fermentation

Review

Application of Fermentation as a Strategy for the Transformation and Valorization of Vegetable Matrices

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Abstract: This review paper addresses vegetable fermentation from a microbiological and technological point of view, with particular emphasis on the potential of lactic acid bacteria to carry out these transformations. This review paper also covers the spectrum of traditional and emerging fermented plant foods. Fermentation with lactic acid bacteria represents an accessible and appropriate strategy to increase the daily consumption of legumes and vegetables. Often, lactic fermentation is carried out spontaneously following protocols firmly rooted in the culture and traditions of different countries worldwide. Fermented plant products are microbiologically safe, nutritious, and have pleasant sensory characteristics, and some of them can be stored for long periods without refrigeration. Controlled fermentation with selected lactic acid bacteria is a promising alternative to guarantee high-quality products from a nutritional and organoleptic point of view and with benefits for the consumer's health. Recent advances in genomics and molecular microbial ecology predict a bright future for its application in plant fermentation. However, it is necessary to promote molecular approaches to study the microbiota composition, select starters aimed at different legumes and vegetables, generate products with nutritional properties superior to those currently available, and incorporate non-traditional vegetables.

Keywords: vegetable; fermentation; functional foods; valorization; by-products

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1. Introduction

Lactic fermentation is one of the most utilized strategies for food preservation. Its importance is associated with the formation of bacteriocins, carbon dioxide, organic acids, ethanol, and metabolites in combination with a reduction in water activity. The impact of these compounds is supported by microbial interference since they reduce the growth of specific contaminating bacteria while others increase in the same substrate. Nevertheless, for this interference to be effective, the flora to be inhibited must be overcome by the added flora [1].

Although most vegetables are consumed without any processing, fermentation represents a significant biotechnology to improve the safety, health-promoting properties, and overall appeal of these vegetables [2]. The main microorganisms involved in the fermentation of vegetables are listed in Table 1 [3,4]. We can see that there are different genera of bacteria, among which lactic acid bacteria (LAB), yeasts, and filamentous fungi stand out.

Table 1. Main microorganisms involved in the fermentation of vegetables.

Microorganism	Genera
Lactic acid bacteria (LAB)	*Aerococcus*, *Alloiococcus*, *Bifidobacterium*, *Carnobacterium*, *Dolosigranulum*, *Enterococcus*, *Globicatella*, *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Oenococcus*, *Pediococcus*, *Streptococcus*, *Tetragenococcus*, *Vagococcus* and *Weissella*
Other bacteria	*Bacillus*
Yeast	*Candida*, *Pichia*, *Saccharomyces* and *Torulaspora*
Fungi	*Rhizopus* and *Aspergillus*

Fermented vegetables can be obtained through spontaneous fermentation or controlled fermentation. The endogenous microbiota, naturally present in fermentable raw material, intervenes in spontaneous fermentation. A starter culture participates in controlled fermentation, which consists of a species or a combination of selected microbial species that, once added to a food matrix, causes a fermentation process. Starter culture microorganisms are isolated from successfully fermented foods and are mainly used at industrial levels to ensure constant fermentation. Furthermore, its use requires prior heat treatment of the vegetables to ensure that only the microorganisms from the starter culture are present and growing [5]. The fermentations that LAB can carry out in vegetables are lactic and malolactic. Although malolactic fermentation can occur exceptionally in some vegetables (e.g., cucumbers), transforming malic acid into lactic acid and carbon dioxide [6], it is lactic fermentation that determines the nutritional and sensory characteristics of these foods [7]. Furthermore, vegetables are excellent matrices for lactic fermentation due to their high content of carbohydrates, polyphenols, vitamins, minerals, and dietary fibers [8]. In lactic fermentation, glucose's anaerobic utilization occurs through two metabolic routes. In the homolactic route, lactic acid is produced as the majority product following the Embden–Meyerhof–Parnas (EMP) glycolytic pathway, while, in heterotactic fermentation, practically equimolar quantities of lactic acid, ethanol, and carbon dioxide are produced via 6-phosphogluconate/phosphoketolase [9,10].

Due to their fermentative action, LAB acidify the medium and lower the pH enough to prevent the development of pathogenic and spoilage microorganisms without breaking down the cellulose or proteins of the vegetables. In addition, lactic acid can considerably improve the flavor of vegetables and the assimilation of calcium, iron, phosphorus, and vitamin D. Finally, some strains of LAB have probiotic character because they can colonize the intestine and promote digestion, improve function, control serum cholesterol levels, reduce intestinal infections, and eliminate harmful substances from the body [11].

Table 2 shows the main fermented vegetables. The starting raw material, the country or region of origin, and the microorganisms involved in the fermentation are included [12]. Out of all of them, we are going to focus on sauerkraut and kimchi since they are two widely consumed products that stand out for their high nutritional quality. This review details the current applications of lactic fermentation for the transformation and valorization of vegetable matrices.

Table 2. Microorganisms in fermented vegetable products.

Food	Raw Material	Origin	Microorganisms
Sauerkraut	· Cabbage	Central Europe	· *Leuconostoc mesenteroides* · *Lactobacillus brevis*, *Lactobacillus plantarum* · *Enterococcus faecalis* · *Pediococcus cerevisiae*
Kimchi	· Cabbage · Radish · Other ingredients	Korea	· *Lactobacillus plantarum* · *Leuconostoc mesenteroides*, *Leuconostoc pseudomesenteroides*, *Leuconostoc gasicomitatum* · *Weissella cibaria*, *Weissella koreensis* · *Lactococcus lactis* · *Pediococcus pentosaceus*
Encurtidos	· Cucumber · Onions · Carrots · Cauliflower	World	· *Pediococcus cerevisiae*, *Pediococcus pentosaceus* · *Lactobacillus plantarum*, *Leuconostoc mesenteroid*
Gundruk	· Mustard · Cauliflower · Cabbage	Nepal, India	· *Yeast*, *Lactobacillus plantarum*, *Lactobacillus lactis* · *Pediococcus pentosaceus*
Sink	· Radish	India	· *Lactobacillus plantarum*, *Yeast*, *Lactobacillus lactis* · *Pediococcus pentosaceus*
Khalpi	· Cucumber	Nepal	· *Lactobacillus plantarum*, *Pediococcus pentosaceus*
Jiang-Gua	· Cucumber	Taiwan	· *Weissella hellenica* · *Lactobacillus plantarum* · *Leuconostoc lactis* · *Enterococcus casseliflavus*
Paocai	· Cabbage · Celery · Cucumber · Radish	China	· *Lactobacillus plantarum*, *Yeast*, *Lactobacillus lactis* · *Leuconostoc mesenteroid*
Yan-Dong-Gua	· Pumpkin	Taiwan	· *Weissella cibaria*, *Weissella paramesenteroides*
Sayur Asin	· Cabbage · Mustard	Indonesia	· *Leuconostoc mesenteroid* · *Lactobacillus plantarum* · *Pediococcus pentosaceus* · *Candida guilliermondii*
Yan-Tsai-Shin	· Broccoli	Taiwan	· *Weissella paramesenteroides*, *Weissella cibaria* · *Leuconostoc mesenteroid* · *Lactobacillus plantarum*
Suan-tsai	· Cabbage · Mustard	Taiwan	· *Pediococcus pentosaceus* · *Tetragenococcus halophilus*
Dhamoui	· Cabbage · Other vegetables	Vietnam	· *Leuconostoc mesenteroid* · *Lactobacillus plantarum*

2. Fermentation of Vegetables to Increase Shelf Life

2.1. Vegetable Fermentation

Perishable and seasonal vegetables, such as leafy greens, radishes, and cucumbers, are traditionally fermented into consumable products (Figure 1). These fermentations are mainly dominated by species of the LAB genera *Lactobacillus* and *Pediococcus*, followed by *Leuconostoc*, *Weissella*, *Tetragenococcus*, and *Lactococcus* [13]. There are works in which the microbiological profile of LAB in fermented vegetable products has been studied, such as kimchi, a traditional Korean food [14], or sauerkraut, a fermented cabbage product from

Germany. Furthermore, LAB also constitute the native populations of many Himalayan plant products [15] and fermented bamboo products from India and Nepal [16].

