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Plant-derived food waste management, valorization, and recycling through sourdough fermentation

Erica Pontonio[a,*], Alessandro Stringari[b], Raffaella Di Cagno[b], Pasquale Filannino[a], Carlo Giuseppe Rizzello[c], Andrea Polo[b], Olga Nikoloudaki[b], Marco Gobbetti[b]

[a] Department of Soil, Plant, and Food Sciences, University of Bari Aldo Moro, Bari, Italy
[b] Faculty of Science and Technology, Free University of Bolzano, Bolzano, Italy
[c] Department of Environmental Biology, "Sapienza" University of Rome, Rome, Italy

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ABSTRACT

Background: The food industry generates a vast amount of food waste. Nevertheless, several types of food waste, i.e. those deriving from fruits, vegetables, grains, and other plant-based food production and processing chains, still contain valuable nutritional and bioactive compounds thus having the potential to be converted into value-added products. Several approaches have been investigated as pre-treatment of food waste to improve the nutritional, functional, and technological properties before to re-inclusion in food production. Sourdough fermentation, either spontaneous or through selected microbial strains, appears to be a suitable and sustainable tool for upcycling plant-derived food waste.

Scope and approach: This review reveals the latest insights into the potential of sourdough fermentation to recycle milling by-products, brewers' spent grain, wasted bread, and miscellaneous plant wastes.

Key findings and conclusions: Sourdough biotechnology is suitable for improving the sustainability of several food chains. Nevertheless, due to the significant effect of the presence, growth, and metabolic activity of specific microorganisms on the quality of the final products, an accurate set-up and optimization of tailored fermentation processes is highly suggested.

1. Introduction

Food waste is any edible or inedible loss from its supply chain (O'Connor et al., 2021). In the European Union, over 58 million tons of food waste (131 kg/inhabitant) are generated annually (Food waste and food waste prevention – estimates, 2023). The most abundant part comes from fruits and vegetables, including cereals as the main ingredients for worldwide staple foods, which generate by-products during pre- and post-harvesting, preparation, and processing (FAO, 2019). The overall estimation is that one-third of worldwide food is wasted at various stages along the food supply chain (FAO, 2019). FAO's Food Loss Index estimates that globally, around 14 percent of all food produced is lost from the post-harvest stage up to, but excluding, the retail stage (FAO, 2019). According to the UNEP Food Waste Index 2021, around 931 million tons of food waste were generated in 2019–61% of which came from households, 26% from food service, and 13% from retail – suggesting that 17% of global food production may be wasted at these stages of the food supply chain. Similarly, in the EU, households generate more than half of the total food waste (54%) with 70% of food waste arising at household, food service and retail (Food waste and food waste prevention – estimates, 2023).

Stockpiling of food wastes poses social, environmental, and economic issues. Global food system causes approximately one-fourth of all greenhouse gas emissions (FAO, 2019). Food wastes require large-scale storage, transportation, and costly disposal applications (FAO, 2019). They have high oxidation potential and water content, and when generated from rendering plants and accidental failure of the cooling system occur, they also suffer from contamination by spoiling and/or pathogen agents (ICMSF, 2000). Given this impact, the United Nations set the Sustainable Development Goals to reduce food waste by 50% per capita by 2030. FAO believes that food waste recycling is the pillar of achieving sustainable development with the concept of a circular economy (FAO, 2019).

Solutions for food waste concern education programs focused on consumers' healthy lifestyles, prevention, improvement of processing efficiency, and valorization. Valorization is the most sustainable

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* Corresponding author.
E-mail address: erica.pontonio@uniba.it (E. Pontonio).

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approach, which should convert wastes into products with added value, thus limiting their disposal in landfills and eliminating greenhouse gas emissions (Al-Obadi et al., 2022). Currently, food wastes are physically, chemically, or biologically transformed to get an array of biofertilizers and soil amendments. Composting and anaerobic digestion are the main large-scale conversion techniques to exploit the potential of food wastes into biofertilizers and soil amendments. Other emerging conversions such as dehydration, biochar production and chemical hydrolysis show promising potentialities in agriculture and soil remediation (O'Connor et al., 2021). Aiming at a "zero waste economy", food waste can be used as raw material for new products and applications. Nevertheless, it was observed that the food waste needs further processing steps before being used. Overall, the use of microorganisms that guide the production of functional ingredients for novel food formulation has been suggested to be helpful for the development of low-cost bioprocesses of food wasted and by-products leading to a transition toward a bio-economy model (Sabater et al., 2020). Lactic acid bacteria isolated from sourdough can be employed as a biotechnological starter to increase the safety of food industry by-products, to provide added value, to design the synthesis of functional molecules in fermentable substrates, and to moderate the technologies for safer alternative stock (e.g., food waste and by-products) incorporation to the main food (e.g., bread) formulas. Sourdough is a mixture of flour and water, spontaneously fermented by lactic acid bacteria and yeasts, and having acidification and leavening capacities (Arora et al., 2021). Sourdough is one of the oldest examples of natural starters, mostly used for making leavened baked goods as an alternative to baker's yeast and chemical leavening. Almost thirty years of literature accumulated on sourdough show the undoubtedly technological, sensory, and nutritional advantages compared to the other leavening agents. A recent systematic review (Arora et al., 2021) highlighted the versatility of sourdoughs to ferment an extraordinary variety of cereal, pseudo-cereal, and legume flours, as well as miscellaneous agri-food by-products.

Here, we review the potential of sourdough fermentation to recycle milling by-products, brewers' spent grain, wasted bread, and miscellaneous plant wastes. Sourdough fermentation should represent a natural, low-cost, sustainable, and flexible approach to create added value within the food chain system (Fig. 1).

1.1. *Recycling of milling by-products*

Milling is the principal conversion procedure in the cereal industry. Dry milling separates by-products such as outer fibrous materials and germs from the grain endosperm. Pearling gradually removes seed coat (testa and pericarp), aleurone and sub-aleurone layers, and germ to get polished grains. Wet milling delivers starch and gluten, leaving steep solids, germ, and bran as by-products. It is estimated that *circa* 13% of all food waste comes from these milling procedures, with 30% of the cereal weight basis lost (FAO, 2019). While milling is inevitable for processing baked goods, most, if not all, milling by-products have high biological and nutritional value to be recycled (Cacace et al., 2022). Chemical and/or physical extraction, and purification procedures are options to separate valuable compounds, but they are quite expensive and contribute *per se* to environmental pollution. On the other hand, the direct reuse of untreated milling by-products as food ingredients causes poor technological and unpleasant sensory attributes. Sourdough fermentation, either spontaneous or driven by an *ad hoc* microbiota (Arora et al., 2021), conjugates the potential to exploit the biological

