacidic and sweet refreshing beverage obtained from fermented sugared tea (Cardoso *et al.*, 2020) or other substrates such as grape juice (Ayed *et al.*, 2017), soursop (Tan *et al.*, 2020), yarrow (Vitas *et al.*, 2018), coffee (Bueno *et al.*, 2021), and milk (Kruk *et al.*, 2021). This fermentation is carried out by a characteristic consortium of yeasts, acetic acid bacteria, and often, but not always, lactic acid bacteria (Figure 1) (Coelho *et al.*, 2020). The popularity of kombucha has spread widely due to its high nutritive and healthy values (Jayabalan *et al.*, 2014; Leal *et al.*, 2018).

Although some studies have summarized the biological activities of kombucha (Coelho *et al.*, 2020; Jayabalan *et al.*, 2014; Leal *et al.*, 2018), knowledge of its antimicrobial activity against foodborne pathogens and potential antimicrobial mechanism is still limited. In the context of above discussion, this review aimed to provide an overview of the current knowledge related to chemical and microbiological compositions of kombucha obtained by fermenting various substrates, the potential antimicrobial agents found in kombucha, and the limitations of kombucha in the food industry. In addition, need for developing antimicrobial agents from kombucha is discussed for potential applications. A comprehensive online literature review was conducted from January 2021 to July 2021 by using the following keywords on the web of science: kombucha and/or foodborne pathogens. In addition, for each selected publication, the reference section was examined to identify additional relevant publications. The information provided in this review indicates that kombucha could serve as an alternative approach to antibiotics to control pathogens.

Knowledge of Kombucha: Microbiological and Chemical Composition

Microbiological composition of kombucha

The difficulty in understanding kombucha fermentation is due to the high diversity of microorganisms and their complex interactions (May *et al.*, 2019). Yeasts such as *Zygosaccharomyces*, *Dekkera*, *Pichia*, *Hanseniaspora*, *Zygowilliopsis*, *Candida*, and *Saccharomyces*, found in kombucha appear to be complicated, with the dominant species changing during the fermentation process (Coton *et al.*, 2017; Villarreal-Soto *et al.*, 2018). Yeasts have high

