Journal of Ethnic Foods

ORIGINAL ARTICLE

Open Access

Immunoenhancing and antioxidant potentials of kimchi, an ethnic food from Korea, as a probiotic and postbiotic food

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Abstract

Kimchi, the traditional lactic fermented vegetables from Korea, is globally praised for its potential as a functional food owing to the presence of beneficial microorganisms known as probiotics. However, the serving of kimchi in traditional Korean dishes often involves cooking at high temperature, thus killing the probiotics. Recently, non-viable or inactivated microorganisms and their metabolites, known as postbiotics, were shown to confer health benefits when consumed, thus giving rise to a novel potential of kimchi as a postbiotic food with health functionalities. The present study aimed to explore the potential of uncooked and cooked kimchi, both as a probiotic and postbiotic food, respectively, using an animal model. Mice were fed by AIN-76 diet enriched in 10% freeze-dried uncooked or cooked kimchi for 28 days prior to kill. Several parameters related to immune system and antioxidant were evaluated. Exposure of kimchi toward heat in steaming process killed the microorganisms in kimchi, but did not alter its antioxidant activity. Interestingly, the consumption of uncooked and cooked kimchi stimulated the growth of lactic acid bacteria in the intestine indifferently, as shown in the fecal matter. In addition, kimchi supplementation, either uncooked or cooked, increased the number of splenic lymphocytes and intestinal IgA, supporting the role of kimchi in the immune system. Furthermore, kimchi supplementation reduced the level of lipid peroxidation in the fecal matter, indicating its antioxidant activity in vivo. Taken together, the findings in this study suggest the potential of kimchi both as a probiotic and postbiotic food with antioxidant and immunoenhancing properties.

Keywords Kimchi, Probiotic, Postbiotic, Antioxidant, Immune system

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Introduction

Kimchi, an ethnic food originating from Korea, encompasses a diverse range of traditional vegetable dishes that undergo lactic acid fermentation involving lactic acid bacteria [1]. Among these, *baechu* kimchi, made primarily from Chinese cabbage or napa cabbage (*Brassica rapa* subsp. *pekinensis*) undergoing fermentation with various seasonings like garlic, ginger, red chili powder, and fish sauce, stands out as the most prevalent type, often referred to simply as kimchi [1]. Considered a dietary staple alongside rice in Korea, kimchi has entrenched itself within Korean food culture for millennia [2]. It holds a consistent presence in the daily Korean diet,

and a traditional Korean meal feels incomplete without it. The average Korean consumes approximately 40–57 pounds of kimchi per year, translating to about 50–70 g of kimchi consumed daily [3]. Presently, kimchi enjoys global recognition as a nutritious food source abundant in dietary fiber, vitamins, minerals, phytochemicals, and various other bioactive compounds believed to contribute to human health [4, 5]. Multiple studies have revealed its properties as a functional food providing health benefits, including antioxidant, anticancer, antimutagenic, antiobesity, antiaging, antiatherogenic, and antidiabetic activities [6–9]. Consuming fermented foods, including kimchi, has also been reported to increase the diversity of gut microbiome, which in turn will decrease inflammation and reinforce the human immune system [10].

With regard to its health-related properties, kimchi has been suggested to serve as a probiotic food [11]. Probiotics are generally defined as live microorganisms that are intended to provide health benefits when consumed [12]. However, the more recent and updated concept in terms of healthy or beneficial microbes defined probiotics as viable or unviable microbial cells (ruptured or intact; spore or vegetative) that is potentially healthful to the host [13]. According to this definition, probiotics are classified into three classes: true probiotic (active and viable cell), pseudo-probiotic (viable and inactive cell), and ghost probiotic (dead/non-viable/inactive cell in forms ruptured) [14]. Many lactic acid bacteria involved in the fermentation of kimchi are probiotics and they have been reported to be further involved in the beneficial effects of kimchi to human health, including *Lactobacillus plantarum*, *Lb. rhamnosus*, *Lb. acidophilus*, *Lb. brevis*, *Leuconostoc mesenteroides*, *Bacillus subtilis*, and *Weissella cibaria* [15–22]. Nevertheless, probiotics are sensitive to heat and do not survive high temperature applied in cooking [23]. Besides being consumed uncooked as a side dish (*banchan*), kimchi is also consumed cooked as a major ingredient in several Korean traditional dishes, such as stew (*kimchi jjigae*), fried rice (*kimchi bokkeumbap*), noodles (*kimchi guksu*), soup (*kimchi jjim*), pancake (*kimchi jeon*), and dumplings (*kimchi mandu*) [2]. In the production of these dishes, kimchi is generally exposed to a high temperature that can reach more than 100 °C, thus killing most or all the probiotics present in kimchi. Probiotics are generally sensitive toward heat and are killed following exposure to temperature of 46 °C or higher due to protein denaturation and their inability to form vegetative spores [24]. Therefore, it appears primordial to investigate whether cooked kimchi may still provide beneficial properties to human health.