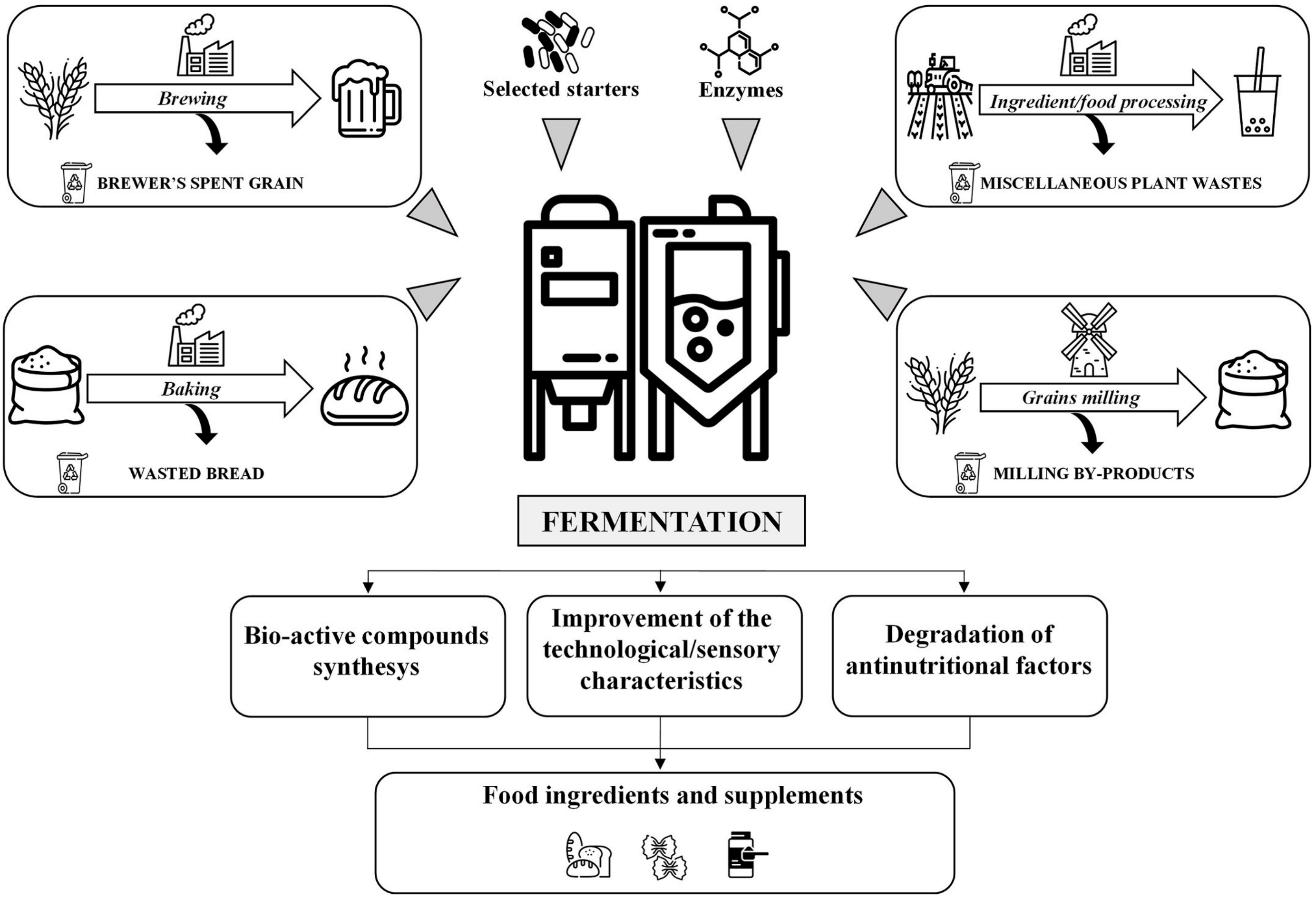

Fig. 1. Schematic approach of food waste fermentation.

Table 1
Non-exhaustive list of the main advantages related to the application of spontaneous or selected sourdough fermentation to cereal milling by-products and their related products.

Cereal source	Fermentation type/species/strain	Effects	References
Bran			
Wheat	*Levilactobacillus brevis* E95612 and *Kazachstania exigua* C81116 with enzymes	Increase of peptides and free amino acids concentration; increase of protein digestibility, soluble fiber concentration. Decrease of pungent flavor and bitter taste of fortified bread.	Coda et al. (2014)
	Lacticaseibacillus rhamnosus (R0011, ATCC 9595, and RW-9595M) and *Saccharomyces cerevisiae*	Exopolysaccharides synthesis; increase of total phenolic content, bioaccessibiity and antioxidant activity.	Bertsch et al. (2020)
	Lacticaseibacillus rhamnosus 1473	Decrease of phytic acid; increase of soluble arabinoxylans; improvement of aroma profile.	Spaggiari, Ricci, et al. (2020)
	Enterococcus faecalis M2	Increase of soluble dietary fiber, alkylresorcinol, flavonoid and total phenol contents, and antioxidant activity	Mao et al. (2020)
	Spontaneous fermentation	Increase of soluble fiber water-extractable arabinoxylans and free ferulic; total degradation of phytic acid.	Manini et al. (2014)
	Commercial baker's yeast, *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus*	Increase of water extractable arabinoxylans and soluble dietary fiber. Reduction of phytic acid content. Improvement of hydration properties and flavor.	Zhao et al. (2017)
	Levilactobacillus brevis E−95612 and *Candida humilis* E−96250 with enzymes	Increase of protein solubilization and *in-vitro* digestibility. Increase of phytase activity and total phenols content.	Arte et al. (2015)
	Kazachstania exigua VTT C-81116 and *Levilactobacillus brevis* VTT E−95612	Increase of free amino acids and phenolic compounds concentration.	Savolainen et al. (2014)
	Spontaneous fermentation	Increase of folates and phenols bioavailability; pentosan solubilization.	Katina et al. (2012)
	Lactobacillus helveticus FAM22155	Reduction of aflatoxin B1	Zhang et al. (2021)
	Companilactobacillus paralimentarius (PB 3, PB 4), *Lactobacillus helveticus* (PB 7), *Levilactobacillus brevis* (PB 12A)	Increase of radical scavenging activity of wheat-rye bread	Mikušová et al. (2013)
	Liquorilactobacillus uvarum, Lacticaseibacillus casei and *Lacticaseibacillus paracasei*	Lowering content of mycotoxin (below the threshold for human consumption) and biogenic amine.	Bartkiene, Zokaityte, et al., 2021; Zokaityte et al., 2021
	Pediococcus acidilactici LUHS29 (DSM 20284)	Reduction in DON content in the sourdough by 44–69% and a removal of 15-acetyldeoxynivalenol (15-AcDON), alternariol (AOH), deoxynivalenol-3-glucoside (D3G), toxins H-2 and HT-2.	Zadeike et al. (2021)
	Lactobacillus helveticus	Decrease of aflatoxin B1 concentration.	Zhang et al. (2021)
Wheat, barley and emmer	*Lactobacillus plantarum* T6B10 and *Weissella confusa* BAN8 with commercial xylanase	Increase of peptides and total free amino acids; Increase of total phenols and antioxidant activity. Decrease of phytic acid. Improvement of the nutritional value of bread.	Pontonio, Dingeo, et al. (2020)
Oat	*Streptococcus thermophilus*, *Lacticaseibacillus rhamnosus, Saccharomyces cerevisiae* and *Candida milleri*	Folic acid fortification.	Korhola et al. (2014)
	Kazachstnia humilis	Increase of fiber solubility.	Degutyte-Fomins et al. (2002)
Rice	*Lacticaseibacillus rhamnosus* and *S. cerevisiae* with enzymes	Reduction of the cytotoxicity and inhibition of melanogenesis in B16F1 melanoma.	Chung et al. (2009)
	Lactobacillus acidophilus GIM1.731 and *Lactiplantibacillus plantarum* subsp. *plantarum* GIM 1.648 with enzymes	Increase of total phenolic content and antioxidant activity.	Liu, Cao, et al. (2017)
	Weissella koreensis DB1	Increase of ornithine and citrulline content. Increases in total amino acid content and antioxidant activity of bread.	Yeong et al. (2020)
	Lactiplantibacillus plantarum EM	High cholesterol removal and strong antimicrobial activity.	Moon and Chang (2021)
	Levilactobacillus brevis	Decrease of mycotoxin concentration. Anti-aflatoxigenic effect on aflatoxin B1.	Sadeghi et al. (2019)
Rye	Baker's yeast with enzymes	Increase of phenolic compounds in bread.	Koistinen et al. (2016)
	Limosilactobacillus reuteri TMW 1.106	Increase of amount and speed production of exopolysaccharides.	Kaditzky and Vogel (2008)
	Weissella confusa	Exopolysaccarides synthesis.	Kajala et al. (2016)
Germ			
Wheat	Spontaneous fermentation	Improve technological and sensory properties of doughs and breads.	Marti et al. (2014)
	Lactiplantibacillus plantarum subsp. *plantarum* DSM 32248 and *Furfurilactobacillus rossiae* DSM 32249	Slow down lipid oxidation by decreasing the activity of lipase and lipoxygenase. Increase of *in-vitro* protein digestibility, the concentration of total phenols and amino acids, phytase and antioxidant activities (sourdough and bread). Improve the texture and sensory properties of bread.	Rizzello et al., 2010a,b
		Ex-vivo anti-proliferative effects colon and ovarian carcinoma cell lines.	Rizzello et al. (2013)
	Lactiplantibacillus plantarum and *Lactobacillus acidophilus*	Decrease of the activity of lipase and lipoxygenase and increase in antioxidant activity.	Khosroshahi et al. (2022)
	Saccharomyces cerevisiae 5022 and *Lactiplantibacillus plantarum* 299v	Increase of peptide and GABA concentrations and scavenging activity.	Bayat et al. (2022)
	Lactiplantibacillus plantarum dy-1	Antiproliferative effects and the induction of apoptosis of human HT-29 colon cancer cells.	Zhang et al. (2015)
	Latilactobacillus sakei TMW1.22 and *Fructilactobacillus sanfranciscensis DSM20451T*	Degradation of wheat germ agglutinin.	Tovar & Gänzle, 2021
	Saccharomyces cerevisiae	Cancer-fighting characteristics: inhibition metastatic tumor dissemination and proliferation.	Boros et al., 2005; Saiko et al., 2009; Comín-Anduix et al., 2002
	Spontaneous fermentation	Anti-aging activity.	Zhao et al. (2021)
Rice	*Latilactobacillus sakei*	Enrich in GABA showing a positive effect on the sleep disturbance of mice.	Mabunga et al. (2015)
Bran and Germ			