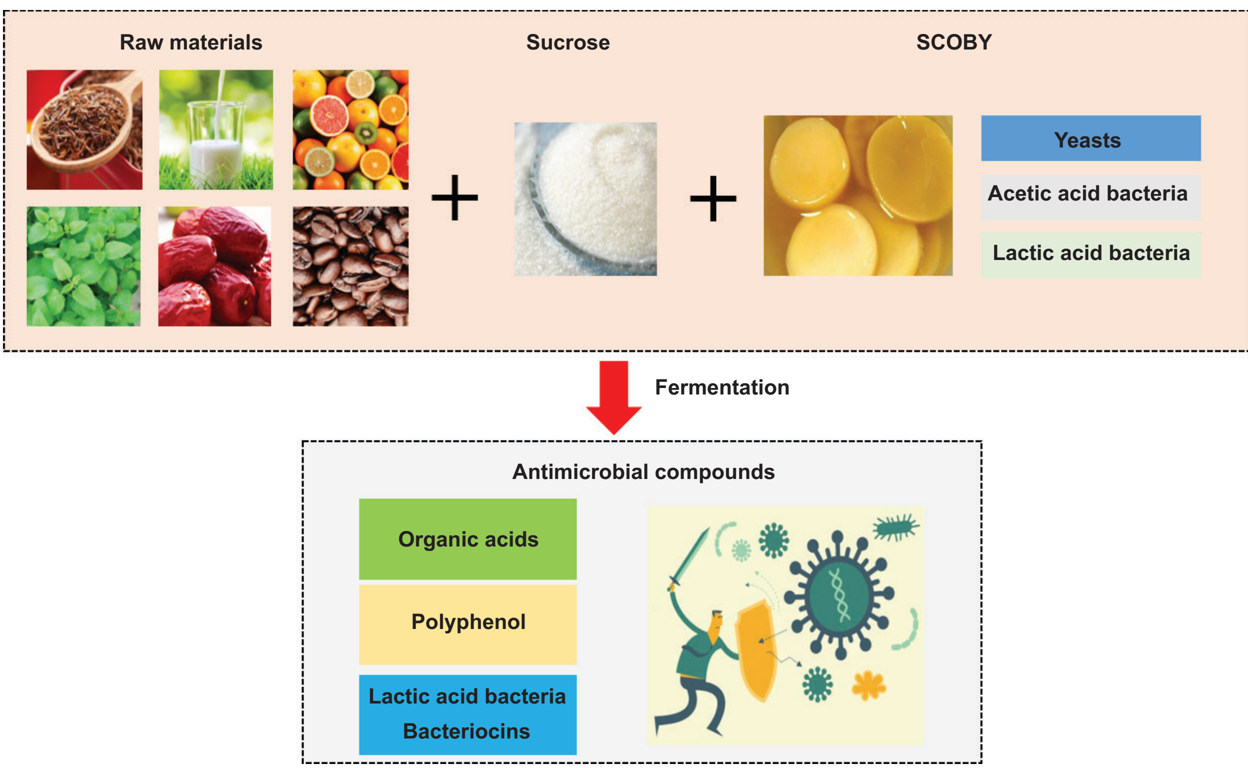

Figure 1. Kombucha fermentation and its antimicrobial activities.

fermentative ability to hydrolyze sucrose into fructose and glucose by action of invertase, followed by the generation of ethanol via glycolytic pathway. However, high concentration of alcohol is harmful to microorganisms through modifications to the structures, functions, and integrities of cellular membranes (Teoh *et al.,* 2004). Ethanol can be reduced by aldehyde and alcohol dehydrogenase produced by acetic acid bacteria that oxidize it and produce acetic acid via the Krebs cycle (Gomes *et al.,* 2018). This acetic acid conversion could be stopped when the desired taste of the beverage is achieved. The acidic conditions in kombucha protect the system from the invasion of pathogenic microorganisms (Coelho *et al.,* 2020). The acetic acid bacteria contained in kombucha is mostly represented by *Komagataeibacter*, *Acetobacter*, *Gluconacetobacter*, and *Gluconobacter* (Arıkan *et al.,* 2020; Tran *et al.,* 2020). Genera of *Komagataeibacter* and *Gluconacetobacter* can also synthesize cellulose chains to form a surface biofilm by oxidation reactions with glucose dehydrogenase. This biofilm protects microorganisms from extreme environmental challenges such as ultraviolet (UV) radiation (Coelho *et al.,* 2020). In addition, lactic acid bacteria (*Lactobacillus*, *Lactococcus*, *Leuconostoc*, and *Oenococcus*) have been reported to be frequently isolated and identified in kombucha from different areas (Marsh *et al.,* 2014). It must be mentioned that the presence of lactic acid bacteria could improve the survival and biological functions of acetic acid bacteria (Nguyen *et al.,* 2015; Pei *et al.,* 2020). However, the microbial composition of kombucha samples, described in separate studies, is affected by various factors, including the incubation temperature and time, raw materials, source of sugar, and selected starter (Morales, 2020; Neffe-Skocińska *et al.,* 2017). Hence, it is not easy to find out an exact consortium of kombucha for industry applications.

In most studies, the production of kombucha was carried out on a low scale, while vital fermentation parameters, such as oxygenation and sugar content distribution, are ignored (Arıkan *et al.,* 2020; Cardoso *et al.,* 2020; Kaewkod *et al.,* 2019). To unravel a core microbial composition essential for controlling the fermentation of kombucha, Coton *et al.* (2017) conducted a study to explore microbial composition from kombucha fermentation on industrial level. Dominated yeasts are identified as *Dekkera*, *Hanseniaspora*, and *Zygosaccharomyces*, while *Gluconobacter oxydans*, *Gluconacetobacter europaeus*, *Acetobacter peroxydans*, and *Gluconacetobacter saccharivorans* are dominant acetic acid bacteria found in kombucha.

Chemical components of kombucha

High nutritive values of kombucha are partly attributed to its microbial community established during the fermentation of kombucha (Coelho *et al.,* 2020). As shown in Table 1, the chemical analysis of kombucha has confirmed the presence of various compounds, such as organic acids (tartaric acid, malic acid, citric acid, acetic acid, quinic acid, oxalic acid, citric acid, succinic acid, D-glucuronic acid, and ascorbic acid), sugars (sucrose, glucose, and fructose), minerals (manganese, zinc, copper, cobalt, nickel, and lead), water-soluble vitamins (C, B_1, B_2, B_6, and B_{12}), and ethanol (Ivanišová *et al.*, 2020; Kaewkod *et al.,* 2019). However, the chemical composition of kombucha varies depending on the microbiological composition of the culture used for kombucha fermentation, types of substrates, and fermentation conditions (Kaewkod *et al.,* 2019; Neffe-Skocińska *et al.,* 2017).

