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## Does kimchi deserve the status of a probiotic food?

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### ABSTRACT

Kimchi is a traditional fermented vegetable side dish in Korea and has become a global health food. Kimchi undergoes spontaneous fermentation, mainly by lactic acid bacteria (LAB) originating from its raw ingredients. Numerous LAB, including the genera *Leuconostoc*, *Weissella*, and *Lactobacillus*, participate in kimchi fermentation, reaching approximately 9–10 log colony forming units per gram or milliliter of food. The several health benefits of LAB (e.g., antioxidant and anti-inflammatory properties) combined with their probiotic potential in complex diseases including obesity, cancer, atopic dermatitis, and immunomodulatory effect have generated an interest in the health effects of LAB present in kimchi. In order to estimate the potential of kimchi as a probiotic food, we comprehensively surveyed the health functionalities of kimchi and kimchi LAB, and their effects on human gut environment, highlighting the probiotics function.

### KEYWORDS

fermented food; kimchi;  
lactic acid bacteria; probiotic

### Introduction

Kimchi is a traditional fermented vegetable side dish in Korea, prepared by blending the pre-brined main vegetables such as kimchi cabbage or radish, various seasonings such as red pepper, garlic, ginger, green onion, sliced radish, salt, sugar, and minor ingredients including fermented seafood, fruits, vegetables, meat, fish, and cereals. The mixture of input ingredients in the fermentation process gives kimchi unique organoleptic characteristics that influence appetite. Kimchi is sorted based on various criteria, including water-iness, main ingredients, and preparation differences. There are hundreds of varieties of kimchi that differ in ingredients and methods, with distinctive nutritional, biochemical, and organoleptic features (Jung, Lee, and Jeon 2014). Broadly, the common characteristics of kimchi are salted ingredients, fermentation at a relatively low temperature (below 10 °C), and fermentative microbes derived from various raw ingredients (Jung, Lee, and Jeon 2014; Lee et al. 2020).


Kimchi is a well-known health food worldwide. Kimchi has low calories (18kcal/100g), several vitamins (vitamin A, vitamin C, thiamin, and riboflavin), minerals (calcium, potassium, iron, and phosphorus), and dietary fiber (24% on a dry basis) (Patra et al. 2016). In addition, kimchi contains functional and bioactive components including gingerol, capsaicin, carotenoids, allyl compounds, isothiocyanate, and indole-3-carbinol. Several health benefits of kimchi consumption in the experimental animal models have been

reported: anticancer activity in mouse with colitic cancer models by kimchi intake (Han et al. 2020b); anti-obesity activity in mice by kimchi or kimchi-derived LAB intake (Park, Oh, et al. 2020; Park, Kwon, et al. 2020); antidiabetic activity in rats by kimchi intake (Islam and Choi 2009); alleviation of obesity-induced neuroinflammation in mice by kimchi intake (Kim, Dang, and Ha 2022b). These health benefits result from the high nutritive raw ingredients as well as fermentation by kimchi microbiota (Patra et al. 2016). Kimchi undergoes spontaneous fermentation, mainly by lactic acid bacteria (LAB) originating from its raw ingredients (Lee, Jung, et al. 2015). A study conducted by Lee et al. (2020) reported that in cabbage kimchi, the LAB count reached approximately 9–10 log colony forming units (CFU) per gram or milliliter of food. Numerous LAB, including the genera *Leuconostoc*, *Weissella*, *Lactobacillus*, and *Pediococcus*, participate in kimchi fermentation (Kim, Dang, and Ha 2022a). The kimchi microbiota, including LAB, varies depending on its raw ingredients (Jeong et al. 2013).

Fermented food is an excellent source of LAB. Accordingly, dietary intake of kimchi may contribute to the enrichment of the microbiota of the gastrointestinal tract. Several reviews have described fermented foods containing identified or potential probiotics, particularly LAB, and human studies have reported that microorganisms in fermented foods can remain alive during the digestion process and reach the colon (David et al. 2014; Han et al. 2015; Heinen, Ahnen,

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and Slavin 2020). These microorganisms are metabolically active in the intestinal environment and produce bioactive compounds (David et al. 2014; Plé et al. 2015). The daily consumption of fermented foods increases the metabolic activity of the ingested microorganisms (Marco et al. 2021). Fermented food-associated LAB can constitute about 0.1–1% of gut bacteria, depending on the dietary habits of individuals (Plé et al. 2015). A study of Pasolli et al. (2020) reported that food-associated LAB have more than 0.1% fecal metagenomic abundance.

The isolation and efficacy of various potential probiotic strains from the kimchi microbiota have been widely reported (Lee et al. 2011; Park et al. 2016). However, there has been no comprehensive review analyzing whether kimchi can function as a probiotic food. Since kimchi is a general and common side dish in Korea with significant consumption, its functionality as a source of probiotics can be explored by studying its influence on the gut microbiota. The potential of kimchi as a probiotic could be investigated by analyzing the types of LAB in kimchi, and their functionality. Here, we review kimchi, its LAB composition and functionalities, and the impact of its consumption on human gut environment, to estimate its potential as a probiotic food.

### Culture and consumption of kimchi

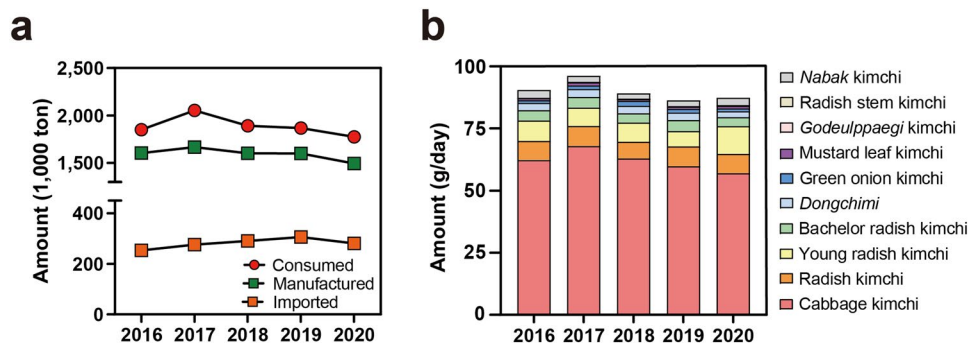
Kimchi is a representative fermented food that originated in Korea. Several ancient documents mentioned the consumption of kimchi in the past. According to *Samkuksaki*, the chronicle of the three kingdoms of Korea, people already consumed kimchi around 1,500 years ago (Yang et al. 2015). Kimchi is consumed as a preserved food even during winter when fresh vegetables are rarely available. Traditionally, Korean households gather to prepare large amounts of kimchi from late November to the middle of December when Korean winter begins. This culture is called *Kimjang*, the making and sharing of kimchi, where kimchi-making practices including recipes, techniques, and culture are passed down through generations (Jang et al. 2015). According to a survey conducted by the Ministry of Agriculture, Food, and Rural Affairs of Korea in 2019, 42% of Korean households still produce their own kimchi. The Korean culture

of *Kimjang* was inscribed on the Representative List of the Intangible Cultural Heritage of Humanity of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in 2013.