(*continued on next page*)

Table 1 (*continued*)

Cereal source	Fermentation type/species/strain	Effects	References
Wheat	*Lactiplantibacillus plantarum* subsp. *plantarum* DSM 32248 and *Furfurilactobacillus rossiae* DSM 32249	Increase of fiber content, protein digestibility and nutritional indexes of fortified bread. Decrease of glycemic index.	Pontonio et al. (2017)
Maize	*Lactiplantibacillus plantarum* subsp. *plantarum* T6B10 and *Weissella confusa* BAN8	Increase of the concentrations of free amino acids and peptides, the antioxidant activity. Degradation of phytate. Improve content of dietary fibers and proteins, the protein digestibility, and the starch hydrolysis index in bread	Pontonio et al. (2019)
	Lactobacillus sakei MI401 and *Pediococcus acidilactici PA-2*	Improve technological properties of albumins and globulins and increase the digestibility and free radical scavenging activity of prolamins. Increase of free amino acids concentration and antioxidant activity.	Zadeike et al. (2022)
Rye/wheat	*Kazachstania unispora* and *Kazachstania servazii* and *Latilactobacillus curvatus*	Improve the complexity of the volatile molecules. Increase in short chain fatty acids, antioxidant activity, total phenol content, bioactive peptides. Decrease in phytic acid content and an increase in prebiotic activity.	Siroli et al. (2022)

value and eliminate the negative attributes of recycled bran and germ in food preparations (Table 1).

1.1.1. *Cereal bran*

With variations depending on the cereal species, bran is a concentrate of dietary fibers (mainly arabinoxylans), phenolic compounds, proteins, and amino acids with high biological value, as well as minerals and vitamins (e.g., folates) (Chen et al., 2023). Unfortunately, these nutritive features has low bio-accessibility for humans, limiting its recycling potential. The bound forms of dietary fibers and phenolic compounds weaken their bioavailability, digestibility and/or intestinal absorption (Holland et al., 2020). The formation of insoluble complexes with phytate (Saurabh et al., 2021) and constraints imposed by the cell wall matrix limit the digestion and bioavailability of proteins (Alzuwaid et al., 2020) and minerals. Furthermore, the direct recycling of bran in food preparations might be responsible for poor hygiene (mycotoxins and other contaminants), and unpleasant rheology and sensory attributes (Ma et al., 2021). Notwithstanding the potential of other microorganisms (Chen et al., 2021; Li et al., 2022; Wu et al., 2022), sourdough fermentation prior to recycling into food preparations, alone or in combination with enzymes, has the potential to overcome most of these nutritional, technological, and sensory constraints (Chen et al., 2021; Li et al., 2022; Wang, Li, et al., 2022a,b).

The *ad hoc* fermentation with two typical sourdough species, *Levilactobacillus brevis*, and *Kazachstania exigua*, in combination with xylanase, endoglucanase, and β-glucanase enzymes, was successful in breaking the wheat bran cell wall, thus increasing the content of soluble arabinoxylans (Coda et al., 2014). Combining the spontaneous sourdough fermentation and the activity of endogenous or microbial enzymes, the same effect was found for rye arabinoxylans. After fermentation with sourdough, the bran was recycled into the bread formula, and volume and texture improved (Courtin & Delcour, 2002). Usually, the extractability of arabinoxylans increased during spontaneous sourdough backslopping and reached the highest value when the microbiota of lactic acid bacteria and yeasts became mature and stable (Manini et al., 2014). Soluble dietary fibers almost quadrupled, free amino acids increased as the hydrolysis of wheat bran proteins proceeded, and the content of phytate decreased (Mao et al., 2020). Almost the same efficiency was observed under solid-state fermentation of wheat bran steered by *Lactobacillus delbrueckii* subsp. *bulgaricus* and *Streptococcus thermophilus* together with baker's yeast (Zhao et al., 2017). Mixing wheat bran and whey permeate, another agri-food by-product, the fermentation with *Lacticaseibacillus rhamnosus* and *Saccharomyces cerevisiae* allowed the solubilization of fibers and increased the level of free phenolic compounds (Bertsch et al., 2020).

The sourdough fermentation does not affect the total content of phenolic compounds but elevates the ratio between free and bounded forms. The sourdough fermentation of both peeled and native rye bran increased the content of free ferulic acid and other hydroxycinnamic acids liberated from the polymeric structure (Katina et al., 2007). It was estimated that the spontaneous sourdough fermentation increased the content of bioavailable ferulic acid by 82% (Manini et al., 2014). Lactic acid bacteria, including those populating the sourdough ecosystem, express ferulic acid esterases (Gaur & Gänzle, 2023). Additionally, *Pediococcus acidilactici* was found to significantly increase the contents of caffeic acid and mainly gallic acid during fermentation (Zhang et al., 2023).

