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Review

Obtaining Antioxidants and Natural Preservatives from Food By-Products through Fermentation: A Review

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Abstract: Industrial food waste has potential for generating income from high-added-value compounds through fermentation. Solid-state fermentation is promising to obtain a high yield of bioactive compounds while requiring less water for the microorganism's growth. A number of scientific studies evinced an increase in flavonoids or phenolics from fruit or vegetable waste and bioactive peptides from cereal processing residues and whey, a major waste of the dairy industry. Livestock, fish, or shellfish processing by-products (skin, viscera, fish scales, seabass colon, shrimp waste) also has the possibility of generating antioxidant peptides, hydrolysates, or compounds through fermentation. These bioactive compounds (phenolics, flavonoids, or antioxidant peptides) resulting from bacterial or fungal fermentation are also capable of inhibiting the growth of commonly occurring food spoilage fungi and can be used as natural preservatives. Despite the significant release or enhancement of antioxidant compounds through by-products fermentation, the surface areas of large-scale bioreactors and flow patterns act as constraints in designing a scale-up process for improved efficiency. An in-process purification method can also be the most significant contributing factor for raising the overall cost. Therefore, future research in modelling scale-up design can contribute towards mitigating the discard of high-added-value generating residues. Therefore, in this review, the current knowledge on the use of fermentation to obtain bioactive compounds from food by-products, emphasizing their use as natural preservatives, was evaluated.

Keywords: fermentation; food by-products; antioxidant; antifungal



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1. Introduction

The processing of food by the industry generates a large amount of by-products that are generally discarded. In some cases, these by-products are reused for animal feed or as fuel for energy, but they still have a low economic value. It has been estimated that 88 million tons of by-products are generated from the agri-food industry, at a cost of 143,000 million euros [1]. These by-products can be converted into a wide variety of compounds with high added value, such as biofuels or bioactive compounds [2].

Fermentation has been used for thousands of years to preserve food or produce compounds of interest such as ethanol. Over time, this process has been gaining importance in research related to nutrition and health, because through fermentation, bioactive compounds of interest are obtained, such as antioxidant compounds [3]. It also raises interest at an industrial level since it allows the reuse of waste to obtain the desired compounds from them. In this way, it contributes to protecting the environment by reducing the environmental impact caused by these wastes [4].

Finally, societal demand increasingly tends toward foods with additives of natural origin and the avoidance of those of chemical origin. An important part of the compounds added to a food are preservatives, since they allow the extension of its shelf-life and reduces economic losses. Therefore, through fermentation, natural compounds can be obtained to replace the chemical products currently used for this purpose. Thus, the present review aimed to evaluate the current knowledge on the use of fermentation to obtain bioactive compounds from food by-products, emphasizing their use as natural preservatives.

2. Fermentation Processes

Although fermentation has been used since ancient times, techniques have been improved to increase productivity, developing increasingly efficient processes. Currently, to carry out the fermentation process, two different strategies are usually used depending on the type of substrate: submerged fermentation or solid-state fermentation. The first process is submerged fermentation (SmF). To perform this, a liquid substrate can be used or water can be added to a solid substrate (Figure 1).