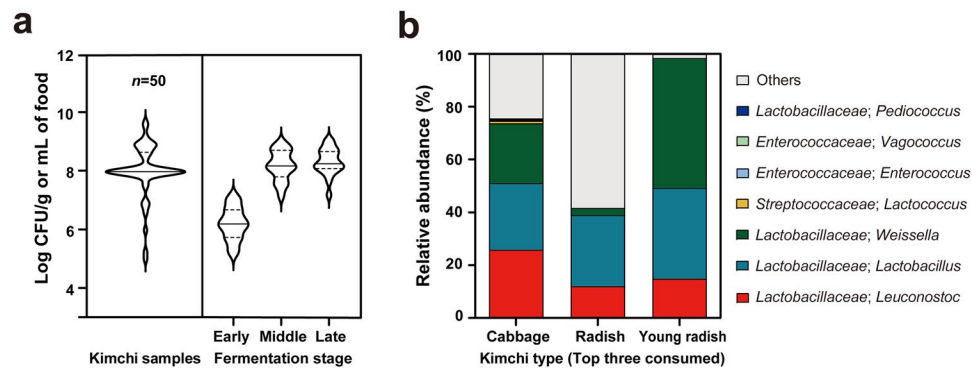
However, kimchi consumption in Korea has decreased over time (Figure 1a). Kim et al. (2016a) reported a declining trend in daily kimchi consumption and portion size. Shifts in dietary patterns from traditional meals containing rice, soup, and side dishes, including kimchi, to westernized meals such as fast or processed foods, meat, and bread seem to be related to the dwindling daily kimchi consumption (Kim et al. 2016a). According to the Korea National Health and Nutrition Examination Survey, cabbage kimchi was ranked as the most frequently consumed food by Koreans in 2020, with a  $55.07 \pm 0.98\%$  portion in the Korean diet, indicating that kimchi is consumed more frequently than rice, which is the staple food for Koreans. Cabbage kimchi was the third-most consumed food in 2020 in Korea, with an average of  $57.06 \pm 1.52$  g of cabbage kimchi consumption per day, and 87.49 g for various types of kimchi including cabbage kimchi, radish kimchi, young radish kimchi, bachelor kimchi, water kimchi made of whole radish (*Dongchimi*), green onion kimchi, mustard leaf kimchi, Korean lettuce kimchi (*Godeulppaegi*), and water kimchi made of sliced radish (*Nabak*) kimchi (Figure 1b). The consumption of rice, the staple Korean food was  $121.88 \pm 1.78$  g per day. The intake amount highlights that the consumption of kimchi is considerable even if it is a side dish. Furthermore, compared to  $12.80 \pm 0.93$  g per day of yogurt consumption (ranked 28<sup>th</sup>), another popular fermented food worldwide, kimchi consumption is significantly higher in the Korean diet. Koreans consumed a total of 1.78 million tons of kimchi in 2020 according to a survey conducted by the Ministry of Agriculture, Food, and Rural Affairs of Korea.

### Characteristics of LAB in kimchi

Alterations of LAB count and pH have been observed as fermentation progressed. The number of LAB in kimchi has been reported extensively. Our survey, which is based on publicly available studies (see [Supplementary Methods](#)), showed that LAB are present at an average of  $8.01 \pm 0.92$



**Figure 1.** The consumption of kimchi by year by Koreans. (a) Annual production and consumption of kimchi in Korea from 2016 to 2020. (b) Personal daily kimchi consumption in Korea from 2016 to 2020. Circle symbol implies consumed amount while square symbol represents production amount.



**Figure 2.** The abundance and taxonomic profile of LAB present in kimchi. (a) LAB viable cell count in kimchi. Data were selected based on the following criteria: selection of control among various groups, selection of maximum value among fluctuated numbers during fermentation, and selection of shown numbers in graph result in rounded down values. (b) The relative abundance of LAB (genus level) present in the three most widely consumed kimchi types (cabbage kimchi, radish kimchi, and young radish kimchi).

(max = 9.70 and min = 5.0) log CFU per gram or milliliter of food (Figure 2a). The mean LAB abundance was 100-fold higher in the middle stage than in the early stage, suggesting that the number of LAB ingested varies depending on the fermentation period. The minimum level of probiotic consumption recommended is 6 log CFU per gram or milliliter of food (Shah 2000). Though not all LAB present in kimchi are probiotic bacteria, it is logical to assume that kimchi could quantitatively qualify as a probiotic food. The bacterial taxonomic distribution of the three most widely consumed kimchi types (i.e., cabbage kimchi, radish kimchi, and young radish kimchi) is shown in Figure 2b. The relative abundance was calculated based on the data from previous studies (see Supplementary Methods). Cabbage kimchi was dominated by the LAB genera *Leuconostoc*, *Lactobacillus*, and *Weissella*. In radish kimchi, *Lactobacillus* was the most abundant LAB genus, while the genus *Weissella* dominated the bacterial microbiota of young radish kimchi. The prevailing LAB genera are mutual in the three different kinds of kimchi, although the ratio of each abundant genus differed among the three depending on the main ingredient.