Recently, the global trend of functional foods was directed toward postbiotics, the derivatives of probiotic cultures [25]. It was found that the dead cells of probiotics could be fractionated and their metabolites exhibited a wide range of bioactivities [26]. According to the International Scientific Association for Probiotics and Prebiotics (ISAPP), postbiotics are a preparation of inanimate microorganisms and/or their components that confers a health benefit on the host [27]. The concept of postbiotics is similar to paraprobiotics in some scientific publications [25], even though in some cases, the term "paraprobiotics" has been seemingly focused on the inactivated microorganism cells without their metabolites. The interest toward postbiotics or paraprobiotics as novel functional foods rose due to their safety compared to probiotics and suitability for people with weak immunity and the elderly [25]. Several studies investigating the health effects of postbiotics or paraprobiotics have become popular in recent years, including *Lb. plantarum* K8 extracted from kimchi that has been shown to suppress lipid accumulation and prevent obesity [28, 29]. However, to our knowledge, there have been no studies on the health-related effects of kimchi as a whole postbiotic food. Therefore, this study accentuates the health benefits of uncooked and cooked kimchi as a probiotic and postbiotic food, respectively. The analyzed properties in this study were focused on kimchi's immunoenhancing and antioxidant properties as the two essential properties of postbiotics [30].

Thus, the main objective of this study was to investigate the immunoenhancing and antioxidant potential of uncooked and cooked kimchi in vivo. Mice were fed with standard diet supplemented with freeze-dried kimchi (10%) for 28 days prior to kill and analyses on spleen, intestine, colon, and fecal matter. Our hypothesis was that both uncooked and cooked kimchi would exert antioxidant activities and enhance the immune system in mice, thus highlighting the potential of kimchi as a probiotic and postbiotic food. The originality of this study relies on our focus on the health benefits of kimchi as a postbiotic food which has never been previously published in any scientific media. This study would also support the development of traditional kimchi-derived dishes as functional foods, thus promoting ethnic foods as potential functional foods supporting human health.

Methods

Preparation and analysis of kimchi

Kimchi was prepared as previously described [31] with some modifications. Briefly, Chinese cabbage procured from a local market in Central Jakarta, Indonesia was washed and cut lengthwise through the stem into quarters. Afterward, the cabbage was salted with coarse salt (cabbage/salt = 10:1 (w/w)) for 2 h and the released water was drained. The seasoning paste was prepared by cooking glutinous rice flour (10 g), anchovy sauce (10 mL),

red chili powder (10 g), garlic powder (5 g), ginger powder (5 g), and caster sugar (3 g) in 100 mL water until a homogenous paste was formed. The paste was applied thoroughly to the salted cabbage prior to fermentation in an enclosed glass jar at room temperature for 3 days followed by storing in kimchi refrigerator (1–3 °C) for 4 days. The cooking of kimchi involved steaming kimchi in a steamer using water vapor generated from boiling water for 20 min. In this study, we also used raw cabbage and fresh kimchi as controls. Fresh kimchi had the same seasoning as the uncooked and cooked kimchi in this study, but did not undergo fermentation.

Kimchi samples were analyzed for their antioxidant activity and microbial content. The antioxidant activity, expressed as DPPH (1,2-diphenyl-1-picrylhydrazyl) scavenging activity, was analyzed as previously described [32] with some modifications and the results were presented as percentage of scavenged DPPH (from a total 0.73 mg DPPH neutralized by the extract of 10 mg sample). Total microorganisms and lactic acid bacteria in kimchi samples were determined using plate count agar (PCA) and MRS (de Man, Rogosa, and Sharpe) agar, respectively, following a 5-day incubation at 35 °C as previously described [33]. For animal experiments, cabbage and kimchi samples at the seventh day of fermentation were crushed using a blender following freeze drying (0.10 mbar, − 25 °C, 48 h) and ground to form powder [31].