When combined with cell wall degrading enzymes, sourdough species such as *Lv. brevis* and *Kazachstania humilis* abundantly released free phenolic compounds (Arte et al., 2015). *Lac. rhamnosus* metabolized conjugated phenolic compounds and broke the linkage with cell wall polysaccharides (Spaggiari, Calani, et al., 2020). The wheat bran solid-state fermentation that started with *Enterococcus faecalis* promoted a remarkable free radical scavenging activity, which depended on the release of free phenolic compounds (Mao et al., 2020). The sourdough fermentation with *Lactobacillus acidophilus, Lactiplantibacillus plantarum* and hydrolyzing enzymes modified the profile of phenolic compounds in rice bran, thus increasing the levels of soluble ferulic acid (Liu, Zhang, et al., 2017). This processed rice bran was used as an ingredient for making functional foods, which, due to the enrichment of free phenolic acids and flavonoids, showed remarkable antioxidant activity.

Although the disruption of the cell wall matrix is the main factor for increasing the bio-accessibility of bran proteins (Li et al., 2023), sourdough fermentation initially solubilized wheat bran proteins because of the activation of endogenous proteases at *circa* pH 4.0 (Arora et al., 2021). Following this primary proteolysis, peptidases by sourdough lactic acid bacteria were responsible for the liberation of small-size peptides and free amino acids (Christensen et al., 2022), which were more readily absorbable at intestinal level comparing to native proteins (Khubber et al., 2022). Processing rye bran with enzymes and sourdough fermentation prior to recycling into bread making led to high *in-vitro* protein digestibility (Nordlund et al., 2013). Sourdough proteolysis also favored the release of biogenic peptides (Pontonio, Verni, et al., 2020; Verni, Verardo, & Rizzello, 2019) and degraded antinutritional factors such as trypsin inhibitors and phytic acid (Patterson et al., 2017; Pontonio, Dingeo, et al., 2020). Pre-fermented wheat bran was used to enhance the nutritional profile of bread. Compared to nonfermented bran, the *in-vitro* protein digestibility increased by 40%, and enriched breads showed pleasant sensory and textural attributes (Pontonio, Verni, et al., 2020). The sourdough fermentation with an *ad hoc* microbiota was also efficient for the treatment of rice bran. *Weissella koreensis* enriched rice bran with ornithine, which is a healthcare supplement to activate the immune system and liver function (Yeong et al., 2020). Water-soluble extracts of sourdough fermented rice bran had an anti-photoaging effect on human skin fibroblasts cultures (Seo et al., 2010). The rice bran co-fermented with *Lac. rhamnosus* and *S. cerevisiae* decreased the cytotoxicity and inhibited melanogenesis in B16F1 melanoma through the downregulation of microphthalmia-associated transcription factors (Chung et al., 2009). Rice bran fermented with *Lp. plantarum* attenuated the levels of cholesterol (45–68%) and exerted inhibitory activities towards foodborne pathogenic bacteria and spoiling fungi (Moon & Chang, 2021).

Cereal endogenous or microbial phytases are responsible for the hydrolysis of phytic acid in cereal bran. Wheat endogenous phytases are almost inactive at neutral pH, but sourdough acidification promotes their activation with the consequent decrease of the phytate content and the increase of protein and mineral bioavailability (Ameur et al., 2022). Phytases by several sourdough lactic acid bacteria and yeasts were characterized. *Lac. rhamnosus* had the capability to degrade phytate in wheat bran (Spaggiari, Ricci, et al., 2020), and *Lp. plantarum* and *Weissella confusa* decreased its level by 25%–60% when used as starters for wheat bran fermentation (Moon & Chang, 2021; Pontonio, Dingeo, et al., 2020). Also, the fermentation of rice bran with a functional strain of *Lp. plantarum* EM decreased the content of phytic acid by 50% (Moon & Chang, 2021). The spontaneous sourdough fermentation of bran increased the level of folates by over 100% and the highest detectable levels coincided with the highest cell density of autochthonous lactic acid bacteria and yeasts. Overall, the increase of folate was mainly due to synthesis by yeasts, while the liberation by lactic acid bacteria was strain-dependent. The *ad hoc* substitution of folate-consuming lactic acid bacteria with folate-synthesizing strains significantly increased the vitamin content in sourdough breads enriched with pre-fermented and recycled bran (Mendez-Vilas, 2007). The capability of yeasts to synthesize folate from oat bran was species dependent, with *S. cerevisiae*, *Pseudozyma* sp., *Rhodotorula glutinis* and *Kluyveromyces marxianus* leading to the highest concentrations (Korhola et al., 2014). Intending to increase the folate concentration in bran processing, sourdough fermentation with yeasts was always the most efficient option. Oat bran fermented with *St. thermophilus* or *Lac. rhamnosus*, and *S. cerevisiae* and *K. humilis* led to a folate concentration of 120 ng/g. The intake of 100 g of fermented oat bran supplied 15% of the recommended daily dose of folate (Korhola et al., 2014). The enrichment of rye and wheat brans with exopolysaccharides (EPS) is another option with multiple outcomes. Sourdoughs made with *ad hoc* lactic acid bacteria, for instance *Limosilactobacillus reuteri* (Kaditzky & Vogel, 2008) or *W. confusa*, was the most efficient choice. Usually, the *in-situ* production of EPS in rye bran reached the concentration of 2–3% on dry matter (Kajala et al., 2016) and represented the way to improve the structure-forming capability of bran, making it a recyclable ingredient with prebiotic and *in-vitro* antitumor and immunomodulating activities (Korcz & Varga, 2021).

1.1.2. *Wheat germ*

The annual world deposit of wheat germ is estimated to be *circa* 25,000,000 tons, which undoubtedly deserves valorization as it corresponds to the most nutritious part of the grain (Rizzello, Nionelli, Coda, De Angelis, & Gobbetti, 2010). The fast development of rancidity because of the presence of unsaturated fats, lipoxygenases and lipases severely limits the use of germ in baked goods processing (Li et al., 2016). Nowadays, sourdough fermentation is the most efficient solution to stabilize and improve the nutritional attributes of germ (Khosroshahi et al., 2022).