Antimicrobial activities

Scientific studies have correlated antimicrobial activity of kombucha with acids production, polyphenols as well as the presence of lactic acid bacteria (Kaewkod *et al.,* 2019; Morandi *et al.,* 2020; Verrillo *et al.,* 2021). However, the exact mechanism of action of kombucha on pathogenesis is still debatable.

Acids

Recent studies have indicated that the antimicrobial activity of kombucha against foodborne pathogens is mostly attributed to its low pH value, especially in the presence of acetic acid. It is known that acetic acid can inhibit a number of microorganisms by cytoplasmic acidification and accumulation of dissociated acid anion to toxic levels (Velićanski *et al.,* 2014). For example, Steinkraus *et al.* (1996) showed that the inhibition effects of kombucha against *E. coli*, *Helicobacter pylori*, and *S. aureus* were attributed to the high concentration of acetic acid. The significance of organic acids found in kombucha was also pointed out by Kaewkod *et al.* (2019), who determined that kombucha tea showed antibacterial activity against *E. coli*, *Salmonella Typhi*, *Vibriocholera*, and *Shigella dysenteriae*, while neutralized kombucha did not reveal any antimicrobial activity against these microorganisms. Moreover, the antibacterial activity of heat-denatured kombucha indicates that this thermo-stable antimicrobial agent could be used in food products to control thermophilic spore-forming bacteria (Kaewkod *et al.,* 2019). Tan *et al.* (2020) proved that acetic acid in kombucha could penetrate Gram-positive bacteria cells more easily than Gram-negative bacteria because of its lipophilic characteristics, and the highest proportion of microbial growth inhibition against *E. coli* and *S. aureus* was 99.83% and 100%, respectively. However, Sreeramulu *et al.* (2000) confirmed the presence of antimicrobial compounds in

Table 1. Chemical compositions of kombucha.

Chemical composition	References
Organic acids: acetic acid (1.55 g/L), citric acid (0.05 g/L), and tartaric acid (0.23 g/L) *Sugars*: sucrose (17.81 g/L), fructose (1.41 g/L), and glucose (9.35 g/L) *Alcohol*: 0.4%	Ivanišová *et al.*, 2020
Minerals: manganese (1.57 mg/L), copper (0.14 mg/L), iron (0.31 mg/L), zinc (0.53 mg/L), lead (0.12 mg/L), cobalt (0.23 mg/L), and nickel (0.42 mg/L)	
Organic acids: quinic acid (0.46–0.47 g/L), oxalic acid (0.04–0.044 g/L), citric acid (0.03–0.086 g/L), malic acid (0.029–0.03 g/L), D-glucuronic acid (0.04–0.063 g/L), and acetic acid (1.42–1.65 g/L) *Sugars*: sucrose (0.93–7.54 g/L), glucose (10.5–37.7 g/L), fructose (8.7–30.9 g/L) *Alcohol:* (6.9–11.0 g/L)	Neffe-Skocińska *et al.*, 2017
Organic acids: glucuronic acid (0.07–1.58 g/L), acetic acid (10.42–11.15 g/L), ascorbic acid (0.61–0.70 g/L), gluconic acid (41.42–70.11 g/L), and succinic acid (3.05 g/L)	Kaewkod *et al.*, 2019
Phenolic compounds: catechin (90.7 μg/mL), epicatechin (0.59 μg/mL), and rutin (7.02 μg/mL)	Velićanski *et al.*, 2014
Phenolic compounds: catechin (8 μg/mL), rutin (30.19 μg/mL), caffeine (177.37 mg/L), and quercetin (1.22 mg/L)	Barbosa *et al.*, 2020
Phenolic compounds: epicatechin gallate (0.04 mg/mL), epicatechin (0.027 mg/mL), catechin (0.031 mg/mL), epigallocatechin (0.041 mg/mL), epigallocatechin gallate (0.135 mg/mL), and gallocatechin gallate (0.075 mg/mL)	Zhao *et al.*, 2018
Vitamins: B_2 (8.3 mg/100 mL) and C (28.98 mg/L)	Malbaša *et al.*, 2011
Vitamins: B_1 (74 mg/100 mL), B_6 (52 mg/100 mL), and B_{12} (84 mg/100 mL)	Bauer-Petrovska and Petrushevska-Tozi, 2000
Anionic minerals: fluoride (1.20–3.20 mg/g), chloride (0.96–3.13 mg/g), bromide (0.04 mg/g), iodide (0.44–1.04 mg/g), nitrate (0.18–0.34 mg/g), phosphate (0.04–0.08 mg/g), sulfate (1.02–4.20 mg/g)	Kumar *et al.*, 2008

