applied sciences

Review

The Role of Fermented Vegetables as a Sustainable and Health-Promoting Nutritional Resource

Alejandro Borrego-Ruiz [1], Carmen M. González-Domenech [2] and Juan J. Borrego [2,*]

[1] Departamento de Psicología Social y de las Organizaciones, Universidad Nacional de Educación a Distancia (UNED), 28040 Madrid, Spain; a.borrego@psi.uned.es
[2] Departamento de Microbiología, Universidad de Málaga, 29071 Málaga, Spain; cmgodo@uma.es
* Correspondence: jjborrego@uma.es

Abstract: The increasing global burden of morbidity and mortality from chronic diseases related to poor diet quality, coupled with the unsustainable depletion of vital planetary resources by current food production systems, threatens future food security and highlights the urgent need to transition to high-quality plant-based diets as a viable solution to mitigate economic, health, and environmental challenges. Taking into consideration the significant role that fermented vegetables may play as a sustainable, healthy, long-lasting, and plant-based nutritional resource, this narrative review analyzes their production and benefits. For this purpose, the mechanisms of the fermentation process are explored, along with the importance of probiotic cultures in plant-based fermented foods, and with the implications of fermentation on food safety within the broader framework of low-impact, organic, plant-derived nutrition. Additionally, the health benefits of fermented vegetables and probiotics are examined, including their effects on mental health. Vegetable fermentation is a versatile method for enhancing food preservation, nutritional quality, and safety. This ancient practice prolongs the shelf life of perishable items, reduces the toxicity of raw ingredients, and improves digestibility. Specific starter cultures, particularly lactic acid bacteria, are essential for controlling fermentation, ensuring safety, and maximizing health benefits. Fermented vegetables, rich in probiotics, support gut health and immune function. Emerging research indicates their potential to alleviate adverse mental health symptoms such as stress and anxiety, highlighting their significance in modern dietary guidelines and chronic health management.

Keywords: fermented vegetable foods; sustainability; food safety; human health; plant-based diets

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Citation: Borrego-Ruiz, A.; González-Domenech, C.M.; Borrego, J.J. The Role of Fermented Vegetables as a Sustainable and Health-Promoting Nutritional Resource. *Appl. Sci.* **2024**, *14*, 10853. https://doi.org/10.3390/app142310853

Academic Editors: Yiannis Kourkoutas, Eugenia Bezirtzoglou, Christina Tsigalou and Gregoria Mitropoulou

Received: 20 October 2024
Revised: 14 November 2024
Accepted: 21 November 2024
Published: 23 November 2024

1. Introduction

A variety of biological, genetic, physiological, psychological, and sociocultural factors shape the food choices of the population [1]. Lately, there has been a growing interest worldwide in the potential benefits of plant-based diets [2,3]. The increasing global burden of morbidity and mortality from chronic diseases related to low diet quality and excessive calorie intake, combined with the unsustainable depletion of vital planetary resources by current food production systems, threatens future food security, highlighting the urgent need to transition towards high-quality plant-based diets as a viable solution to mitigate economic, health, and environmental challenges [4–6].

Dietary patterns are important determinants of health, as they may exert effects through several mechanisms, including inflammation, oxidative stress, tryptophan metabolism, epigenetics, central nervous system (CNS) and hypothalamic–pituitary–adrenal functions, mitochondria, and the gut microbiome (GM) [7,8]. In addition, epidemiological studies have reported the involvement of diets in the development of psychological and psychiatric disorders [7,9,10], as well as their application as potential therapeutic tools for these mental conditions [11,12]. Variations in a healthy GM depend on age, lifestyle, ethnicity, and eating habits [13,14]. Human–microbial interdependence is driven by the co-evolution of the human immune system and the GM's adaptation to available nutrient substrates [15]. Diets supply specific nutrients for the proliferation kinetics of gut bacteria such as glycans, which are indigestible for animals, including humans [16]. The primary degraders of GM can break down glycans and include the genera *Bacteroides*, *Bifidobacterium*, and *Ruminococcus* [17]. Furthermore, the diet can impact the metabolism and immune system of the host via several bioactive substances, including vitamins A and D, indole-derived compounds, and polyunsaturated fatty acids [18]. In turn, secondary plant metabolites, including terpenes (e.g., volatiles, glycosides, carotenoids, sterols), phenolics (e.g., phenolic acids, flavonoids, tannins), nitrogen-containing compounds (e.g., alkaloids and glucosinolates), and sulfur-containing compounds (e.g., glutathione, thionins, phytoalexins), are known for their antioxidant, anti-inflammatory, antimicrobial, and potential anticancer effects, which contribute to overall health when included in the diet [19].

Plant-based diets are characterized by a predominant focus on the consumption of vegetables, legumes, whole grains, seeds, and fruits, while significantly reducing or excluding animal-derived products. The nutritional profiles of plant foods are linked to higher levels of essential vitamins, minerals, and dietary fiber, as well as to lower levels of saturated fats and cholesterol. Within this spectrum, vegetarian diets are often considered the most authentic and representative of plant-based eating, reflecting a clear prioritization of plant foods and a distinctive approach to dietary choices [20–23].

Although vegetarian diets are probably the most sustainable dietary pattern existing and provide well-documented health benefits [24,25], they may still present challenges, including food waste due to their short shelf life [26], as well as detrimental effects on both environmental and human health due to their reliance on toxic products for large-scale production [27]. In this complex scenario, fermented vegetables constitute a suitable option by effectively extending the shelf life of plant-based foods, reducing spoilage-associated waste, diminishing the levels of chemicals in vegetables, preserving overall nutritional quality, and aligning with consumer preferences for health-conscious and environmentally friendly food alternatives [28–30].

Taking into consideration the significant role that fermented vegetables may play as a sustainable, healthy, long-lasting, and plant-based nutritional resource, this narrative review analyzes the context, production, and benefits of these products. For this purpose, the mechanisms of the fermentation process are explored, along with the importance of probiotic cultures in plant-based fermented foods, and with the implications of fermentation on food safety within the broader framework of low-impact, organic, plant-derived nutrition. Additionally, the health benefits of fermented vegetables and probiotics are examined, including their effects on mental health.

2. Determinants for Environmentally Responsible and Healthy Food Systems

To address the challenges related to ecological sustainability, human health, and food security, it is becoming essential to adopt integrated approaches that recognize the value of all living beings, and that aim to balance the needs of food production with the preservation of ecosystems. A prominent framework that partly aligns with this perspective is the One Health approach, which highlights the interconnectedness of animal, environmental, human, and plant health [31]. Another notable approach is the EAT–*Lancet* Commission's planetary health diet, which aims to improve human health and reduce the environmental impact of food systems by promoting sustainable dietary patterns that balance nutrition and ecological sustainability [32]. In addition, there are other global movements that encourage individuals to reduce meat consumption for the health of the planet and also for their own health, such as Green Monday, Meatless Monday, and Veganuary [33–35]. However, some of these initiatives require further refinement to better address practical challenges and broader implementation [32,36], but share a clear common foundation in promoting plant-based diets, reinforcing the sustainability of food systems, and preserving health, underscoring the critical need for a transformative shift in food consumption practices worldwide. In light of this, vegetarian diets, organic farming practices, and the identification of core priorities for food system development constitute pivotal steps in operationalizing these frameworks to enhance sustainability and health outcomes.

2.1. Vegetarian Diets

Vegetarianism consists of a diet free of all animal flesh, including terrestrial species, aquatic species, birds, and even insects [37]. There are different variants of vegetarian diets, such as lacto-ovo-vegetarianism (includes the consumption of dairy products and eggs), lacto-vegetarianism (includes only dairy products), ovo-vegetarianism (includes only eggs), and veganism, which does not include any derivative of animal origin [13,38,39]. In industrialized nations, the prevalence of individuals adopting plant-based diets has significantly increased in recent years, driven by a combination of ethical, cultural, economic, health, and environmental factors [40]. These key influences include growing concerns over animal welfare, an enhanced sense of moral satisfaction and vegetarian community belonging, heightened awareness of sustainability and therapeutic benefits, and the broader availability of information and vegan products, all of which contribute to this ongoing dietary transition, a trend expected to persist moving forward [21,41–46].

Several studies have positively correlated vegetarian diets with various physiological health indicators [47–50], such as a lower risk of blood cholesterol [51], type 2 diabetes [52], metabolic syndrome [53], ischemic heart disease [54], coronary artery disease [55], chronic kidney disease progression [56], prostate cancer [57], or colorectal cancer [58]. Furthermore, it has been established that vegetarian diets provide important health benefits due to their antioxidant, anti-inflammatory, immunomodulatory, anti-proliferative, and antihypertensive capacity, as well as their potential for inducing the microbial synthesis of short-chain fatty acids (SCFAs) and postbiotics, such as equol, urolithin, enterolignans, vitamins, isothiocyanates, coprostanol, and secondary bile acids [59]. However, the relationship between vegetarian diets and mental health has been studied to a lesser extent [60], and the evidence obtained to date is contradictory, which may be due to several limitations not addressed within the studies conducted [37]. In this regard, it has been suggested that this type of diet is linked to a higher incidence of anxiety, stress, and depression [61–66], but different findings associate this diet with higher levels of psychological well-being [67–70]. In contrast, additional studies report that there is no evidence to support the causal role of vegetarian diets in mental health [39,71–75].

Vegetarian diets are more environmentally sustainable than meat-based diets, requiring fewer resources and reducing greenhouse gas emissions, deforestation, and biodiversity loss [13,20]. However, to promote a sustainable transition from current dietary habits to plant-based diets, it is essential to identify and address potential barriers. Important measures and interventions to promote plant-based diets include updating dietary guidelines, establishing urban gardens, fortifying foods, developing plant-based alternatives, and imposing taxes on unhealthy food products [49]. Additionally, incorporating organic and sustainable farming practices, as well as emphasizing the benefits of vegetable fermentation processes, may constitute pivotal strategies for enhancing the environmental impact and preserving the nutritional quality of plant-based foods.