Lowering the value of pH by sourdough fermentation inactivates lipase and lipoxygenase enzymes (Marti et al., 2014; Rizzello, Nionelli, Coda, Di Cagno, & Gobbetti, 2010). Compared to nonfermented wheat germ, the sourdough fermentation with *Lp. plantarum* and *Furfurilactobacillus rossiae* almost inhibited the synthesis of volatile compounds from lipid oxidation during 40 days of storage (Rizzello, Nionelli, Coda, Di Cagno, & Gobbetti, 2010). Other sourdough starters were proven to behave similarly (Khosroshahi et al., 2022). In summary, the sourdough fermentation abolished the technological obstacles to incorporating wheat germ into the bread formula. Improved *in-vitro* protein digestibility, decreased phytase activity, and extended shelf life were the main nutritional benefits derived from the germ supplementation into wheat bread formula (Rizzello, Nionelli, Coda, Di Cagno, & Gobbetti, 2010). The sourdough fermentation also decreased the content of anti-nutritional factors such as phytic acid and raffinose and raised the content of free amino acids to 50%, mainly lysine (Lys) and γ-amino butyric acid (GABA), a non-protein amino acid with functional features (Bayat et al., 2022; Rizzello, Nionelli, Coda, De Angelis, & Gobbetti, 2010; Rizzello, Nionelli, Coda, Di Cagno, & Gobbetti, 2010). One of the most promising achievements for sourdough fermented wheat germ was represented by the cytotoxic activity towards cancer cell lines. Wheat germ fermented with *Lp. plantarum* dy-1 inhibited the proliferation of HT-29 cells via apoptosis suggesting its use as a potential anticarcinogenic (Zhang et al., 2015). Avemar®, a commercial product made of wheat germ fermented with *S. cerevisiae* (Boros et al., 2005; Saiko et al., 2009), showed *in-vitro* anticancer and autoimmune properties on various human cancer cell lines (Comín-Anduix et al., 2002). Two-methoxy benzoquinone and 2,6-dimethoxybenzoquinone are naturally present in wheat germ but in a glycosylated and non-active form. After activation through β-glucosidase activity of *Lp. plantarum* and *Fu. rossiae*, they exerted *ex-vivo* anti-proliferative effects on colon and ovarian carcinoma cell lines (Rizzello et al., 2013). Based on the metabolism of thiols, sourdough fermentation decreased the content of agglutinins in wheat germ, which is one of the triggering factors for non-celiac wheat sensitivity (Tovar & Gänzle, 2021). A sourdough made combining wheat germ and bran was recycled and used in the bread formula (Pontonio et al., 2017). The bread was enriched in dietary fibers, free amino acids, and phenolic compounds, and as shown by *in-vitro* and *in-vivo* assays, it was classified as a low glycemic index food. After fermentation with *Latilactobacillus sakei*, the rice germ fermented was enriched in GABA, showing a positive effect on the sleep disturbance of mice (Mabunga et al., 2015). *Lp. plantarum* and *W. confusa* were used to ferment raw maize or heat-treated germ and bran (Pontonio et al., 2019). The concentrations of free amino acids and peptides, the antioxidant activity, and the phytate degradation increased during sourdough fermentation. Incorporation of these fermented maize by-products in bread positively affected the content of dietary fibers and proteins, the protein digestibility, and the starch hydrolysis index (Pontonio et al., 2019).

1.1.3. *Mycotoxins degradation*

Compared to whole grains, by-products from cereal milling suffer from higher levels of mycotoxin contamination (Hoffmans et al., 2022). Although using implemented good practices, the bio-accumulation of mycotoxins in milling by-products is almost inevitable, especially under suboptimal storage conditions (Khodaei et al., 2021). Decontamination before recycling is a priority. Available options include physical, chemical, and biological methods, with the latter attracting considerable interest (Piotrowska, 2021). Although the effect of sourdough fermentation is somewhat controversial, the degradation of aflatoxins, fumonisins, ochratoxins, deoxynivalenol, and zearalenone was demonstrated with various species of lactic acid bacteria (Bartkiene, Zokaityte, et al., 2021; Muhialdin et al., 2020; Sadeghi et al., 2019; Zokaityte et al., 2021). The mechanism for mycotoxin decontamination occurs through the adhesion of significant amounts of mycotoxins to microbial cells and/or the degradation of mycotoxins into non-toxic metabolites (Muhialdin et al., 2020; Piotrowska, 2021).

Extrusion combined with the fermentation by *Lacticaseibacillus casei* and *Lacticaseibacillus paracasei*, or *Liquorilactobacillus uvarum* reduced the levels of several mycotoxins in wheat bran to levels below the threshold for human consumption (Bartkiene, Zokaityte, et al., 2021; Zokaityte et al., 2021). In addition, the sourdough fermentation with *Lp. plantarum* and *P. acidilactici* alone decreased the mycotoxin contamination of whole wheat flour and rye by 10%–40% (Pontonio et al., 2021). *Lv. brevis* was capable of decreasing the contamination by aflatoxins B1, B2, G1, and G2 (Sadeghi et al., 2019), and *P. acidilactici* decontaminated deoxynivalenol (44–69%), and removed 15-acetyldeoxynivalenol, alternariol, deoxynivalenol-3-glucoside, and toxins H-2 and HT-2 (Zadeike et al., 2021). Usually, the highest level of decontamination was observed during long-time (48 h) sourdough fermentation with mixed sourdough starters (Zadeike et al., 2021). Under solid-state fermentation of wheat bran, *Lactobacillus helveticus* synthesized

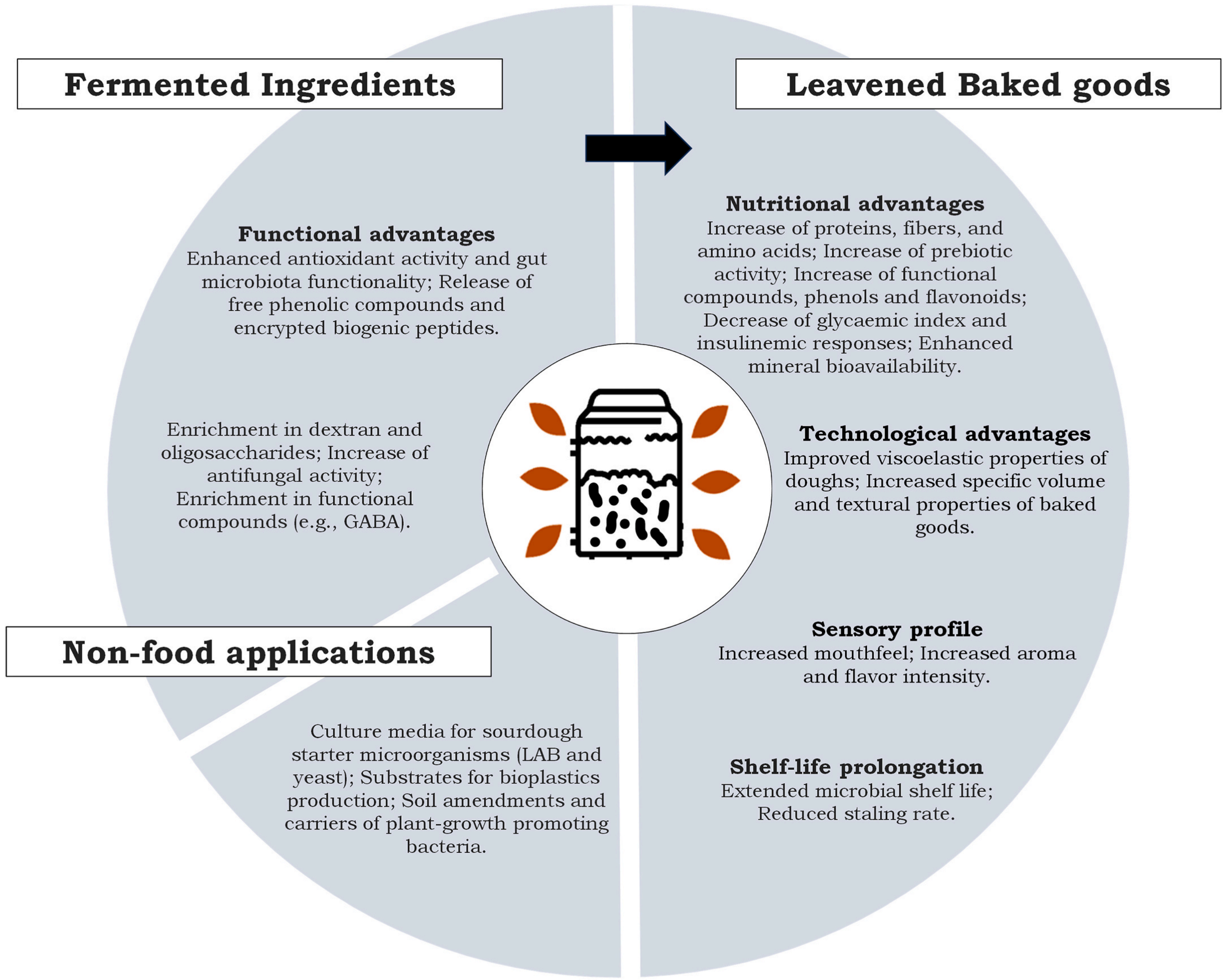

Fig. 2. Main advantages of fermentation on brewers' spent grains and wasted bread.

enzymes capable of degrading aflatoxin B1 into four low-toxin derivatives without a lactone ring structure (Zhang et al., 2021).