Animal experiments

Forty male C57BL/6 mice aged 4 weeks old were purchased from the Bogor Life Science and Technology (West Java, Indonesia). They were housed with a 12-h light/dark cycle at room temperature and had access to food and water ad libitum. The mice were given modified AIN-76 diet [34] with freeze-dried cabbage or kimchi (10%). This concentration of kimchi in the ration represents a high kimchi consumption as observed in Korean diet [33]. The mice were then randomly divided into five groups, each of which consisted of eight mice kept in individual cages: group 1 (fed with modified AIN-76 diet), group 2 (fed with diet enriched with freeze-dried cabbage), group 3 (fed with diet enriched with freeze-dried unfermented fresh kimchi), group 4 (fed with uncooked kimchi-enriched diet), and group 5 (fed with cooked kimchi-enriched diet). The modified AIN-76 diet used in this study came in powdered form and was not sterilized to reflect the real human consumption of daily food. All the mice consumed, on average, 3.41 ± 0.55 g diet on daily basis for 28 days and there was no significant difference in terms of diet consumption observed among all the groups during the feeding duration ($p > 0.05$). The feeding period of 28 days was chosen based on our preliminary study since such a feeding period has been shown to successfully alter gut microflora in mice in a stable manner as observed in longer feeding periods. Their feces were collected at day 25–28 and pooled. At the end of the experiment, all the mice were euthanized by CO_2 asphyxiation. Their spleens and intestines were collected for further analyses. The protocol for our animal study has been approved by the Ethics Committee of University of Indonesia (KET-89/UN2.F12.D1.25/PPM.00.09/2019).

Analysis of spleens and intestines

The spleens were extracted from mice and weighed. To isolate splenocytes, the spleens were gently pressed with a syringe and forced through a 70 µm cell strainer. Cells were treated with red blood cell lysis buffer (Sigma-Aldrich), and the isolated splenocytes were incubated in RPMI-1640 containing FBS (10%) and antibiotics (penicillin and streptomycin, 1%) with LPS in an incubator supplemented with CO_2 (5%). The number of splenic lymphocytes was determined using a hemocytometer under a light microscope (Leica LMD6).

The distal ileum and proximal colon parts of the intestines (± 30 mg) were extracted from mice and weighed. The extracted intestines were then longitudinally opened and incubated in phosphate-buffered saline (PBS) for 20 min at room temperature prior to centrifugation (10,000×*g*, 5 min) and isolation of the supernatant as a mucosal suspension. The IgA in the suspension was analyzed using a commercial IgA ELISA kit (Abcam) according to the manufacturer's instructions.

RT-qPCR analysis

The mRNA expression of several genes in the ileum and colon mucosa, as well as in the splenocytes, was quantified using RT-qPCR following tissue lysis and mRNA extraction using mRNA isolation kit (Roche, Mannheim, Germany) according to manufacturer's instructions. The RT-qPCR analysis was done according to the previously described method [35]. The synthesis of cDNA was done using High-Capacity cDNA Reverse Transcription Kit (Thermo Fisher Scientific) with 1 µg RNA and the quantitative PCR was conducted using AriaMx Real-Time PCR systems (Agilent Technologies) according to the manufacturer's instructions with β-actin as the housekeeping gene. The thermocycling conditions were set as follows: initial denaturation at 95 °C (5 min), denaturation at 94 °C (30 s), annealing at 56 °C (30 s), extension at 72 °C (40 s), and final extension at 72 °C (5 min). The sequences of the primers (5′–3′) used are listed below: IgA or CD79A (F-ACG CTC CTG TGG TAC TTA CCT C, R-CCT TCT GCT GTG ATG ATG CGG T), CD86 (F-ACG TAT TGG AAG GAG ATT ACA GCT, R-TCT

GTC AGC GTT ACT ATC CCG C), iNOs or NOS2 (F-GAG ACA GGG AAG TCT GAA GCA C, R-CCA GCA GTA GTT GCT CCT CTT C), IL-1α (F-ACG GCT GAG TTT CAG TGA GAC C, R-CAC TCT GGT AGG TGT AAG GTG C), IL-1β (F-TGG ACC TCC CAG GAT GAG GAC A, R-GTT CAT CTC GGA GCC TGT AGT G), TNF-α (F-GGT GCC TAT GTC TCA GCC TCT T, R-GCC ATA GAA CTG ATG AGA GGG AG), and β-actin or ACTB (F-CAT TGC TGA CAG GAT GCA GAA GG, R-TGC TGG AAG GTG GAC AGT GAG G).