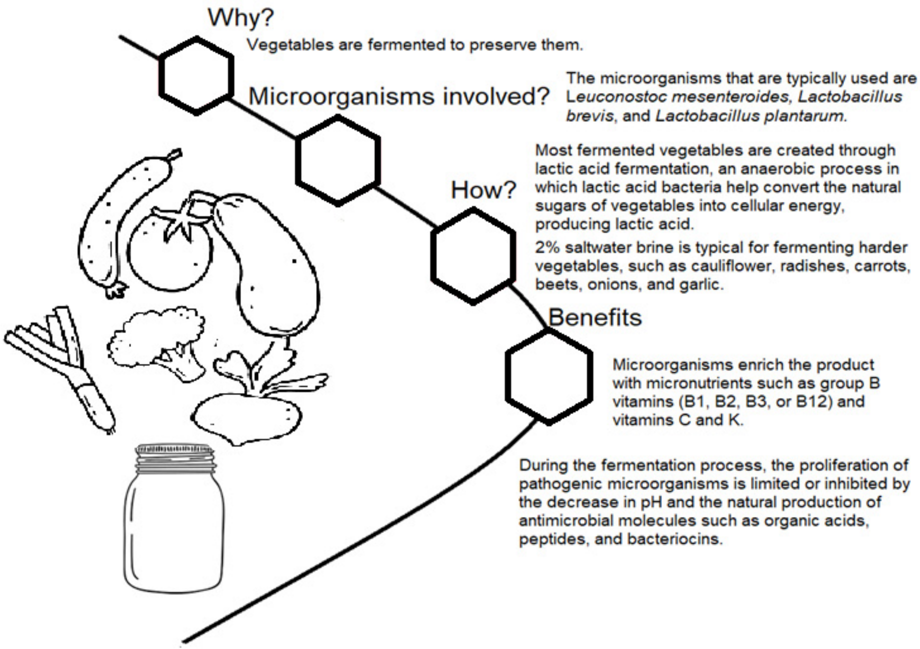

Figure 1. Vegetable fermentation as a traditional method of preserving and enriching nutrients.

Many of the products with probiotic characteristics available in the market are of dairy origin. Due to some disadvantages, such as their cholesterol and lactose content, growth is observed in the demand for functional non-dairy products. This is why the possibility of using fruits and vegetables as a vehicle for probiotic microorganisms is valued. Research for the development of this type of product focuses on achieving the survival of a high number of microorganisms and a minimum alteration of the sensory characteristics of foods [17]. On the other hand, the microbial population in plant products varies according to the plant, the chemical composition, the buffering capacity of the food, the competition generated between the strains present, and the postharvest conditions. Variations in the microbial population are also observed with the ripening of the fruit, and in many cases, a succession of strains is present. Therefore, to obtain the desirable properties of fermented plant products, it is necessary to control the conditions of the fermentation process or reduce the initial microbial load and inoculate the previously isolated microorganisms, since, as occurs in the fermentation of other types of foods, the microbiota composition and development are essential factors for the quality of the final product [17].

It should be considered that spontaneous fermentations result from the competitive activities of a variety of microorganisms; those that best adapt to the conditions during the fermentation process tend to dominate. Therefore, the risks of (1) inadequate inhibition of spores and pathogens and (2) generation of undesirable aromatic and nutritional components are high [17]. It should be noted that, in different cultures, spontaneous fermentations are carried out by controlling the action of the native microflora through the process conditions (temperature), the addition of salt or sugar to increase the osmotic pressure, and the inclusion of spices or aromatics with antimicrobial compounds (cinnamon, cloves, rosemary, and thyme, among others). Some examples of lactic fermentation in foods of plant origin are presented in Table 3.

Table 3. Microorganisms in lactic fermentation of fruits and vegetable.

Matrix	Strains	Reference
Cabbage, lettuce, and garlic	*Weissella cibaria* and *Lactobacillus plantarum*	[18]
Carrots, beans, and zucchini	*Leuconostoc mesenteroides*, *Lactobacillus plantarum*, *Weissella soli*, *Weissella koreensis*, *Enterococcus faecalis*, *Pediococcus pentosaceus* and *Lactobacillus fermentum*	[19]
Cherry and broccoli	*Lactobacillus* spp.	[20]
Tomato	*Lactobacillus acidophilus*	[21]
Cherries, pineapple, carrot, and tomato	*Lactobacillus plantarum*	[22]
Lettuce and apple	*Lactobacillus plantarum*	[23]
Pepper	*Lactobacillus plantarum*, *Lactobacillus curvatus* and *Weissella cibaria*	[24]
Green olives	*Lactobacillus pentosus*, *Lactobacillus plantarum* and *Candida diddensiae*	[25]
Yucca (Gari)	*Lactobacillus plantarum*	[26]

2.2. Fermentation of Vegetables as an Alternative Preservation and Added Value

Given the necessity to preserve fruits and their by-products and minimally changing their characteristics, lactic fermentation derives as an option for biopreservation (one of the oldest strategies to prolong the shelf life of perishable foods) (Figure 2) [27]. Because of the upheld growth in the demand for plant-based beverages with the high applicable value of healthy, nutritious, delicious, and fresh fermented products, the recent tendency regarding veganism and vegetarianism and the prevalence of lactose intolerance, fruit juices fermented by lactic acid bacteria include a favorable option to satisfy the demands mentioned before. Lactic fermentation is a practical technology with low cost and sustainable advantages to support and enhance fruit and vegetable sensory properties and nutritional characteristics and extend shelf life. Fermented foods emanating from lactic fermentations have been produced for thousands of years for their nutritional content and are accepted by consumers without limitations.

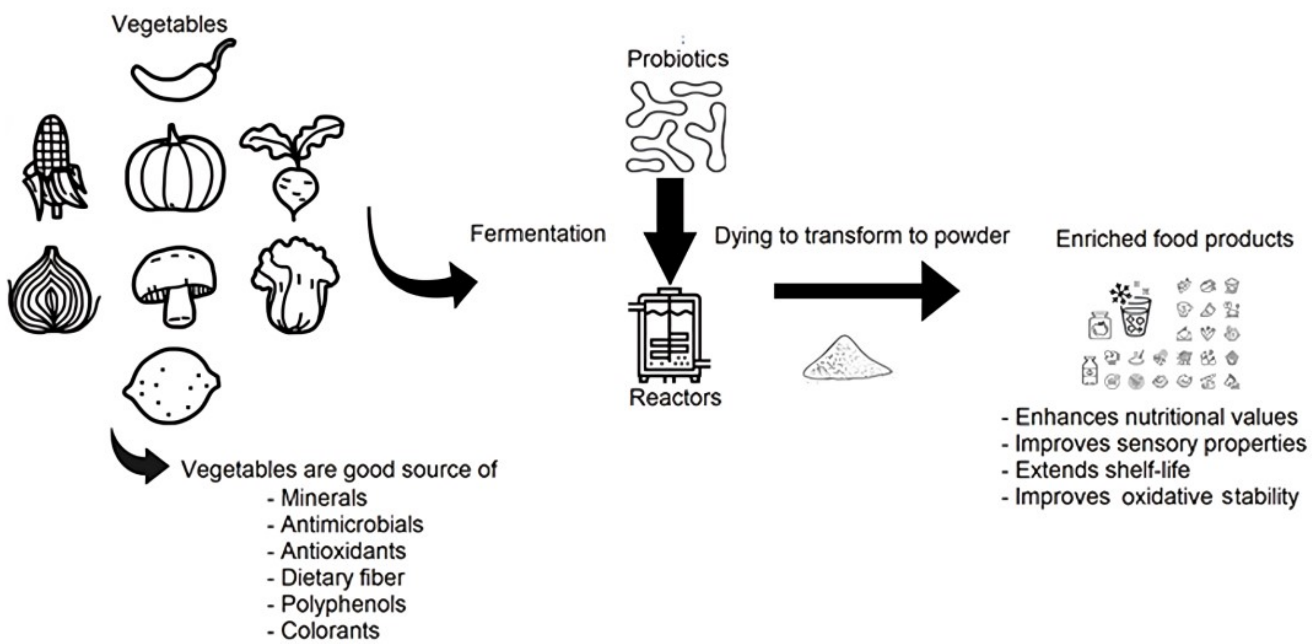

Figure 2. Various effects of fermentable vegetable enrichment on the quality of food.

The fermentation of vegetables enhances food safety mainly because of the development of organic acids such as formic, propionic, acetic, and lactic acids and ethanol, which reduce pathogenic bacteria, eradicate toxic compounds, enhance their nutritious characteristics, and maintain their sensory properties. Biopreservation by lactic fermentation is mainly because of the synthesis of a wide variety of antagonistic compounds such as bacteriocins, hydrogen peroxide, organic acids, ethanol, carbon dioxide, diacetyl, fatty acids, antibiotics, and phenyl-lactic acid by the lactic acid bacteria utilized [28]. Vegetable fermentation can arise spontaneously from the indigenous lactic microbiota present in the vegetables, such as *Leuconostoc* spp., *Pediococcus* spp., and *Lactobacillus* spp., under advantageous circumstances of salt concentration, water activity, temperature, and anaerobiosis. Nevertheless, starter cultures that contain, for example, *L. Gasseri*, *L. rhamnosus*, *L. acidophilus*, and *L. plantarum*, grant control, reliability, reproducibility, and consistency in the fermentation procedure, delivering safe, constant quality, and standardized fermented products [29].