1.2. Brewers' spent grain

Malting for making beer leaves brewers' spent grains (BSG), whose elevated organic load is critical for environmental pollution (Teixeira et al., 2020). The recycling of BSG has gained attention due to biogenic components such as alkaloids, plant growth factors, food-grade pigments, and phenolic compounds (Verni, Pontonio, et al., 2020). BSG is also rich in cellulose and arabinoxylans and contains proteins up to 20%, particularly rich in lysine (Verni, Pontonio, et al., 2020). The high moisture content (*circa* 80%), along with the richness in polysaccharides and proteins, make BSG highly prone to microbial contamination with a short lifespan (7–10 days) (Kavalopoulos et al., 2021). Various conservative treatments of BSG have been assessed (Lynch et al., 2016), and among these, sourdough fermentation was one of the most promising (Fig. 2).

The sourdough fermentation with lactic acid bacteria enriched BSG with dextran and oligosaccharides (Koirala et al., 2021). The supplementation with sucrose (4% w/w) and fermentation with *Leuconostoc pseudomesenteroides* and *W. confusa* yielded 11 g/kg of dextran, which improved the BSG viscosity and taste. This fermented BSG was used as an ingredient for wheat bread formula. Compared to control bread without addition, the bread enriched with BSG had a higher content of proteins and fibers, and positively influenced the gut microbiota functionality. Along with an increase of several essential amino acids, a consistent increase of GABA was also observed during the simulated digestion (Koirala et al., 2022). BSG was also used for making a beverage fermented by *Lp. plantarum*. The beverage had antioxidant potential because of the high content of phenols and flavonoids, which were released through acidification and microbial metabolism (Gupta et al., 2013). The combination of xylanase and sourdough fermentation with *Lp. plantarum* released free phenolic compounds and liberated encrypted biogenic peptides with antioxidant activity and protective effect toward oxidative stress on human keratinocytes (Verni, Pontonio, et al., 2020). Given these attributes, the bioprocessed BSG was used for making pasta. Compared to pasta containing nonfermented BSG, the enriched pasta had higher protective effects against oxidative stress caused by human colon carcinoma cells under simulated gastro-intestinal digestion (Schettino et al., 2021). Positive effects of fermented BSG were also observed when used as an ingredient in bread formula. The rheology and sensory attributes of the enriched bread improved, and the nutritional profile was optimal because of the supplementation with proteins, fibers, and essential amino acids (Waters et al., 2012). The enrichment of bread with spontaneously sourdough-fermented BSG also decreased the phytate content (Ktenioudaki et al., 2015).

BSG was also used as a solid-state substrate to cultivate and preserve (up to 10 weeks at *circa* 6 Log cfu/g) sourdough cultures. The fermented BSG was used (10% p/p) in an experimental baking trial leading to sourdough breads characterized by optimal organic acids ratio and acceptability according to a consumer-based study (Vriesekoop et al., 2021).

1.3. *Wasted bread*

On a global scale, bread is one of the major wasted foods. Industrial waste is generated because of substandard products, crust removal for sandwich production, and unsold bread at retail (Verni, Rizzello, & Coda, 2019). In most cases, the huge amount of wasted bread is still under safe conditions for human consumption. Indeed, innovative, and sustainable recycling solutions must focus on keeping wasted bread - within the food chain. Recycling wasted bread through sourdough fermentation has shown an undoubted potential.

Recycling of wasted bread to prepare a culture medium (wasted bread medium, WBM) for the cultivation of lactic acid bacteria was considered (Verni, Minisci, et al., 2020). The protocol included bread (20%) homogenization with water and hydrolysis with amylases. Its suitability as a valid alternative to common synthetic media was demonstrated for almost all sourdough lactic acid bacteria reaching the most common cell densities after cultivation. The sourdough was also proposed to ferment wasted bread and recycle it as an ingredient for bread making. Sourdough was made from wasted bread crumbs. Several lactic acid bacteria demonstrated the capability of using the bread crumb as a fermentation substrate. *Lp. plantarum* and *P. acidilactici* were capable of a long-time (48–96 h) fermentation without the genesis of off-flavors (Gélinas et al., 1999). A sourdough made with wasted bread was used as an aroma and flavor enhancer for making bread. The formula included 50% whole wheat bread crumb and fermentation with *Lp. plantarum*. The synthesis of lactic and acetic acids resembled that of the traditional sourdough fermentation, and a positive effect on glycemic index and insulinemic responses was hypothesized (Poutanen et al., 2009). Bread is mainly subjected to fungal spoilage during its shelf life. Salts of propionic and sorbic acids and ethanol are the most common chemical preservatives to extend the shelf life, although their negative consumer perception and the healthy recommendations to markedly decrease their use. A protocol to synthesize bioactive peptides from wasted bread was standardized (Nionelli et al., 2020). After hydrolysis by microbial proteases and fermentation with *Lv. brevis*, the wasted bread showed a broad inhibitory spectrum against some of the most diffuse fungal-contaminating species. Nine antifungal peptides, encrypted in wheat protein sequences, were released during sourdough fermentation and identified as the main responsible for fungal inhibition. The shelf-life of the bread was extended up to 10 days (Nionelli et al., 2020). The direct recycling of wasted bread negatively affects the specific volume and softness of the newly manufactured bread. Gelatinized starch and denatured proteins are not reassembled into a new gluten network (Immonen et al., 2020). The hydrolysis of gelatinized starch improved the viscoelastic properties of wasted bread (Immonen et al., 2021), but the most suitable option is the use of sourdough lactic acid bacteria capable of synthesizing EPS (dextran and β-glucan) *in-situ* (Immonen et al., 2020). The dextran synthesis occurring during sourdough fermentation of wasted bread compensated for the adverse effect of the recycled bread increasing the specific volume and decreasing the crumb hardness. EPS synthesized by *Weissella* species also exerted antioxidant and prebiotic activities (Kavitate et al., 2020). A blend of wasted bread and wheat bran was used as the substrate to synthesize GABA (Verni et al., 2022). *Lp plantarum* yielded the highest content of GABA (*circa* 800 mg/kg). This fermented wasted bread/bran slurry was used as an ingredient for the manufacture of GABA-enriched bread. In conclusion, tailored sourdough fermentations with selected lactic acid bacteria are key options for recycling wasted bread, gaining suitable technological features, and creating added functional value along the food chain.