Preparation and analysis of fecal water

Fecal water was prepared as previously described [33] from the feces collected at day 25–28 of experiment and pooled. Briefly, feces (2 g) was mixed with distilled water (5 mL), ground, and centrifuged (10,000 g, 10 min). The supernatant was then collected, diluted 10× in Cell Biologics' culture complete epithelial cell medium (Cell Biologics), and sterilized using microfilter (pore size 0.2 µm) for further assays. The concentration of thiobarbituric acid reactive substances (TBARS) in the fecal water, expressed in malondialdehyde (MDA) equivalent, was analyzed by colorimetric assay [33] using a UV/Vis spectrophotometer (Multiskan SkyHigh, Thermo Fisher Scientific). The microbial load analysis of fecal water was done by diluting fecal water in peptone water containing 10% NaCl in serial tenfold steps prior to application onto agar. The total plate count (TPC) and lactic acid bacteria (LAB) count were determined using plate count agar (PCA) and MRS (de Man, Rogosa, and Sharpe) agar, respectively, following a 5-day incubation at 35 °C as previously described [33].

Statistical analysis

All data ($n \geq 5$) were analyzed using analysis of variance (ANOVA) followed by Tukey HSD post hoc test when the results showed significant differences among the samples ($p < 0.05$). The heatmap illustrating gene expression was generated using online application Displayr.

Results and Discussion

Effects of consuming uncooked and cooked kimchi on fecal microbiota

Figure 1A shows a significant increase in total plate count and lactic acid bacteria (LAB) count in uncooked kimchi owing to fermentation compared to napa cabbage and fresh kimchi. During the fermentation of kimchi, the amount of viable microorganisms increased by more than four logarithmic cycle from 1.4×10^4 g^{-1} in raw cabbage to 3.0×10^8 g^{-1} in uncooked kimchi. Interestingly, LAB were the most dominantly multiplying microorganisms during the fermentation process, as shown by a significant increase by more than five

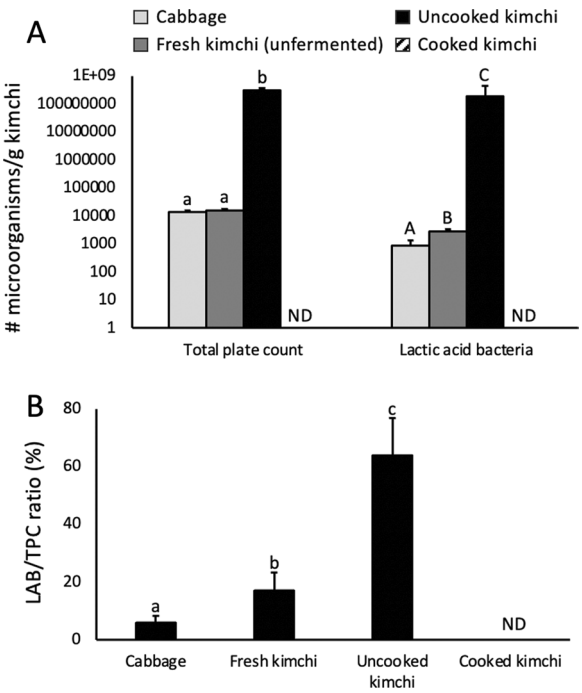

Fig. 1 **A** Microbial load (total plate count and lactic acid bacteria count) in cabbage and kimchi samples presented in logarithmic scale. **B** Ratio of lactic acid bacteria (LAB) count reported to total plate count (TPC) in cabbage and kimchi samples. Data ($n = 5$) are expressed in mean ± SD. Different lettering indicates statistically significant difference among samples ($p < 0.05$) based on ANOVA and Tukey HSD post hoc test. ND: not detected