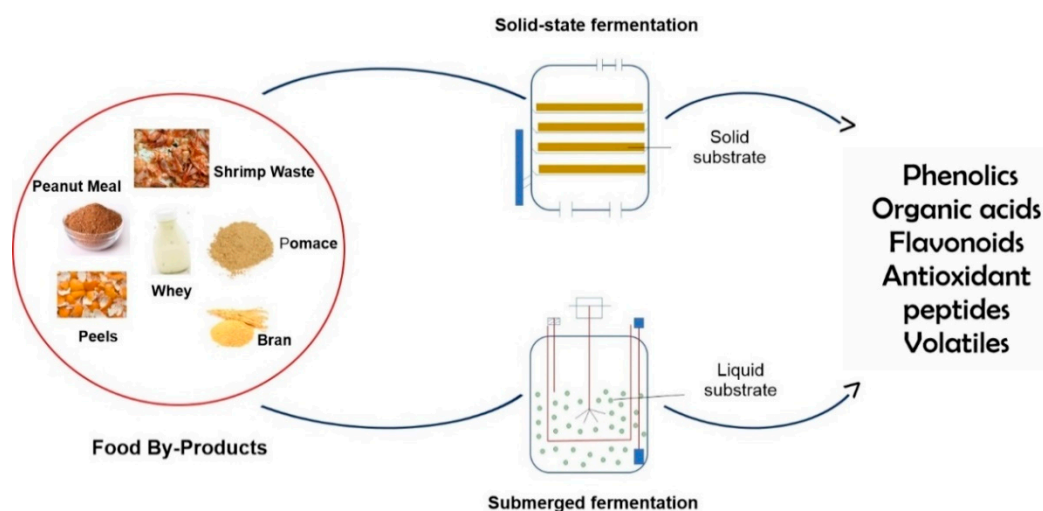


Figure 1. Overview of food by-product fermentation to produce antioxidant compounds or natural preservatives.

This fermentation method is the one chosen when bacteria or yeasts are used to ferment, since they need high humidity [5]. The bioactive compounds produced by microorganisms during fermentation are secreted into the liquid medium. Therefore, SmF is commonly used for the production of secondary metabolites in the liquid state [6]. Among its main advantages we can highlight the production of compounds on a large scale, a good transfer of mass and heat during the process, and a better diffusion of microorganisms. However, its drawbacks are low performance, high energy consumption, and that it is not environmentally friendly due to the high volume of waste water that is generated [5].

Although SmF is not the most widely used technique for the reuse of food by-products, some authors have explored its use to obtain bioactive compounds (Table 1). In this sense, Zhang et al. [7] used shrimp by-products as substrate to obtain chitin and chitosan using SmF. *Mucor sp.* strains produced gamma-linolenic acid and beta-carotene after SmF fermentation of agro-industrial waste (brans, spent malt grains, distiller grains, etc.) [8]. On the other hand, Bartkiene et al. [9] used SmF to obtain different antioxidant and antimicrobial compounds by fermenting barley by-products with the bacterium *Pediococcus acidilactici*. In addition, Zou et al. [10] also used SmF to enhance antioxidant activity of ginkgo seeds suspension through fermentation with *Eurotium cristatum*. Finally, agri-food waste cannot only serve as a substrate, but also as a support for fermentation. In this sense, Das et al. [11] used the eggshell as a support for the fermentation of wastewater from a brewery with the *Rhizopus oryzae* fungus, obtaining fumaric acid.

Table 1. Antioxidant and antifungal compounds obtained from food processing by-products.