Nevertheless, the usage of probiotics in producing fermented vegetables and fruits is yet an area for expansion, unlike other foods fermented with dairy or meat products [30]. The primary condition that probiotics must meet is environmental adaptation to the stress conditions that plant matrices normally present. The concentration of fermentable carbohydrates, the extremely buffering capacity, the presence of non-digestible nutrients (fructooligosaccharides, inulin, fiber, etc.), the presence of antinutritional factors and inhibitory compounds (phenolic compounds and tannins), and acidic environments are the primary aspects that impact the growth and acidification of lactic acid bacteria in vegetables and fruits. The usage of a high number of probiotic cells (8.0–9.0 log CFU/mL) ensures the hygiene of the product and the potential probiotic effects of the lactic acid bacteria utilized. The adaptation of lactic acid bacteria to vegetables and fruit matrices is very assorted between strains and species, and, despite the significance of fermentation, the response and adaptation to vegetables and fruit matrices have been very little studied when compared with other foods fermented with dairy or meat products [31].

The usage of preferred aboriginal probiotics in producing fermented foods ensures more promising yields than non-native strains or instinctive fermentation processes, improving the fermented products' rheological, sensory, and nutritional characteristics and providing a prolonged shelf life. Therefore, using indigenous probiotics in vegetable and fruit-fermented products would conserve antioxidant activity, natural color, firmness, and metabolites. This impact may result from changing the organic acid profile by the synthesis of acetic and lactic acids and the metabolism of free amino acids. All these biochemical transformations can have immediate (pH) or indirect repercussions on enzymes accountable for browning and sensory characteristics such as aroma, flavor, and color of the vegetable matrices. On the other hand, maintaining bacterial survival in the stationary phase in the vegetable matrix's conditions ensures extended shelf life, particularly those that incorporate probiotic bacteria. The selection of lactic acid bacteria to develop fermented products should be based mainly on nutritional, sensory, and pro-ecological criteria [32]. Likewise, lactic acid bacteria could show specific metabolic characteristics as a result of adaptations to the vegetable matrix. Currently, the usefulness of different vegetables for developing fermented juices and using vegetables in the fermentation process has been considered [33]. Native vegetables have benefits such as high cell growth, inhibition of harmful microorganisms, rapid acidification, sensory properties, and antioxidant activity [34].

Vegetable-based drinks produced through managed fermentation with lactic acid bacteria are somewhat new products that have adapted to customer demand for minimally processed and functional foods and are options other than dairy-fermented products. Ingesting vegetables fermented with lactic acid bacteria could enhance human nutrition through the proportional intake of carbohydrates, minerals, and vitamins and contain illnesses according to the probiotic characteristics that specific strains could offer. Furthermore, vegetable-based fermentations contain colored pigments such as lycopene, anthocyanin, flavonoids, glucosinolates, and β-carotene that function as antioxidants in the organism and can eradicate dangerous free radicals implicated in degenerative diseases such as arthritis, aging, and cancer [35,36].

2.3. The Sensory Effect of Fermentation on Plant-Based Products

The sensory effect emanating from incorporating probiotics in fermented plant-based products is necessary in designing functional beverages. Some studies have explored this parameter; for example, sour and salty flavors and perfumed odors have been reported in fruit drinks with the incorporation of probiotics [37]. Novel blackcurrant juices having probiotic cultures (*Lactobacillus plantarum*) concluded that orange juices with probiotics (*Lactobacillus casei*, *Lactobacillus rhamnosus*, and *Lactobacillus paracasei*) showed undesirable sensory characteristics expressed as medicinal flavors with dairy characteristics. Nevertheless, these studies indicate that exposure and familiarity with probiotic drinks help improve consumers' acceptance and liking of the sensory attributes of fruit drinks with probiotics.

Fruit drinks formulated with microbiologically stable probiotics and prebiotics provide a convenient way to complement daily diets and improve digestive health and immunity. Therefore, functional beverages can successfully deliver health benefits, nutrition, broad sensory profiles, and convenience in today's demanding world. Fruit and vegetable drinks present refreshing sensory profiles and are a preferred choice for people of all ages. A significant advantage is that fruit drinks remain in the stomach for less time, so the transit probiotic species have less exposure to the stomach's acidic environment. Multiple studies show the feasibility of developing these products in emerging markets in response to the changing needs of consumers and the technological use of these food matrices [37].

Few studies have been conducted on the sensory effect of adding prebiotics to fruit and vegetable drinks. However, studies carried out on papaya nectars with oligofructose by Braga et al. [38] have shown preference analyses that nectars with the addition of oligofructose and inulin are appreciated concerning taste and general acceptability to the same extent as nectars containing only sugar. Additionally, in other non-dairy beverages, such as fruit smoothies containing *Bifidobacterium lactis* HN019 and fructooligosaccharides, it has been shown that the formulation containing the prebiotic contributes to the sensory profile, the nutritional composition of the smoothie, and possibly changes its physicochemical properties through the reduction of water activity. It has also been reported that prebiotics can provide attributes in the final texture of the product.

Undoubtedly, the different compounds formed due to the metabolism of the other substrates mentioned will contribute to the flavor of fermented vegetables to a greater or lesser extent. The most straightforward case is cabbage, in which the growth of *L. mesenteroides* during the early stages is desirable since it forms relatively large quantities of acetic acid. Fermentation is carried out at a low temperature (18 °C or lower) to favor the development of this microorganism. At higher temperatures, *L. plantarum* predominates, which gives rise to lower amounts of volatile acids. The product obtained has a sharp acid flavor, unlike that obtained at low temperatures, which has a milder flavor. Although some work has been published on the analysis of volatile components responsible for the aroma in olives [39] and gherkins [40], it is unknown what the relative contribution of each of these components is, or its evolution throughout fermentation. One of the few complete works published in this regard is that of Karki et al. [41], who carried out the study with a typical oriental preparation—a mixture of various vegetables fermented by lactic acid bacteria.

In addition to their preservative effect and influence on flavor, fermentation processes produce changes in other quality attributes, such as texture and color, making fermented products more palatable and digestible (Figure 3). Regarding the texture, generally, there are no significant changes during fermentation if it proceeds normally and the anaerobiosis conditions are adequate. Nevertheless, if the preparation needs to be corrected, it can represent a severe problem. Softening has been the cause of significant economic losses for the industrial sector. However, thanks to the research carried out, the origin of this alteration and the means to prevent it are now known [42]. The decreases in texture are attributed to the modification of the pectin constituents, mainly due to the action of pectinolytic enzymes involved in the biological degradation mechanism. In both gherkins and black olives, it has been shown that adding calcium salts to the initial brine significantly reduces texture losses during fermentation [43]. In the case of pickles, research continues at a basic level to know precisely the type of interaction between the Ca^{+} ions and the polysaccharides of the cell wall that explains its positive effect on texture [44]. On the other hand, it has been found that high concentrations of lactic acid can lead to softening in fermented vegetables. Thus, Etchells et al. [45] found that dressed green olives fermented by *L. plantarum* have a worse texture than those fermented by *L. mesenteroides*. As a possible mechanism, it has been suggested that lactic acid interacts with calcium in pectin substances, giving rise to the observed texture losses [46].