logarithmic cycle from 8.5×10^2 g^{-1} in raw cabbage to 1.9×10^8 g^{-1} in uncooked kimchi. Figure 1B presents the increasing ratio of LAB reported to total microorganisms during the fermentation of kimchi. While LAB only composed 6.07% of total microorganisms in raw cabbage, their population rose significantly to 64.00% in uncooked kimchi. LAB have been reported to be the most dominant microorganisms in kimchi [36]. The fermentation of kimchi involves a series of LAB succession, with *Leuconostoc* spp. and *Weissella* spp. present in abundance at the early stages of fermentation to the dominance of *Lactobacillus* spp. and *Pediococcus* spp. developing the flavor of kimchi at the later stages of fermentation [36]. The main microbial activity in the fermentation of kimchi consists in degrading carbohydrates (starch, fiber, and simple sugars) to mainly lactic acid via an anaerobic metabolism involving LAB [37]. Cooking process through steaming was shown to kill all the microorganisms in kimchi, including LAB, as shown in Fig. 1A,B. In general, most LAB are heat-sensitive and die at temperature above 46 °C due to protein denaturation and incapability to form endospores as a survival mechanism under stress [24].

Figure 2A demonstrates that the consumption of uncooked kimchi led to a significant increase in LAB in the fecal matter (from 3.2×10^5 g^{-1} in mice fed with control diet to 2.00×10^7 g^{-1} in mice fed with uncooked kimchi-enriched diet), thus supporting the role of kimchi as a probiotic food. The consumption of cabbage or kimchi did not significantly affect the total microbial load of fecal matter. However, the abundance of LAB rose following the consumption of cabbage and kimchi samples (Fig. 2B). In general, cabbage is rich in fiber (cellulose) that can act as a substrate for gut microbiota. Furthermore, fiber is also categorized as a prebiotic which serves as a nutrient source for beneficial bacteria (probiotics) in the digestive system [38]. While the fecal matter of mice consuming control diet contained as little as 0.8% LAB, such a ratio was significantly improved to 31.6% following consumption of uncooked kimchi.

Interestingly, consuming bacteria-free cooked kimchi also improved the amount and abundance of LAB as depicted in Fig. 2A,B. Thus, these findings suggested that inanimate microbes, as well as nutrients, microbial metabolites, and other compounds present in kimchi could modulate the gut microbiota and support the growth of LAB initially present in low amount in the colon of mice. In the fecal matter of mice consuming cooked kimchi, LAB composed 25.1% of total microorganisms, compared to 0.8% in mice fed with control diet (Fig. 2B). For further studies, it would be interesting to identify the LAB in the fecal matter and compare the profile of LAB present in the colon of mice fed with cooked kimchi and uncooked kimchi.

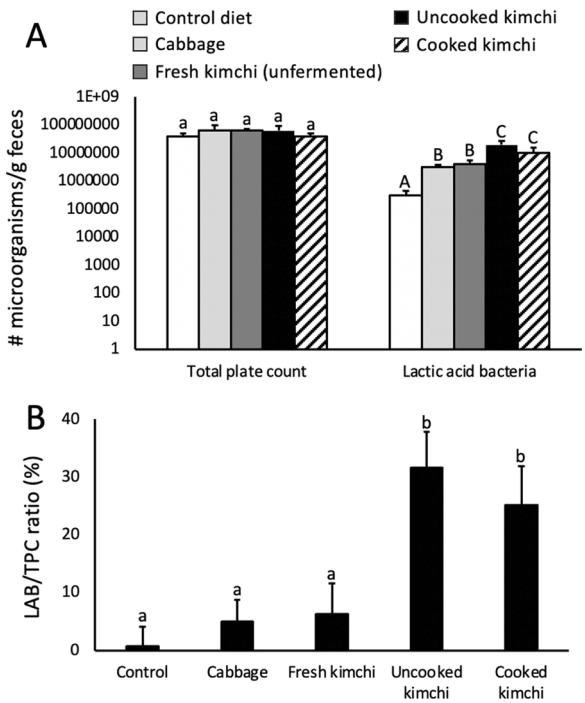

Fig. 2 **A** Microbial load (total plate count and lactic acid bacteria count) in the fecal water of mice fed with cabbage and kimchi samples presented in logarithmic scale. **B** Ratio of lactic acid bacteria (LAB) count reported to total plate count (TPC) in the fecal water of mice fed with cabbage and kimchi samples. Data ($n=8$) are expressed in mean ± SD. Different lettering indicates statistically significant difference among samples ($p<0.05$) based on ANOVA and Tukey HSD post hoc test

Immunoenhancing properties of kimchi as probiotic and postbiotic food

Previously, Korean foods including kimchi were suggested to exert immunomodulatory properties to support immune system [39]. Enhancement of immune system is a functional benefit expected from a postbiotic food. In this study, the immunoenhancing properties of kimchi were determined by analyzing different parameters of spleen and intestine.