Food By-Product (Substrate)	Microorganism	Fermentation	Compounds Obtained	Reference
Pomelo peels	F33 activated yeast	SmF	Flavonoids	[12]
Grapefruit by-products	<i>Aspergillus niger</i>	SSF	Antioxidant compounds	[13]
Hass avocado seeds	<i>A. niger</i> GH1	SSF	Phenolic compounds	[14]
Plum by-products (pomaces, spent fruit pulp and peels)	<i>A. niger</i> and <i>Rhizopus oligosporus</i>	SSF	Phenolic compounds (mainly isoquercitrin, cinnamic acids and rutin) and flavonoids	[15]
Chokeberry pomace	<i>A. niger</i> and <i>R. oligosporus</i>	SSF	Polyphenols and flavonoids	[16]
Grape, apple and pitahaya by-products	<i>Rhizomucor miehei</i> NRRL5282	SSF	Phenolic compounds	[17]
Grape pomace	<i>Actinomucor elegans</i> and <i>Umbelopsis isabellina</i>	SSF	γ -linolenic acid, carotenoids, phenolic compounds and flavonoids	[18]
Wheat and oat bran	<i>Saccharomyces cerevisiae</i>	SSF	Polyphenols	[19]
Peanut meal	<i>Bacillus subtilis</i>	SmF	Antioxidant peptides	[20]
Peanut press cake	<i>Aspergillus awamori</i>	SSF	Phenols and flavonoids	[21]
Brewer's spent grain	<i>A. awamori</i> , <i>Aspergillus oryzae</i> , <i>Aspergillus terreus</i> , <i>A. niger</i> and <i>R. oryzae</i>	SSF	Phenolic compounds (mainly ferulic, p-coumaric and caffeic acids)	[22]
Barley bran	<i>A. oryzae</i>	SSF	Phenolic compounds	[23]
Wheat bran	<i>Enterococcus faecalis</i> M2	SSF	Phenols, flavonoids and alkylresorcinols	[24]
Rice starch extraction by-product	<i>Bacillus</i> spp.	SmF	Antioxidant peptides	[25]
Whey proteins	<i>Bacillus subtilis</i>	SmF	Antioxidant peptides	[26]
Whey (cheese manufacturing by-product)	<i>Bacillus clausii</i>	SmF	Antioxidant peptides	[27]
Camel milk whey	<i>Lactobacillus delbrueckii</i> subsp. <i>lactis</i>	SmF	Antioxidant peptides	[28]
Porcine liver proteins	<i>Monascus purpureus</i>	SmF	Antioxidant peptides	[29]
Chicken eggshell membrane	<i>Lactiplantibacillus plantarum</i>	SmF	Antioxidant peptides	[30]
Sea bass by-products	<i>L. plantarum</i>	SmF	Antioxidant compounds	[31]
Turbot skin	<i>A. oryzae</i>	SmF	Antioxidant peptides	[32]
Carp heads	<i>Pediococcus acidilactici</i> and <i>Enterococcus faecium</i>	SmF	Antioxidant and antifungal peptides	[33]
Fermented fish sauce by-product	-	SmF	Antioxidant peptides	[34]
Shrimp waste (cephalothoraxes and carapaces)	<i>Bacillus cereus</i>	SSF	Antioxidant chitoooligosaccharides	[35]
Shrimp waste	<i>P. acidilactici</i>	SmF	Antioxidant compounds	[36]
Rice bran	<i>R. oryzae</i>	SmF	Phenolic compounds	[37]
Rice bran	<i>R. oryzae</i>	SmF	Phenolic compounds	[38]
Apple by-products	<i>Weissella cibaria</i> and <i>S. cerevisiae</i>	SmF	Dietary fibers and volatile compounds	[39]
Whey (cheese manufacturing by-product)	<i>L. plantarum</i>	SmF	Antifungal compounds	[40]
Whey (cheese manufacturing by-product)	<i>L. plantarum</i>	SmF	Antifungal compounds	[41]
Sea bass by-products	<i>L. plantarum</i>	SmF	Antifungal compounds	[42]
Shrimp and crab shell	<i>B. cereus</i>	SmF	Antifungal compounds	[43]

“-”: microorganisms were not reported in the article. SmF: Submerged Fermentation; SSF: Solid-State Fermentation.

The other fermentation process is known as solid-state fermentation (SSF). In this case, a solid substrate is used in the absence of water and the fermenting microorganisms grow on it [44]. For this fermentation technique, microorganisms that do not require a high water level in the medium are used, such as fungi [6]. With this method, the nutrients in the solid substrate are used to the maximum. The advantages of SSF over SmF are a high yield, obtaining a final product with high activity, low water consumption, being more environmentally friendly, and greater resistance to contamination. Another advantage of this method is the possibility of using agricultural by-products as substrate for fermentation, allowing the recovery of compounds of biological interest and reducing the waste generated. Through this process, products of high economic value can be obtained. The main drawbacks are the difficulty to scale-up the process, the accumulation of heat, and the difficulty to correctly control the process parameters [5]. In fact, the main compounds produced from agricultural by-products by SSF are enzymes [45]. Agricultural residues contain all the necessary nutrients for the good growth of the microorganisms used for fermentation; therefore, a very good process performance is obtained. Some of the most commonly used by-products in this process are molasses, pomace, bagasse, roots, seeds, husks, peels, stems, stalks, and leaves [46]. Therefore, SSF is considered a promising and ecological process with significant future prospects for obtaining compounds of interest [47].

Several authors have investigated the use of this process to obtain different bioactive compounds from agro-industrial by-products. SSF is very useful to that aim, since through the action of bacterial enzymes the hydrolysis of the cell walls is achieved, releasing different compounds such as polyphenols, vitamins, organic acids, or bioactive peptides [48]. In this sense, Fang et al. [49] used SSF to obtain poly- γ -glutamic acid with *Bacillus amyloliquefaciens* and a natural complex microbial community from corn stalk and soybean meal. One of its main uses is to obtain antioxidant compounds, although it can also be used for other compounds of interest in the food industry, such as antifungals (Table 1). Lastly, food by-products can be also used to obtain different enzymes, which are used later to obtain bioactive compounds. In this sense, Teles et al. [50] used grape pomace and wheat bran as a substrate for the production of several hydrolytic enzymes through fermentation with *Aspergillus niger*, which were later applied to grape pomace to recover polyphenols.