When wasted bread is not edible and recycling into the food chain implies microbiological risks (e.g., presence of mycotoxins), alternative biotechnological solutions are exploited. It is known that lactic acid bacteria act as plant growth-promoting microorganisms (PGPM), indirectly favoring nutrient acquisition in the alkaline soils characterizing the Mediterranean area. Besides, lactic acid bacteria act as biocontrol agents, improving the ability of the host plant to withstand biotic and abiotic stress or producing compounds that directly stimulate plant growth (Lamont et al., 2017). A bioprocessed wasted bread, which was obtained by enzyme treatments coupled with sourdough fermentation was used as an amendment in pot trials. The aim was to evaluate the modification of the soil physicochemical properties and the plant growth-promoting activity using escarole (*Cichorium endivia* var. Cuartana) as the indicator crop (Cacace et al., 2022). Compared to non-amended soils, the supplementation with sourdough fermented wasted bread raised the content of soil organic carbon up to 37% and total nitrogen up to 40%. In addition, the lower pH and the higher organic acid content favored a higher availability of Mn, Fe, and Cu. Escaroles showed improved growth with a higher number of leaves.

Recently, a biotechnological protocol for recycling bread waste at the industrial level has been set up and patented (Ampollini et al., 2023). The approach includes the preliminary drying and fine milling of bread resulting from sandwich production (bread crust). A slurry was obtained with waste bread powder and water, and food-grade proteases were added to the semiliquid formulation to promote fermentation. Lactic acid bacteria (*Lp. plantarum*) and yeast (*S. cerevisiae*) strains were selected for sourdough fermentation in automatic fermenters. It was demonstrated that waste bread sourdough can be added up to 50% of the final weight of bread dough without negatively affecting the textural properties of the bread. Sensory properties were moreover those typical of a sourdough bread.

1.4. *Miscellaneous plant wastes*

Miscellaneous plant by-products and wastes comprise a very heterogeneous set of matrices (e.g., fruit and vegetables hulling and peeling wastes, pomaces, food surplus) sharing an unquestionable nutritional value. Nevertheless, they are characterized by sources heterogeneity, variation of their chemical composition, and microbial instability. Being rich in carbohydrates, organic acids, mineral salts, and vitamins, these compounds can be utilized as substrates for contaminant (either pathogenic or not) microorganisms. Furthermore, the high fiber and phenolic contents can negatively affect the sensory profile and technological properties of fortified foods (Kosseva, 2020). The exploitation of their potential needs to overcome these weaknesses, either through technological treatments or exploiting fermentation processes, with the latter proven to be an effective, sustainable, and mild approach.

Apples are among the most widely processed fruits, which inevitably generate large amounts of residues. Such availability together with high contents of fibers and phytochemicals make these by-products and wastes ideal ingredients to enrich the wheat bread formula. Fermentation of apple by-products with a binary culture of *Weissella cibaria* and *S. cerevisiae* was proposed for recycling in breadmaking at a rate of 5–10% (w/w of flour) (Cantatore et al., 2019). The fruit and vegetable by-products addition in baked goods causes low acceptability because of the poor sensory and rheological attributes. The dilution of gluten with fruit or vegetable by-products implies a decreased capability of the dough to retain gas, which leads to low volume and high hardness. Fortification with fruit or vegetable by-products does not exceed 10% (w/w of flour) (Gómez & Martinez, 2018). The formula enriched with 5% apple by-products fermented with sourdough improved the wheat dough stability and water absorption and did not interfere with the bread specific volume and color (Cantatore et al., 2019). The sourdough fermentation maximized the hydration properties of apple by-products

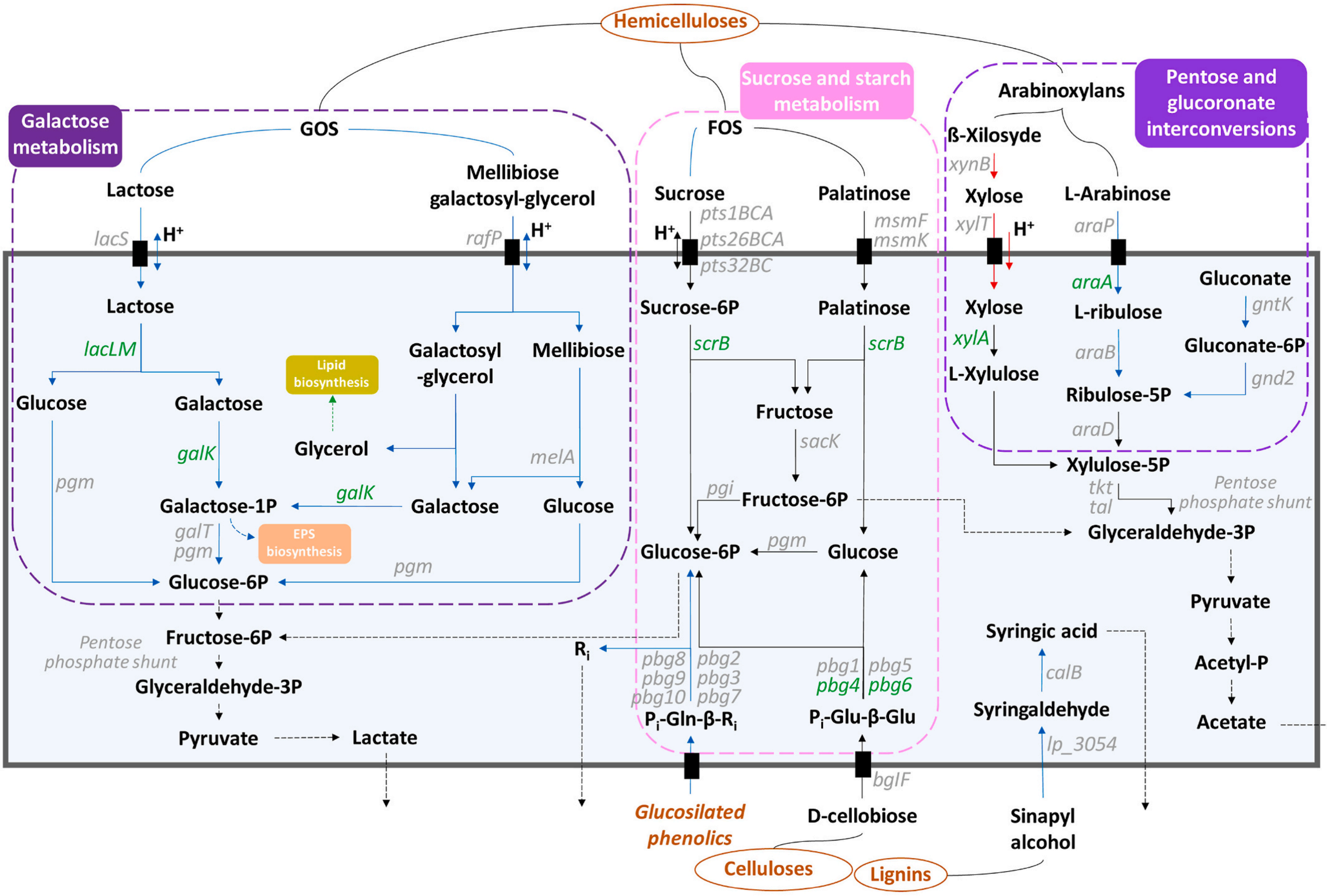

Fig. 3. Schematic reconstruction of putative pathways characterizing the fermentation (30 °C for 24 h) of a brewer spent grain -based medium by *Leuconostoc pseudomesenterides* and *Lactiplantibacillus plantarum* strains. Red colored pathways were unique to *Leuc. pseudomesenteroides*, while blue colored pathways were unique to *Lp. plantarum*. Black colored pathways were present in both species. Genes that were over-expressed compared to growth in standard reference medium (MRS broth) are shown in green (Acin-Albiac et al., 2022). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