2.2. Organic and Sustainable Farming Practices

Conventional intensive farming can harm soil structure, increase erosion, and reduce fertility. This can lead to reduced farming productivity and profitability, as well as environmental problems [76,77]. Therefore, it is necessary to develop alternative production systems that maintain productivity but that minimize these shortcomings.

Nature-positive agricultural production aims to balance the needs of the growing population with environmental restoration by improving soil quality, conserving biodiversity, and managing natural resources sustainably, which includes protecting and restoring ecosystems while optimizing land and water use [78,79]. Organic farming supports sustainability by avoiding synthetic chemicals and genetically modified organisms and focusing on nutrient recycling, animal welfare, lower greenhouse gas emissions, reduced pesticide exposure, and improved diet quality [80,81]. Nevertheless, although organic agriculture is often associated with higher-quality and safer food, the scientific evidence regarding its superiority in terms of nutritional content or phytochemical composition remains inconclusive [82,83].

The use of agrochemicals such as glyphosate poses several risks to public health and ecosystems, highlighting the urgent need for effective risk assessment and sustainable practices [84]. On the other hand, replacing synthetic fertilizers with livestock manure use, either alone or in combination with mineral fertilizers, can increase crop yields and reduce ammonia and greenhouse gas emissions, thereby supporting sustainable agriculture and improving air and soil quality [85,86]. However, despite the growing international involvement in organic agriculture research, increased support for less active regions could strengthen global research efforts [87].

Biostimulants, both microbial and non-microbial, are able to enhance plant nutrient uptake, physiological health, productivity, and resilience through synergistic combinations of these compounds [88]. However, concerns regarding microbial-based fertilizers highlight the importance of thorough risk assessments to ensure safety, considering potential interactions with native soil microorganisms and the introduction of pathogens, and underscore the need for comprehensive long-term studies [89].

Recent research has underlined a range of outcomes in the field of organic farming, focusing on different practices and their effects on crop quality, yield, and environmental impact. For instance, organic rice had fewer pesticide residues than conventionally grown rice, but was more likely to be contaminated by mycotoxin-producing fungi [90]. Environmental factors such as cultivar, seasonality, and soil conditions often had a greater influence on the crop nutritional and functional properties of crops than the farming system itself; for example, tomato genotype and environmental conditions significantly influenced their metabolomic profiles and antioxidant capacities, highlighting the importance of considering multiple variables when evaluating the health benefits of plant-derived food [91]. Research on tomato landraces under low-input farming conditions identified cultivars with improved nutritional value through selective breeding while maintaining high yields, supporting the production of nutrient-rich tomatoes with a reduced environmental impact [92]. Ye et al. [93], using *Trichoderma*-enriched bio-organic fertilizer with reduced chemical fertilizers in tomato production, showed improvements in crop quality, such as increased total soluble sugars and vitamin C, and reduced nitrate accumulation. This approach maintained yields comparable to those achieved with full chemical fertilizer rates, demonstrating that bio-organic fertilizers can reduce chemical dependency while enhancing soil microbial activity and crop quality. In wheat production, Khan et al. [94] applied biochar at 20 t ha^{-1} in combination with nitrogen from poultry manure and significantly improved grain protein content, yield, and nitrogen uptake compared to other treatments, with the benefits becoming more pronounced in the second year, suggesting that biochar improves nitrogen use efficiency and crop productivity over time. Moreover, Wang et al. [95] found that biochar at 20 t ha^{-1} was more effective than organic fertilizer in improving soil quality and wheat yield on saline alkaline soils, with biochar having a more pronounced effect on soil properties and crop performance. Interestingly, in grape production, varietal differences were the main factor influencing antioxidant capacity, phenolic content, and anthocyanin levels, with the production system (organic vs. conventional) having a lesser effect [96]. Fracchiolla et al. [97], who conducted a study on broccoli rabe, found that while living mulches did not significantly affect crop yield or quality, increased nitrogen and phosphorus fertilization notably improved yield and nutrient content, especially for magnesium and iron. In addition, Duddigan et al. [98] reported that alternative management practices incorporating mulches resulted in higher yields and improved soil conditions compared to conventional and organic practices. In addition, wheat varieties from organic and traditional breeding programs generally had lower yields but provided better disease resistance and nutritional quality compared to modern high-yielding varieties from conventional programs; however, comparative data in organic systems are still limited [99].

2.3. Core Priorities for Sustainable Food Development

Considering the implications for food production sustainability, it is reasonable to assert that the effectiveness of environmental conservation, even in a broader sense, is fundamentally an issue shaped by human influence [100–102]. If the consumption of environmentally harmful food products like meat continues to rise, meeting future food demands will increasingly burden natural resources and those who rely on them, which highlights the urgent need for widespread sustainable food production and consumption [103]. In fact, effective global biodiversity conservation requires understanding the diverse values that influence attitudes and behaviors, emphasizing the need for strategies that align with specific contexts to enhance conservation outcomes [104–106]. Consumer concern for sustainability does not always lead to ethical purchasing, but increasing their understanding of the environmental, social, and economic aspects of sustainable production could strengthen their commitment to making more conscious and responsible food choices [107,108]. In this regard, population preferences and willingness to adopt a diet consisting of plant-based sustainable products, as well as for supporting sustainable farming practices, are significantly influenced by factors such as knowledge, food security implications, economic issues, product attributes, past behaviors, animal concerns, environmental awareness, and health consciousness [109–115].

However, transforming cultivation and consumption patterns to a sustainable model, while necessary given the economic, health, and environmental requirements, involves important challenges. A pivotal problem related to plant crops is their short half-life [116]. As the demand for plant-based products continues to grow, there is an increased emphasis on minimizing waste and ensuring safety. Microbial food spoilage represents a widespread problem that leads to increased food waste and to dissatisfaction among customers [117]. According to the Food and Agriculture Organization (FAO), a considerable amount of global fruit and vegetable production is discarded annually [118]. Producing spoilage carries significant socioeconomic consequences as it is directly linked to food shortages, aliment waste, and hunger in certain world regions, as well as water stress, unnecessary biodiversity loss, and elevated greenhouse gas emissions. When food spoils, it emits harmful gases like methane and carbon dioxide into the atmosphere, worsening the climate crisis [116]. These series of complications could be greatly mitigated with strategies that allow a longer shelf life of plant food, which highlights vegetable fermentation as a viable alternative to make food sustainability also viable in terms of conservation.

The processing of fruits and vegetables generates a significant amount of underutilized and discarded organic waste, including seeds, pulp, skin, and rinds. These organic wastes are potential sources of bioactive and functional compounds that offer health benefits [119,120]. Therefore, the utilization of food waste streams should involve the development of value-added products that can be reintegrated into the food supply chain [120]. The recovery of bioactive compounds from agro-waste, through recycling and fermentation processes, is of increasing interest [120–122]. Several fermentative microorganisms, including lactic acid bacteria (LAB), *Bacillus subtilis*, *Aspergillus*, *Fusarium*, *Penicillium*, *Rhizopus*, *Trichoderma*, and *Yarrowia*, have been used to obtain by-products from vegetable waste [121]. The sustainable incorporation of these bioactive compounds into food and beverages requires their equally sustainable recovery from waste and by-product streams. In this regard, novel and "green" extraction methods have been developed to effectively and economically recover these compounds [123].

By adopting circular economy principles, single-cell protein (SCP) production can transform plant-based food waste and agricultural residues into high-quality, sustainable protein sources. This approach provides an ecological model for food production, where what is considered waste in one part of the system becomes a valuable resource in an-other. Furthermore, combining SCPs with fermented vegetables, which are rich in probiotics and beneficial microbes, can enhance the nutritional value and flavor of plant-based meals, making them even more appealing [124,125].

3. Fermented Vegetables

Marco et al. [126] defined fermented foods as "foods produced by desired microbial growth and enzymatic conversion of food components". This definition implies microbial activity, although enzymes from other sources may be complementary. However, fermentation must be distinguished from food spoilage, which also occurs through microbial growth and enzymatic activity on food components, but is not intentional. In contrast, fermentation is deliberate and controlled to produce the desired products and does not contain living microorganisms.

Humans learned early on that fermentation offers important advantages for managing valuable food resources. Fermentation can enhance the functional attributes of agricultural crops and convert them into nutritious, palatable and non-toxic products [126]. In addition, fermentation is recognized as one of the most effective methods for preserving aliments, in part because fermentative microorganisms produce alcohols, bacteriocins, organic acids, and other antimicrobial agents [127]. Fermentation-associated microorganisms typically outcompete potential pathogens and spoilage organisms, thereby improving food safety and stability.

The prolonged shelf life of fermented foods and the elimination of harmful plant compounds through fermentation continue to play essential roles in world areas where food security is low and access to clean water, electricity, and refrigeration is limited. Even in communities where sanitation and preservation issues are minimal, fermented foods remain a vital component of the human diet. It is estimated that, at present, over 5000 varieties of fermented foods and beverages are produced and consumed worldwide [128].

In addition to their significance for public health, food preservation, and quality, current epidemiologic evidence indicates that diets high in fermented foods may reduce disease risk and improve health, longevity, and quality of life [129]. However, aside from yogurt and other cultured dairy products, there are few well-designed randomized controlled trials that have been published on the health benefits of additional fermented foods. Similarly, studies exploring the mechanisms by which fermented foods influence human physiology are scarce.