3. Preservative Compounds Obtained from Food By-Products Fermentation

3.1. Antioxidants

As mentioned above, some of the main products obtained after fermentation are antioxidant compounds. Antioxidant compounds are interesting from a health point of view, since, as it is known, oxidative stress is related to a wide variety of diseases such as cancer, cardiovascular diseases, diabetes, and neurodegenerative diseases [51]. However, these compounds are also interesting for industry, specifically the food industry, since they can be used as natural preservatives in processed foods to prevent their oxidation [52]. The main antioxidant compounds obtained from plant matrices are phenolic compounds, like phenolic acids or flavonoids, which have a remarkable antioxidant activity. Moreover, other vegetal compounds such as carotenoids or vitamins are also important antioxidants [53]. Fermentation processes can increase the extraction of antioxidant molecules from food matrices, including vegetable by-products. Moreover, fermentation can also modify the profile and types of antioxidant bioactive compounds, or even produce new compounds with biological activities of interest. Fermentation can also act on the activity of the compounds or on their bioaccessibility/bioavailability [54–58]. Bioaccessibility is primarily modulated during fermentation by deaggregation and deglycosylation of phenolic compounds or carotenoids and even by the release of monomeric phenolic compounds, or by isomerization as in the case for lycopene. However, the bioavailability of dietary polyphenols in the human body remains unclear. Extensive glycosylation of these compounds causes a poor intestinal absorption. Hence, increased bioaccessibility resulting from fermentation is seen as a positive factor for bioavailability, which depends on numerous

factors related to diet composition and also relies on the metabolic activity of large intestine microbiota able to release aglycones.

Regarding animal by-products, the main source of antioxidant compounds are bioactive peptides, originated after the fermentation process, or a chemical or enzymatic hydrolysis of proteins. Finally, fermentation processes can also release antioxidant compounds which were not present before, like exopolysaccharides, which are produced by microorganisms using sugars as substrate [59].

The main substrates used to obtain antioxidant compounds come from by-products of plant matrices. The industrial processing of fruits and vegetables generate by-products such as skin, peel, pomace, and seeds, which represent around 30% of the weight of the product. These by-products are rich in bioactive compounds such as vitamins, pigments (chlorophylls, carotenoids, lycopene, etc.), flavonoids, and phenolic compounds, as well as containing dietary fibers. This, together with the presence of water in these by-products, makes them a perfect substrate to carry out SSF (Figure 2), as can be seen in the existing literature. In this sense, Tian et al. [12] observed an increase in the presence of flavonoids after fermentation of grapefruit peels with F33 activated yeast. Larios-Cruz et al. [13] also observed that grapefruit by-products could be used as a source of antioxidant compounds after fermentation with *A. niger*. Yepes-Betancur et al. [14] used SSF to ferment hass avocado seed with *A. niger* GH1 to release bioactive compounds with antioxidant capacity. They reported an increase in antioxidant activity measured by DPPH and ABTS due to the release of phenolic compounds by the activities of the enzymes cellulase and xylanase. Dulf et al. [15] also used generally recognized as safe (GRAS) fungi, specifically *A. niger* and *Rhizopus oligosporus*, to ferment different plum by-products (pomaces, spent fruit pulp, and peels). These authors reported an increase in phenolic compounds (mainly isoquercitrin, cinnamic acids, and rutin) and flavonoids after the fermentation process, which was correlated with an increase in the antioxidant capacity of the fermented samples. In another study, Dulf et al. [16] also reported an increase in the extraction of polyphenols and flavonoids after the fermentation of chokeberry pomace with *A. niger* and *R. oligosporus*, improving antioxidant activity. Zambrano et al. [17] fermented grape, apple, and pitahaya by-products with *Rhizomucor miehei* NRRL5282, increasing the recovery of polyphenolic compounds and antioxidant activity (measured by DPPH and FRAP). Lastly, the production of other compounds such as carotenoids has been also explored. In this sense, Dulf et al. [18] used *Actinomucon elegans* and *Umbelopsis isabellina* to obtain higher production of γ -linolenic acid and carotenoids, like lutein or β -carotene, from grape pomace. Moreover, the fermentation of this by-product with *A. elegans* increased the total flavonoid and phenolic content, and then improved antioxidant activity.