Spleen is an important organ of the immune system whose roles include storing and filtering blood, controlling the level of blood cells, producing white blood cells, and fighting against invading germs in the blood [40]. Figure 3A,B demonstrates an increase in relative splenic mass and the amount of splenic lymphocytes in the mice fed with uncooked and cooked kimchi, thus indicating the enhancement of immune system. These parameters were found to be similar between the mice consuming uncooked and cooked kimchi. Furthermore, the importance of fermentation process in kimchi's immune-related properties was reflected from the higher amount of splenic lymphocytes in the mice fed with uncooked and cooked kimchi compared to those fed with unfermented fresh kimchi (Fig. 3B). The increase in splenic mass and splenic lymphocytes has been associated with an enhancement in the immune system because both the spleen and the lymphocytes play critical roles in the body's immune response. Splenic mass and lymphocytes have been shown to increase following the body's response to immune-related stimuli, thus allowing the body to effectively combat pathogens and maintain overall health. The mechanism by which kimchi consumption could lead to immune system enhancement is suggested to involve the presence and activities of probiotics through the production of short-chained fatty acids (SCFAs), cytokines and other molecules with immunomodulatory effects that can influence immune cell proliferation, differentiation, and function [41].

Secretory immunoglobulin A (IgA) is the most abundant antibody present on the surface of intestinal mucosa that protects the tissues from foreign substances and microbial invasion [42]. Figure 3C shows that the consumption of cabbage and kimchi samples

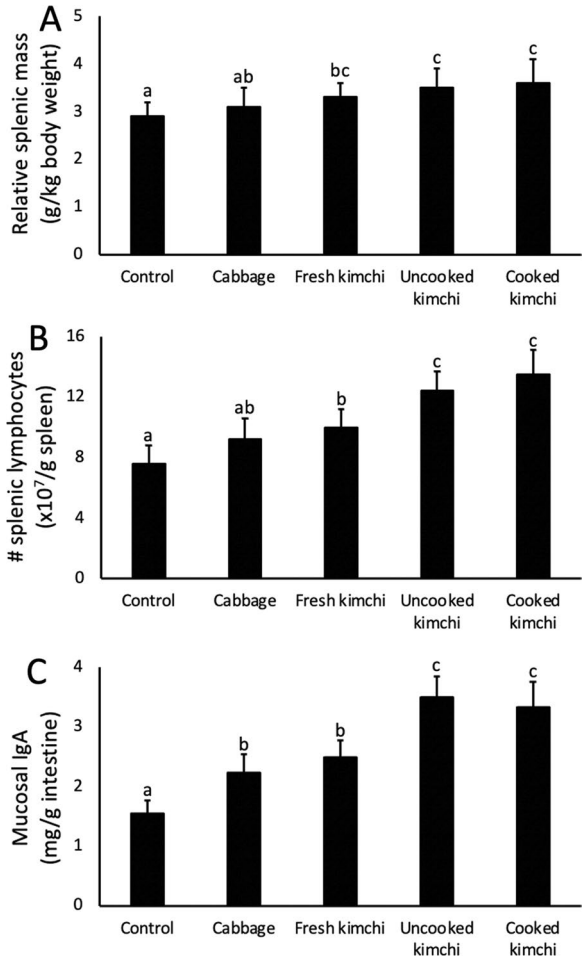

Fig. 3 Effects of consuming cabbage and kimchi samples on immune system-related parameters of mice, including **A** relative splenic mass, **B** number of splenic lymphocytes, and **C** concentration of mucosal IgA in the colon. Data ($n = 8$) are expressed in mean ± SD. Different lettering indicates statistically significant difference among samples ($p < 0.05$) based on ANOVA and Tukey HSD post hoc test

