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Review

Health Benefits of Kimchi, Sauerkraut, and Other Fermented Foods of the Genus *Brassica*

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Abstract: Fermented foods made through microbial growth and enzymatic conversions have been integral to human diets for at least 10,000 years. Recent interest in fermented foods has surged due to their functional properties and health benefits. Cruciferous vegetables of the genus *Brassica*, such as cabbage, broccoli, and cauliflower, are commonly used to produce fermented foods like sauerkraut, kimchi, pao cai, fermented turnips, and others. These foods are rich in lactic acid bacteria (LAB) and bioactive compounds, which contribute to their potential health-promoting properties. We examined 12 clinical trials investigating fermented foods of the genus *Brassica*. These studies, which mainly assessed the health benefits of kimchi or sauerkraut consumption, found that regular intake can alleviate symptoms of irritable bowel syndrome (IBS), aid weight loss, and enhance metabolic health. Seven observational studies also observed health benefits when consuming fermented foods of the genus *Brassica*. Six of the seven observational studies on kimchi intake linked kimchi intake to reduced obesity risk and other health benefits. An observational study linked sauerkraut and cabbage consumption to reduced breast cancer risk. Despite these findings, the exact roles of various microorganisms and bioactive compounds within these health effects require further investigation. This review underscores the potential of fermented cruciferous vegetables as functional foods, and advocates for more clinical trials and mechanistic studies to understand and optimize their health benefits.

Keywords: fermented vegetables; *Brassica*; fermented cabbage; kimchi; sauerkraut

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1. Introduction

According to the expert panel of the International Scientific Association of Probiotics and Prebiotics (ISAPP), fermented foods are, by definition, "foods and beverages made through desired microbial growth and enzymatic conversions of food components" [1]. Fermented foods have been an important part of the human diet for at least 10,000 years, and the process of fermentation represents one of the oldest methods of preserving and producing foods and beverages [2]. Traditional fermented foods have a long history. They were among the first processed food products consumed by humans and have important nutritional and functional properties [3,4]. Recently, fermented foods have been gaining more attention due to their functional characteristics, biologically active compounds, and proposed and established health benefits [5,6]. ISAPP has also published consensus statements on the exact definitions of probiotics [7], prebiotics [8,9], synbiotics, and postbiotics [10] and emphasizes that fermented foods and these terms should not be used interchangeably.

Many foods have historically undergone fermentation, including meat and fish, dairy, vegetables, soybeans, other legumes, cereals, and fruits [5]. Some of the most well-known fermented foods and beverages include kefir, yoghurt, kombucha, cheese, sourdough, sauerkraut, miso, tempo, natto, kimchi, beer, and wine. Fermentation can occur spontaneously by the microorganisms naturally occurring in or on the raw food (i.e., sauerkraut, kimchi, and fermented soy products), with the addition of starter cultures (kefir, kombucha, and natto), using small amounts of a previously fermented batch, known as backslopping (i.e., sourdough), or with commercial staters in commercially processed fermentation (i.e., yoghurt, cheeses, wine, and beer) [5,6]. The most common microorganisms involved in fermentation include various genera of bacteria such as lactic acid bacteria (e.g., *Lactobacillus* spp., *Lactiplantibacillus* spp. and other genera of the lactobacilli complex, *Lactococcus* spp., *Leuconostoc* spp., *Enterococcus* spp., *Pediococcus* spp., *Tetragenococcus* spp., *Streptococcus* spp., *Weissella* spp.), acetic acid bacteria (e.g., *Acetobacter* spp., *Gluconobacter* spp., *Gluconacetobacter* spp., *Komagataeibacter* spp.), and several other bacteria species (e.g., *Bacillus* spp., *Staphylococcus* spp., *Brevibacterium* spp., *Propionibacterium* spp.), as well as certain yeasts (e.g., *Saccharomyces* spp., *Pichia* spp., *Candida* spp.) and molds (e.g., *Penicillium* spp., *Aspergillus* spp., *Rhizopus* spp.) [1,2,11].