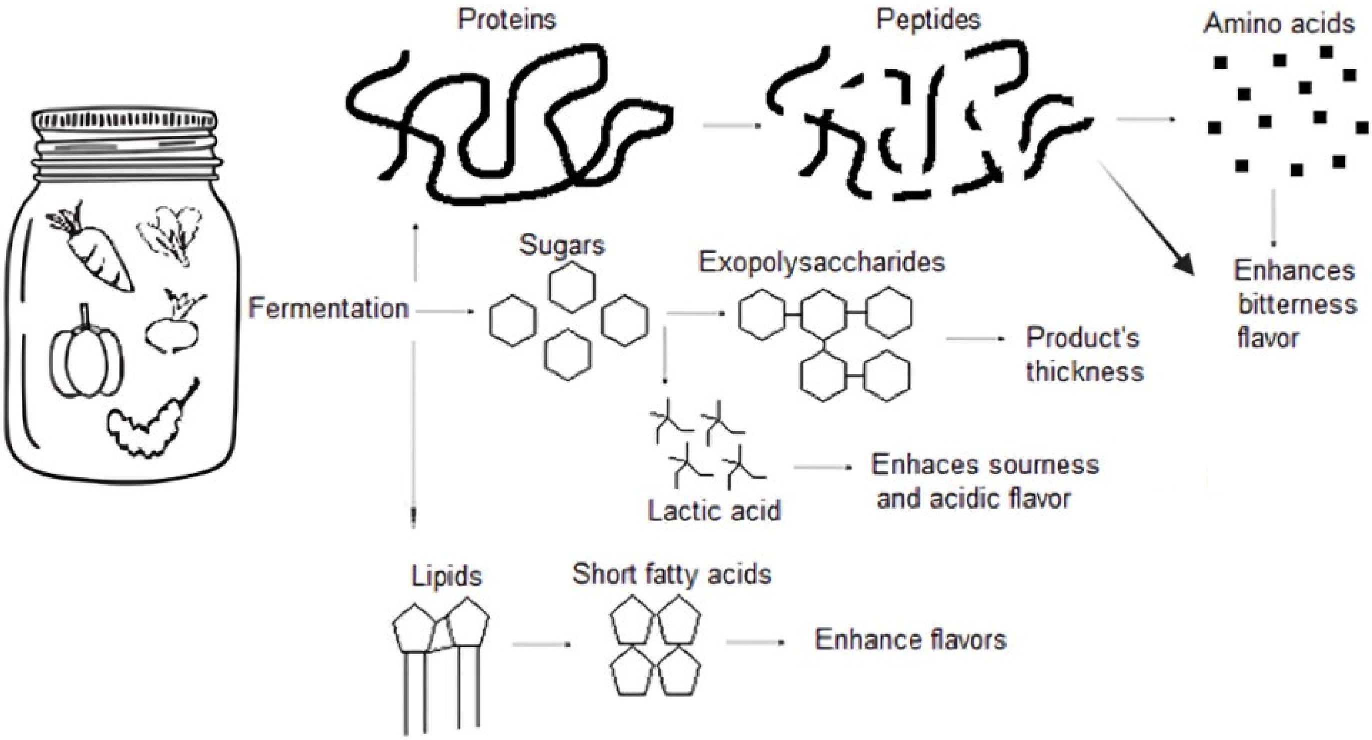

Figure 3. Effects of vegetable fermentation on sensory attributes.

The color of a food is also a determining factor for its acceptability, since it produces the first impression of acceptance or rejection in the potential consumer. Pickles and green olives are the fermented vegetables most investigated in this aspect [47]. Lactic fermentation results in the transformation of some of the pigments responsible for color (chlorophylls a and b and carotenoids violaxanthin and neoxanthin) due to the acidic pH of the medium, while others remain unchanged during the process (lutein and B-carotene). This causes the color changes from green to yellowish green in seasoned olives and from bright green to dark green in pickles.

3. Fermentation of Vegetables to Increase Functional Properties

3.1. The Importance of Fermented Products for Consumer Health

These days, fermentation is not simply considered a method of food preservation. As already mentioned, fermented foods are products that have been subjected to the action of microorganisms, which, when fermenting the substrate, cause biochemical and organoleptic changes that are pleasant and attractive to the consumer. Additionally, resulting from the presence and action of microorganisms, we also obtain foods with greater nutritional value (higher concentration of proteins, essential amino acids, essential fatty acids, vitamins, and minerals) and, on the other hand, foods where it is possible to eliminate undesirable compounds, namely antinutritional factors. Fermented foods can also have beneficial effects on health through the presence of bioactive compounds—small molecules that give the food a biological action that can be made available during the fermentation process.

Well-known bioactive compounds produced and bioavailable through fermentation include phenolic compounds, which can act as natural antioxidants and immune modulators [48]. Another point of extreme relevance for human health is that fermented products naturally contain live microorganisms in high concentrations ($>10^{-7}$), particularly LAB, whose activity in the consumer's digestive tract can confer different benefits to their health. Consequently, and according to the definition of the Europe International Life Sciences Institute (ILSI) [49], they can confer a probiotic effect, an effect that has been extensively mentioned in studies carried out in vivo and in vitro, emerging as an important dietary strategy for improving human health. The health benefits of fermented vegetable products are described for all the reasons mentioned above. They prevent multiple diseases related to metabolic changes, namely obesity, various allergies, and food intolerances (lactose intolerance, gluten intolerance, etc.). In addition, they contribute to reducing the risk of certain types of cancer, improving the immune system, protecting the health of the gastrointestinal system and urogenital tract, and alleviating the symptoms of certain diseases, such as Crohn's disease. On the other hand, these products are often associated with lifestyles such as vegetarianism and veganism, which have become more evident recently. Thus, this technology, being a tool applied to the conservation of vegetables and creating organoleptic attributes, allows in itself to obtain foods with high nutritional and functional value, contributing significantly to the diet of populations in general and can also be considered a method of delivering specific nutrients to certain unique population groups. Reflecting on this knowledge, consumers have shown a growing interest in fermented vegetable products, which are considered natural products promoting health and longevity.

3.2. Health Benefits of Fermented Vegetables

Due to plants' high soluble fiber content, their consumption favors intestinal transit and reduces the absorption of sugars and fats [50]. In addition, being an important source of vitamin C, provitamin A, and folic acid, vegetable-origin food products strengthen the immune system, promote tissue regeneration, and collaborate in forming and maintaining red blood cells [50]. They also contain essential minerals such as magnesium, potassium, calcium, phosphorus, and iron necessary to develop healthy bones and muscle contraction. However, what makes this group of fruits so special is their high content of flavonoids, a group of various metabolites responsible partly for the colors, aroma, and flavor of the fruits [51].

The antioxidant capacity of flavonoids reduces vulnerability to oxidative stress produced by damage caused by environmental agents (ultraviolet rays, environmental pollutants, food chemicals) or cellular aging associated with age or various degenerative diseases. Likewise, flavonoids reduce inflammation and increase neuronal signaling, so consuming vegetables could help prevent cardiovascular diseases, cancer, and multiple pathologies such as high blood pressure and Alzheimer's, or they could reduce the symptoms of these diseases [51].

Additionally, various scientific studies have suggested that fermentation of plant-based products not only helps develop different aromas and flavors but can also increase the availability of their nutrients and antioxidant compounds immersed in the matrix of these fruits, thus enhancing their beneficial properties such as anticholesterolemic activity, vitamin production, antimicrobial peptide production, and antinutrient compound production [52]. Among these potential effects, choleretic (stimulation of the production and secretion of bile, which facilitates the digestion of fats), antiparasitic, and anti-ischemic (promotion of the restoration of the morphology and functions of the heart and vessels after an injury) stand out as protectors of the gastric mucosa [52]. These results lay the scientific foundations for developing new studies that establish the preventive potential as an adjuvant treatment of different diseases through consuming fermented vegetables (Figure 4).

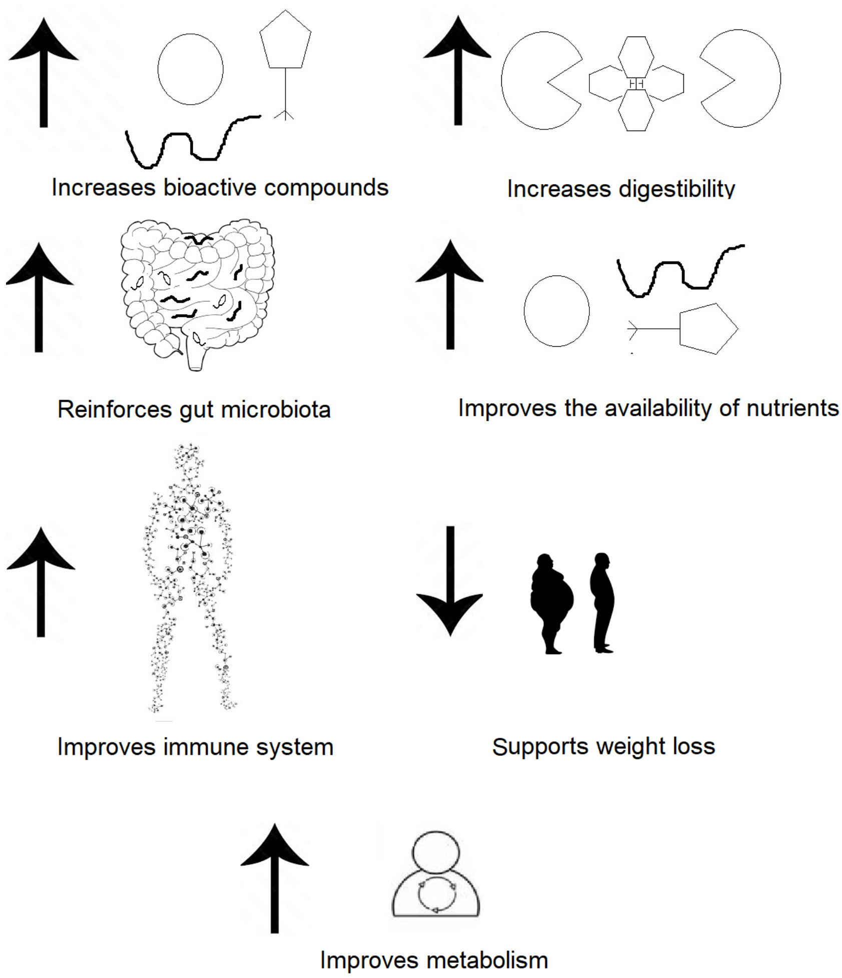

Figure 4. Health benefits of vegetable fermentation.