Although diverse microorganisms are involved in kimchi fermentation, the dominant fermentative microbes are LAB (Patra et al. 2016). Raw kimchi ingredients contain a low number of LAB, but their abundance increases four-fold during the brining process. The post-brining rinsing and washing steps reduce the number of overall bacteria, yeasts, and molds. At the fermentation step, LAB dominated the kimchi microbial community under anaerobic and low-temperature conditions (Jung, Lee, and Jeon 2014). Several factors including acidity, types of major (e.g., main vegetables, red pepper, and garlic) and minor ingredients (e.g., fermented seafood, fruits, and meat), the harvest season of raw ingredients, and fermentation temperature, affect the structure and composition of the microbial community present in kimchi (Cheigh, Park, and Lee 1994). Classification of the kimchi fermentation stages based on acidity and pH was suggested by Codex Alimentarius Commission (2001) and Jung, Lee, and Jeon (2014), respectively. The dominant LAB species were different at each fermentation stage. During the early to middle fermentation

stages, *Leuconostoc mesenteroides* was the predominant species, which mainly produced lactic acid, acetic acid, carbon dioxide, and ethanol as major end products. In the late fermentation stage, the dominant bacteria changed to *Latilactobacillus sakei*, *Streptococcus faecalis*, *Levilactobacillus brevis*, *Pediococcus cerevisiae*, and *Lactiplantibacillus plantarum* (Cheigh, Park, and Lee 1994). The types of kimchi ingredients also affected the kimchi microbiota. A recent study by Song et al. (2021) revealed that the dominant LAB species and distributions of major LAB species (*Leuconostoc gellidum*, *Weissella kandleri*, and *Latilactobacillus sakei* groups) and the concentration of produced metabolites differed depending on the type of the main ingredient. The addition of the minor ingredients, red pepper powder, and fermented fish sauce (i.e., *jeotgal*) also altered the bacterial community in kimchi. Red pepper powder elevated the abundance of *Weissella* spp. at the middle and late fermentation stages and initial ornithine production in kimchi (Jung, An, and Lee 2021). Kimchi containing fermented fish sauce was dominated by *Weissella koreensis* or *Latilactobacillus sakei*, depending on the type of fish, whereas microbial abundance in kimchi without fish sauce was dominated by *Leuconostoc gasicomitatum* (Jung et al. 2018). The LAB achieving microbial dominance and distribution differed based on the harvest season and storage period of the main ingredient. A study of Lee et al. (2018b) showed different microbial distributions according to seasonality (spring, autumn, and winter). All kimchi samples were dominated by *Lactobacillus*, *Leuconostoc*, and *Weissella*, but with altered species abundance. The storage period of kimchi cabbage resulted in differences in the abundance of *Lactobacillus* and *Leuconostoc*, and these genera were more abundant in kimchi made with fresh and stored kimchi cabbage, respectively. Comparing the two fermentation temperature conditions (i.e., 4 and 10°C), more *Leuconostoc* species were observed than *Lactobacillus* species at 4°C, and more diverse LAB were detected at 10°C (Hong et al. 2013). These studies demonstrated the key characteristics of kimchi fermentation; kimchi bacterial structure altered by diverse conditions and microbial dominance during fermentation was accomplished by species from three major genera: *Lactobacillus*, *Leuconostoc*, and *Weissella*.

## Probiotic functions of kimchi and kimchi LAB

### Health-promoting effects of kimchi

Kimchi possesses prebiotic, probiotic, and postbiotic properties through various compounds originating from the raw ingredients of kimchi; the diverse LAB involved in kimchi fermentation; and various metabolites in a large quantity produced by the LAB. The plants belonging to the *Brassicaceae* family are the main ingredients of kimchi, that harbor potential health-promoting compounds, such as dietary fibers, minerals, various amino acids, vitamins, carotenoids, glucosinolates, and polyphenols (Patra et al. 2016). LAB produce diverse organic acids, carbon dioxide, ethanol, mannitol, bacteriocins, ornithine, conjugated linoleic acid, and oligosaccharides (Lee, Jang, et al. 2015). Kimchi consumption has a variety of health-promoting benefits. Intake of kimchi to mammalian hosts (e.g., humans and mice) in various disease models or clinical trials (e.g., cancer, obesity, cardiovascular diseases, and decreased cognitive/memory/brain functions) showed an improvement in their health status as a result of kimchi consumption (Table 1). Several studies have tested the effects of kimchi consumption on human gut microbiota. Of the six studies identified in this literature review, three used healthy participants, one study included patients with two statuses of colon adenoma, one study included patients with metabolic disorders, and one study included patients with *Helicobacter pylori* infection. Park et al. (2021) reported altered fecal microbiota taxa after ten weeks of fermented kimchi intake in 32 individuals with normal colon, simple and advanced colon adenomas. Kimchi consumption resulted in an increased proportion of *Clostridium sensu stricto* 1 and *Turicibacter* in the patients with simple colon adenoma, and a decreased proportion of *Clostridium sensu stricto* 1 and *Terrisporobacter* in the patients with advanced colon adenoma. The major genera of kimchi LAB, *Weissella* and *Lactobacillus* tended to increase in both the patient groups. A study of Kim and Park (2018) analyzed the effect of kimchi consumption on colon health in 28 healthy individuals. After four weeks of kimchi intake, the average abundance of *Firmicutes*, *Proteobacteria*, and *Tenericutes* was reduced, while *Bacteroidetes* and *Actinobacteria* levels increased compared to week zero and week four. *Faecalibacterium*, *Roseburia*, and *Phascolactobacterium*, the short-chain fatty acid production-related genera, and *Bifidobacterium*, which contains a number of probiotic strains, were also elevated, while the average abundance of *Clostridium* and *Escherichia coli* was decreased. Other obesity-related markers, inflammation-related markers, and harmful fecal enzyme activities also improved, indicating that kimchi can influence metabolic disease-related indices and colon health. Another interventional study on healthy adults (Lee, Choi, and Ji 1996) reported increased cell counts of *Lactobacillus* and *Leuconostoc*, indicating that kimchi may function as a probiotic food. Kim et al. (2016b) assessed the effect of different amounts of kimchi consumption for seven days on the gut microbiota of 12 Korean female adults, and observed similar bacterial diversity