Cruciferous vegetables belong to the genus *Brassica* and include green, white, and red cabbage (lat. *Brassica oleracea* var. *capitata*), broccoli (lat. *Brassica oleracea* var. *italica*), cauliflower (lat. *Brassica oleracea* var. *botrytis*), Brussels sprouts (lat. *Brassica oleracea* var. gemmifera), napa cabbage (lat. *Brassica rapa* subsp. *pekinensis*), also known as Chinese cabbage, and baechu cabbage (lat. *Brassica rapa* subsp. *rapa*), green turnip (lat. *Brassica rapa* L.), Savoy cabbage (lat. *Brassica oleracea* var. *sabauda*), tuber mustard (*Brassica juncea* var. *tumida*), and other vegetables [12–15]. These vegetables are a rich source of carbohydrates, fibers, minerals, and important micronutrients, such as vitamins, polyphenols, and carotenoids [16,17]. Cruciferous vegetables have been investigated for their antioxidant [18], anti-carcinogenic [19], and other health-promoting properties [20], which is in part attributed to their contents of organosulfur compounds and phytochemicals (e.g., indole-3-carbinol, sulforaphane) [17,21–23].

Well-known fermented products from these cruciferous vegetables include sauerkraut, kimchi, pao cai, sunki, and others [3,24,25]. Sauerkraut, also known as German kraut, is a fermented cabbage product that is very popular in Europe and gained popularity in the United States, primarily due to German immigrants who brought their culinary traditions [26–28]. Kimchi is a spicy and pungent blend of fermented Napa cabbage, radish, red chilies, garlic, fish, and salt. It is a traditional Korean dish and is served as a side dish with almost every meal [24,25,29–31]. Pao cai or paocai, also known as Sichuan sauerkraut, is a fermented vegetable product made from brine-salted napa cabbage or other vegetables and is a symbol of Southwestern Chinese culture [24,32]. Northeastern Chinese sauerkraut is called suan cai [33]. Zha cai is also a Chinese fermented food, made by the spontaneous fermentation of tuber mustard [34]. Sunki is an unsalted, lactic acid-fermented pickle which is produced using turnip leaf in Japan [35]. Similarly, Nozawana is a Japanese fermented food made from green turnip leaves [36]. Other fermented cruciferous foods include fermented turnips (Sauerruben or Ruebenkraut), fermented broccoli, fermented Brussels sprout, and fermented Savoy cabbage. While production methods vary, the primary process includes pretreatment of raw materials, brining, seasoning, and fermenting either naturally or with starter cultures, lasting from several days to months [6]. The main fermentation process is lactic acid fermentation by naturally present lactic acid bacteria (LAB) [27,37–40]. These fermented foods exhibit a rich diversity of microorganisms [5,37,41–55]. The primary lactic acid bacteria (LAB) involved in the fermentation of cruciferous vegetables include *Lactiplantibacillus pentosus*, *Lactiplantibacillus paraplantarum*, *Lactiplantibacillus plantarum*, *Latilactobacillus curvatus*, *Latilactobacillus sakei*, and *Levilactobacillus brevis*. These bacteria are crucial for producing lactic acid, which lowers the pH and preserves the vegetables while contributing to their characteristic tangy flavor [37,56–58]. Lactic acid fermentation can augment the bioactivity of the raw ingredients by elevating the levels of selected vitamins (e.g., B group vitamins), functional phytochemicals (e.g., glucosinolate breakdown products and their derivatives), short-chain fatty acids, polyphenols, flavonoids, minerals, dietary fiber, beneficial microorganisms, and many other bioactive compounds [3,5,6,12,24,29,59–64].

Various reviews on the health benefits of kimchi have been published, and have emphasized the lack of clinical trials. However, convincing in vitro, in vivo, and observational studies concluded that high-quality clinical trials investigating the health benefits of fermented *Brassica* vegetables are warranted [5,65–73]. In this review, we focused on human studies examining the effects of kimchi, sauerkraut, and other cabbage-containing fermented foods established from published clinical trials, observational studies, and surveys.