On the other hand, by-products from industrial cereal processing also represent an inexpensive and abundant source of bioactive compounds. Regarding this, Călinoiu et al. [19] studied the fermentation of wheat and oat bran by *Saccharomyces cerevisiae* using solid-state yeast fermentation. They found the highest levels of total polyphenols after 3 (0.84 ± 0.05 mg of gallic acid equivalents (GAE)/g dry weight (DW)) and 4 (0.45 ± 0.02 mg GAE/g DW) days of fermentation for wheat and oat bran, respectively. Sadh et al. [21] reported an increase in antioxidant compounds such as phenols and flavonoids when fermenting peanut press cake with *Aspergillus awamori*. Da Costa Maia et al. [22] applied SSF to brewer's spent grain, using several fungi strains to increase the recovery of phenolic compounds. The most effective fungus was *Aspergillus oryzae*, and the main extracted polyphenols were ferulic, p-coumaric, and caffeic acids. Bangar et al. [23] also used *A. oryzae* to ferment barley bran, showing after fermentation a significant increase in phenolic compounds, specially gallic acid (from 12.75 to 405.5 $\mu\text{g/g}$), catechin (from 9.9 to 88.3 $\mu\text{g/g}$), and scorbic acid (from 20.44 to 107.15 $\mu\text{g/g}$), among others. As a result, antioxidant activity was enhanced significantly. Wheat bran was fermented by Mao et al. with *Enterococcus faecalis* M2, increasing the total phenolic compounds, flavonoids, and antioxidant capacity significantly. These authors reported an increase of gallic acid (1.5-fold), p-coumaric acid (1.4-fold), ferulic acid (2.6-fold), and cinnamic acid (1.4-fold) after the fermentation pro-

cess compared with raw wheat bran content [24]. Lactic acid bacteria (LAB) are known to be capable of producing bioactive peptides after fermentation of high-protein plant by-products. It has been observed that after fermenting peanut meal with *Bacillus subtilis*, peptides with an antioxidant capacity of 63.28% were obtained, in comparison with BHT, whose antioxidant activity was 99.16% [20]. It has also been seen that after fermentation of rice starch extraction by-product with *Bacillus* spp., bioactive peptides with antioxidant activity are obtained [25].

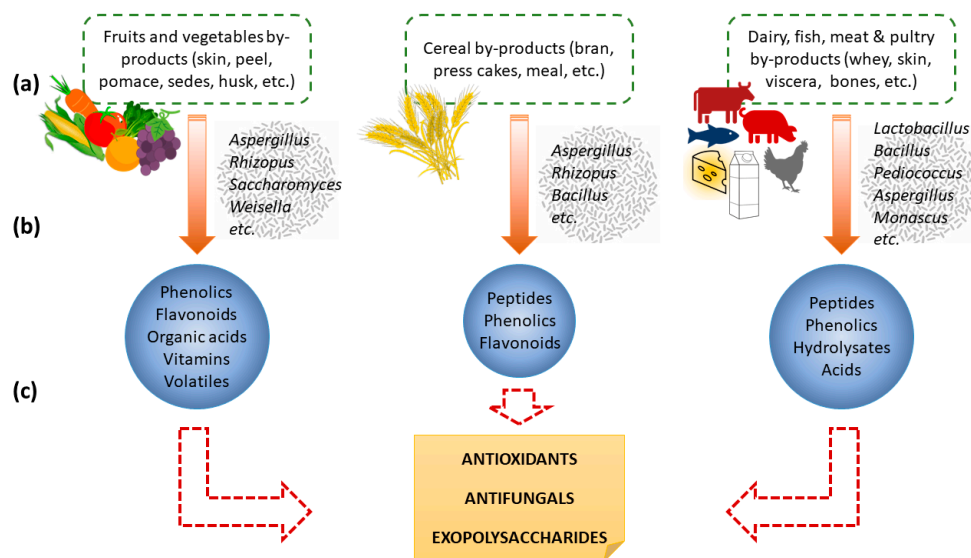


Figure 2. Flow-chart for antioxidants, antifungals, and exopolysaccharides from food by-products sources using fermentation: (a) categories of food by-products; (b) major microbes involved in fermentation; (c) fermentative microbial metabolites acting as antifungals or antioxidants.