because of the synthesis of EPS, and the partial breakdown of insoluble fibers, which resulted in an increased porosity and surface area. Enrichment with sourdough-fermented apple by-products also provided bio-accessible polyphenols (Tlais et al., 2021). In addition, apple pomace was used to fortify sourdough started with a selected culture of *Fructilactobacillus florum* DSM 22689 and baker's yeast (single and co-culture). The sourdough nutritional value was positively affected by the incorporation mainly thanks to the presence of valuable compounds like organic acids and fibers. Additionally, the abundance of glucose and fructose in apple pomace led to higher microbial viability and growth (Martău et al., 2021). Research efforts also focused on the potential of plant by-products as sources of antimicrobial compounds to extend the bread shelf life. By-products having relevant protein contents represent ideal substrates for the biosynthesis of antimicrobial peptides. The sourdough fermentation of palm kernel cake with *Lc. casei* favored the accumulation of antifungal peptides, which, once added to the bread formula, were effective in counteracting the spoilage up for to 10 days (Asri et al., 2020). Another constraint to recycle non-conventional ingredients is their eventual association with increased levels of acrylamide during baking (Bartkiene, Bartkevics, et al., 2021). Oat has a higher potential for acrylamide formation than wheat because of the higher levels of soluble carbohydrates and free asparagine. Sourdough fermentation of oat by-products prevented acrylamide accumulation in baked goods (Bartkiene, Bartkevics, et al., 2021). Solid-state fermentation and the subsequent recycling as ingredients for breadmaking demonstrated how agri-food by-products also served to deliver microbial enzymes (e.g., feruloyl esterase, xylanase) with appreciable properties (dos Santos Costa et al., 2021). Date seed flour was proposed as an innovative ingredient for sourdough breadmaking (Ameur et al., 2022). Autochthonous lactic acid bacteria and yeasts were isolated from date seeds and selected based on various technological criteria. A mixed starter, comprising *Leuconostoc mesenteroides*, *Lp. plantarum* and *S. cerevisiae*, was used to prepare type I sourdough after consecutive refreshments. An aliquot of durum wheat flour was replaced by date seed flour. The sourdough fermented bread showed an increased radical scavenging activity because of the consistent release of free phenolic compounds, while the perceived bitterness and astringency diminished due to microbial degradation of tannins. Being an economic and sustainable alternative to animal-based proteins, rapeseed proteins isolated from defatted rapeseed press cake have the potential for food applications. Rapeseed protein concentrations higher than 5% in wheat breadmaking led to detrimental effects on textural and sensory attributes. Rapeseed proteins became suitable ingredients for making sourdough bread when fermented with *W. confusa*, which synthesized dextran *in-situ*. Compared to control bread, the sourdough fermentation improved the *in-vitro* protein digestibility, enriched the free amino acid profile mainly with lysine, methionine, and isoleucine, and guaranteed suitable specific volume and low crumb hardness (Wang, Li, et al., 2022a,b).

1.4.1. Lactic acid bacteria glycosyl hydrolases

One of the main secrets beyond the sourdough fermentation as valuable biotechnology to recycle plant by-products and wastes concerns the hydrolysis of complex polymers (e.g. arabinoxylans, cellulose, and hemicellulose fraction) and the bio-accessibility of phenolic compounds. Sourdough lactic acid bacteria have the aptitude to metabolize diversified carbon sources. This aptitude relies on key metabolic pathways mediated by an extensive set of glycosyl hydrolases. These enzymes undertake the ambivalent role of releasing a wide range of phenolic compounds from glycosylated precursors and degrading the resulting sugar moiety. Glycosyl hydrolases also have the potential to remove undesired bitterness or release aroma compounds. Encoding genes for glycosyl hydrolases are widespread among lactic acid bacteria. Phospho-β-glucosidase genes show a high degree of redundancy. Phospho-β-glucosidases catalyze the degradation of phosphorylated glucosides and fibers-related disaccharides (e.g., cellobiose and gentiobiose), which are activated through the phosphoenolpyruvate (PEP)-dependent carbohydrate phosphotransferase systems (PEP-PTS) (Acin-Albiac et al., 2021). Recently, the complete framework describing the metabolism drift of *Lp. plantarum* and *Leuc. pseudomesenteroides* caused by the lignocellulosic BSG was provided by implementing molecular and phenomics approaches (Fig. 3) (Acin-Albiac et al., 2021, 2022). As confirmed by gene overexpression, *Lp. plantarum* preferred arabinose among pentosans, while *Leuc. pseudomesenteroides* mainly uses xylose. The phenotype switching towards galactose metabolism suffered the greatest fluctuation in *Lp. plantarum*. All lactic acid bacteria strains utilized sucrose more intensively and its plant-derived isomers. Sucrose-6-phosphate hydrolases activity in *Leuc. pseudomesenteroides* likely mediated the increased consumption of raffinose. The increased levels of some phenolic compounds suggested the involvement of 6-phospho-β-glucosidases in β-glucosides degradation. Expression of genes encoding β-glucoside/cellobiose-specific EII complexes and phenotyping highlighted an increased metabolism for cellobiose (Acin-Albiac et al., 2022). The glycoside hydrolase group includes fructan-β-fructosidases and β-fructofuranosidases, which undertake the hydrolysis of inulin and fructooligosaccharides, and β-D-Xylosidases and α-L-arabinofuranosidases, which are responsible for xylooligosaccharides and arabino-xylooligosaccharides utilization by several lactobacilli (Petrova & Petrov, 2017).

2. Conclusion

Valorizing food waste, mainly using sustainable and biological approaches, i.e., either spontaneous or selected sourdough fermentation, is a tool for reducing its environmental and economic burden and transitioning to a circular economy. Fermentation with lactic acid bacteria and/or yeasts has been demonstrated to be an optimal approach to improve the nutritional and functional features (e.g., improved *in-vitro* protein digestibility, antioxidant activity) of several plant-derived food waste and by-products, and to overcome the drawbacks (e.g., decreased concentration of anti-nutritional compounds, improved textural properties) which might impede their re-use in food production. Aiming at facing the advancement of large-scale fermentations and the need for the implementation and diversification of available products on the market, the use of well-adapted and *ad hoc* selected microorganisms for industrial processing is of main importance. Also given the differences among the food waste composition, several studies have involved the selection of strains with various and specific functional properties to be used in tailored fermentation inspired to the sourdough biotechnology. The effects of this approach, suitable for significantly improving the sustainability of several food chains and the quality of the products, depend on the presence, growth, and metabolic activity of specific microorganisms, therefore requiring the accurate set-up and optimization of tailored fermentation processes.

Credit author statement

Erica Pontonio: Writing- Original draft preparation, Investigation, Writing- Reviewing and Editing, Supervision. **Alessandro Stringari**: Data curation, Investigation. **Raffaella Di Cagno**: Writing- Original draft preparation, Investigation. **Pasquale Filannino**: Writing- Original draft preparation, Investigation. **Carlo Giuseppe Rizzello**: Data curation, Investigation, Writing- Original draft preparation. **Andrea Polo**: Original draft preparation. **Olga Nikoloudaki**: Data curation, Investigation. **Marco Gobbetti**: Conceptualization, Methodology, Writing-Original draft preparation, Supervision.

Declaration of competing interest

The authors report there are no competing interests to declare.

Data availability

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