2. Clinical Trials Investigating the Health Benefits of Consuming Kimchi, Microbes Isolated from Kimchi, Sauerkraut, or Other Fermented Foods Containing Vegetables of the Genus *Brassica*

We used the search strategy: ("fermented cabbage" OR "*Brassica oleracea*" OR "*Brassica rapa*" OR "sauerkraut" OR "kimchi" OR "*Brassica*" OR "fermented cauliflower" OR "fermented broccoli") AND "health benefits" in various databases (PubMed, ScienceDirect), and included placebo-controlled clinical trials, which investigated fermented foods containing vegetables of the genus *Brassica* and their potential health benefits. Animal model studies, and reports of human studies without the full text available or not in English, were excluded. Clinical trials that assessed the influence of individual strains isolated from the fermented foods were also excluded. Some of the references were found in the reference list of previously published reviews [5,65,74]. Based on these criteria, a total of 12 clinical studies investigating the health effects of fermented vegetables of the genus *Brassica* were found (up to 1 June 2024) (Table 1).

Table 1. Main characteristics and main findings of 12 clinical trials investigating the influence of consumption of fermented foods containing vegetables of the genus *Brassica* noted in descending chronological and alphabetical order.

References and Country	Investigated Aim	Population that Completed the Trial	Intervention (Daily Regime, Duration, Other Information)/Control	Main Findings
Clinical trials investigating the influence of kimchi consumption				
Kim et al., 2022 [75], Republic of Korea.	Effects of kimchi intake on symptoms of IBS and intestinal microbiota community.	90 participants with IBS. 30 in group A. 30 in group B. 30 in group C.	Three types of kimchi: Group A: standard kimchi. Group B: standard kimchi with added *L. plantarum* nF1 *. Group C: functional kimchi (added mistletoe and other sub-ingredients). 210 g a day for 12 weeks.	- Alleviation of IBS symptoms, reduction of TNF-α, β-glucosidase and β-glucuronidase (fecal enzymes) (all groups). - Increased Bacillota (previously Firmicutes) # and decreased Bacteroidota (previously Bacteroidetes) # gut microbiota population (pyrosequencing method). - Reduction of inflammatory cytokines (Il-4, Il-10) (groups B and C). - Increased population of *Bifidobacterium adolescentis* (group C).
Kraft et al., 2019 [76], United States of America.	Effect of kimchi intake on GI symptoms, characteristics and consumer acceptability of kimchi.	20 participants. One group.	Kimchi. 75 g twice daily for 14 days.	- Decrease in abdominal pain, heartburn, acid regurgitation, abdominal rumbling and distention, and eructation and gas production. - Homemade kimchi had a lower concentration of LAB compared to commercial kimchi (plating methods). - Majority of participants willing to consume kimchi in the future.

Table 1. *Cont.*

References and Country	Investigated Aim	Population that Completed the Trial	Intervention (Daily Regime, Duration, Other Information)/Control	Main Findings
Kim et al., 2018 [77], Republic of Korea.	Effect of kimchi intake on colon health and other health metabolic parameters.	28 healthy young adults. 14 in group A. 14 in group B.	Group A: standardized kimchi. Group B: functional kimchi with added *L. plantarum* PNU *, derived from kimchi (1×10^6 cfu per serving). 210 g (3 times 70 g) daily for 28 days.	- Reduced body fat, LDL and increased HDL levels and concentration of short-chain fatty acids (both groups). - Reduction of triglycerides, IL-6 levels and increase in adiponectin levels (group B). - Reduced abundance of Bacillota and increased levels of Bacteroidota (both groups).
Kim et al., 2016 [78], Republic of Korea.	Effect of kimchi intake on adult females' intestinal microbiota.	12 females. 6 in group A. 6 in group B.	Group A: high kimchi intake (150 g daily). Group B: low kimchi intake (15 g daily). For 7 days.	- Influence on intestinal microbiota (16S rRNA sequencing using customized microarray chips) (both groups). - Decreased percentage of Gammaproteobacteria and increased percentage of kimchi-dominant species (group A).
Han et al., 2015 [79], Republic of Korea.	Effect of kimchi intake on the association between gut microbiota and anti-obesity.	23 women with BMI $\geq$ 25 kg/m^2. 11 in group A. 12 in group B.	Group A: fermented kimchi (60 g per serving). Group B: fresh kimchi (60 g per serving). 180 g daily for 8 weeks.	- Decrease of HDL-cholesterol, systolic blood pressure (group A). - Decrease of waist circumference, body fat percentage (group B). - Changes in gut microbial population (pyrosequencing) more evident group A.
Lee et al., 2014 [80], People's Republic of China.	Effect of kimchi intake on immunomodulatory effects in healthy Chinese college students.	39 students with BMI 18–23 kg/m^2. 20 in group A. 19 in group B.	Group A: kimchi. Group B: control (radish). 100 g daily for 4 weeks.	- No significant changes observed in T-cell, B-cell, NK-cell concentration, proinflammatory cytokines (IL-6, TNF-α), anti-inflammatory cytokines (IL-4, IL-10) (both groups).
Choi et al., 2013 [81], Republic of Korea.	Effect of kimchi intake on serum lipid concentrations.	100 volunteers. 50 in group A. 50 in group B.	Group A: high kimchi intake (210 g daily). Group B: low kimchi intake (15 g daily). For 7 days.	- Decreased fasting blood glucose and serum total cholesterol (both groups), however, the effects were greater in group A.
An et al., 2013 [82], Republic of Korea.	Effect of kimchi intake on glucose metabolism in patients with prediabetes.	21 participants with prediabetes. 8 in group A. 13 in group B.	Fresh or fermented kimchi for 8 weeks. 4-week washout period. Fermented or fresh kimchi for 8 weeks.	- Decreased body weight, body mass index, and waist circumference (both groups). - Decreased insulin resistance and systolic and diastolic blood pressure and increased insulin sensitivity during fermented kimchi intake.
Kim et al., 2011 [83], Republic of Korea.	Effect of kimchi intake on metabolic parameters in overweight and obese subjects.	22 patients with BMI $\geq$ 25 kg/m^2. 10 in group A. 12 in group B.	Fresh or fermented kimchi for 4 weeks. 2-week washout period. Fermented or fresh kimchi for 4 weeks.	- Decrease in body weight, body mass index, and body fat (both groups) - Decrease in the waist/hip ratio and fasting blood glucose, and total cholesterol during fermented kimchi intake.