For a product to be labeled as a probiotic fermented food, there must be evidence of a strain-specific benefit derived from a well-controlled intervention study, along with evidence of safety and assurance that adequate quantities of that strain are present in the final product to provide the claimed benefit [130]. However, the majority of fermented foods available on the market today do not fall into the category of probiotic foods. For instance, traditional, spontaneously fermented sauerkraut likely contains multiple strains of *Lactiplantibacillus plantarum*, but these uncharacterized and unidentified strains, at unknown dosages, would not meet the criteria to be classified as probiotics.

The identification of prebiotics has been documented for several fermented foods, including fermented grains or vegetables that are rich in oligosaccharides, β-glucans, and phenolic compounds [131]. Additionally, other fermented foods may contain prebiotics produced in situ by microorganisms involved in the fermentation process [132]. These foods may also harbor microorganisms, although such products would not be considered synbiotic foods unless a proven health benefit resulting from the interaction between prebiotics and probiotics is demonstrated [133].

3.1. Mechanisms of the Fermentation Process

Fermentation is the most ancient biotechnological technique for preserving vegetables. Since vegetables are highly perishable, various preservation methods such as canning, refrigeration, and freezing have been established to extend their shelf life. However, in underdeveloped and developing nations, these preservation methods are often unavailable, forcing reliance on traditional, well-established natural preservation techniques. Fermentation continues to be the longest-standing biotechnological approach to vegetable preservation, resulting in alterations to organoleptic properties and improvements in nutritional quality [134].

Historically, food fermentation has been utilized to extend the shelf life of food substrates that would otherwise spoil rapidly, being an essential practice during periods of scarcity [127], whilst concurrently enhancing flavor profile [135]. It also serves to decrease the toxicity of raw materials, control pathogenic microorganisms, and facilitate digestion [136]. Fermented foods are primarily categorized based on the substrate used, such as cereals, dairy, legumes, and vegetables [137]. These categories vary according to their main food substrate and the type of fermentation employed, which may include defined starter cultures, back-slopped cultures, or spontaneous fermentation.

Fermented foods serve as a substantial source of beneficial microorganisms that may function as potential probiotics [138], as well as bioactive peptides [139], phytochemicals, and vitamins [140]. In addition, various dietary intervention strategies and regular eating habits can influence the composition and/or diversity of the gut microbiota [13,141]. Consequently, their metabolites, such as SCFAs, phenolic compounds, tryptophan, and bile metabolites can modulate the routes that transmit signals from the gut to the brain [142–144].

Regarding the fermentation process, it is important to consider the following issues: (i) the production of fermented foods is affected by a range of environmental factors and processing conditions [145]; (ii) the genetic polymorphisms of starter cultures differ in a way that indicates their geographical provenance [146]; (iii) the scale of production and the conditions under which manufacturing occurs can partly account for the differences observed in the microbiome of fermented foods, influenced by geographical context [147]; (iv) distinct communities of LAB were identified in fermented products, varying by the geographical zone of production and the types of starter cultures used [148]; and (v) vegetable foods produced via commercial fermentation typically contained higher levels of LAB compared to those produced via artisanal methods [149], with the viral community also showing stronger ties to geographical location in kimchi samples [150], although certain non-vegetable artisanal products, such as cheese, may serve as a rich source of novel functional microbial strains [151]. Table 1 presents the fermentation processes of several vegetables, a practice rooted in centuries of tradition in East Asian countries.

Table 1. Typical fermented vegetables in Asian countries: microbiology, bioactive components, and health benefits.

Fermented Food/Raw Source	Country	Microorganisms Involved	Bioactive Compounds	Health Benefits	References
Tempeh (tempe)/Soybean	Indonesia	*Rhizopus* spp.	Riboflavin, niacin, iron, vitamin B_{12}, isoflavones, and polyunsaturated fatty acids (mainly linoleic acid)	Antioxidant, anticancer, antidiabetic, antihypertensive, and hypocholesterolemic effects	[152–154]
Natto (Douchi and Tembe)/Soybean	Japan (China and Indonesia)	*Bacillus subtilis* var *natto*, *Aspergillus oryzae*, and *Mucor racemosus*	Peptides, nattokinase enzyme	Antimicrobial, anticancer, antioxidant, and anti-aging effects;	[152,155–158]
Miso/Soybean	Japan	*Aspergillus sojae*, *A. oryzae*, LAB, *Starmerella etchellsii*, *Zygosaccharomyces rouxii*, and *Wickerhamiella versatilis*	Polyamines (spermidine and putrescine), acids and amino acid contents, isoflavones, and bacteriocins	Antimicrobial, antidiabetic, antioxidant, anti-inflammatory, anticancer, and antihypertensive effects	[152,159–161]
Fermented tofu/Soybean	Japan (tofuyo), China (furu)	*A. oryzae*, *Mucor* spp. *Rhizopus* spp., *Fusarium* spp. and *Monascus* spp.	Isoflavones, amino acids, GABA, sterols, pigments, organic acids, flavonoids, terpenoids, and polysaccharides	Antihypertensive antimicrobial, antioxidant, anti-inflammatory, and anticarcinogenic activity	[152,162–164]
Sufu/Soybean	China	Sufu fermentation fungi (*Actinomucor*, *Mucor*, *Rhizopus*), Sufu fermentation bacteria (*Enterobacteriaceae*, *Bacillus*, *Chishuiella*, *Enterococcus*, *Lactococcus*, *Leuconostoc*, *Micrococcus*, *Tetragenococcus*, *Weissella*), and others (naturally inoculated, like *Trichosporon* spp.)	Biogenic amines (histamine, phenylethylamine, spermidine, cadaverine, putrescine, and tyramine), peptides, GABA, isoflavones	Antihypertensive activity increased glucose and lipid metabolism	[152,165–167]
Cheonggukjang (Chungkuk-jang)/Soybean	Korea	*Bacillus* species (*B. subtilis*, *B. cereus*, *B. amyloliquefaciens*, *B. licheniformis*, and *B. megaterium*), *Rhizopus oryzae*	Antioxidant peptides, levans, polyglutamates, isoflavones	Anti-inflammatory, anticancer, and anti-obesity effects, antimicrobial and antioxidant activity	[152,168,169]
Doenjang/Soybean	Korea	*B. subtilis*, *Staphylococcus sciuri*, *Enterococcus faecalis* and *E. faecium*, *Citrobacter*, *Enterobacter*, *Leuconostoc mesenteroides*, *Tetragenococcus halophilus*, and *Mucor plumbeus*, *A. oryzae*, *Debaryomyces hansenii*, *R. oryzae*, and *Pichia*	Isoflavones, vitamin E, and unsaturated fatty acids	Antioxidant, anti-obesogenic, antimicrobial, hypocholesterolemic, and neuroprotective effects	[152,170–174]

Table 1. *Cont.*

Fermented Food/Raw Source	Country	Microorganisms Involved	Bioactive Compounds	Health Benefits	References
Kanjang/Soybean	Korea	LAB	Indole alkaloids	Anti-neuroinflammatory and anticolitic effects	[152,175]
Meju/Soybean	Korea	*Bacillus*, *Lactococcus*, *Leuconostoc*, *Enterococcus*, *Monascus*, *Aspergillus*, and *Scopulariopsis*	Amino acids, peptides, sugars, organic acids, isoflavonoids	Antidiabetic effect	[152,176–178]
Thua-nao/Soybean	Thailand	*B. subtilis* var. *thua-nao*	Aglycones, amino acids, phenolic compounds	Antioxidant potential and cytotoxic effect	[179,180]
Kinema/Soybean	Nepal/India	*Bacillus* species (*B. subtilis*, *B. licheniformis*, *B. cereus*, *B. circulans*, *B. thuringiensis*, and *B. sphaericus*), *E. faecium*, *Candida parapsilosis*, *Geotrichum candidum*	Antibiotics, terpens, bioactive amino acids, linoleic acid, poly-γ-glutamic acid, essential fatty acids	Antimicrobial and antioxidant effects	[152,181,182]
Hawaijar/Soybean	India	*B. subtilis*, *B. licheniformis*, *B. cereus*, *Staphylococcus aureus*, *S. sciuri*, *Brevibacillus*, *Alkaligenes*, *Providencia*, and *Xanthomonas*	Essential amino acids, nucleotide sugars, vitamins, and polyunsaturated fatty acids	Fibrinolytic, thrombolytic, antioxidant, and antidiabetic effects.	[152,183–185]
Bekang/Soybean	India	*Bacillus* species (*B. subtilis*, *B. brevis*, *B. circulans*, *B. coagulans*, *B. licheniformis*, *B. pumilus*, and *B. sphaericus*), *Pediococcus acidilactici*, *Lysinibacillus fusiformis*, *Ignatzschinaria*, *Corynebacterium*, and *Oceanobacillus*	Short-chain fatty acids	Anti-inflammatory effect	[184,186]
Akhone/Soybean	India	*Bacillus*, *Ignatzschinaria*, *Corynebacterium*, and *Oceanobacillus*	Polyunsaturated fatty acids, prebiotics	Not established	[184]
Tungrymbai/Soybean	India	*B. licheniformis*, *B. pumilus*, *B. subtilis*, *Enterococcus*, *Lactobacillus*, and *Lactococcus*	Menaquinone-7 (vitamin K2)	Antibacterial activity and hepatic steatosis prophylactic effect	[152,186,187]
Kimchi/Cruciferous vegetables (mainly cabbage and radishes)	Korea	*Weissella confusa* and *W. kimchii*, *L. mesenteroides*, *L. plantarum*, and *Lactococcus kimchii*	Bacteriocins, GABA, ornithine, polysaccharides, mannitol	Antimicrobial, anti-inflammatory and anticancer effect, and anti-obesogenic activity	[188–190]