regardless of the consumption amount. In the large intake group, no difference was observed in the abundance of *Firmicutes*, but a lower proportion of *Bacteroidetes* was reported. Moreover, harmful bacteria such as *Listeria*, *Clostridium*, *Enterobacter*, *Prevotella*, and *Shigella* had smaller proportions in the high intake group than in the low intake group, while no differences were observed in the beneficial bacterial abundance. *Enterococcus*, which might be beneficial or harmful, had a higher abundance, while *Bacteroides* accounted for a smaller proportion, and *Eubacterium* showed no difference in the large kimchi intake group. Statistical analyses revealed that among the 34 species that differed in intake amount, 16 species, including potentially pathogenic *Gammaproteobacteria*, were reduced. *Bifidobacterium breve*, *Lactobacillus acidophilus*, *Companilactobacillus mindensis*, *Limosilactobacillus reuteri*, *Levilactobacillus brevis*, *Lactobacillus amylolyticus*, and *Leuconostoc mesenteroides*, which are the dominant species in kimchi, were found in the gut microbiota of the high intake group, suggesting their function as probiotics. A study conducted on obese patients also reported on kimchi (fresh or fermented) consumption and its impact on the gut microbiota (Han et al. 2015). After eight weeks of kimchi intake, the proportions of *Proteobacteria* and *Actinobacteria* were increased. The relative abundance of *Bacteroides*, which negatively correlated with obesity, and *Prevotella* were increased, while the abundance of *Blautia* was decreased after the consumption of fermented kimchi. Altered expression of several genes related to metabolism and immunity after the consumption of fermented kimchi reportedly to correlates with bacterial taxa such as *Blautia*, *Prevotella*, and *Bacteroides*. Thus, it is conceivable that the intake of fermented kimchi can either directly influence gene expression related to metabolism, digestion, blood circulation, and immunity, or indirectly influence human metabolism by altering the composition of the gut microbiota. Lastly, a study of the effect of kimchi consumption on *Helicobacter pylori*-infected patients showed significantly increased cell numbers of *Lactobacillus* sp. and *Leuconostoc* sp. in the feces, after kimchi intake (Kil et al. 2004). The studies described in this review provide introductory evidence on the relationship between kimchi intake and the modification of the gut microbiota. However, very few studies have suggested any patterns of alteration in the gut microbiota after kimchi consumption.

A common observation from studies involving gut microbial alteration according to kimchi intake is an increase in the LAB abundance in the gut after kimchi intake. Research on the effect of overall gut LAB abundance on human health is lacking. However, it is known that LAB have no main bacterial pathogenicity characteristics (e.g., toxins and/or invasion potential) and could supply beneficial traits to gut ecosystems (acidification, biosynthesis of prebiotic fructooligosaccharides, release of bacteriocins, and/or modulation of the immune system) (Pessione 2012). Accordingly, the increased abundance of gut LAB via kimchi intake could help retain human health status and help to alleviate the effects of various diseases. Further research on the clinical role of kimchi consumption in human health should be

Table 1. The health-promoting effects of kimchi consumption.

Effect	Model/Participant	Type of kimchi	Kimchi dose and duration of treatment	Alteration of gut microbiota	Ref
<i>Animal model</i> Anticancer activity	Azoxymethane-initiated and DSS-promoted colitic cancer mice models Germ-free male C57BL/6 mice	Fermented cabbage kimchi extract	1.7 g/kg and 5.1 g/kg Once a week, two weeks before chemical treatment for DSS group Once a week, 13 weeks for azoxymethane-initiated DSS group	-	Han et al. (2020b)
Anti-obesity activity	High fat diet-induced male C57BL/6 mice	Washed, fermented kimchi soup	A volume that satisfying amount for 8 log CFU of LAB/day. For three weeks	Increase of <i>Muribaculaceae</i> and decrease of <i>Akkermansiaceae</i> , <i>Coriobacteriaceae</i> , and <i>Erysipelotrichaceae</i> after ingestion of kimchi soup	Park, Kwon, et al. (2020)
Anti-obesity activity	High fat diet-induced male C57BL/6J mice	Homogenized, fermented kimchi	120 mg/day, six times per week, for ten weeks	Increase of <i>Verrucomicrobia</i> and <i>Akkermansia</i> after kimchi intake	Kim, Dang, and Ha (2022b)
Improvement effect on cognitive and memory function	A $\beta$ 25-35 infected male ICR mice	Fermented cabbage kimchi extract	200 mg/kg bw/day, for two weeks	-	Woo, Kim, et al. (2018)
Inhibitory effect on endoplasmic reticulum stress-induced apoptosis	A $\beta$ 25-35 infected male ICR mice	Fermented cabbage kimchi extract	200 mg/kg bw/day, for two weeks	-	Woo, Kim, et al. (2018)
Attenuate effect on atherosclerosis	apoE knockout male mice	Bioactive compound of kimchi, HDMPPA	10 mg/kg bw/day, for eight weeks	-	Noh et al. (2009)
Protective effect on vascular	apoE knockout male mice	Bioactive compound of kimchi, HDMPPA	10 mg/kg bw/day, for eight weeks	-	Noh, Choi, and Song (2013)
<i>Human cohort</i> Alteration of gut microbiota, inhibitory effect on formation or advancement of colon adenoma	Human with normal colon, simple colon adenoma, or advanced colon adenoma	Fermented cabbage kimchi extract	100 g/day, for ten weeks	Increase of <i>Actinobacteria</i> , <i>Cyanobacteria</i> , <i>Clostridium sensu stricto 1</i> , <i>Turicibacter</i> , <i>Gastromonadiales</i> , and <i>Haemophilus pittmaniae</i> in patients with advanced colon adenoma	Park et al. (2021)
Alteration of gut microbiota, reduction of LDL-C and $\beta$ -glucosidase levels, increase of HDL-C level	Randomly assigned healthy adults into the group intake of standardized kimchi or functional kimchi	Fermented cabbage kimchi	210 g/day, for 28 days	Decrease of <i>Enterococcus</i> , <i>Roseburia</i> , <i>Coriobacteriaceae</i> , <i>Bifidobacterium</i> spp., and <i>Akkermansia</i> in patients with advanced colon adenoma	Kim and Park (2018)
Alteration of gut microbiota, anti-obesity effect	Healthy adults assigned into the group of low and high intake kimchi	Fermented cabbage kimchi	15 g/day for low kimchi intake group and 150 g/day for high kimchi intake group, seven days	Increase of short chain fatty acid production-related genera ( <i>Faecalibacterium</i> , <i>Roseburia</i> , <i>Phascolactobacterium</i> ) and <i>Bifidobacterium</i> in both groups	Kim et al. (2016b)
Alteration of gut microbiota	Randomly assigned obese women into the group intake of fresh or fermented kimchi	Fresh or fermented kimchi	180 g/day, for eight weeks	Decrease of <i>Clostridium</i> in both groups Large portion of LAB species (species belonging <i>Bifidobacterium</i> , <i>Lactobacillus</i> , <i>Leuconostoc</i> , and <i>Weissella</i> ) in high intake group Less portion of <i>Bacteroidetes</i> and potential harmful organisms in high intake group	Han et al. (2015)
Alteration of gut microbiota, reduction of $\beta$ -glucosidase and $\beta$ -glucuronidase levels	Crossover intervention of Human with infection of <i>Helicobacter pylori</i>	Fermented cabbage kimchi	300 g/day for four weeks and 60 g/day for four weeks (total of 16 weeks)	Increase of <i>Bifidobacterium</i> Increase of <i>Bacteroides</i> and <i>Prevotella</i> in the group intake fermented kimchi	Kil et al. (2004)
Alteration of gut microbiota, reduction of $\beta$ -glucosidase and $\beta$ -glucuronidase levels	Crossover intervention, healthy human	Fermented kimchi	200 g/day, for two weeks	Increase the counts of <i>Lactobacillus</i> and <i>Leuconostoc</i>	Lee, Choi, and Ji (1996)

The LAB count in kimchi was estimated by multiplying the average log CFU per gram or milliliter of cabbage kimchi by the daily consumption of the intervention. DSS, dextran sulfate sodium; CFU, colony forming unit; HDMPPA, 3-(4'-hydroxy)-3',5'-dimethoxyphenyl)propionic acid; bw, body weight; LDL-C, low-density lipoprotein cholesterol; HDL-C, high-density lipoprotein cholesterol; LAB, lactic acid bacteria.

conducted to elucidate the detailed mechanisms of how kimchi intake helps in improving human health in various diseases.