3.3. Solid-State Vegetable Fermentation for Improvement of the Nutritional and Functional Profile

Solid-state fermentation (SSF) gained particular importance in 1940 (called the Golden Age of industrial fermentation) with the production of antibiotics such as penicillin [53]. In the 1960s and 1970s, SSF was consolidated as a solution for using agro-industrial waste and reducing the environmental impact it generates [54,55]. With sufficient oxygen and a suitable habitat, SSF allows obtaining significant quantities of compounds with high added value (citric acid, enzymes, phenolic compounds, etc.) using low-cost plant waste as a substrate, which guarantees the economic profitability of this process [56].

SmF involves the growth of microorganisms in a liquid culture containing nutrients, a high free water content, and an oxygen concentration where resources are rapidly consumed [57]. This technique is most suitable for microorganisms, such as bacteria, requiring higher moisture content. In contrast, SSF involves the growth of microorganisms on solid substrates surrounded by a continuous gas phase in which, despite the presence of water droplets between the spaces between particles, the amount of free water is scarce or non-existent, and the spaces fill with gas, favoring the growth of microorganisms [54]. This fermentation technique would favor the growth of fungi or other microorganisms with lower humidity needs, such as yeasts or actinomycetes.

The lower availability of water in SSF provides other advantages to the process, such as the lower possibility of contamination by other microorganisms or less foam formation, a recurring problem in SmF. On the other hand, the metabolite produced after SSF is more concentrated and is usually quickly recovered by washing, generating a smaller amount of effluent than SmF and facilitating subsequent recovery operations (downstream). Additionally, the possibility of using agro-industrial waste reduces the costs of the culture medium, in addition to being mediums in which some microorganisms (fungi, yeasts) find their natural habitat. Regarding the productivity of the fermentation process, generally, the amount of metabolite generated per unit of substrate consumed is more favorable when the microorganism is grown in a solid state. This is because the microorganism finds a natural habitat for its growth in which nutrients are progressively released, reducing inhibition by substrate. However, the lower homogeneity of the solid-state culture and the difficulty in scaling these processes means that the size of the bioreactors is notably smaller than the stirred tank bioreactors usually used for submerged culture, so production is significantly lower than those obtained through SmF.

Furthermore, SSF has a series of general advantages over SmF [58], such as greater ease in obtaining and applying the inoculum (with spores being able to be used directly in most cases), reduced solvent needs for product extraction, high aeration of the system, which make it especially suitable for those processes that involve an intense oxidative metabolism, and low energy requirements.

Another exciting application of solid-state fermentation is based on the transformation experienced by the substrates on which the fermentation is carried out, since, in many cases, products with more excellent nutritional properties are obtained, which makes them attractive as ingredients or functional foods.

Among the improvements in the nutritional profile associated with the fermentation of plant residues, it is worth highlighting the increase in the number of compounds with antioxidant activity. The primary mechanism by which this increase in antioxidant capacity is the degradation of cell walls by microbial enzymes and the consequent release of phenolic compounds linked to them [59]. Added to this is the production of compounds with antioxidant activity by the microorganisms involved in the fermentation process [60] and the transformation of some antioxidant compounds into others with more significant activity [61]. Additionally, some microorganisms secrete proteases that transform high-molecular-weight proteins into low-weight proteins with antioxidant activity and the ability to chelate metal ions [62]. In this regard, the species of the genus *Bacillus* are the leading producers of proteases, with *Bacillus subtilis* being the most used industrially [63]. The extraction of active peptides is also of great importance for the food industry and may have nutraceutical and functional potential since they protect against cellular oxidative damage [64].

Notably, in the study carried out by Gulsunoglu et al. [59] (apple peel fermentation with fungi of the genus *Aspergillus* spp.), it reduced the concentration of quercetin and its glycosides in favor of the appearance of isomers of eriodictyol and catechin, allowing an increase of up to four times the content of total phenols and flavonoids and up to five times the antioxidant activity. On the other hand, Bier et al. (2019) [61] found that the fermentation of dried and crushed bagasse and orange peel with endophytic fungi of the genus Diapothe produced the biotransformation of R-(+)-limonene into limonene-1,2-diol, α-terpineol, and α-tocopherol, among other volatile compounds, which represented an increase of more than eight times in the total phenol content. In addition to its high antioxidant capacity, the product obtained is of great interest for its use as a flavoring and flavoring agent. In the study by El-Katony et al. [65], it was shown that the use of ascomycete fungi (*Aspergillus fumigatus* and *Paecilomyces variotii*) increased the phenolic and flavonoid content of pomegranate peel, the antioxidant activity of pea pods and rice straw, and the content of enzymes with antioxidant activity in banana peel and citrus peel.

The latter is probably due to essential oils or citric acid in the bark that prevents oxidation reactions. Sadh et al. [66] reported a significant improvement in the phenolic and antioxidant properties, in addition to an improvement in the protein and mineral content and morphological characteristics of peanut pressed cake through fermentation with the fungus *Aspergillus awamori*.

On the other hand, Sousa and Correia [67] evaluated the effect of supplementation with soy flour as a carbon source on the phenolic content and antioxidant and anti-amylolytic activity of pineapple and guava residues fermented with the food-grade strain *Rhizopus* *oligosporus.* Since no correlation was found between the total phenol content (which reached maximum values for a fruit/soy ratio of 1/1 (*w/w*) and 10 days of fermentation) and the ability to sequester the DPPH radical or to inhibit the enzyme α-amylase (which took maximum values for a fruit/soy ratio of 9/1 (*w/w*) and 2 days of fermentation), it was possible to verify that the beneficial health effect associated with phenolic compounds does not depend only on the amount of substrate but also on the type. During the fermentation of soy flour with different microorganisms (*Bacillus amyloliquefaciens* U304, *Lactobacillus acidophilus*, *Lactobacillus plantarum*, and *Saccharomyces cerevisiae* CJ1697), Chi and Cho [62] verified that, with the lactic acid bacteria *B. amyloliquefaciens* U304, a greater average increase is achieved by antioxidant activity due not only to the increase in the concentration of phenolic compounds but also to the increase in the amount of bioactive peptides. Furthermore, due to its ability to secrete amylases and proteases, the levels of raffinose, stachyose, and trypsin inhibitors were significantly reduced. However, fermentation with *S. cerevisiae* CJ1607 or any other *lactobacilli* only affected one or other antinutritional factors. Hence, the improvement in the nutritional quality and bioactivity of the substrate was minor. Another study that confirms the increase in the number of phenols and antioxidant activity and that demonstrates the role of fermentation in the development of new healthy food ingredients is the one carried out by Bei et al. [59] on oat fermentation with the filamentous fungus *Monascus anka*. The results obtained in this case showed a significant increase in the amount of total and specific phenols (catechin, rutin, caffeic acid, and ferulic acid), mainly in the free fraction, and the appearance of some phenolic compounds (quercetin and chlorogenic acid) after 14 days of fermentation with the consequent increase in the capacity to sequester DPPH and ABTS+ radicals. Another improvement in the nutritional profile resulting from the fermentation of plant waste is the increase in the content of quality proteins and/or their digestibility.

Legume derivatives stand out among the raw materials used as a substrate to achieve this purpose, especially the residue from extracting the water-soluble phase of soybean and chickpea, pea, bean, peanut flour, etc. Among the fermenting microorganisms, lactic acid bacteria, such as *Lactobacillus rhamnosus*, *Lactobacillus paracasei*, or *Pediococcus* spp., are common. The yeasts include *Saccharomyces cerevisiae*, *Saccharomyces kluyveri*, and *Kluyveromyces lactis*. In addition, the most common fungi are *Rhizopus oryzae* and *Aspergillus oryzae*, selected for their β-glucosidase activity (responsible for the hydrolysis of low-availability isoflavone glycosides into bioactive aglycones), its phytase activity (involved in the hydrolysis of phytic acid and the release of essential minerals), and/or its proteolytic activity (which allows transforming proteins into free amino acids and easily assimilated bioactive peptides). Some of these transformations are favored by the reduction in the pH of the medium due to the production of lactic acid by lactic acid bacteria [68–70]. Cobaxin [71] studied the influence of different types of lactic acid bacteria, yeasts, and fungi on the nutritional quality of soybean paste, concluding that *S. kluyveri* improved the amount of isoflavones (genistein and daidzein, with values of 859 and 792, 55 μg/g of substrate, respectively) and that *K. lactis* decreased the amount of phytic acid from 1.81 to 1.43 g/g of substrate. Xing et al. (2020) [72] evaluated the spontaneous fermentation of chickpea flour using different strains of *Pediococcus* spp. increasing from 7.8% to 13.7% in protein content, an increase from 6.9 to 15 mg of GAE/g substrate in the content of phenolic compounds, and a decrease in antinutritional factors of 1.07 up to 0.8 mg of phytic acid/g of the substrate. Queiroz-Santos et al. (2018) [68] were interested in the effect of thermal pretreatment of the substrate on the nutritional quality of soybean paste. Their study found a greater production of phenolic compounds from the substrate treated at 121 °C for 15 min (74 mg GAE/10 g to 123 mg GAE/10 g) than from the untreated substrate (88 mg GAE)/10 g to 116 mg of GAE/10 g), which implies a greater increase in its capacity to sequester the DPPH radical.