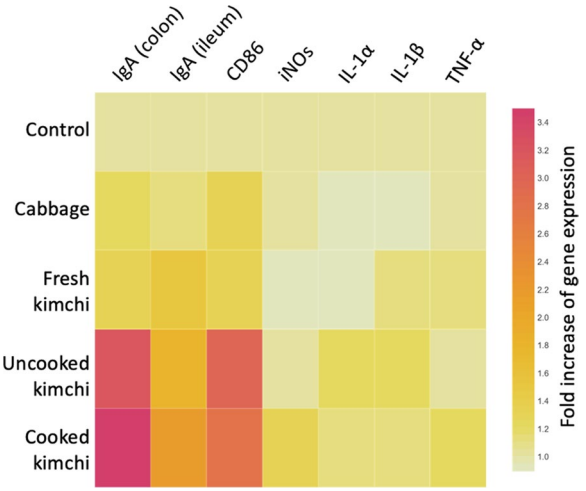

Fig. 4 Heatmap representing relative expression level of genes in the spleen and intestine of mice consuming diet enriched in cabbage and kimchi samples. Gene expression in all groups was normalized relatively to control group receiving standard diet without cabbage or kimchi

led to an increase in the secretion of mucosal IgA in the ileum and colon of mice. In particular, the mucosal IgA secretion appeared to be the highest in the intestine of mice consuming uncooked and cooked kimchi indifferently. Indeed, the intestinal immune system is the largest and most complex party of the animal immune system [43]. Mucosal surfaces in the intestine are colonized by large communities of commensal bacteria and represent the primary entry site for pathogenic agents [43].

To investigate the immunoenhancing properties of cabbage and kimchi samples at the molecular level, we analyzed the expression of some immune system-related genes by RT-qPCR and the results are presented in Fig. 4. Supporting our previous findings (Fig. 3C), the expression of IgA was shown to be strongly upregulated in the intestine of mice fed with uncooked and cooked kimchi. Such an expression appeared to be stronger in the colon than in the ileum.

Macrophages, essential immune cells, play a crucial role in the body's primary defense against pathogens [44]. Macrophages express inducible nitric oxide synthase (iNOS), an enzyme involved in producing nitric oxide (NO), a potent antimicrobial molecule. Upon activation by microbial products or inflammatory signals, macrophages release cytokines like interleukin-1 alpha (IL-1α), interleukin-1 beta (IL-1β), and tumor necrosis factor-alpha (TNF-α) [44]. Figure 4 shows that the consumption of uncooked and cooked kimchi strongly stimulated the expression of splenic CD86 (cluster of differentiation 86), a marker gene for macrophages, thus indicating an increase in the expression of macrophages [44]. In addition, the expression of iNOs and cytokines was also upregulated in the spleen following the consumption of uncooked and cooked kimchi compared to control diet, but to a lesser extent compared to the expression of CD86.

Overall, these findings indicate the immune-enhancing properties of uncooked and cooked kimchi by increasing splenic mass and the number of splenic lymphocytes, as well as upregulating the expression of IgA, macrophages, and some cytokines related to cellular defense. Macrophages are critical effector cells of the innate immune system [44] while IgA has been proposed to exert an interactive role in both innate and adaptive immune

system [43]. Interestingly, the expression of macrophages and IgA has been reported to be dependent on commensal bacteria present in the intestine [45, 46]. Moreover, our findings highlight the potential of kimchi as a probiotic as well as postbiotic food in improving the immune system.

Antioxidant properties of kimchi as probiotic and postbiotic food

Postbiotic foods are expected to exert a potent antioxidant activity. Several heat-inactivated postbiotics extracted from kimchi have been reported to exhibit antioxidant potential [28, 29]. Indeed, consuming foods rich in antioxidants has been associated with overall human health and strong immune system [47].

Figure 5A demonstrates the antioxidant activity of cabbage and kimchi samples. Fresh kimchi showed a higher antioxidant activity compared to cabbage due to the addition of kimchi sauce (*yangnyeom*) containing natural spices rich in antioxidants, such as chili pepper, garlic, and ginger [48]. The antioxidant activity of uncooked and cooked kimchi appeared to be the highest. During fermentation, chemical reactions and microbial activities result in the formation of metabolites with antioxidant activity, such as organic acids [4]. In addition, the softening texture of cabbage allows the release of bioactive compounds and antioxidant from the food matrices, thus increasing the antioxidant activity of kimchi [4].

To evaluate the antioxidant activity of cabbage and kimchi samples in vivo, we analyzed the TBARS (thiobarbituric acid reactive substances) concentration in the fecal matter. TBARS are molecules formed as byproducts of lipid peroxidation and the consumption of kimchi rich in antioxidants has been shown to correlate inversely with TBARS concentration in fecal matter [33]. Figure 5B shows that consuming uncooked and cooked kimchi reduced the amount of fecal TBARS. Previously, high level of fecal TBARS has been strongly associated with excessive lipid peroxidation in the digestive tube and the promotion of colorectal cancer in animal models [49]. Therefore, these findings also suggest the anticancer potential of kimchi consumed as probiotic or postbiotic food against colorectal cancer for further research.