Table 1. *Cont.*

Fermented Food/Raw Source	Country	Microorganisms Involved	Bioactive Compounds	Health Benefits	References
Mesu and Soibum/Bamboo shoots	India	*Enterococcus durans*, *L. plantarum*, *Latilactobacillus curvatus*, *Leuconostoc* species (*L. mesenteroides*, *L. fallax*, *L. lactis*, and *L. citreum*), *Levilactobacillus brevis*, *Pediococcus pentosaceus*	Proteins, amino acids, carbohydrates, vitamins, flavonoids, and phenolic compounds	Antioxidant	[191–195]
Soidon/Bamboo shoots	India	*L. fallax*, *L. lactis*, and *L. brevis*	Flavonoids and phenolic compounds	Antioxidant	[194,196]
Sauerkraut/White cabbage	Thailand, India, China, Vietnam, Japan, Korea and Taiwan	*Lactobacillus*, *Pseudomonas*, *Alcaligenes*, *Arcobacter*, *Pseudarcobacter*, *Lactococcus*, *Leuconostoc Comamonas*, *Lactiplantibacillus Pediococcus*, *Prevotella*, and *Insolitispirillum*	Organic acids, phenolic compounds, alcohols, isothiocyanates, and hydrocarbons	Antioxidant and immunomodulatory activity	[196–198]
Kanji/Rice	India	*P. acidilactici*	Sugars, flavonoids, phenols, organic acids	Antioxidant activity	[199]
Gochujang/Red chilies and rice	Korea	*Bacillus velezensis* and *Oceanobacillus* spp.	Flavonoids, alkaloids, and ginsenoside	Antihypertensive effects, metabolic syndrome prophylactic, immune-boosting properties, anti-inflammatory effects, antioxidant effects	[200–202]

3.2. Probiotic Starter Cultures in Plant-Based Fermented Foods

Spontaneous fermentation is prone to contamination by undesirable microorganisms, often resulting in inconsistent and subpar products, which presents a challenge for the industrial production of fermented vegetables [203]. To ensure product quality and safety, the strategic use of starter cultures can be paramount. In that sense, probiotic starters, generally recognized as safe (GRAS), have emerged as indispensable drivers of vegetable fermentation, not only referring to the process itself but also offering a plethora of benefits. Among these probiotic microorganisms, LAB are typically dominant in the microbiota of fermented vegetables. By introducing specific LAB, producers can effectively control the fermentation process and prevent spoilage and foodborne transmission, while enhancing the nutritional value of the final product [204,205]. These carefully selected microbial strains not only accelerate fermentation but also contribute to the singular flavors and health-promoting properties of fermented vegetables [203].

Probiotics actively promote diverse metabolic pathways and demonstrate a remarkable ability to metabolize various carbohydrates and organic acids [206]. Notably, the phenolic derivatives produced by probiotic metabolism significantly influence the sensory and health-promoting properties of fermented vegetables. Lactobacilli and *Pediococcus* spp., renowned LAB, exhibit exceptional metabolic potential for the bioconversion of volatile compounds in vegetables during the fermentation process (especially phenols, terpenes, alcohols, and aldehydes) [207,208]. Additionally, probiotics actively reinforce the biosynthesis of vitamins, antioxidants, and bacteriocins [209–214]. Fermented vegetables are rich in vitamins, which are essential for a variety of energy-yielding metabolism pathways and support fundamental cellular functions, including DNA synthesis, oxygen transport, and neuronal functions [215]. The fermentation process plays a crucial role in preserving the vitamin content of raw materials [216]. Specifically, the co-fermentation of the *Pediococcus pentosaceus* strain AL and the *Cyberlindnera rhodanensis* strain J52 substantially enhances the concentration of vitamin C in fermented capsicum [217]. Moreover, certain LAB possess the capability to synthesize vitamins. For instance, the *Limosilactobacillus reuteri* strain F2 has demonstrated a remarkable capacity for the extracellular production of vitamin B_{12} [218]. Consequently, fermenting vegetables with probiotic strains can be an effective strategy for augmenting their health benefits.

Mannitol, a 6-carbon alcohol found naturally in certain microorganisms and plants, is absorbed slowly in the intestinal tract and does not elevate blood sugar levels [189,219]. Species of the genus *Leuconostoc*, including the *L. mesenteroides* strain SKP88 and the *L. citreum* strain SKP92, which were isolated from pa (green onion)-kimchi, have the ability to convert fructose into mannitol [219]. Ornithine, a non-proteinogenic amino acid derived from arginine, serves multiple functions, including anti-obesity and anti-fatigue effects, promotion of muscle growth, and treatment for cirrhosis [189]. The *Weissella koreensis* strain DB1 is capable of producing high amounts of ornithine, although it did not pose a health risk, making it suitable for incorporation into fermented foods [220].

Moreover, probiotics possess a remarkable capacity for producing gamma-aminobutyric acid (GABA), a key inhibitory neurotransmitter within the CNS, potentially leading to the reduction of anxiety [189,221]. Certain strains isolated from fermented vegetables, such as the *L. curvatus* strain K285 isolated from gat-kimchi, the *Lactiplantibacillus pentosus* strain 9D3 isolated from Thai pickled weed, the *L. brevis* strain R2 from fermented bamboo shoots, and the *Companilactobacillus allii* strain WiKim39 and the *Lactococcus lactis* strain WiKim0124 isolated from kimchi, have exhibited exceptional GABA production capabilities, making them promising candidates for developing functional foods [222–225].

The choice of probiotic LAB for vegetable fermentation depends on the specific product. As aforementioned, the specific starter culture selected plays a pivotal role in determining the final product's sensory characteristics [198,203]. Single-strain cultures, often consisting of a unique LAB, can accelerate acidification, leading to the quicker transformation of vegetables, minimized commercial losses, and decreased production expenses [226,227]. Thus, employing a high inoculum of *L. plantarum* and *P. pentosaceus* strains has proven to be effective in controlling lactic acid fermentation and in ensuring the quality of fermented cucumbers due to their promising functional and technological attributes [228]. Table 2 shows the metabolic products and the health benefits of probiotic strains in several fermented vegetables.

Table 2. Metabolic products and health benefits of probiotic strains in several fermented vegetables.

Probiotic Strains	Isolation Source	Metabolic Products	Health Benefits	References
L. mesenteroides B1 *L. plantarum* LRCC5314	Kimchi	Benzyl isothiocyanate, indole compounds, thiocyanate, β-sitosterol, and dietary fiber	Anticancer, anti-inflammatory activities, anti-atherosclerotic, and cholesterol-lowering effects and inhibition of adipogenesis	[188,190,229,230]
Weissella species (*W. cibaria* and *W. paramesenteroides*)	Yan-dong-gua (Dong quai)	Organic acids, hydrogen peroxide, and bacteriocins	Antibacterial activity	[231]
B. subtilis subsp. *natto*	Natto	Nattokinase, dipicolinic acid, menaquinone-7	Anti-thrombotic, promotes bone health	[232]
L. plantarum NPL 1258 *L. brevis* *P. pentosaceus* NPL 1264	Fermented cucumber	Extracellular polymeric substances, GABA	Antihypertensive, antidepressant, anticancer, and antimicrobial effects	[191,228,233]
L. pentosus LPG1	Table olive	Bacteriocin, exopolysaccharides	Anti-inflammatory, reduces cholesterol levels, and inhibits foodborne pathogens	[234]
Limosilactobacillus fermentum SHY10	Chinese pickles	Antibacterial peptides	Antibacterial activity	[235,236]
L. pentosus CF2-10N	Fermented aloreña green table olives	Vitamin, exopolysaccharide	Immunomodulatory effect	[237]
L. plantarum ZJ316	Pickled chili pepper and mustard		Antibacterial activity	[205]
L. lactis 3C1_QSA *W. cibaria* DSM 15878T	Fermented beetroot	Niacin, riboflavin	Antagonistic properties against pathogenic bacteria	[204]
L. plantarum, *Lactobacillus acidophilus*, *Lacticaseibacillus* species (*L. paracasei* and *L. rhamnosus*), *Ligilactobacillus acidipiscis*, and *Saccharomyces cerevisiae*	Fermented blueberry juice	Organic acid and phenolic compounds	Antidiabetic, antimicrobial, and antioxidant properties	[214]
L. plantarum CCMA 0743 *L. paracasei* LBC-81	Tropical fruit juices	Organic acids, carotenoids, anthocyanins, and yellow flavonoids	Antioxidant activity	[238]

Probiotics, including LAB, possess the capability to inhibit pathogenic bacterial growth and to mitigate the adverse effects of harmful compounds through their substantial lactic acid production, thus enhancing the quality and safety of fermented foods [205,226]. Specific LAB, such as *L. brevis* and *L. plantarum* ZJ316, have been shown to suppress the proliferation of *Enterobacter*, *Ralstonia* spp., *Pseudomonas*, and *Proteus* in pickled chili pepper and pickled mustard [205,208]. Functional foods abundant in probiotic LAB have the ability to directly counteract unintentionally ingested pesticides in the gastrointestinal tract [140]. The significant lactic acid production by LAB like *L. plantarum* ZJ316 plays a role in lowering nitrite residue levels [205]. Pesticides commonly utilized during olive cultivation, such as deltamethrin, dimethoate, and imidacloprid, pose serious risks to human health. Fermented natural black olives with the *L. plantarum* strains 112 and 123 demonstrated greater degradation of these pesticides compared to unfermented olives [239]. Consuming probiotics found in fermented vegetables can substantially influence the composition of the GM. The Bacillota/Bacteroidota (B/B) ratio serves as an indicator of gut microbiota health, with a higher B/B ratio indicating reduced microbial diversity [240,241]. The *L. pentosus* strain P2020, sourced from Chinese pickles, effectively decreases the B/B ratio and aids in restoring the GM, offering protection against hyperuricemia development [242]. These results point to the potential of vegetables fermented with probiotics as valuable assets in therapeutic strategies focused on restoring gut microbiota.