Another food by-product with great nutritional value is whey, which is estimated to contain around 55% of the nutrients originally present in milk and can represent 90% of the weight of the milk used to make cheese. Through fermentation, bioactive compounds of interest with antioxidant capacity can be obtained [60] (Figure 2). The compounds obtained, as well as their antioxidant activity, vary depending on the substrate and the microorganism used for fermentation [61]. Among the compounds obtained, we can highlight lactobionic acid, which has antioxidant capacity, or exopolysaccharides, some of which also have antioxidant properties [62,63]. Production of exopolysaccharides by LAB, especially *Leuconostoc pseudomesenteroides*, *Leuconostoc mesenteroides*, or *Weissella cibaria*, can reach several tens of g/L [64].

Bioactive peptides with antioxidant activity derived from whey proteins can also be obtained. An example is the study carried out by Alvarado Perez et al. [26], in which whey proteins were fermented with *Bacillus subtilis*, obtaining peptides less than 3 kDa which had significant antioxidant capacity. Rochín-Medina et al. [27] used the whey resulting from the manufacture of cheese as a substrate for the growth of the bacterium *Bacillus clausii*. They reported the generation of peptides with antioxidant activity capable of inhibiting the ABTS and DPPH radicals by 95% and 80%, respectively. Finally, Gammoh et al. [28] reported an increase in antioxidant activity after fermenting camel milk whey with *Lactobacillus delbrueckii* subsp. *lactis*.

Finally, by-products from animal origin, coming from the livestock and fishery industries, are also good substrates. Due to the high protein content of these by-products, the use of fermentation allows the release of bioactive peptides.

Regarding meat by-products, Yu et al. [29] fermented porcine liver proteins with *Monascus purpureus*. They reported a high antioxidant capacity of the obtained hydrolysate, even more than those obtained with enzymes. However, there are not many more studies

related to obtaining bioactive peptides with antioxidant activity from by-products of the meat industry, so future research in this regard would be interesting [63].

Another by-product of animal origin is the eggshell. It represents 11% of the total weight of the egg, and contains essential nutrients for microorganisms, such as Fe, Mg, Zn, and Ca^{2+} [65,66]. Jai and Anal [30] fermented chicken eggshell membrane with *Lactiplantibacillus plantarum*, obtaining a hydrolyzate with significant antioxidant power (70.5% inhibition of the DPPH radical).

Finally, the fishing industry and aquaculture also generate a large quantity of by-products, representing a great environmental and economic problem. Therefore, revaluing these by-products would help to make the fish industry more ecological, sustainable, and efficient. Fish waste usually includes the head, skin, viscera, bones, and scales, and they represent around 60% of the total weight of the product [67]. On the other hand, shellfish by-products are mainly the exoskeleton, shells, and heads, and represent 75% of the product weight.

Regarding fish by-products, Marti-Quijal et al. [31] reported high antioxidant activity after fermentation of fish by-products broth by *L. plantarum* isolated from sea bass colon (6.502 mM Trolox equivalents (TE)) and stomach (4.797 mM TE). The main antioxidant compounds obtained from the fermentation process of fish by-products are bioactive peptides with antioxidant capacity. In this sense, Fang et al. [32] fermented discarded turbot skin with *A. oryzae* to obtain bioactive antioxidant peptides. Ruthu et al. [33] also obtained protein hydrolysates with high antioxidant capacity by fermenting carp heads with *P. acidilactici* and *Enterococcus faecium*. Finally, Choksawangkarn et al. [34] found antioxidant peptides in fermented fish sauce by-product.

On the other hand, concerning shellfish by-products, we can highlight the production of antioxidant chitooligosaccharides when shrimp waste (cephalothoraxes and carapaces) was fermented. The chitooligosaccharides obtained had an antioxidant activity of 55.89 $\mu\text{g TE/mg}$ measured by DPPH assay [35]. Sachindra and Bhaskar [36] also obtained compounds with antioxidant activity by fermenting shrimp waste with *P. acidolactici*. The extracts obtained showed strong radical scavenging of ABTS and DPPH radicals. At a concentration of 0.5 mg/mL, ABTS radical scavenging was 95%, while at a concentration of 1 mg/mL DPPH radical scavenging was 40%.