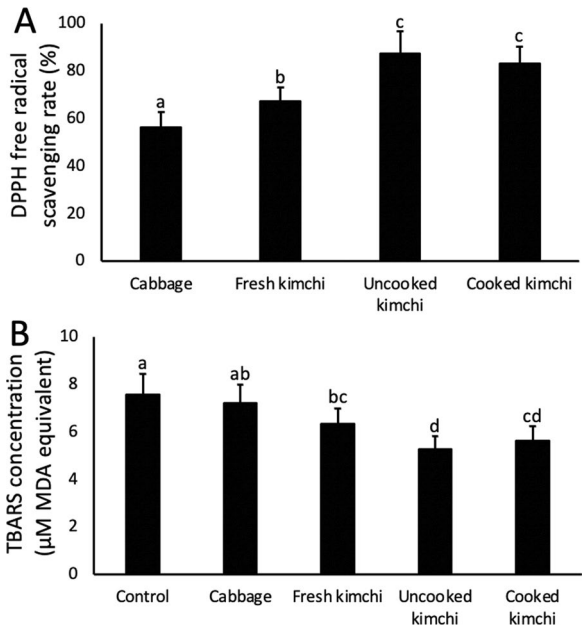

Fig. 5 **A** Antioxidant activity of cabbage and kimchi samples expressed as DPPH scavenging rate. **B** TBARS (thiobarbituric acid reactive substances) concentration of the fecal water of mice consuming diet enriched in cabbage and kimchi samples. Data ($n \geq 5$) are expressed in mean ± SD. Different lettering indicates statistically significant difference among samples ($p < 0.05$) based on ANOVA and Tukey HSD post hoc test

Conclusion

Taken together, the findings in the present study highlighted the potential of kimchi to be developed as a functional food for human health, both as a probiotic and postbiotic food. The functionalities of kimchi presented in this study included antioxidant activity and enhancement of host's immune system. In particular, this study suggests that consuming kimchi, either uncooked or cooked, would both provide health benefits. Therefore, the presence of probiotics in kimchi is not the only determining factor of kimchi's health-related potential. Such findings are essential since kimchi is traditionally used as an ingredient of traditional Korean dishes, such as soup, stew, dumpling, pancake, and fried rice. The present study revealed that these dishes, which may contain very little or no probiotics due to heat exposure during cooking process, would also provide health-related benefits as uncooked kimchi. Thus, this study would reinforce the global image of kimchi as a healthy food and support the development of traditional kimchi-derived dishes as functional foods beneficial for human health.

Abbreviations

AIN-76	American Institute of Nutrition-76
CD86	Cluster of differentiation 86
DPPH	1,2-Diphenyl-1-picrylhydrazyl
IgA	Immunoglobulin A
IL-1α	Interleukin-1 alpha
IL-1β	Interleukin-1 beta
iNOS	Inducible nitric oxide synthase
LAB	Lactic acid bacteria
MDA	Malondialdehyde
MRS	De Man, Rogosa, and Sharpe
PCA	Plate count agar
TBARS	Thiobarbituric acid reactive substances
TNF-α	Tumor necrosis factor-alpha
TPC	Total plate count

Acknowledgements
The authors would like to thank Fransisca Nathania, Michella Lestari, Ha-Nui Kim, and Hae-Geun Jeong for their precious help regarding the animal experiment and analysis.

Author contributions
ES, JSO, and JGJ contributed to collaboration and project conceptualization. DN, AT, ES, H, JGJ, and RS were involved in data collection and analysis. DN and RS contributed to manuscript production. JSO and RB were involved in manuscript review and editing.

Funding
This study was partially funded by The Korea Foundation and Tzu Chi Foundation.

Availability of data and materials
The data and materials related to this study are available upon request.

Declarations

Ethics approval and consent to participate
The protocol for animal experiments performed in this study has been approved by the Ethics Committee of the Faculty of Medicine, University of Indonesia (Jakarta, Indonesia).

Consent for publication
All the authors have read and approved the content of this manuscript for a publication.

Competing interests
The authors declare no competing interests.

Received: 18 December 2023 Accepted: 25 April 2024
Published online: 09 May 2024

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