### Kimchi-derived LAB and their human health benefits

Kimchi is a potential probiotic food with an ideal habitat for LAB, which has led researchers to focus on the health-promoting effects of LAB isolated from kimchi. LAB possess diverse functional properties including antimicrobial, antifungal, and antiviral activities, contributing to the inhibition of colonization by undesired allochthonous microbes in the gut environment, maintaining gut homeostasis (Servin 2004; Zeise, Woods, and Huffnagle 2021). Moreover, the antioxidant and anti-inflammatory properties of LAB combined with their probiotic potential in complex diseases including obesity, cancer, atopic dermatitis, and immunomodulatory diseases, make kimchi LAB important for human health. Detailed information regarding the health-promoting effects of kimchi-derived LAB is summarized in Table 2.

We showed that kimchi-derived LAB harbor health-promoting potentials based on previous research. Most recently, researchers highlighted the health-promoting benefits of specific LAB-derived compounds and their producing pathways: improved behavioral abnormalities by gamma-aminobutyric acid (GABA)-producing lactobacilli (Patterson et al. 2019); enhanced learning and memory behaviors by gut *Lactobacillus*-modulated tryptophan metabolism (Kaur, Bose, and Mande 2019; Zhang et al. 2022); and proangiogenic, pro-osteogenic, and antiapoptotic effects of *Ligilactobacillus animalis*-produced extracellular vesicles (EV) (Chen et al. 2022). We analyzed the potential pathways at the genomic level to expand our view of the health-promoting effects of kimchi-derived LAB. We surveyed the functional genes from publicly available LAB genomes of the three major genera, the drivers of kimchi fermentation (*Lactobacillus*, *Leuconostoc*, and *Weissella*) in the National Center for Biotechnology Information (NCBI). The accession numbers of these genomes were searched using *esearch*, provided by NCBI's Entrez Direct (EDirect) toolkit. These genomes were selected when the term was specified "kimchi" in BioSample information (i.e. isolation source or environmental medium). Protein prediction and gene annotation of the selected genomes were performed using Prokka v.1.14.5 (Seemann 2014) and eggNOG-mapper v.2.1.7 (Cantalapiedra et al. 2021), respectively. A total of 129 genomes of kimchi-isolated LAB (66, 37, and 26 genomes belonging to the genera *Lactobacillus*, *Leuconostoc*, and *Weissella*, respectively) were used for the genomic analysis. They were subjected to a survey of the gene(s) related to GABA production, tryptophan metabolism, and production of EV components, which encode the metabolites that mediate host-microbiota interactions (Supplementary Table S1) (Chen et al. 2022; Kaur, Bose, and Mande 2019; Kim et al. 2015; Patterson et al. 2019). As shown in Table 3, several species belonging to the genera *Lactobacillus*, *Leuconostoc*, and *Weissella* possess more than one gene that is involved in GABA production. Partial GABA production

pathways from succinate were observed in the species belonging to the three genera, but the pathway from glutamate was identified in *Lactobacillus* species only. Moreover, several *Leuconostoc* species contained gene(s) involved in kynurenine or indole acetic acid production for tryptophan metabolism. Finally, our genomic survey showed that many LAB species isolated from kimchi are capable of producing EV components. The microbial EV production is particularly interesting because of the potential application of EVs in drug delivery systems (Herrmann, Wood, and Fuhrmann 2021).

Taking all into account, the consumption of kimchi and its isolated LAB may have various health-promoting effects. The variation in the kimchi microbiota based on various factors might be considered a limitation for constant and defined impact on humans. Quality-controllable probiotic kimchi could be a potential solution for introducing LAB into kimchi. The microbial dominance of LAB and LAB-supplemented kimchi would be significantly beneficial to humans. The sufficient number of LAB and the therapeutic benefits of kimchi-derived LAB and kimchi itself imply that kimchi can meet potential properties of a probiotic food.

### Can kimchi be served as a probiotic?

By consuming cabbage kimchi in average, one can intake 10.08 log CFU of LAB per day. For radish kimchi and young radish kimchi, 7.91 log CFU and 8.77 log CFU were consumed daily, respectively. Collectively, one can intake 10.11 log CFU LAB per day from average kimchi consumption (data not shown). Compared with commercial probiotics that contain 9 log CFU per serving size, daily kimchi consumption could be considered to contain a sufficient LAB count. The kimchi microbiota profile is also important for evaluating the probiotic potential of kimchi. To weigh up the portion of LAB strains each kind of kimchi contains, we calculated the average of relative abundance data at the genus level. Multiplying portion size with the LAB count shows the viable cell count of each LAB strain. For example, in cabbage kimchi, the most widely consumed type, *Leuconostoc* is the most dominant (25.98%) genus, followed by *Lactobacillus* (25.17%), *Weissella* (22.60%), *Lactococcus* (0.93%), and *Pediococcus* (0.22%). With an average intake of cabbage kimchi, one can possibly intake 9.62 log CFU of *Leuconostoc*, 9.61 log CFU of *Lactobacillus*, 9.56 log CFU of *Weissella*, 8.17 log CFU of *Lactococcus*, and 7.55 log CFU of *Pediococcus* from cabbage kimchi per day. Compared with commercial probiotics, which contain a single probiotic strain of 9 log CFU per serving size, kimchi contains sufficient amounts of various LAB considered to be probiotic microbes.

Kimchi undergoes spontaneous fermentation, which indicates that the microbiota remains unidentified and uncharacterized, with an unknown viable cell number at the time of consumption. Based on the International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on fermented foods (Marco et al. 2021), to label

Table 2. Health-promoting effects of consumption of kimchi-derived lactic acid bacteria (LAB).