However, the freshly fermented okara experienced an increase in protein content of 23.5% compared with the 11% experienced by the heat-treated one. In these cases, the increase is due to the single-cell protein content in the microorganisms themselves (bacteria, molds, or algae), representing up to more than 40% of the dry weight. Yeasts and bacteria are particularly important for producing this type of protein since man has consumed their biomass as fermented foods since ancient times. The production of single-cell protein by SSF is usually used to increase the protein content of substrates that do not stand out for being especially rich in this nutrient. Muniz et al. [73] found an increase of up to 11 times in the protein content of guava skins and cashew bagasse, increasing after fermentation for 6 h with the yeast *Saccharomyces cerevisiae*. The subsequent use of fermented residues in the formulation of cereal bars resulted in a product with a protein contribution similar to the control formulated with oats and quite highly rated by the panel of tasters. This same yeast increased the protein content of grapefruit bagasse, banana peel, and mesquite pods by 157%, 98%, and 82%, respectively [74]. In this case, the co-culture of *Saccharomyces cerevisiae* and *Bacillus subtilis* did not significantly improve the protein concentration achieved in each substrate. However, it offers an additional benefit based on its probiotic potential.

3.4. Solid-State Vegetable Fermentation to Obtain Extracts with Antioxidant Properties

Antioxidant compounds have interest and application beyond their direct consumption in foods. For this reason, SSF can be used to produce antioxidant compounds to be recovered from the culture medium later and used outside of it. The waste used as substrates includes a more significant proportion of inedible or usually not consumed parts such as seeds, shells, straw, and pods, unlike the application discussed in the previous section. Among the most used substrates are some based on cereals, such as rice and wheat bran, cobs, and corn flour [75], also rice seeds and flour [76], legumes, including tamarind peels and seeds [77] or lentil flour [78], as well as waste from the processing of fruits and vegetables, such as mango seeds [79], sugar cane bagasse [73], dehydrated grapes, apple pomace, and pitaya peel [80], or byproducts of industrial pineapple processing [81].

Endophytic filamentous fungi stand out regarding the microorganisms used, but bacteria and yeasts are also used daily. The most common genera are *Aspergillus* spp., *Mucor* spp., *Penicillium* spp., and *Rhizomocur* spp., belonging to the family *Mucoraceae*, order *Mucorales* and class *Zygomycetes*. Fungi of the genus *Aspergillus* spp. stand out for some characteristics already noted in this review, such as their great adaptation to SSF conditions or being GRAS microorganisms, and also for their ability to synthesize more than 19 types of enzymes, including cellulases, pectinases, and proteases, which promote the release of phenolic compounds from the solid matrix [77], in addition to producing new bioactive compounds with antioxidant capacities. On the other hand, yeasts such as *Kluyveromyces marxianus* or lactic acid bacteria such as *Bacillus subtilis* and *Lactobacillus casei* can also be used to obtain these compounds, highlighting the antioxidant activity of the latter and their preservation power due to the ability to produce antimicrobial metabolites such as organic acids [82]. Most of the studies reviewed focus on evaluating the effect of process variables, especially the type of substrate and microorganism, but also temperature, time, humidity, substrate pretreatment, and addition of carbon or nitrogen source, on process performance.

The supplementation of the substrate with carbon and nitrogen sources is a variable to highlight since they provide nutrients that allow the microorganism to grow in more significant proportions and more quickly, release more antioxidants from the structures, or favor the conversion of some antioxidants into others with more substantial activity. Substrate pretreatment is another critical parameter to achieve high phenolic yield during fermentation since it determines the growth of microorganisms and the stability of the substrate and phenolic compounds. However, causing excessive stress to the microorganism can cause the loss of free phenols during fermentation. Zambrano et al. [80] evaluated the possibility of obtaining bioactive phenolic compounds with great antioxidant capacity by applying two types of pretreatment (hot air-drying and freeze-drying) to the following three different substrates: skin, stems and grape seeds resulting from the pressing of the juice and hearts, peduncles and apple and pitahaya seeds. All substrates were dehydrated and ground to a particle size of 3 mm. It has been reported that the intensity of grinding can affect the release of bioactive compounds from the β-glucosidase matrix and decrease the rigidity of plant tissue. In addition to obtaining phenolic compounds, SSF is also applied to obtain other products with antioxidant properties, such as bioactive peptides, polyunsaturated fatty acids, or carotenes. The use of different extraction solvents also determines the yield of antioxidant compounds. The polarity of the solvents plays a fundamental role since it increases the solubility of phenolic compounds. Alves-Magro et al. [83] tested different solvents (water, methanol, choline acetate, choline hydroxide, and choline lactate) to determine their effect on the phenolic yield of lentil extracts after SSF. The authors concluded that water, methanol, and choline lactate significantly increased the total phenolic content during fermentation, the latter being the best extraction solvent, giving rise to 6.57 mg of GAE/g dry substrate compared with approximately 4 and 2 mg GAE/gH achieved with water and methanol, respectively.

3.5. Solid-State Vegetable Fermentation to Obtain Enzymes and Other Metabolites of Interest

This section collects evidence from recent studies to improve the effectiveness or performance of SSF of waste of plant origin to obtain enzymes and other compounds of interest, such as preservatives, pigments, or aromas. The research delves into fundamental aspects of SSF, such as the selection of the microbial strain and the type of substrate or the establishment of the physicochemical and biological conditions that ensure adequate growth and microbial activity to achieve maximum production of these compounds.

Industrial enzymes are one of the most commercially successful products [84]. They tend to be mainly of microbial origin, and very few are of animal or plant origin. They have many technological functions in the food industry and in detergent, paper, leather, etc. Many enzymes of microbial origin are of interest to the food industry; others have found applications of interest due to their contribution to the recovery of waste or the extraction of compounds of interest from them. For example, cellulase improves the extraction of phenolic compounds with excellent antioxidant capacity and the recovery of single-cell proteins [85]; α-amylase acts as a texture improver for bread and pasta, in addition to improving their organoleptic properties, avoiding unpleasant flavors and excessive darkening [86]; protease facilitates the obtaining of polypeptides and essential amino acids [87,88]; chitosanase acts as a thickener, gelling agent, and emulsifier, is an edible protector, and facilitates the recovery of proteins from food industry waste [89]; and, finally, invertase acts as an improver of intestinal flora [90].

As has been confirmed in this review, most enzymes used in the food industry are synthesized by fungi of the *Aspergillus genus* [91], considered the model organism for producing fungal enzymes. In addition, other types of endophytic fungi are usually used, such as *Rhizopus* spp. and *Trichoderma* spp. There are also some references to enzymes produced by probiotic yeast, Yarrowia lipolytica, and by bacteria such as *Bacillus subtilis*, *Bacillus velezenzis*, *Lysinbacillus* spp., *Serratia marcescens*, or *Streptomyces* spp. It should be noted that the raw materials differ depending on the microorganism type. For example, the most common substrates for fungi and yeast are soy flour or any other cereal, while the skins of fruits such as bananas and citrus are used for bacteria.

In many cases, the substrate is conditioned by applying crushing and drying treatments with hot air prior to fermentation. These stages provide a particle size and water activity more favorable for microbial growth and, consequently, for the adequate production of the metabolite of interest. On the one hand, grinding breaks the structures, contributing to faster drying and the release of nutrients, making them more easily accessible. On the other hand, drying is important to stabilize the raw material and concentrate the nutrients [92]. Other parameters such as temperature, time, amount of inoculum, humidity, and pH notably affect the performance of the solid-state fermentation process [93,94].

SSF is also successfully applied to produce other metabolites of interest, such as aromatic compounds, dyes, or preservatives. Among the aromatic compounds, 2-phenylethane and 2-phenethyl acetate stand out, which are involved in the bioconversion of L-phenylalanine into aromatic compounds with a rose odor [93]; aldehyde alcohols and ketones, with an intense fruity aroma [95]; and the unsaturated δ-lactone 6 pentyl-α-pyrone appreciated for its coconut aroma [96]. On the other hand, there are preservatives such as astaxanthin, a red/yellow carotenoid pigment used as a preservative in the encapsulation of oils due to its high antioxidant activity [97]; citric acid, which, in addition to being used as a flavor enhancer, prevents oxidation reactions [98]; and lactic acid. Also, monascorubrin can be highlighted as a natural dye [99]. Another metabolite of interest is γ-linolenic acid, commonly used as a dietary supplement because it is an essential omega-6 fatty acid [100].