kombucha other than acetic acid and large proteins, as the antimicrobial activities against *E. coli*, *Shigella sonnei*, *Salmonella typhimurium*, *S. enteritidis*, and *C. jejuni* were shown even at neutral pH. Silva *et al.* (2021) also indicated that bioactivity could be more related to compounds present in kombucha than the total acidity produced during fermentation. Different varieties and quantities of substrates used in the production of kombucha result in beverages with different levels of organic acids and antimicrobial activity.

Polyphenols

Besides organic acids, tea-derived phenolic compounds have been described as potential antimicrobial agents that regulate the composition of intestinal microbes to prevent foodborne diseases by destabilizing microbial cell surface and cytoplasmic membranes (Verrillo *et al.*, 2021). A total of 127 phenolic compounds were identified in the green and black tea kombucha by ultra-high performance liquid chromatography-quadrupole time-of-flight mass spectrometry (UPLC-QTOF-MS), most of which were flavonoids (70.2%), followed by phenolic acids (18.3%), other polyphenols (8.4%), lignans (2.3%), and stilbenes (0.8%) (Cardoso et al., 2020). The high diversity of phenolic compounds in kombucha is due to their bio-transformation or degradation in tea varieties by enzymatic action or low pH during the fermentation of kombucha (Cardoso *et al.*, 2020; Kaewkod *et al.*, 2020).

Mizuta *et al.* (2020) proved the antibacterial activity of green tea kombucha fermented at different periods, even at low concentrations, against *Alicycobacillus* species, including *Alicyclobacillus hesperidum*, *Alicyclobacillus herbarius*, *Alicyclobacillus cycloheptanicus*, *Alicyclobacillus acidiphilus*, and *Alicycobacillus acidoterrestris* in orange juice. After exposure to the polyphenolic fractions of kombucha, the cell wall disruption and bacillus integrity deformation of *Alicycobacillus* species were observed by scanning electron microscopy (SEM). In addition, the increased antimicrobial activity of kombucha was due to the presence of metabolites produced by the kombucha consortium. In another study, the fermented sugared black tea exhibited potent bactericidal activity against enteric bacterial pathogens, including *S. flexneri*, *E. coli*, *S. Typhimurium*, and *V. cholera*. Isorhamnetin and catechin were proved as the main antimicrobial agents in the polyphenolic fraction of kombucha (Bhattacharya *et al.,* 2016). It is hypothesized that the presence of hydroxylation at positions 5 and 7 of the A ring and position 3 of the C ring, and free hydroxyl group(s) in the B ring of flavonoids contributes to the antimicrobial activity of polyphenolic compounds. Moreover, *in vivo* studies have been carried out to confirm the promising antimicrobial activity. For example, Bhattacharya *et al.* (2020) suggested that these two polyphenolic fractions from kombucha can significantly inhibit the motility and gene expressions (*motY* and *flaC*) of *V. cholera* related to flagellar regulatory, and prevent bacterial colonization in intestinal epithelial cells at sub-inhibitory concentrations. On the other hand, phenolic compounds are reported to increase the abundance of probiotics, maintain intestinal homeostasis, and prevent the infections caused by foodborne pathogens (Faria *et al.,* 2014).

Nevertheless, there are some studies that conflict the antibacterial activity of polyphenols. For example, Chou *et al.* (1999) reported that the tea fermentation process decreased its antibacterial activity with increasing fermentation time, which indicated that the antibacterial activity of tea-derived phenolic compounds could be partly destroyed by reduction in the concentration of catechins during enzymatic oxidation.