Table 1. *Cont.*

References and Country	Investigated Aim	Population that Completed the Trial	Intervention (Daily Regime, Duration, Other Information)/Control	Main Findings
Clinical trial investigating the influence of sauerkraut consumption				
Nielsen et al., 2018 [84], Kingdom of Norway.	Effect of sauerkraut intake on symptoms of IBS and intestinal microbiota community.	58 IBS patients. 31 in group A. 27 in group B.	Group A: unpasteurized sauerkraut. Group B: pasteurized sauerkraut. 75 g daily for 6 weeks.	- Reduced IBS patients' symptoms (both groups). - Changes to the gut microbiota composition (16S rRNA sequencing of V3 region). - The effect can be attributed to potential prebiotics in sauerkraut rather than LAB.
Clinical trial investigating the influence of consumption of fermented cabbage or fermented cucumbers				
Galena et al., 2022 [85], United States of America.	Effects of regular consumption of fermented cabbage and/or cucumbers.	93 healthy women. 31 in group A. 31 in group B. 31 in group C.	Group A: fermented cabbage and/or cucumbers. Group B: pickled cabbage and/or cucumbers. 100 g a day for six weeks. Group C: control group (usual diet).	- No change in levels of C-reactive protein (CRP), TNF-α, lipopolysaccharide binding protein (all groups). - Consumption of fermented cabbage and/or cucumbers is feasible and may result in beneficial changes in the gut microbiota composition.
Clinical trial investigating the influence of nozawana consumption				
Tanaka et al., 2021 [86], Japan.	Effect of fermented *Brassica rapa* L. (Nozawana) intake on immune function and intestinal bacterial community.	20 volunteers. One group.	30 g of fermented *Brassica rapa* L. per day For 4 weeks	- Increase of defecation frequency after intervention. - Increased population of fiber-degrading bacteria and butyrate-producing bacteria (terminal-restriction fragment length polymorphism methodology).

* Novel nomenclature and taxonomy of *Lactobacillus* group according to Zheng et al. [87], # new phyla nomenclature [88]; BMI: body mass index; GI: gastrointestinal; IBS: irritable bowel syndrome; LAB: lactic acid bacteria.

A total of 12 clinical trials or interventional studies on the effects of fermented foods of the *Brassica* genus on human health were found [75–86]. Two studies were conducted in the USA [76,85], one study in Norway [84], one study in China [80], one study in Japan [86], and the remaining seven studies were conducted in the Republic of Korea (Table 1).