Effect	Taxon	Strain	Model	Reference
<i>in vitro</i>				
preventive effect on cholesterol absorption	<i>Leuconostoc mesenteroides</i>	FB111	Caco-2 cells	Le and Yang (2019)
Anti-adipogenic activity	<i>Lactiplantibacillus plantarum</i>	KU15117	3T3-L1 cells	(Han et al. 2022)
Anti-obesity activity	<i>Levilactobacillus brevis</i>	OPK-3	3T3-L1 cells	Park, Oh, and Cha (2014)
Anti-obesity and antioxidant activities	<i>Lactiplantibacillus plantarum</i>	KU15120	3T3L-1 cells	Lee et al. (2022)
Anticancer, antioxidant, and immunostimulating activities	<i>Lactobacillus acidophilus</i>	KFR1342	CHO-K1, SNU-C4, RAW 264.7 and Hepa-1c1c7 mouse hepatoma cells	Chang et al. (2010)
Anti-adhesion and antidiabetic activities	<i>Levilactobacillus brevis</i>	KU15006	<i>Escherichia coli</i> and <i>Salmonella Typhimurium</i>	Son et al. (2017)
Anti-adhesion and antagonistic activities	Cell free supernatants from lactic acid bacteria strains:	KCCM 43119	<i>Escherichia coli</i> O157:H7 ATCC 35150, <i>Salmonella Enteritidis</i> KCCM 12021, <i>Salmonella Typhimurium</i> KCTC 1925, and <i>Staphylococcus aureus</i> KCCM 11335	Choi et al. (2018)
	<i>Latilactobacillus curvatus</i>	KCTC 3746		
	<i>Leuconostoc mesenteroides</i>	KCCM 41517		
	<i>Weissella cibaria</i>			
	<i>Weissella koreensis</i>			
Antimicrobial activity	<i>Pediococcus pentosaceus</i>	K23-2	<i>Listeria monocytogenes</i>	Shin et al. (2008)
Antimicrobial and antioxidant activities	<i>Levilactobacillus brevis</i>	KU15153	<i>Escherichia coli</i> ATCC 25922, <i>Listeria monocytogenes</i> ATCC 15313, <i>Salmonella Typhimurium</i> P99, and <i>Staphylococcus aureus</i> KCCM 11335	Jang, Lee, and Paik (2019)
Antimicrobial and anti-inflammatory activities	<i>Lactiplantibacillus plantarum</i>	LB5	Caco-2 cells	Sohn et al. (2020)
Antiviral activity	<i>Weissella cibaria</i>	BLS13	Avian H5N1, H7N7, and H9N2 viruses	Rho et al. (2012)
Antifungal activity	<i>Lactobacillus curvatus</i>	KC-116	<i>Aspergillus fumigatus</i> , <i>Asp. flavus</i> , <i>Fusarium moniliforme</i> , <i>Penicillium commune</i> , and <i>Rhizopus oryzae</i>	Kim (2005)
	<i>Lactobacillus delbruekii</i> subsp. <i>lactis</i>	KC-304		
	<i>Lactocaseibacillus casei</i>	KC-324		
	<i>Lactiplantibacillus pentosus</i>	KC-817		
	<i>Latilactobacillus sakei</i>	KC-1004		
Antifungal activity	<i>Latilactobacillus sakei</i>	ALI033	<i>Penicillium brevicompactum</i> F102	Huh and Hwang (2016)
Antifungal activity	<i>Lactiplantibacillus plantarum</i>	HD1	<i>Pichia kudriavzevii</i> GY1, <i>Saccharomyces servazzii</i> GY2, <i>Saccharomyces bulderi</i> HY, <i>Kazachstania exigua</i> WY3, <i>Candida albicans</i> ATCC 11006, <i>Asp. flavus</i> ATCC 22546, <i>Asp. fumigatus</i> ATCC 96918, <i>Asp. petrakii</i> PF-1, <i>Asp. ochraceus</i> PF-2, <i>Asp. nidulans</i> PF-3, <i>Cladosporium gossypicola</i> KF-2, and <i>Penicillium roqueforti</i> ATCC 10110	Ryu et al. (2014)
Antifungal activity	<i>Lactiplantibacillus plantarum</i>	AFI	<i>Asp. fumigatus</i> , <i>Asp. flavus</i> , <i>Asp. petrakii</i> , <i>Asp. ochraceus</i> , <i>Asp. nidulans</i> , and <i>Penicillium roqueforti</i>	Yang, Kim, and Chang (2011)
Antifungal activity	<i>Lactiplantibacillus plantarum</i>	AFI	<i>Asp. flavus</i> ATCC 22546	Yang and Chang (2010)
Antifungal activity	<i>Lactiplantibacillus plantarum</i>	YML007	<i>Asp. niger</i> , <i>Asp. oryzae</i> , <i>Asp. flavus</i> , and <i>Fusarium oxysporum</i>	Ahmad Rather et al. (2013)
Antioxidant activity	<i>Lactiplantibacillus plantarum</i>	Ln1	–	Jang et al. (2018)
Antioxidant and anti-inflammatory activities	<i>Lactiplantibacillus plantarum</i>	KU15149	RAW 264.7 cells	Han et al. (2020a)
Antioxidant and immune-enhancing activities	<i>Lactiplantibacillus plantarum</i>	200655	RAW 264.7 cells	Yang et al. (2019)
Antioxidant and immunomodulatory activities	<i>Lactiplantibacillus plantarum</i>	WiKim0112	Caco-2 cells	Jeong et al. (2021)
Immunomodulatory activity	<i>Lactiplantibacillus plantarum</i>	CJLP55	Ovalbumin (OVA)-sensitized mouse splenocytes (Six-week-old male BALB/c mice), J774A.1, RAW264.7, and JAWSII cells	Won et al. (2011a)
	<i>Lactiplantibacillus plantarum</i>	CJLP56		
	<i>Lactiplantibacillus plantarum</i>	CJLP133		
	<i>Lactiplantibacillus plantarum</i>	CJLP136		
	<i>Lactiplantibacillus plantarum</i>	ND	RAW 264.7 cells	Huh, Lee, and Lee (2004)
Immunopotentiating activity	<i>Lactiplantibacillus plantarum</i>	LRCC5314	RAW 264.7, 3T3-L1, and H295R cells	Yoon et al. (2022)
Anti-inflammatory activity and inhibitory effect on enzyme activity, adipogenesis, and stress hormone level	<i>Lactiplantibacillus plantarum</i>			
<i>in vivo</i>				
Anti-allergic activity	<i>Enterococcus faecium</i>	FC-K	Ovalbumin (OVA)-induced allergy model Male BALB/c mice	Rho et al. (2017)

(Continued)

Table 2. (Continued).