On the other hand, mixed-strain probiotic cultures can enhance their intrinsic properties and fermentation abilities, potentially shortening the maturation period of the product [243]. The mixed-fermentation microbiota is composed of prevalent microorganisms, which significantly influence the unique characteristics of the fermented vegetables [198]. Accordingly, *L. plantarum*'s strong acid tolerance and its ability to thrive alongside *L. mesenteroides* make this starter culture combination particularly effective in producing the distinctive flavor of northeastern sauerkraut [203]. Likewise, kimchi can be inoculated with different probiotic starter strains, exhibiting varying ratios of species belonging to the genus *Leuconostoc*, or specific species such as *L. plantarum* and *L. brevis*. According to the specific starters, the levels of organic acids, different amino acids, alcohols, and sugars can vary in the fermented product [190,208]. Hence, the judicious selection of probiotic starter cultures allows producers to tailor the sensory characteristics of fermented vegetables to meet diverse consumer preferences and market demands [198].

3.3. Fermentation and Food Safety

Several studies have shown that microbial fermentation improves food safety, on the basis that the fermented foods contain significant amounts of organic acids, low water activity, nitrite, and other salts, all of which have antimicrobial properties that minimize the risk of foodborne illness linked to their intake [244]. Many LAB, whether naturally occurring in the microbiota or introduced as starter cultures, are recognized for their production of bacteriocins that effectively inhibit harmful bacteria, including *Clostridium*, *Listeria*, and *Staphylococcus* [245].

Food fermentation can also improve food safety and nutritional quality by eliminating toxic compounds from the fermentation of cereals, legumes, and other vegetables [246,247]. For example, several vegetables contain cyanogenic glycosides which need to be neutralized through fermentation, soaking, or other appropriate methods to prevent acute toxicity upon consumption [248,249]. Throughout sourdough fermentation, certain LAB promote the breakdown of phytate, a compound linked to cereal grains that binds divalent cations and hinders their absorption in the gastrointestinal tract [250]. It is also thought that sourdough fermentation decreases the levels of other immunoreactive proteins, such as the amylase–trypsin inhibitor found in wheat, which may lead to better tolerance in individuals with non-celiac wheat sensitivity or irritable bowel syndrome compared to traditional breads [251].

Fermented foods are rarely associated with intestinal disorders, although any food product may present safety concerns related to pathogenic microorganisms and their toxins or metabolites that may have adverse effects. For example, biogenic amines (e.g., histamine and tyramine) are produced by some LAB through the decarboxylation of amino acids during the fermentation of vegetables and soybeans [252]. In the absence of detoxification systems mediated by the host, these amines can lead to mild or severe effects, including nervous system problems, headache, hypertension, fever, and sometimes vomiting and sweating [253]. Diverse strategies have been implemented to decrease or mitigate the formation of biogenic amines, such as hygiene to limit the presence of microorganisms that produce these compounds and the use of decarboxylase-negative starter cultures [254,255].

Several factors of fermented foods have been proposed for health promotion, including the nutritional modification of raw materials, the biosynthesis of bioactive compounds, the modification of the human gut microbiota, and the modulation of the immune system [126,256]. Microbial activity during food fermentation leads to a reduction in the levels of high-calorie monosaccharides and disaccharides, such as fructose, glucose, and sucrose, found in plants through catabolic pathways. The reduction in determinate sugars may also lower the glycemic index and enhance food tolerance (e.g., fructans or raffinose found in wheat, as well as stachyose and verbascose present in legumes and soybeans) [257]. Additional enzymatic processes with significant nutritional consequences also take place, encompassing detoxification reactions and the removal of anti-nutritive factors (e.g., deactivation of trypsin inhibitors in soybeans and the breakdown of phytic acid in cereals like sorghum) [258–260]. In foods rich in phenolics, the transformation of phenolic compounds by lactobacilli enhances the bioavailability of flavonoids, tannins, and various other bioactive substances [140]. Furthermore, the biosynthesis of vitamins, amino acid derivatives, and organic acids produced during fermentation may have beneficial effects on the gastrointestinal system [261].

Several human studies have indicated that microorganisms in plant-fermented foods are capable of surviving gastric passage and of reaching the colon [262,263], on the basis that fermented foods have intrinsic properties that enhance their ability to survive gastric transit (i.e., acid and bile tolerance) [264]. While these microorganisms are unable to establish permanent residence in the intestine, certain strains from fermented food are recognized for their metabolic activity within the gastrointestinal tract [262]. In this regard, even brief colonization may suffice to produce bioactive compounds, suppress enteric pathogens, and mediate epithelial modulatory effects [265]. Fermented foods can also impact the composition of the GM and its metabolomes [266,267]. These effects are variable and likely depend on the ecological resilience of the gut microbiota in reaction to the intake of transient foodborne microorganisms [268].

The GM is susceptible to colonization by microorganisms during the first months of life [269], which may potentially represent a crucial period for the effects of microbial stimuli on the immune system [270]. Fermented vegetable consumption in early childhood has been related to a diminished risk of childhood atopic dermatitis [271]. In addition, a lifestyle rooted in anthroposophy, characterized by minimal antibiotic and vaccination usage alongside an elevated consumption of fermented vegetables, was linked to variations in the infant microbiome composition, including an increased presence and diversity of LAB, as well as increased levels of acetate compared to infants raised in more conventional lifestyles [272,273]. The consumption of fermented foods is also one of the synergistic factors related to an agricultural upbringing, a lifestyle factor that has been reliably linked to diminished allergy and asthma risk [274]. These associations may suggest that the absence of fermented foods in contemporary, industrialized societies represents a significant reduction in exposure to non-harmful microorganisms that are pivotal for the development and upkeep of the immune system.

4. Health Benefits of Fermented Vegetables and Probiotics

Fermented vegetables are increasingly being recognized as an important dietary component, particularly of plant-based diets, to achieve a sustainable healthy gut because of their microbial diversity, antioxidant properties, and beneficial effects of probiotics. The lactose intolerance of a larger segment of the world population together with the undesirable cholesterol content of fermented dairy products has opened a window of opportunities for developing non-dairy probiotic products [275]. The genera of LAB present in fermented vegetable foods include members of the actual and former genus *Lactobacillus*, and the genera *Lactococcus*, *Pediococcus*, *Enterococcus*, *Streptococcus*, *Leuconostoc*, and *Weissella* [276]. Additionally, the LAB found in fermented vegetables influence both the quality and safety of these products, as they have probiotic properties and contribute to the formation of biogenic amines, biologically active compounds, and other bioactive substances derived from phenolic compounds [138,145].

Classic research has shown that the *P. pentosaceus* strain MP12 and *L. plantarum* strain LAP6, obtained from pickled cabbage, had antagonistic effects against *Salmonella* spp. in mice, while both strains successfully adhered to the intestinal epithelium of the mice [277]. In clinical studies, Wang et al. [278] found that the *L. plantarum* strain CO6 and *L. acidophilus* strain C11 adhered to the duodenum, resisted gastrointestinal stress from gastric juices and bile salts, and demonstrated antimicrobial properties against pathogenic bacteria. Strains of *L. plantarum* isolated from fermented olives were capable of adhering to the epithelial cells of porcine jejunum and of producing bacteriocins (antimicrobial peptides synthesized by other bacteria) against several pathobionts, including *Helicobacter pylori*, *Propionibacterium* spp., and *Clostridium perfringens* [279]. The presence of bacteriocin-producing bacteria has been previously reported in several fermented vegetable foods, such as fermented cucumber [280], fermented carrot [281], inziangsang [282], and fermented Chinese cabbage [283], to name a few.

Strains of *L. lactis*, *L. plantarum*, and *L. mesenteroides* isolated from kimchi, a traditional Korean fermented vegetable food, exhibit antioxidant, anti-inflammatory, and anticancer effects, in addition to improving energy homeostasis, and are therefore potential novel probiotics in functional foods [284–286]. Lee et al. [287] reported a significantly higher response to oxidative damage within the cell membrane, intracellular metabolism, and cellular functions in LAB strains derived from kimchi, particularly *L. curvatus*, *C. allii*, and *L. lactis*. More recently, Ngamsamer et al. [288] examined the microbial diversity and antioxidant potential of three different formulas of fermented vegetables (standard, enhanced with the *L. rhamnosus* strain GG, and enriched with the phenolic compound vitexin) at days 0 and 15. The findings showed a variety of microorganisms in the taxonomic composition of the various fermented vegetable formulas, with different LAB genera being the most prevalent. Supplementation with the strain of *L. rhamnosus* and vitexin efficiently enhanced the functional significance of foods by fostering cellular protection against oxidative stress, due to the likely role of phenolic compounds with antioxidant activity, bacterial antioxidant enzymes (catalase and superoxide dismutase), and microbial metal-chelating activities [289–291]. Table 3 shows the health benefits of fermented vegetable foods.

Table 3. Health beneficial outcomes of the fermented-vegetable foods.