To cite some examples, in the study carried out by Ali et al. [98], the effect of temperature (between 20 and 40 °C), fermentation time (between 2 and 6 days), humidity of the medium (between 50 and 80%), and supplementation with essential amino acids (arginine) were evaluated (glycine, glutamine, tyrosine, and aspartic acid) regarding the production of citric acid through the fermentation of apple bagasse and peanut shell with *Aspergillus ornatus* and *Alternaria alternata*, concluding that the co-culture of both microorganisms in the presence of bagasse apple at pH 5, 50% humidity, and 30 °C for 48 h in the presence of arginine results in greater production of citric acid. On the other hand, Certik et al. [101] evaluated the use of various oleaginous microorganisms (*Cunninghamella*, *Mortierella*, *Mucor*, *Rhizopus*, and *Thamnidium*) to produce gamma-linolenic acid (GLA). These microorganisms have favorable characteristics for industrial use, such as genetic stability, not being pathogenic or harmful to health, and, for this particular application, being capable of accumulating high amounts of lipids. For this application, it was necessary to supplement the medium with sunflower oil and restrict other nutrients, especially nitrogen. Among the microorganisms tested, *T. elegans* had a higher capacity to synthesize GLA (20 g of GLA/g of dry substrate), which was improved after enriching the substrate with vegetable oils and plant extracts.

For their part, Vidhyalakshimi et al. [102] evaluated the effect of the type of strain (*Xanthomonas* spp.) and the type of plant residue (vegetable skins such as potatoes and fruit peels, citrus, or banana) on the production of the exopolysaccharide xanthan gum and verified that the supplementation of the substrate with carbon and nitrogen sources allows an increase in process performance. Similarly, in the study carried out by Martínez et al. [95], supplementation of sugarcane bagasse with 25% (*w/w*) sugar beet pulp increased the production of aromatic compounds from 70 to 105 mg/g of substrate by the yeast *Kluyveromyces marxianus*.

4. Vegetable Fermentation as a Sustainability Strategy

Food waste is a global issue of growing concern. The term "food waste" refers to all waste produced during the food chain, harvesting, processing, and distribution of food products and also generated in domestic and commercial preparation (Figure 5). There is widespread interest in finding new ways of valuing this waste, mainly fruit and vegetable waste, and transforming it into value-added products, such as food ingredients, nutraceuticals, and fresh food products. The aim is, therefore, to find alternatives to commonly used methods, such as composting, incineration, landfilling, or use in animal feed. With these objectives, the application of the fermentation process to agro-industrial horticultural waste has been evaluated in several studies. It could play a significant role in the transition from the current linear economy to a circular economy. Plant matrices with a high content of compounds of interest, such as bioactive compounds and fibers, can be extracted and recovered from these by-products and valued in food ingredients, supplements, nutraceutical formulations, and new functional foods. In this way, manufacturing companies can receive a financial return instead of incurring disposal costs and contribute to reducing this waste with environmental benefits. Recent studies have demonstrated the feasibility of fermentation for valuing different fruit and vegetable waste. In the survey developed by Cantatore et al. (2019) [103], in apple waste, BAL, an ingredient suitable for fortifying wheat bread, was produced. Ricci et al. [104] used by-products from carrot and tomato pulp to produce antimicrobial compounds that, when inserted into other foods, help guarantee their safety and extend their shelf life. Nanis et al. [105] describe that fermented olive pastes, obtained from mill waste through spontaneous fermentation, result in a functional ingredient that can be used in the food industry. In summary, the application of fermentation increased digestibility, increased nutritional value, and reduced the levels of antinutritional factors in these substrates. However, the most significant interest in applying fermentation processes to fruit and vegetable waste comes from its potential for recovering underused compounds beneficial to health that can be introduced into foods or used directly as nutraceuticals. Therefore, based on the above, LAB's fermentation of agriculture waste is expected to present excellent opportunities for a sustainable circular economy.

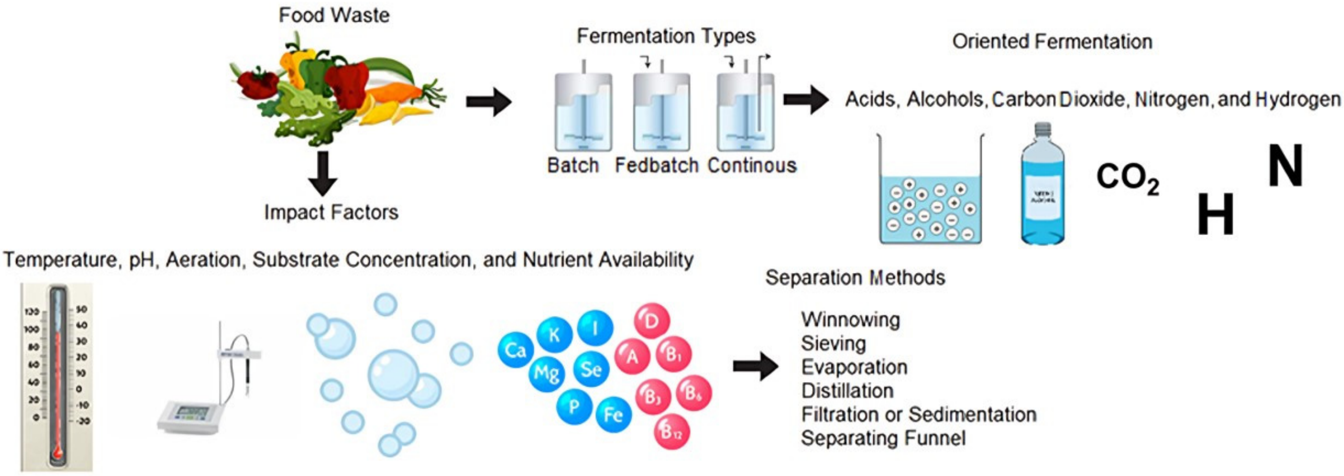

Figure 5. Fermentation of vegetable waste.

4.1. Parameters of Relevance in Vegetable Fermentation

4.1.1. pH

The pH of fermentation can be placed at the beginning and allowed to decline because of acid production, or it can be managed by titration, electrodialysis, extraction, or absorption of lactic acid. Most fermentations demand pH management. This control permits the management of microbiological activity, the capacity of an enzyme to achieve its function, or the final flavor characteristics. Nevertheless, it can induce this acidity, or it is the product of the fermentation activity itself, displaying an activity developed by acid, acetic, lactic, or citric bacteria. Its effect has been studied under different values. In all cases, titration to a constant pH has resulted in equal or higher concentrations than in cases without control [106]. Acid removal by electrodialysis and extraction, including aqueous two-phase systems, has been used satisfactorily in several methods, while, in others, titration has given the same or better results [107]. The optimal pH for lactic acid production varies between 5.0 and 7.0. A pH lower than 5.7 has been optimal for *Lactobacillus* strains, which are known to tolerate lower pH than *Lactococci* [108].

4.1.2. Carbon Source

Carbon sources have been utilized in the fermentation process to produce metabolites. The most refined product is received when purified substrates are fermented, reducing process costs. Nevertheless, this is an economically negative aspect because refined substrates are expensive, and alcohol, acetic acid, and lactic acid are economical. Instead, waste products from agriculture and forestry are used. Compared with different carbon sources, it is observed that glucose yields higher concentrations of lactic acid than other sugars. Xylose, galactose, arabinose, lactose, fructose, and hydrolyzed cellulose have been less effective [106].

4.1.3. Nitrogen Source

The composition of the medium has been investigated in many aspects, including the addition of various nutrients in the form of yeast extract, peptone, or corn syrup. The concentrations of the nitrogen source in the culture medium are generally between 10 and 25 gr/L, showing that the addition of nutrients and higher concentrations of these positively affect the production of metabolites. Nitrogen is involved in the growth of the yeast population, in the kinetics of sugar transport by bacteria during fermentation, in the continuation of alcoholic fermentation when active growth has ceased, and in the protection of bacteria from osmotic stress and toxicity caused by ethyl alcohol in the final stages of fermentation. With yeast extract alone, greater metabolite production is obtained in low quantities than with yeast extract and peptone; however, the opposite occurs when the concentration of yeast extract is kept constant and peptone is added [109].

4.1.4. Temperature

The effect of temperature on lactic acid production has been studied in a few reports. The temperature that gives higher productivity is sometimes lower than the temperature that results in the highest yield and concentration of lactic acid. In contrast, the same temperature obtained the same results in others in all categories. For example, for *Lactobacillus casei* and *Lactobacillus paracasei*, the optimal temperature was reported between 37 and 44 °C [110]. Fermentation is an exothermic process, so it naturally increases the must's temperature (proportional to the amount of sugar it has). The temperature must not stay high since bacteria can die and fermentation will stop.