3.2. Antifungals

Antifungals are another group of useful compounds for the preservation of food, since they prevent its contamination by fungi and therefore extend its shelf-life. Fungal contamination produces changes in food. These changes can be visual alterations, the smell or taste of the food can be altered, or toxins that are harmful to the health of the consumer can be produced. The use of antifungal compounds is necessary to prevent the spoilage of food and the economic losses that this entails. Currently, some fungicides of chemical origin are used, which can lead to both environmental and health problems [68]. Therefore, it is necessary to search for antifungal compounds of natural origin that avoid these problems and are more sustainable.

Currently, the main antifungal compounds of natural origin are essential oils and the use of microorganisms as preservatives, either through fermentation or through the use of their metabolites [68]. In this context, the fermentation of food by-products to obtain antifungal compounds creates a significant opportunity to reduce environmental impact and revalue these wastes. The nature of antifungal compounds is diverse: organic and fatty acids, peptides, volatiles, and even enzymes.

Christ-Ribeiro et al. [37] reported a positive correlation between antifungal properties and phenolic compounds. After fermenting rice bran with *R. oryzae*, these authors found a 39.8% inhibition of the fungal growth of *Penicillium verrucosum*, related to the polyphenol content of the fermented sample. This is consistent with that described by Denardi-Souza et al. [38], who also fermented rice bran with *R. oryzae*, obtaining an extract rich in phenolic compounds. This extract was tested against fungi of the genera *Aspergillus*, *Penicillium*,

and *Fusarium*, obtaining values for the minimum inhibitory concentration (MIC) from 390 to 3100 µg/mL, and for the minimum fungicidal concentration (MFC) from 780 to 6300 µg/mL. The authors also reported that the most sensitive fungi to the phenolic extracts were *A. niger*, *Penicillium roqueforti*, *Penicillium expansum*, *Fusarium graminearum*, *Fusarium culmorum*, and *Fusarium poae*. These extracts were tested on bread, resulting in a three-day increase in the half-life of the bread. Cantatore et al. [39] fermented apple by-products with a binary mixture of *W. cibaria* and *S. cerevisiae* for 48 h. It was observed that by including the fermented extract in the breadmaking, mold contamination was delayed.

On the other hand, antifungal compounds have also been obtained after the fermentation of by-products of the dairy industry. In this sense, we can highlight the study carried out by Izzo et al. [40], in which *L. plantarum* fermented whey was used for the production of pita bread, obtaining a complete reduction in contamination by fungi when the water was completely replaced by fermented whey during the process of elaboration. In another study, Luz et al. [41] used fermented whey to prevent the growth of *P. expansum* in sliced bread. After the application of the treatment, an inactivation of 0.5–0.6 log CFU/g was achieved.

Compounds with antifungal activity have also been obtained from animal by-products. In this sense, Marti-Quijal et al. [42] fermented sea bass by-products with *Lactobacillus plantarum*, obtaining extracts with antifungal activity against fungi of the *Aspergillus*, *Penicillium*, and *Fusarium* genera. The values obtained from MIC and MFC ranged from 1 to 32 g/L and from 8 to 32 g/L, respectively. The main inhibited fungi were *Aspergillus parasiticus*, *P. expansum* and *Fusarium verticillioides*. Ruthu et al. [33] fermented Indian major carp (Rohu and Catla) heads with *E. faecium* and *P. acidilactici*. When applying the hydrolysates obtained as antifungal agents, they obtained a MIC of 60 mg/mL against *Aspergillus ochraceus* and 96 mg/mL against *Penicillium chrysogenum*.

Lastly, antifungal compounds have also been obtained by fermenting shellfish by-products. Chang et al. [43] fermented shrimp and crab shell powder with the bacteria *Bacillus cereus*. The extract obtained showed antifungal activity against *Fusarium oxysporum*, *Fusarium solani*, and *Pythium ultimum* by inhibiting spore germination and germ tube elongation.

4. Conclusions

As was observed, fermentation is a useful tool for obtaining antioxidant and antifungal compounds. In addition, by-products from the food industry can be used for this process, making the process more sustainable, giving an added value to these by-products, and reducing their environmental impact. Regarding the fermentation process, it was observed that SSF is the best due to its high yield and low cost. However, more research focused on the scaling process is still necessary to take advantage of all the knowledge acquired in the laboratory and to put it into practice at an industrial level.

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