Fermented Vegetable	Properties	Outcomes	Reference
Kimchi	Anticancerous effects	Effect of *W. cibaria* and *L. plantarum* on *H. pylori*, a candidate of colorectal carcinogenesis. Effect of organosulfur compound in garlic plant facilities the dexotification of carcinogens by glutathione-S-transferase and modulates the activity of metabolizing enzymes such as cytochrome P450. Effect of capsaicin that produces apoptosis of neoplasic cells by generating cell-cycle reactive oxygen species.	[292]
Kimchi	Anticancerous effects	β-sitosterol and linoleic acid derivative from kimchi show anticancer activity. Dichloromethane fraction induces apoptosis of H-29 human colon cancer cells by expression of cellular Bax protein. Inhibition of inflammation.	[229]
Kimchi	Anti-cholesterol effects	Cholesterol was removed by the cell wall fraction of the probiotic effect.	[293]
Kimchi	Anti-obesity effects	Decreases HDL-cholesterol and body fat percentage.	[263]
Kimchi	Antioxidant, anticancer, and microbial effects	Inhibition of *Listeria monocytogenes* and *S. aureus*. Nitric oxide reduction. Inhibited gastric, colon, breast, and lung carcinoma cells.	[284]

Table 3. *Cont.*

Fermented Vegetable	Properties	Outcomes	Reference
Kimchi	Anti-cholesterol and microbial effects	Reduces body fat, triglycerides, LDL, HDL, and IL-6 levels. Increases SCFA-producer bacteria (*Faecalibacterium*, *Roseburia*, and *Phascolactobacterium*). Reduces pathobionts (*Escherichia* and *Clostridium*).	[294]
Kimchi	Hypolipidemic effect	Decreases obesity and insulin resistance by means of changes in glucose and lipid metabolism.	[295]
Kimchi	Anti-inflammatory and microbial effects	Alleviates IBS symptoms. Changes Bacillota/Bacteroidota ratio and increases bifidobacteria levels. Reduces inflammatory cytokines (IL-4 and IL-10).	[296]
Kimchi (beachu and radish)	Anti-obesity effects	Beachu: Lower risk of obesity in men. Radish: Consumption is inversely associated with obesity in men and women.	[297]
Idli batter	Anti-cardiovascular and antioxidant effects	Inhibition of the formation of biofilm by *Pseudomonas aeruginosa*. Strong anti-cholesterol and antioxidant properties.	[298]
Idli batter	Antioxidant and microbial effects	Antioxidant properties. Antimicrobial properties against pathogens.	[299]
Natto	Hypolipidemic effect	Increases glucose uptake into adipocytes.	[300]
Sauerkraut	Anti-inflammatory and microbial effects	Reduces IBS symptoms. Changes GM composition (increased *Prevotella* and *Bacteroides*, and decreased *Blautia*).	[301]
Chinese sauerkraut	Anticancerous effects	Cytotoxic activities against Hela, MCF-7, and BT474 cell lines related to cervical and breast cancer.	[302]
Ganjangs	Anticancerous effects	Prevents AOM/DSS-induced colon damage and suppresses the carcinogens by nullifying the expression of TNF-α, IFN-γ, IL-6, IL-17α, COX-2, and iNOS. Induces the expression of tumor suppressor gene *p53*.	[303]
Chungkookjang	Dyslipidemia and anti-atherosclerosis effects	Chungkookjang significantly improved the lipid profiles and high-sensitivity CRP of women. The atherogenic indices of apolipoprotein B/apolipoprotein A1 decreased in both the placebo and the intervention groups. Chungkookjang may improve body composition and risk factors for cardiovascular disease in overweight and obese adults.	[304]
Faba bean	Antihypertensive and antioxidant effects	Improves metabolic syndrome	[305]
Axone, bastenga and chatur	Immunomodulation and microbial effects	DNA repair. Inhibition of biofilm formation, and anti-virulence microbial factors.	[306]
Tempeh	Insulinotropic effect	Increases insulin response, arginine levels, and acyl-ghrelin.	[307]
Pozha	Antimicrobial effects	Increases the expression of genetic regions coding for bacteriocins.	[308]
Nozawana	Antimicrobial effects	Increases butyrate-producing bacteria (*Prevotella*), *Lachnospira*, and members of the family *Ruminococcaceae*.	[309]
Cabbage and cucumbers	Antimicrobial effects	Beneficial changes in GM composition. Decreases *Ruminococcus torques* and increases *Faecalibacterium prausnitzii*.	[310]
Ash Kardeh	Antidiabetic effects	Improves high blood glucose, lipid profile, and hypertension in type 2 diabetic patients. Increases the concentration of HDL-cholesterol.	[311]

HDL: high-density lipoprotein; LDL: low-density lipoprotein; IL: interleukin, SCFA: short-chain fatty acid; IBS: irritable bowel syndrome; GM: gut microbiome; AOM/DSS: azoxymethane–dextran sulfate–sodium; TNF: tumor necrosis factor; IFN: interferon; COX: cyclooxygenase; iNOS: nitric oxide synthase; CRP: C reactive protein.

The intake of fermented vegetables has been linked to various health benefits as a result of their bioactive compounds generated during the fermentation process and the activity of probiotic bacteria present, although the precise mechanisms underlying the health benefits of probiotics remain incompletely understood. Nevertheless, the most significant positive impacts of probiotics include the exclusion or antagonism of pathogen interference, modulation of immune response, anti-inflammatory effects, anti-carcinogenic and anti-mutagenic activities, hypolipidemic effects, antihypertensive effects, antidiabetic properties, antioxidant activity, alleviation of lactose intolerance symptoms, reduction in serum cholesterol levels, lowering blood pressure, and maintenance of mucosal integrity [134,145]. Figure 1 shows the effects of the intake of fermented vegetables regarding nutritional components.

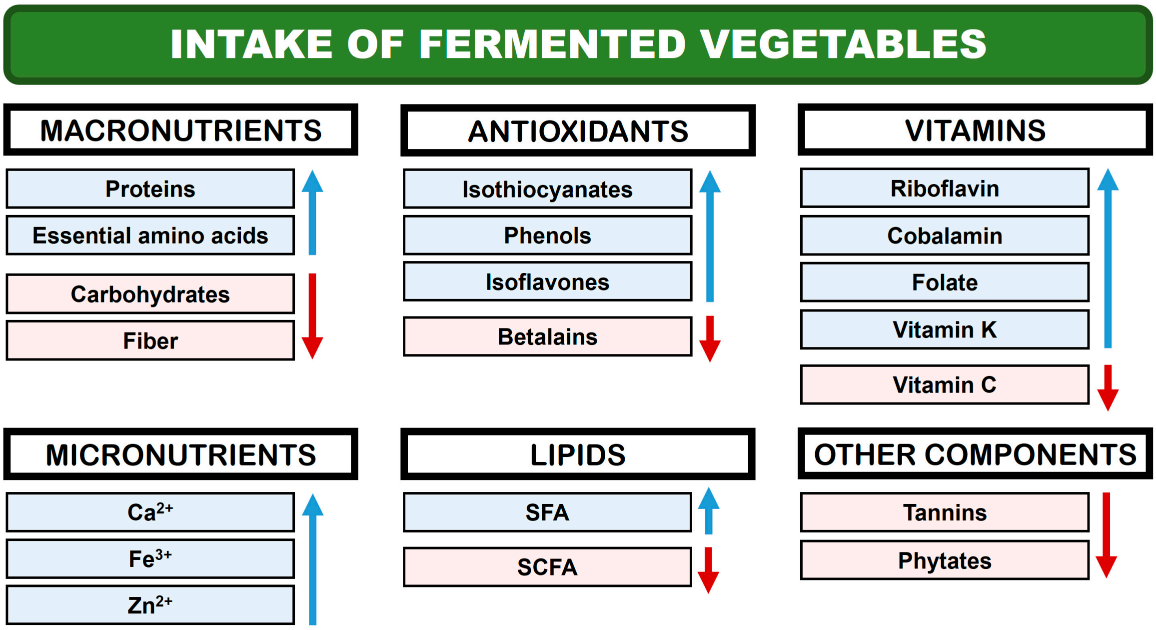

Figure 1. Effects of the daily intake of fermented vegetables regarding nutritional components (according to Knez et al. [191]). SFA: saturated fatty acid; SCFA: short-chain fatty acid. Blue arrows: increase in daily intake of particular nutritional components from fermented vegetables compared to fresh ones. Red arrows: decrease in daily intake of particular nutritional components from fermented vegetables compared to fresh ones.

5. Influence of Vegetable-Fermented Foods on Mental Health

There is a growing body of knowledge suggesting that the GM is a critical mediator that responds to external signals and triggers endogenous functions in the organism. The microbiome-gut–brain (MGB) axis consists of a bidirectional communication network between the GM and the CNS [312]. The GM is influenced by different factors, such as diet [13,313], age [314,315], medication use [316], sex [315], ethnicity, and geographical location [317,318].

The GM and its metabolites influence several host functions, including intestinal [319], immunological [320], and neural components [13,321] of the MGB axis. Several studies have related mental health and dietary patterns, highlighting the resulting potential influence of dietary intervention strategies on the cognitive well-being of individuals [322,323]. Consequently, interest is growing in the use of the diet to target the microbiota to promote mental health benefits for the host [324]. Recent research has explored fermented foods as a promising approach for microbiota-targeted interventions, since they serve as vehicles for delivering beneficial microbes and compounds, and they can be utilized therapeutically across several socioeconomic groups due to their potential affordability and accessibility across cultures [325].

The MGB axis enables a continuous bidirectional exchange of information between the gut and the brain through the enteric nervous system. This communication pathway involves a dynamic interaction among diverse elements of the intestinal environment, including cytokines, microbial communities, microbial metabolites, peripheral immune cells, and gut-associated lymphoid tissue. These components relay signals to the brain and vice versa, utilizing the sympathetic and parasympathetic nervous system, neurotransmitters, and the circulatory immune system [326]. In addition to microorganisms and their metabolites, fermented foods are rich in phytochemicals, which can take the form of neurotransmitters, neuroactive substances, and neuromodulators [327], and thus activate the pathways associated with the MGB axis: the circulatory, immune, neuroendocrine, and enteric nervous systems. During digestion, they can lead to the generation of microbial metabolites that may influence the permeability of both the intestinal barrier [328] and the blood–brain barrier (BBB) [329] (Figure 2).