Effect	Taxon	Strain	Model	Reference
Immunomodulatory activity	Mixture of lactic acid bacteria strains: <i>Companilactobacillus alimentarius</i> <i>Levilactobacillus brevis</i>	RBK-13 RBK-5 RBK-8	2,4-Dinitrochlorobenzene (DNCB)-treated male NC/Nga mice	Kim et al. (2021)
Anti-inflammatory and immunomodulatory activities	<i>Lactiplantibacillus plantarum</i> <i>Levilactobacillus brevis</i>	NS1401	House dust mite-induced female NC/Nga mice	Choi et al. (2017)
Anti-inflammatory activity	<i>Lactocaseibacillus paracasei</i>	LS2	DSS-induced experimental colitis model	Park et al. (2017)
Anti-inflammatory activity	<i>Lactiplantibacillus plantarum</i>	KCTC 3104	Female C57BL/6 mice	Hong et al. (2010)
Anti-inflammatory activity	<i>Latilactobacillus curvatus</i>	KCTC 3767	Aerosolized ovalbumin-induced allergy model	
Anti-inflammatory activity	<i>Limosilactobacillus reuteri</i>	EFEL6901	Female BALB/c mice	Seo et al. (2021)
Anticancer activity	<i>Latilactobacillus curvatus</i>	WiKim38	DSS-induced colitis female BALB/c mice	Jo et al. (2016)
Anti-obesity activity	<i>Levilactobacillus brevis</i>	OPK-3	HT-29 Cells DSS-induced experimental colitis model Female C57BL/6 mice	Park, Oh, et al. (2020)
Protective effect on memory deficit	<i>Lactiplantibacillus pentosus</i> var. <i>plantarum</i>	C29	High-fat diet-induced obesity model	Jung et al. (2012)
Ameliorate effect on hypercholesterolemia	<i>Lactiplantibacillus plantarum</i>	LRCC 5273	Scopolamine-induced male ICR mice	Heo et al. (2018)
Ameliorate effect on atopic dermatitis-like skin lesions	<i>Latilactobacillus sakei</i>	WIKIM30	Diet-induced hypercholesterolemia female C57BL/6 mice DNCB-treated male BALB/c mice	Kwon et al. (2018)
Suppressive effect on dermatitis	<i>Lactiplantibacillus plantarum</i>	CJLP55 CJLP133 CJLP136 nF1	House-dust mite-induced female NC/ Nga mouse	Won et al. (2011b)
Antiviral activity	<i>Lactiplantibacillus plantarum</i>		Influenza A (H1N1 and H3N2 subtypes) and influenza B (Yamagata lineage) viruses-infected female BALB/c mice	Park et al. (2018)

Table 3. Functional genes from the publicly available lactic acid bacteria genomes.

Category	Role	Gene	KEGG Orthology	Lactobacillus	Leuconostoc	Weissella
GABA	Ameliorate symptoms of metabolic syndrome, neurotransmitter	Succinate-semialdehyde dehydrogenase, 4-Aminobutyrate aminotransferase	K00135, K00823	<i>Lactiplantibacillus plantarum</i> (35/35) <i>Limosilactobacillus fermentum</i> (1/1) <i>Secundilactobacillus malefermentans</i> (1/1)	<i>Leuconostoc carnosum</i> (2/2) <i>Leuconostoc citreum</i> (7/7) <i>Leuconostoc gelidum</i> (3/3)  <i>Leuconostoc inhae</i> (1/1) <i>Leuconostoc kimchii</i> (1/1) <i>Leuconostoc mesenteroides</i> (11/11) <i>Leuconostoc pseudomesenteroides</i> (1/1) <i>Leuconostoc sp.</i> (2/2)	<i>Weissella hellenica</i> (3/3)
		Glutamate decarboxylase	K01580	<i>Lactiplantibacillus plantarum</i> (35/35) <i>Latilactobacillus sakei</i> (1/9) <i>Lentilactobacillus buchneri</i> (1/1) <i>Levilactobacillus brevis</i> (5/5) <i>Limosilactobacillus fermentum</i> (1/1)		
		Arylformamidase (kynurenine formamidase)	K07130	<i>Lactiplantibacillus plantarum</i> (2/35)	<i>Leuconostoc inhae</i> (1/1) <i>Leuconostoc kimchii</i> (1/1) <i>Leuconostoc mesenteroides</i> (11/11) <i>Leuconostoc miyukkimchii</i> (1/1) <i>Leuconostoc sp.</i> (1/2) <i>Leuconostoc gelidum</i> (1/3)	-
Indole acetic acid	Effect on cellular elongation, differentiation, cellular division, apoptosis, and morphogenesis	Aldehyde dehydrogenase (indole-3-acetaldehyde oxidase)	K00128	-		
		N-Acetylmuramoyl-L-alanine amidase	K01447, K01448, K01449, K13714, or K22409	<i>Companilactobacillus paralimentarius</i> (1/1) <i>Latilactobacillus curvatus</i> (3/3) <i>Latilactobacillus sakei</i> (7/9) <i>Lentilactobacillus buchneri</i> (1/1) <i>Levilactobacillus brevis</i> (5/5) <i>Secundilactobacillus malefermentans</i> (1/1) <i>Lactocaseibacillus casei</i> (1/1) <i>Lactocaseibacillus paracasei</i> (6/6) <i>Lactocaseibacillus rhamnosus</i> (1/1) <i>Lactiplantibacillus plantarum</i> (35/35) <i>Latilactobacillus curvatus</i> (1/3) <i>Latilactobacillus sakei</i> (2/9) <i>Limosilactobacillus fermentum</i> (1/1) <i>Lactobacillus sp.</i> (2/2)	<i>Leuconostoc citreum</i> (3/7) <i>Leuconostoc gelidum</i> (3/3) <i>Leuconostoc lactis</i> (4/7) <i>Leuconostoc miyukkimchii</i> (1/1) <i>Leuconostoc carnosum</i> (2/2) <i>Leuconostoc citreum</i> (4/7) <i>Leuconostoc garlicum</i> (1/1) <i>Leuconostoc inhae</i> (1/1) <i>Leuconostoc kimchii</i> (1/1) <i>Leuconostoc lactis</i> (3/7) <i>Leuconostoc mesenteroides</i> (11/11) <i>Leuconostoc pseudomesenteroides</i> (1/1) <i>Leuconostoc sp.</i> (2/2)	<i>Weissella koreensis</i> (1/4) <i>Weissella soli</i> (2/2) <i>Weissella cibaria</i> (15/15) <i>Weissella confusa</i> (1/1) <i>Weissella hellenica</i> (3/3) <i>Weissella koreensis</i> (3/4) <i>Weissella viridescens</i> (1/1)
		Killing Competing Bacteria				
<b>Components of Extracellular Vesicle</b>						

(Continued)

Table 3. (Continued).