Lactic acid bacteria

Some studies have proved that the antimicrobial activity of kombucha is not exclusively due to organic acids and phenolic compounds but possibly because of lactic acid bacteria and their biologically active components such as bacteriocins (Alizadeh *et al.,* 2020; Kadyan *et al.,* 2021). The most important antimicrobial mechanism is the production of acid by lactic acid bacteria, as acidification may alter cell metabolism by damaging enzymes and the substructure and function of cell walls and membranes, interrupting nutrient absorption and inhibiting protein synthesis (Gao *et al.,* 2019). In addition, bacteriocins are antimicrobial agents produced by diverse bacterial species that can alter the membrane by corrupting potassium ion and ATP and cause cell failure to balance intracellular pH (Simons *et al.,* 2020). Therefore, the antimicrobial activity of bacteriocins against foodborne pathogens has gained increasing interest for their applications in the food industry.

Pediococcus pentosaceus and *Pediococcus acidiliactici* isolated from kombucha showed high antimicrobial activity against *S. enterica* Typhimurium, *L. monocytogenes*, *Listeria ivanovii*, *B. cereus*, *Proteus hauseri*, and *S. aureus*. Moreover, their antimicrobial activities were also proved against foodborne molds, including *Penicillium expansum* and *Penicillium digitatum* (Diguta *et al.,* 2020). In another study, a novel bacteriocin

Table 2. Antimicrobial activities of kombucha.

Antibacterial ability	References
Listeria monocytogenes (22 mm), *Staphylococcus epidermidis* (22 mm), and *Micrococcus luteus* (21.5 mm)	Battikh *et al.*, 2013
Vibriocholera (20.667 mm), *Shigella flexneri* (20.44 mm), *Salmonella typhimurium* (19 mm), *Escherichia coli* (20.67 mm), and *Staphylococcus aureus* (18 mm)	Bhattacharya *et al.*, 2016
Candida krusei (15.81 mm), *Candidaglabrata* (16 mm), *Candidaalbicans* (12 mm), *Candidatropicalis* (14 mm), *Haemophilus influenzae* (10 mm), and *Escherichia coli* (4 mm)	Ivanišová *et al.*, 2020
Microsporum canis (>32 mm), *Escherichia coli* (16 mm), and *Salmonella typhi* (32 mm)	Júnior *et al.*, 2009
Escherichia coli (22.67 mm), *Shigella dysenteriae* (24.33 mm), *Staphylococcus aureus* (26 mm), and *Bacillus cereus* (26 mm)	Valiyan *et al.*, 2021
Staphylococcus aureus (2.6–4.5 mm) and *Escherichia coli* (1.0–4.5 mm)	Lopes *et al.*, 2021
Escherichi coli (15–15.33 mm), *Pseudomonas aeruginosa* (13.33 mm), *Salmonella enterica serovar typhimurium* (18–18.66 mm), *Listeria monocytogene* (10.33–12.66 mm), *Enterococcus faecalis* (12–12.33 mm), *Micrococcus luteus* (11–14 mm), *Staphylococcus aureus* (13.66–14 mm), and *Staphylococcus epidermidis* (10.66–14 mm)	Deghrigue *et al.*, 2013
Salmonella enteritidis (13.85 mm), *Escherichi coli* (13.67 mm), *Proteus mirabilis* (15 mm), *Pseudomonas aeruginosa* (14.4 mm), *Erwinia carotovora* (17.83 mm), *Staphylococcus aureus* (16 mm), and *Bacillus cereus* (14.33 mm)	Četojević-Simin *et al.*, 2012
Escherichia coli (2.7 mm), *Pseudomonas aeruginosa* (2.8 mm), *Klebsiella pneumoniae* (2.8 mm), *Staphylococcus aureus* (3 mm), *Enterococcus faecalis* (2.2 mm), *Bacillus cereus* (2.9 mm), *Staphylococcus epidermidis* (2.2 mm)	Ayed *et al.*, 2017
Escherichia coli (21–24.7 mm), *Escherichia coli* O157:H7 (20.3–24.3 mm), *Shigella dysenteriae* (19.3–21.7 mm), *Salmonella Typhi* (20–24.7 mm), *Vibrio cholera* (20–21 mm)	Kaewkod *et al.*, 2019
Escherichia coli (green tea kombucha MIC: 15.33 µL/mL; black tea kombucha MIC: 15 µL/mL), *Pseudomonas aeruginosa* (green tea kombucha MIC: 13.33 µL/mL; black tea kombucha MIC: 13.33 µL/mL), *Salmonella enterica serovar typhimurium* (green tea kombucha MIC: 18 µL/mL; black tea kombucha MIC: 18.66 µL/mL), and *Listeria monocytogenes* (green tea kombucha MIC: 12.66 µL/mL; black tea kombucha MIC: 10.33 µL/mL)	Deghrigue *et al.*, 2013
Escherichia coli (95.66–99.91%) and *Staphylococcus aureus* (97.7–100%)	Tan *et al.*, 2020
Escherichia coli (green tea kombucha MIC: 250 µL/mL; black tea kombucha MIC: >250 µL/mL), *Staphylococcus aureus* (green tea kombucha MIC: 250 µL/mL; black tea kombucha MIC: 250 µL/mL), *Salmonella* (green tea kombucha MIC: 250 µL/mL; black tea kombucha MIC: >250 µL/mL), and *Listeria monocytogenes* (green tea kombucha MIC: 250 µL/mL; black tea kombucha MIC: 250 µL/mL)	Cardoso *et al.*, 2020
Staphylococcus aureus (MIC: 78.12–312.5 µL/mL), *Klebsiella pneumoniae* (MIC: 19.53–312.5 µL/mL), *Escherichia coli* (MIC: 39.10–312.5 µL/mL), *Bacillus subtilis* (MIC: 9.77–156.25 µL/mL), *Proteus vulgaris* (MIC: 78.13–312.5 µL/mL)	Vitas *et al.*, 2018