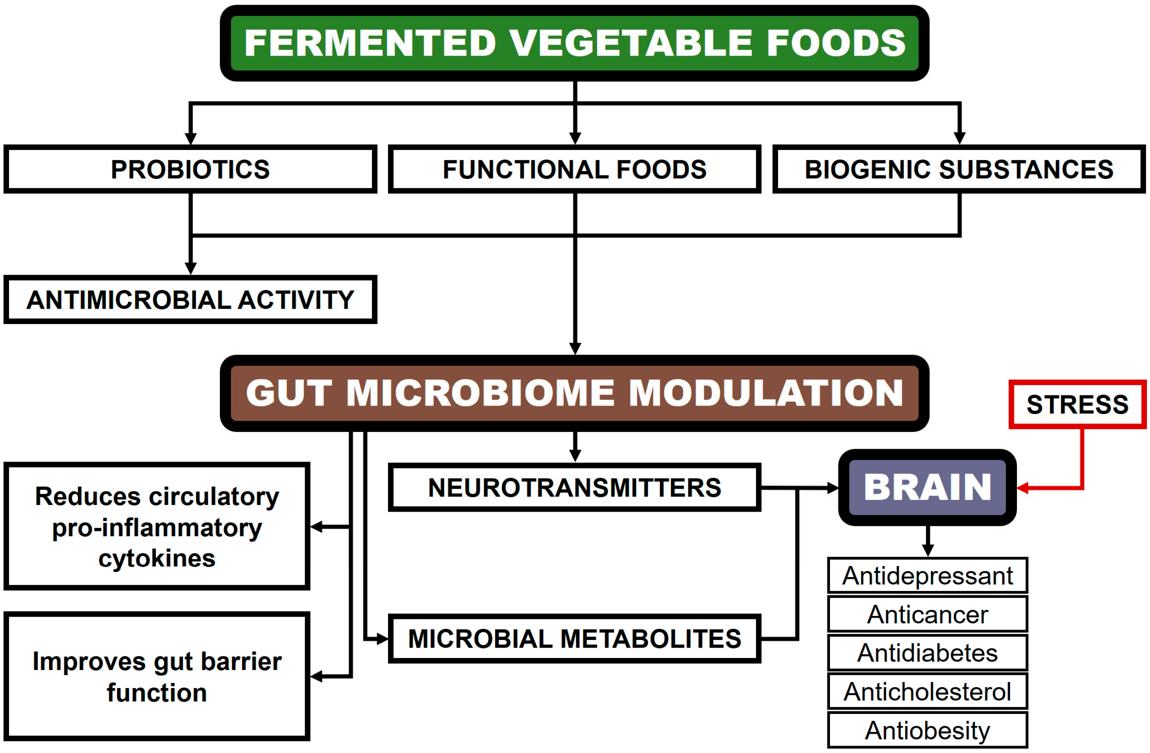

Figure 2. Hypothetical role of functional components of fermented vegetables in the GM and the brain, as well as related beneficial consequences (based on Aslam et al. [330]).

Microbial gut dysbiosis is an imbalance in the GM characterized by a decrease in beneficial microorganisms, the development of pathobionts, and the alteration of both alpha- and beta-diversity. This state may lead to the development of several mental disorders, such as anxiety, depression, stress, and cognitive or behavioral disturbances [240]. These psychological disorders can be modulated by consuming fermented vegetable foods that contain active probiotics which produce SCFAs and neurotransmitters, mitigating gastrointestinal inflammation, reducing circulating pro-inflammatory cytokines, and improving gut barrier function [330] through systemic circulation [331], or via the vagus nerve [332]. Figure 2 shows the hypothetical roles of the functional components of fermented vegetables in the GM and the brain.

Numerous components of fermented foods are currently under investigation for their capacity to influence the immune system. One possible mechanism through which these foods exert their immunomodulatory effects is by activating the hydrocarboxylic acid receptor (HCA3R) resulting from the consumption of foods fermented by LAB. For instance, sauerkraut, which is abundant in LAB, has been demonstrated to trigger a chemotactic response in monocytes through D-phenylacetic acid, a strong agonist of the HCA3R receptor [333]. In addition, microbial surface molecules and microbial metabolites (i.e., SCFAs, methylamines, bile acid, and amino acid metabolites) are involved in the integrity of the intestinal epithelial barrier and of the BBB [328,329,334,335].

Only a few interventions on the neurological benefits of fermented vegetable foods have been conducted recently. These studies on the influence of fermented vegetable-based products, such as miso, natto, tempeh, tofu, and other types of fermented vegetables, showed that a greater intake of soy-based products positively correlated with improved cognitive function in female participants [336]. This consumption was also linked to the mitigation of age-related memory impairment [327] and cognitive deterioration [319]. The isoflavone constituents of fermented soy products are known to exhibit estrogenic protective properties, potentially contributing to the neuromodulatory effects of these products in women [336]. Conversely, certain studies have underscored negative outcomes associated with tofu consumption, linking it to diminished cognitive performance in multiple cross-sectional observational investigations [337,338]. It has been posited that formaldehyde, utilized in tofu production to enhance shelf stability, may lead to oxidative damage, thereby influencing cognitive decline [337]. Table 4 shows several clinical studies on the relationship between fermented vegetable food consumption and mental health outcomes.

Table 4. Clinical studies on the relationship between fermented vegetable food consumption and mental health outcomes.

Reference	Fermented Vegetable	Intervention	Outcomes
[336]	Tofu, miso, and natto	*N* = 776 (403 men and 343 women).	Soybean and isoflavone consumption was associated with lowered cognitive impairment in elderly women and no impact in men.
[337]	Tofu and tempeh	*N* = 719 (52–98 years of age).	Consumption of higher amounts of tofu was associated with memory decline. Tempeh consumption was related to better performance in memory-associated tasks.
[338]	Tofu	*N* = 521 (>50–95 years of age). Of the total, *N* = 115 were patients with dementia.	High tofu consumption was negatively associated with verbal learning, immediate recall, and increased cognitive impairment.
[339]	Tofu and tempeh	*N* = 142 (56–97 years of age).	Tofu and tempeh consumption in rural Javanese elderly both have a positive association with immediate recall memory. These findings are significant in those with an average age of 67 years, but not in those with an average age of 80 years. Estrogenic compounds present in fermented vegetables can exert positive effects on verbal memory, but not in older men and women.
[340]	Tofu, miso, and natto	*N* = 1105 (>65 years of age).	Soy-based food intake was negatively associated with cognitive impairment.
[341]	Fermented algae *Laminaria japonica*	*N* = 60 (32 treated and 28 placebo). 6 weeks (>70 years of age).	Treatment increased working memory and visual and spatial reasoning in the intervention group. Algae consumption improved neuropsychological test scores.
[342]	Fermented soybean	*N* = 100 MCI (50 treated and 50 placebo). 12 weeks.	Increase cognitive function in treated group.
[343]	Miso and natto	*N* = 72,624 mother and child pairs. 9 months.	Reduced risk of inadequate sleep in infants at 1 year of age from mothers with high miso intake during pregnancy.

Table 4. *Cont.*

Reference	Fermented Vegetable	Intervention	Outcomes
[344]	Tempeh	*N* = 90 MCI (60 treated with tempeh and 30 with protein biscuit control). 24 weeks (>60 years of age).	Consumption of tempeh resulted in improved of both global cognitive and language domain scores.
[345]	Fermentd aguamiel with probiotics	*N* = 45 students (27 experimental group and 18 placebo). 12 weeks (20–25 years of age).	The intake of the fermented food provoked a reduction in stress-related symptoms in students.
[346]	Tempeh	*N* = 93 MCI (two doses of tempeh supplemented by the probiotic *Limosilactobacillus fermentum*). 12 weeks (>60 years of age).	Increase in the cognitive domains of memory, learning process, and verbal fluency.
[347]	Sauerkraut and pickled cucumber	*N* = 372 students (average 22.7 years of age).	Under psychological stress, moderate consumption of fermented foods appeared not to be associated with cognitive performance, although high consumption may be associated with more severe depressive and anxiety symptoms experienced before a stressful event.

MCI: mild cognitive impairment.

Several authors have suggested that the beneficial effects of fermented vegetables are due to the presence of probiotic microorganisms. In this sense, the *L. plantarum* strain P8 alleviates stress and anxiety and improves memory and cognitive symptoms in stressed adults [348]. In addition, Rudzki et al. [349] reported that the *L. plantarum* strain 299v improved cognitive performance and decreased kynurenic acid concentration in major depression disorder (MDD) patients. Similarly, the administration of the *L. plantarum* strain PS128 has been shown to decrease depression symptom scores in MDD patients [350]. The daily administration of this same strain may result in a reduction in cortical excitation, depressive symptoms, and fatigue levels, and in an improvement in sleep quality during the deep sleep stage [351]. The *L. plantarum* strain JYLP-326 alleviated anxiety, depression, and insomnia among college students experiencing anxiety. The possible mechanism driving this effect may be linked to the modulation of gut microbiota and fecal metabolites [352]. In addition, the *L. plantarum* strain HEAL9 significantly reduced the perceived stress and awakening cortisol in subjects aged 21–52 years. In addition, the intake of the strain HEAL9 significantly enhanced cognitive functions compared to the placebo, potentially by improving facets of mood and sleep [353].

6. Discussion

To understand the scope of fermented foods in nutrition and health, it is necessary to acknowledge the wide diversity of microorganisms used for fermented food production. The most common fermented foods require LAB, acetic acid bacteria, bacilli or other bacteria, yeasts, or filamentous fungi. These microorganisms have long served as a source of industrial chemicals and bioactive molecules [354], and they were integral to the discovery and application of CRISPR technology [355].