Category	Role	Internalin A	Gene	KEGG			
				Orthology	Lactobacillus	Leuconostoc	Weissella
Internalin A	Virulence Factor Delivery	Internalin A		K13730	<i>Companilactobacillus paralimentarius</i> (1/1)	<i>Leuconostoc garilicum</i> (1/1)	<i>Weissella cibaria</i> (15/15)
					<i>Lacticaseibacillus casei</i> (1/1)	<i>Leuconostoc lactis</i> (7/7)	<i>Weissella confusa</i> (1/1)
					<i>Lacticaseibacillus paracasei</i> (6/6)		<i>Weissella hellenica</i> (3/3)
					<i>Lacticaseibacillus rhamnosus</i> (1/1)		<i>Weissella viridescens</i> (1/1)
					<i>Lactiplantibacillus plantarum</i> (35/35)		
					<i>Latilactobacillus curvatus</i> (3/3)		
					<i>Lentilactobacillus buchneri</i> (1/1)		
					<i>Levilactobacillus brevis</i> (5/5)		
					<i>Limosilactobacillus fermentum</i> (1/1)		
					<i>Lactobacillus</i> sp. (2/2)		
Internalin B	Virulence Factor Delivery	Internalin B		K13731	<i>Companilactobacillus paralimentarius</i> (1/1)	-	<i>Weissella soli</i> (2/2)
					<i>Latilactobacillus sakei</i> (1/9)		
					<i>Lentilactobacillus buchneri</i> (1/1)		
					<i>Levilactobacillus brevis</i> (5/5)		
					<i>Secundilactobacillus malefermentans</i> (1/1)		

Numbers in parentheses indicate the number of genomes for which the targeted gene was observed from the total number of genomes used in the survey.

a probiotic fermented food, it is necessary to establish evidence of the beneficial effects of specific strains from an intervention study with proof of safety and confirmation of a sufficient number of specific strains in the final material to meet the claimed functionality. For a kimchi product to be labeled as a probiotic fermented food, it should be confirmed that a genetically characterized strain with defined probiotic effects is present in the product in sufficient amounts during its shelf-life. Also, no verified inhibitory effect on the physicochemical environment of kimchi should be confirmed while maintaining an optimal dose of the probiotic strain. The confirmed product can be claimed as “probiotic kimchi containing the specific strain(s) that may improve intestinal well-being.” Labeling a product as probiotic, however, depends on the legislation applied in the country/region in which it is being marketed. Lastly, it is important to note that categorizing products and/or strain(s) as probiotics requires further research on defined products rather than individual findings on undefined composition or unrepeatable properties of products and isolates. Though kimchi contains plenty of species with considerable viable cells, only the product where the strains in kimchi are defined to the strain level with known genome sequences and the strains that are viable at a claimed number during the shelf-life of the product can be labeled as “contains probiotics”.

### Pros and cons of consuming kimchi as a probiotic food

The various types of kimchi containing several microorganisms at different stages of fermentation can provide a variety of health benefits. For example, a study showed different influences of fresh kimchi and fermented kimchi on the gut microbiota and gene expression profiles, suggesting that effect of kimchi differs in the fermentation stage (Han et al. 2015). Kimchi may also have different effects on microbial development during fermentation depending on the type and amount of ingredients (Lee et al. 2018a). Therefore, it is difficult to standardize kimchi due to several factors, such as type, ingredients, temperature, and fermentation stage, that affect its characteristics (Kim et al. 2020). However, several lines of evidence indicate that kimchi intake is superior to defined probiotic consumption.

Probiotic microorganisms must be delivered regularly to the human gastrointestinal tract for probiotics to be effective. Kimchi, a universal side dish in Korea, is easily accessible to Koreans, who consume it in considerable amounts unintentionally. As fermented foods such as kimchi undergo natural fermentation, the fermentation process may lead to pathogenic contamination of such food products (e.g., *Escherichia coli* and norovirus derived from the raw materials) (Cho et al. 2014; Park et al. 2015). To avoid and minimize this possibility, kimchi manufacturers can get certified under the Hazard Analysis Critical Control Points (HACCP) system and individuals who make kimchi by themselves could take care of personal and environmental hygiene. Moreover, the LAB present in kimchi might have

negative effects on human health. A study conducted by Jeong and Lee (2015) reported that LAB isolated from kimchi might possess gene(s) related to antibiotic resistance in their genomes and/or produce biogenic amines (BAs). Adverse effects of excessive BA intake on human health may include food poisoning and hypertension (Shalaby 1996). Tracing both the raw materials related to BA production (e.g., fish sauce) (Kim, Dang, and Ha 2022) and microbial BA producers (Jeong and Lee 2015), combined with suggestions for a reduction methodology (e.g., inoculation of BA degrading LAB) (Lee et al. 2021), might reduce the BA content of kimchi.

### Challenges and perspectives

This review revealed that Koreans consume sufficient amounts of various LAB strains from kimchi. The intake of LAB from kimchi and its benefits to human health suggest that kimchi can function as a probiotic food. However, large-scale clinical studies are required to demonstrate the effects of kimchi consumption on the human body. In addition, it is necessary to elucidate the probiotic efficacy and mechanism of action of each species among the various LAB present in kimchi. Since the number and species of LAB in kimchi differ depending on the type of kimchi, raw ingredients, and fermentation period, there may be limitations to identifying the probiotic effects of non-standardized kimchi. Therefore, controlling or predicting the LAB present in kimchi will be an important area of research in the future. The control of LAB can be achieved using a starter culture. However, LAB inoculated as starters often fail to compete with microorganisms derived from raw kimchi ingredients. Therefore, it is necessary to study various methods for the inoculated starter to become the dominant species during kimchi fermentation. Taken collectively, kimchi with a desired/manipulated microbial community and/or metabolites can be used as functional probiotics customized for individuals or generations who want to change their diet, improve health, and treat gastrointestinal diseases.

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