4.1.5. Cell Density

The highest cell densities (48–103 gr/L) have been achieved with recirculation, but concentrations between 60 and 77 g/L of cells occur in fermentations without recirculation. The fermentation of LAB is generally accompanied by an increase in cell mass, which constitutes an unwanted by-product if the objective of the process is the production of metabolites. However, obtaining high concentrations of microorganisms can be used as the primary raw material in producing probiotics [106].

4.2. Fermentation Method

Lactic acid is generally produced in batch mode, but there are numerous examples of continuous culture as well as fed-batch and semi-continuous repeated batch fermentations. When comparing batch and continuous fermentation modes, the former results in higher lactic acid concentrations and better yields in most studies. This is because all the substrate is used in batch mode. On the other hand, the continuous mode results in higher productivity because it works at high dilution rates, where the advantage over the batch mode is pronounced. Generally, the fed-batch, semi-continuous, and repeated batch modes have obtained higher yields than the batch mode [111].

Cell immobilization and recirculation: LAB cells can be recirculated or immobilized on solid supports in different modes to increase cell density. However, this has kept lactic acid yield and productivity the same. On the other hand, the recirculation of cells has given higher concentrations of lactic acid and equal or greater yields [106].

Fed-batch fermentations: The batch process consists of carrying out an initial feeding with all the nutrients necessary for the microorganism inside the reactor so that it reproduces exponentially until the substrate is exhausted. Subsequently, the fermentation reaches the stationary. In contrast, the fed-batch methodology supplies nutrients to the microorganism during fermentation without removing the spent medium. This feed stream can be supplied continuously, with variable or constant flows, or discontinuously in pulses [112].

4.3. Microencapsulation in Improving the Viability of Microorganisms in the Development of Products in Matrices of Plant Origin

Encapsulation is a process that is applied to the microorganisms (active material) selected for inoculation to protect them from environmental factors that represent a risk to their viability, as well as their stability, bioavailability, and conservation, isolating it using a coating material or wall material (encapsulating material), forming miniature capsules that can range from microns to 2 mm, varying in shape depending on the methods and materials used [113].

The wall material forms semipermeable microcapsules with a spherical morphology, covered by a solid or solid–liquid resistant membrane. For the appropriate selection of the wall material, aspects such as food grade and costs; physical–chemical properties such as solubility, molecular weight, glass transition/melting, crystallinity, diffusivity, film formation; and emulsifying properties, biodegradability and ability to form a barrier between the interior of the capsule and its surroundings, resisting stomach acidity, preventing the inactivity of the strain before it arrived at the site of action. The coating materials of plant origin most used in the encapsulation of bioactive are lipids, polysaccharides (starch and its derivatives, amylose, amylopectin, dextrins maltodextrins, cellulose, and derivatives), and exudates and plant extracts (gum arabic, gum tragacanth, gum mesquita, pectins, among others), carrageenans, alginates, and soy protein isolate [113].

In general terms, polysaccharides can easily form spherical microparticles during drying, which is why they are widely used. Ideally, the encapsulant should provide the film with emulsifying properties, be biodegradable, be resistant to the intestinal tract, have low viscosity and a high solids content, have low hygroscopicity, be non-reactive with the core, be able to seal and hold the core in the interior of the capsule, be able to provide maximum protection to the core against adverse conditions, have an absence of unpleasant taste for application in food, and have economic viability. Generally, mixtures of materials are used to meet these characteristics [114].

The active material (microencapsulated) maintains its structure for prolonged periods and is released into the environment at controlled rates under specific conditions. There are different release mechanisms, among which we find fusion or dissolution, where the capsules are decomposed by the addition of a solvent or by the action of heat; increasing humidity when the coating is water-soluble; physical pressure, where capsules are released by external forces; or by friction and diffusion, where capsules leave their matrix guided by concentration gradients, attractive bonding forces such as hydrogen bonds, Van der Waals forces, degree of cross-linking, and crystallinity. This latter mechanism is controlled by the solubility and permeability of the agent encapsulated in the protective material [114].

Various microencapsulation methods are applied, isolated, or combined (Table 4). To choose the most appropriate, physical factors specific to the technique must be considered, such as temperature, humidity, heat exposure times, oxidative mechanisms, and agitation that affect its survival, as well as the substance to be encapsulated, the quantity and size of the capsules to be developed so that they do not interfere with the consumer's perception, and the desired release mechanism. The chemical properties necessary for its application, scale, production costs, processing conditions, packaging material, and storage conditions are also considered [115]. Table 5 illustrates the application of microencapsulation techniques in probiotics.

Table 4. Microencapsulation methods according to the nature of the process.

Processes	Classification
Physical	- Spray-drying - Freeze-drying - Extrusion - Spray-cooling - Spray-coating
Chemical	- Interfacial polymerization - Molecular inclusion
Physicochemical	- Coacervation - Entrapment in liposomes or reverse micelles - Ionic gelation - Emulsification

Table 5. Microencapsulation technologies for probiotics and characterization of produced microcapsules.

Microencapsulation Technique	Probiotic	Encapsulating Matrix	Reference
Rennet-gelled protein encapsulation	*Bifidobacterium animalis* and *Lactobacillus paracasei*	Milk proteins	[116]
Fluid bed	*Enterococcus faecium*, *Bifidobacterium bifidum*, and *Lactobacillus reuteri*	Alginate, shellac, hydroxyoropil methylcellulose, and glycerol	[117]
Chilling spray	*Bifidobacterium lactis* and *Lactobacillus acidophilus*	Palm interesterified fat	[118]
Spray-dried with vacuum and sound	*Lactobacillus paracasei* and *Lactobacillus casei*	Maltodextrin and trehalose	[119]
Hybridization systems	*Lactobacillus acidophilus*	Insulin, sorbitol, mannitol, and	[120]
Incident aerosol technology	*Lactobacillus acidophilus* and *Lactobacillus rhamnosus*	Alginate	[121]
Electrocentrifugation	*Bifidobacteria* sp.	Whey proteins	[122]
Electrospray	*Lactobacillus plantarum* and *Bifidobacterium lactis*	Alginate, chitosan, inulin, and resistant starch	[123]
Extrusion technology	*Lactobacillus bulgaricus*	Alginate–milk	[124]
Vacuum-drying	*Lactobacillus plantarum*	Resistant starch from unripe saba banana	[125]

5. Trends and Challenges in Vegetable-Fermented Products

Health concerns are at the forefront of food purchasing decisions worldwide for all population (age) groups. In industrialized societies, where a large part of the population has minimum nutritional needs covered, more and more functional foods with quality sensory attributes are demanded. Consumers look for health benefits in their foods and drinks. However, it is also true that different groups have different interests and needs. For example, a millennial consumer is prone to conducting research before making purchases; a young consumer focuses on the benefits that the food gives him in terms of physical appearance, education, and work, that is, he has a holistic approach to well-being; an older and middle-aged consumer (40 to 50 years)'s approach has a greater emphasis on physical and cognitive health.

Manufacturers face challenges in creating vegetable-fermented products that ensure that consumers receive sustainable nutrition. Therefore, understanding the importance of demographic factors such as age and activity levels can help food manufacturers create innovative functional products while preserving traditional flavors. In this way, they have established three generations of fermented products. The first generation emerged in the 1970s, a time characterized by consuming foods with little processing, such as fermented fruit juices, yogurt, and whole-grain bread. The second generation of vegetable-fermented products emerged in the 1980s, characterized by products modified in fat and sugar content, thus giving rise to products called "light", "low in calories", "low in fat", and "low in sugar", together with those "rich in fiber" products. This era was significant for the food industry since it led to extensive sugar- and fat-substitute research to develop modified and safe products for the population. The third generation of functional properties emerged, highlighting the development of products with functional properties, such as products with probiotics, prebiotics, phytosterols, and fibers. The population's excellent knowledge of the properties of certain foods and the greater availability of functional processing and supplements raise the need to review the traditional approach to nutritional food education.

6. Conclusions

Manufacturers encounter challenges in producing vegetable-fermented products that assure that customers obtain sustainable nutrition. Thus, comprehending the significance of demographic aspects such as age and activity levels can allow food manufacturers to make creative functional products while maintaining standard flavors. The application of fermentation for the conservation of products of plant origin represents an effective method of extending their life span, ensuring their safety, and promoting desired organoleptic characteristics. Traditionally, food was preserved through fermentations that occurred spontaneously. However, current production also explores the use of starter cultures to ensure consistency and standardization of quality in the final product. In the lactic acid fermentation of fruit and vegetables, the appropriate selection of lactic acid bacteria strains can also increase the nutritional value, probiotic functions, and digestibility of the materials that gave rise to them. Finally, optimized fermentation processes, applied to residues from plant matrices, can allow the production of functional ingredients for new food formulations, extraction of high-value compounds, and development of new products, contributing to the transition to a bioeconomy model.

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