Overall, fermented foods are widespread and the multiple combinations of matrices and fermentation technologies contribute to the establishment of ecological niches that contain microbial communities with distinct compositions and functions, many of which remain partially understood. This review delved into the intricate and singular nature of fermented food microbiota, emphasizing that traditional products possess specifically selected microbial populations. Additionally, it presented a current overview of the literature concerning the impact of fermented food consumption on human health, incorporating the latest observational and intervention studies, which reinforce the notion that human health can benefit from the intake of fermented foods. Indeed, these foods may actively influence both the composition and functionality of the human GM, facilitating the selection of species and functions that promote health. Moreover, given that microorganisms encounter comparable environmental pressures in certain fermented foods and the human gut, it is proposed that traditional fermented foods represent an underexplored reservoir of novel probiotic strains capable of resisting gastrointestinal transit [356,357]. Unfortunately, the direct transfer of these microorganisms from fermented foods to the human gut has yet to be substantiated, and the mechanisms elucidating the relationship between fermented foods and human health are still not fully understood. Nevertheless, the domain of fermented food microbiome research is experiencing exciting developments, with promising advancements forthcoming. Next-Generation Sequencing (NGS) technologies combined with machine learning methodologies will enable researchers to elucidate the molecular interactions that exist between microbial communities in fermented foods and their health-related outcomes, as well as to identify new probiotic strains that could enhance human health. As the molecular dynamics within fermented foods are investigated, more specific, precise, and customized dietary recommendations are anticipated, taking into account both health advantages and ecological implications.

Developing consistent and reliable probiotic starter cultures is essential for guaranteeing the quality and health benefits of fermented vegetable products. To better understand the mechanisms underlying the benefits of fermented foods, multi-omics analysis has emerged as a cutting-edge tool for studying the complex interactions between microorganisms and their metabolic products, as exemplified in kimchi. By combining techniques like gas chromatography–mass spectrometry, NGS, and metabolomics, researchers can gain insights into the functions of diverse microbiota and their impact on health [138]. Precision fermentation, a biotechnology process that uses genetically engineered microorganisms to produce specific compounds, benefits greatly from the information provided by multi-omics techniques [358,359]. Unlike traditional fermentation, precision fermentation allows for greater control over the process and the final products [138]. While cost reduction remains important, the field of precision fermentation now faces the challenge of balancing economic considerations with the growing demand for consumer-driven innovations in fermented plant-based products [360].

Therefore, the integration of innovative research, technological advancements, and dietary guidelines positions fermented foods not merely as culinary products or occasional appetizers consumed in social settings, but as significant contributors to both planetary sustainability and human well-being. Furthermore, beyond the potential effects of fermented foods that are yet to be fully discovered, it is worth highlighting their significance as long-lasting products in situations that may lead to food shortages among populations. For example, the recent pandemic has drawn attention to issues of malnutrition, particularly among vulnerable demographics such as the elderly, who faced barriers in accessing food due to strict lockdown measures [361,362]. In such circumstances, fermented foods could assume a critical role in meeting nutritional demands, yet they are often overlooked as a valuable food source. For this reason, given their beneficial properties and extended shelf life, fermented foods should also be considered as potential nutritional tools in preparation for possible future pandemics.

Nevertheless, in addition to their recognized advantages in terms of health, durability, and sustainability, fermented vegetables are also the subject of diverse perspectives that deserve further discussion. For instance, although LAB strains offer very promising probiotic effects and benefits in the GM, their consistency in modulating gut health could be questioned due to the variability of the individual microbiome and strain-specific actions. Furthermore, LAB may produce several bioactive catabolites, such as histamine and tyramine, that act on the CNS, causing hypertension and allergies [363]. More recently, Burakova et al. [364] found that LAB was related to the presence of the genera *Megasphaera*, *Faecalibacterium*, *Subdoligranulum*, *Pseudobutyrivibrio*, *Catenibacterium*, *Clostridium sensu stricto 1* and *2*, *Phascolarctobacterium*, and members of the *Oscillospiraceae* NK4A214 group, which are associated with the development of several metabolic disorders, including inflammatory bowel diseases.

Another important issue is the safety of fermented foods, especially in uncontrolled or small-scale fermentations, where the risk of pathogen contamination is higher. In many cases, traditional practices persist in which certain products, often prepared in homemade settings, are fermented without strict adherence to food safety guidelines, thereby ignoring microbiological control and pH regulation. Despite this, these products are sometimes marketed without triggering health concerns, which can pose significant risks to consumer health and may also contribute to negative perceptions of fermented vegetables. A clear example would be classics like homemade pickles, which are frequently sold by local vendors without standardized quality controls. In these cases, the risks can include contamination with pathogens such as *Listeria monocytogenes*, *Salmonella*, or *Escherichia coli*, all of which pose serious health risks, particularly to vulnerable populations. In fact, the presence of various groups of pathogenic and spoilage microorganisms has been documented in fermented foods. These include spore-forming pathogenic bacteria such as *Bacillus* spp. and *Clostridium* spp., as well as non-spore-forming pathogens like *Listeria monocytogenes*, *Salmonella* spp., and *Shigella* spp. Bacterial toxin producers, such as *Staphylococcus aureus*, are also a concern, along with yeasts like *Candida* spp. and *Saccharomyces cerevisiae*, molds such as *Rhizopus* spp. and *Penicillium* spp., and toxigenic fungi like *Aspergillus* spp. In tropical regions, the contamination of fermented vegetable foods by these microorganisms has been primarily linked to poor handling and production practices, in addition to the influence of the native microbiota involved in the fermentation process [365]. Furthermore, several outbreaks associated with the consumption of kimchi contaminated by pathogens such as *Listeria*, *E. coli*, or norovirus have occurred, indicating that safety cannot be guaranteed in all cases. These incidents are attributed to factors related to both the raw materials used and the adaptability of the pathogens involved [366]. Similarly, a study examining pathogens in 68 fermented vegetable samples sold at the Phnom Penh market found *E. coli* and *Cronobacter sakazakii* in 10% and 1% of samples, respectively, with pH levels ranging from 3.6 to 6.5 [367]. Moreover, reports have documented the presence of traces of fecal matter in certain food products sold in markets [368], and it would not be surprising for such contamination to be present in some homemade ferments as well. Thus, uncontrolled fermentation may lead to the growth of fungi or other undesirable microorganisms that produce harmful toxins, further compromising product safety and potentially causing gastrointestinal infections, foodborne illness, or allergic reactions among consumers [369]. In this sense, there is no doubt that a person experiencing food poisoning from a fermented product may be unlikely to consume them again, and may even develop a lasting negative perception, partially influenced by a conditioned aversion resulting from that experience.

In cultural terms, fermented vegetables can face significant barriers to acceptance in regions where their distinct flavors, textures, and sensory profiles are unfamiliar or perceived as undesirable. For example, the sour and tangy taste of kimchi or sauerkraut, which results from the LAB fermentation process, may be unappealing to populations accustomed to milder flavor profiles, such as those prevalent in many Western diets. Furthermore, the textures of certain fermented vegetables, such as the soft or mucilaginous consistency often found in fermented cucumbers, may be associated with spoilage or microbial contamination in cultures where fermentation is not traditionally practiced. This can lead to an aversion to these foods, inhibiting their widespread acceptance in non-fermented food cultures. In addition, the adoption of fermented vegetables, particularly those marketed as probiotic-rich, can be hindered by the cost of production, distribution, and quality assurance. The fermentation process itself, along with the maintenance of optimal storage conditions such as refrigeration for preserving live cultures, increases production costs. Products marketed as containing live probiotics often require specific packaging, certification, and logistics to ensure the viability of the microorganisms, all of which contribute to a higher retail price. These economic factors limit accessibility, especially in lower-income regions where consumers may prioritize cost-effective food options. Moreover, the prices of commercial probiotic fermented products, when compared to non-fermented alternatives, can discourage the consumption of fermented vegetables in favor of cheaper, non-fermented options.

7. Conclusions

The fermentation of vegetables serves as a multifaceted approach to enhancing food preservation, nutritional value, and safety, thereby addressing significant public health concerns. This ancient practice not only extends the shelf life of perishable substrates but also diminishes the toxicity of raw materials and enhances digestibility. The incorporation of specific starter cultures, particularly LAB, is pivotal for controlling fermentation processes and ensuring product safety, as well as for maximizing health benefits. The presence of LAB in fermented vegetables provides a substantial source of probiotics, which are integral to gut health and immune function. The health-promoting properties of these foods can be attributed to their bioactive compounds, which facilitate various physiological processes, including immune modulation, anti-inflammatory effects, and the inhibition of pathogenic microorganisms. Furthermore, the potential for fermented vegetables to serve as therapeutic agents in managing chronic conditions, such as obesity, diabetes, and mental health disorders, underscores their relevance in contemporary dietary guidelines. Recent investigations into the neuroprotective effects of fermented vegetable consumption suggest that these products may play a pivotal role in cognitive function and mental well-being, particularly through the modulation of the MGB axis. The findings related to specific LAB strains, such as *L. plantarum*, highlight their promising potential in alleviating symptoms of stress, anxiety, and cognitive decline. Ultimately, the integration of fermented vegetables into plant-based diets presents a sustainable approach to achieving optimal health outcomes. As ongoing research continues to reveal the potential of these foods, it is imperative to recognize their significant contributions to both human well-being and environmental sustainability. The exploration of fermented vegetables as essential dietary components could potentially mitigate the impacts of future food insecurity and health crises, emphasizing their importance in contemporary and future nutrition strategies.

Author Contributions: Conceptualization, A.B.-R.; investigation, A.B.-R., C.M.G.-D. and J.J.B.; writing—original draft preparation, A.B.-R., C.M.G.-D. and J.J.B.; writing—review and editing, A.B.-R.; supervision, J.J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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