These studies investigated kimchi, sauerkraut, fermented cabbage, fermented cucumbers and fermented green turnip (Table 1). The majority focused on kimchi, whereas Nielsen and coauthors and Galena and coauthors investigated the health benefits of sauerkraut [84] and fermented cabbage [85], respectively. Tanaka and co-authors focused on fermented green turnip or nozawana [86].

Most interventional studies were randomized controlled clinical trials [75,77,79–85], and two of these studies used a cross-over design with washout periods [82,83]. One study did not contain any information on randomization [78] and two studies examined the influence of the fermented food before and after intake on the same group of people [76,86]. Among the studies examining kimchi, several control groups consumed fresh kimchi, which means fermentation did not occur [79,82,83], or lower amounts of kimchi, [78] as placebo. (Table 1).

Among the different endpoints, two clinical trials [75,84] reported that kimchi [75] and sauerkraut [84] could alleviate IBS symptoms (Table 1). In those studies, it was found that consumption of either food was associated with reduced serum inflammatory cytokines, reduced harmful fecal enzyme activities (β-glucosidase and β-glucuronidase), and changes in gut microbiota composition.

Immune modulatory effects after intake of fermented foods of the genus *Brassica* were observed in several clinical trials (Table 1). After kimchi intake, a reduction of IL-6 levels in healthy adults [77] was observed. On the other hand, there was no change in the levels of C-reactive protein (CRP) and TNF-α after sauerkraut intake [85]. Similarly, in the clinical study on healthy Chinese college students [80], no significant changes in T-cell, B-cell, NK-cell concentration, proinflammatory cytokines (IL-6, TNF-α), or anti-inflammatory cytokines (IL-4, IL-10) between the kimchi and non-kimchi groups were observed. However, when comparing the immunological parameters in the kimchi group at baseline and after consumption, a statistically significant reduction in IL-6 and TNF-α was observed in both groups, which could be attributed to the fact that the control group consumed radish, which could also exhibit immune-modulating effects. In vitro and in vivo animal studies have also established that components of kimchi and other fermented foods can have anti-inflammatory effects by upregulating anti-inflammatory markers and downregulating inflammatory markers [89–91].

Several clinical trials (Table 1) assessed weight loss, body fat, or metabolic health [77,79,82,83,92] and found that kimchi consumption was associated with weight loss, a reduction in body fat, and improved metabolic parameters, such as fasting blood glucose, total cholesterol, and insulin sensitivity. With regard to possible weight loss, the authors hypothesized that consumption of fermented kimchi can either directly influence the expression of human genes related to metabolic and immunity pathways or indirectly influence human metabolism by altering gut microbial composition [79].

An and co-authors [82] also found that fermented kimchi intake resulted in decreased insulin resistance and systolic and diastolic blood pressure, and increased insulin sensitivity. A higher intake of kimchi was also linked to decreased fasting blood glucose and serum total cholesterol, and kimchi supplementation in various forms (fresh, fermented, or as pills) significantly improved HDL levels and reduced LDL/HDL cholesterol ratios [81,93].

Skin health was assessed in one study [94], finding that kimchi-derived probiotics promoted healthier skin by increasing epidermal lactate and maintaining an acidic skin pH.

Consumption of kimchi and sauerkraut also influenced the gut microbiota as found in several clinical trials (Table 1) [75,77–79,84–86,95]. The influence on gut microbiota after kimchi intake included changes to the Bacillota (previously Firmicutes)/Bacteroidota (previously Bacteroidetes) ratio [75,77,79]. Other influences on the gut microbiota after kimchi intake included an increase in the population of fiber-degrading bacteria and butyrate-producing bacteria [86], a decreased percentage of Gammaproteobacteria and an increased percentage of kimchi-dominant species [78], and increases in lactobacilli and *Leuconostoc* in feces [95]. After sauerkraut intake, an increase in populations of sauerkraut-related bacteria (*L. plantarum* and *L. brevis*) in fecal samples [84] and an increase in *Faecalibacterium prausnitzii* with a decrease in *Ruminococcus torques* and greater alpha diversity [85] were observed.