produced by *Lactobacillus plantarum* isolated from the kombucha consortium was found to have antibacterial activity against Gram-negative (*E. coli*) and Gram-positive bacteria (*Listeria innocua*, *Bacillus subtilis*, *L. monocytogenes*, *Clostridium butyricum*, *B. cereus*, *Bacillus megaterium*, *Micrococcus luteus*, *Brochothrix thermosphacta*, and *S. aureus*) because of increasing cell membrane permeability and release of potassium ions (Pei *et al.,* 2020).

However, the only concern is that the resistance genes may be transferred from pathogens to lactic acid bacteria, and the consumption of lactic acid bacteria carrying resistance genes may pass these genes to humans.

Interestingly, kombucha was reported to modulate gut microbiota in humans and its subsequent effect on health status. Jung *et al.* (2018) reported that genera of *Allobaculum*, *Turicibacter*, and *Clostridium* involved in the pathogenesis of non-alcoholic fatty liver disease were significantly decreased, whereas *Lactobacillus* increased after the consumption of kombucha, which could suppress accumulation of fat in the human liver. However, more clinical trials are required to evaluate the effects of kombucha on human microbiome.

It is worth mentioning that the antimicrobial activity of kombucha is not always positively affected by the fermentation process. Silva *et al.* (2021) proved that antimicrobial agents could be more related to the compounds present in tea infusion than to those produced during the fermentation process.

Toxicity and Limitation of Kombucha

Some pathogenic microorganisms, including *Salmonella enterica*, *C. albicans*, and *Penicillium*. spp, were isolated and identified from kombucha prepared without hygiene environments (Villarreal-Soto *et al*., 2020). Migration of ceramic containers used to store kombucha was reported to cause lead poisoning and gastrointestinal toxicity (Phan *et al.*, 1998). Allergic reactions, nausea and dizziness, lactic acidosis, headache, and other potential toxicities have been reported in individuals (Jayabalan *et al.,* 2014). Therefore, further studies involving more *in vivo* trials are required to validate the toxicity of ingredients found in kombucha.

Conclusion and Perspectives

Antibiotics are widely used to control infections caused by foodborne pathogens. However, the emergence of antibiotic-resistant bacteria has increased with the overuse of antibiotics. Therefore, towing to their health benefits and antimicrobial activities, natural products such as kombucha could be considered as effective, cheap, and easily available alternatives against foodborne pathogens without negative effects on the health of consumers. However, control of kombucha production is mostly empiric despite the increasing knowledge provided by scientific community, and its antimicrobial property is also not well understood. Besides the organic acids, phenolic compounds, and lactic acid bacteria, alcohol and aldehydes are other important antimicrobial agents found in kombucha but not considered. Utilization of omics technology is encouraged to further reveal the molecular-level antimicrobial mechanisms. Moreover, clinical trials are required to confirm the effects of kombucha consumption on gastrointestinal microbiota composition and health risks in humans.

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