Two clinical trials (Table 1) included groups that consumed kimchi or kimchi with added strains *Lactiplantibacillus plantarum* nF1 [75] and *L. plantarum* PNU [77]. We also found six studies that assessed the influence of specific strains derived from kimchi, *L. plantarum* CJLP243 [96], *L. plantarum* HAC01 [97], *Latilactobacillus sakei* CJLS03 [98], an undefined strain of *Leuconostoc holzapfelii* [99], *L. plantarum* CJLP55 [94], and undefined *Lactobacillus* spp. [100], as well as five studies written in the Korean language [92,93,95,101,102]. However, we did not include these in Table 1 as they did not meet the inclusion criteria.

3. Observational Studies on the Health Benefits of Consuming Fermented Foods Containing Vegetables of the Genus *Brassica*

Observational studies on fermented vegetables have been conducted on kimchi. A cross-sectional analysis of 115,726 participants found that the consumption of 1–3 servings/day of kimchi was associated with a lower risk or lower prevalence of obesity in adults [74]. Similarly, in a cohort study by Tan and co-authors [103], a correlation analysis among all participants (N = 58,290) showed that moderate kimchi intake was associated with weight loss among middle-aged and older Koreans, especially in men [104,105]. In the observational study by Min et al., 2004 [106], 1682 participants were divided into four groups according to their constant kimchi intake at each meal (none, low, moderate, and sufficient kimchi intake), however, no differences in mean plasma lipid, fasting glucose level, and blood pressure were found among the groups, suggesting that differences in kimchi intake did not affect cardiovascular risk factors.

Immune function was assessed in other studies. Namely, a cross-sectional analysis found that a higher kimchi consumption was significantly associated with a lower presence of atopic dermatitis [107] and a lower prevalence of asthma [108]. Pathak and coauthors investigated the dietary pattern of Polish migrant women with regard to cabbage and sauerkraut consumption, and found that a greater consumption of total and raw/short-cooked cabbage/sauerkraut foods either during adolescence or adulthood was associated with a significantly reduced breast cancer (BC) risk among Polish migrant women [109]. Despite the use of salt when making kimchi, the studies [104,105] found that high consumption of salt-fermented kimchi and other vegetables was not associated with the risk of developing hypertension.

4. Main Limitations of Analyzed Studies

On the one hand, randomized clinical trials prospectively assign a random group of participants to the intervention group, whilst comparing the effects of the intervention to a control group to establish health benefits under controlled conditions [110,111]. On the other hand, observational studies observe real-life scenarios to identify possible predictors of outcomes without intervening [112].

We found only 12 clinical trials and 8 observational studies on the health benefits of fermented foods of the genus *Brassica*, mainly kimchi and fermented cabbage. Even though there are several other fermented foods of the genus *Brassica* with potential benefits, we focused our review on the studies that examined the health benefits. Of the 12 clinical trials, the main limitation was small sample size, which ranged from 12 participants [78] to 100 participants [81]. Although a few studies calculated sample sizes, these were mainly based on previous clinical trials with small sample sizes [76,81,83–85], and the outcomes may not apply to the general population due to the underpowered studies. The authors themselves also emphasized the need for further clinical trials with greater statistical power to assess validity of the outcomes [84]. Another important limitation is the short duration of food intervention as noted in several studies [79–81,83,86]. Using radish [80], fresh kimchi [79,82] or low kimchi intake [78,81] as the control group may have also affected the outcomes as pointed out by the authors. The main limitations of the observational studies according to the authors included focusing only on one particular group, such as Korean participants who regularly consume kimchi [74], Polish migrant women [109], different definitions of obesity [74,103], underestimation of kimchi intake [74,104,106], and cohort design that prevents conclusions about causal relationships [104,106–108], thus, limiting the possibility of generalizing the potential impacts of kimchi consumption, as well as a greater possibility of selection bias.

5. Conclusions

While there are only a limited number of clinical trials primarily examining the health outcomes of consuming kimchi and sauerkraut, they do show that the consumption of these fermented vegetable foods could alleviate symptoms of IBS, improve gut microbiota composition, aid in weight loss, and positively influence various metabolic parameters. These findings suggest that the dietary incorporation of fermented vegetables could be a practical approach to enhancing overall health.

Future well-designed clinical trials should continue to explore the specific bacterial strains with a desired capacity to produce selected bioactive compounds, fermentation conditions, and ingredient variations (e.g., extending studies to non-cabbage substrates) that optimize these health benefits, as well as further investigate the comparative advantages of fermented versus fresh vegetables.

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