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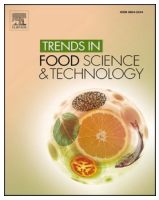

The food by-products bioprocess wheel: a guidance tool for the food industry

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ABSTRACT

Background: The reduction of food waste yields significant environmental and economic advantages, increasing the interest in the conversion of food by-products into functional ingredients. Biotechnologies, particularly enzymatic-assisted extraction (EAE) and fermentation-assisted extraction (FAE) have emerged as sustainable and cost-effective methods for upcycling food by-products. In the past few years, different processes have been explored using EAE and FAE.

Scope and approach: In this article, we developed the food by-products bioprocess wheel (FBBW), a tool to guide academic researchers through the upcycling possibilities offered by biotechnological processes. The wheel also gives hints on the most promising scalable strategies for industry innovators. The FBBW considers several by-products resulting from the processing of the most common fruits, vegetables, crops, and cereals. FBBW is supplemented with analytical tables indicating the best processing conditions to upcycle vegetable, fruit, and cereal by-products.

Findings and conclusions: The application of EAE and FAE technologies is still in its early stages. While EAE can be tailored to specific by-products and is generally more efficient, its cost depends on the use of commercial enzymes. Conversely, FAE is an economically viable promising strategy for repurposing agro-industrial by-products, its limitations are related to the readily available carbon sources to start the fermentation and in general to the sustained growth of fermenting microorganisms. The FBBW tool indicates the potential uses of both technologies depending on the by-product. Its use could be extended to pilot-plant scaled-up processes and facilitate the technological transfer from research laboratories to industrial settings.

1. Introduction

To face the rapid increase in global population, food production should increase, resulting in a higher volume of by-products as well. Food by-products harbor substantial reserves of bioactive compounds, often entrapped in the insoluble food matrix, making the use of emerging technologies an important part of current research and their application quite challenging (Galanakis, 2013). The current utilization of these agro-industrial by-products is, however, limited due to a dearth of dedicated research projects with practical application at the industrial level. The underutilization of food by-products not only represents a significant loss of valuable resources but also contributes to environmental issues such as greenhouse gas emissions and landfill burden (Gómez-García et al., 2021). This issue demands research efforts to find proper upcycling strategies for these by-products. In a nutshell, this means to reduce waste and maximize the utilization of food resources. In this regard, upcycling fruit and vegetable by-products has emerged as a promising approach, aiming to convert food by-products into valuable ingredients, avoiding their way out from the food supply chain (Thorsen et al., 2022). Upcycling agro-industrial by-products helps to mitigate the environmental burden, enhance resource efficiency, reduce greenhouse gas emissions, and alleviate food insecurity. This aligns with the 12th objective among the 17 development goals delineated in the 2030 Agenda for Sustainable Development (United Nations, 2015).

The majority of by-products from agro-industrial processes are solid and insoluble, predominantly composed of lignin, hemicellulose, and

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cellulose in different percentages. These polymers form the matrix within which various valuable compounds, such as phenolic compounds (PC), are embedded in different ways. Additionally, inside the plant cells, there are other molecules like lipids, carotenoids, and xanthophylls that are of interest for their technological functionality or health effects. However, these compounds are also bound or trapped within the insoluble materials, making them inaccessible. Consequently, one of the most common methods for upcycling these agro-industrial by-products involves extracting these beneficial components by breaking down the plant cell wall structure. In other words, the idea relies on the solubilization of (formerly) insoluble plant material.

Many strategies have been employed to increase the extraction of bioactive compounds from agro-industrial by-products. Mechanical pretreatments can make the matrix more accessible whereas chemical extractions have been exploited to recover these compounds. In the past years, other greener, novel techniques have been introduced and implemented, such as microwaves and ultrasounds, increasing the efficiency of the process while reducing the use of chemicals (Sagar et al., 2018). Other physical methods, like hydrodynamic cavitation, can be used as cheap, green alternatives to break down the cell wall and induce the release of beneficial components (Wu et al., 2019).

The use of biological processes like enzymatic-assisted extraction (EAE) and fermentation-assisted extraction (FAE) as a viable, green alternative for the upcycling of food by-products has been increasing over the last years (Lemes et al., 2022). Nevertheless, the use of EAE and FAE to upcycle food by-products is still in its infancy. Mounting evidence points to the potential application of these two technologies in different food by-products but also many factors that limit their applications. We recently summarized the applications of EAE and FAE in some food by-products (Vilas-Franquesa et al., 2023), but no categorization has been applied to identify the research gaps. In the present review, we developed a guidance tool named the "food by-product bioprocess wheel" (FBBW) to facilitate the assessment of the potential application of FAE and EAE on three different groups of agro-industrial by-products, namely fruits, vegetables, crops and cereals. The proposed tool will (1) help to understand the challenges of using FAE and EAE on the recovery of functional ingredients from agro-industrial by-products; (2) identify the research gaps, and (3) provide strategic ideas to food companies on how to upcycle agro-industrial by-products to lessen the environmental impact of food production.

2. FBBW: A tool for the food industry

The FBBW was built to be easily understandable by a wide range of professionals and academics, while more details are described in tables and a critical approach is discussed for each by-product in the appropriate text section. The research articles provided in the accompanying tables were the starting point for compiling the wheel.

2.1. EAE and FAE to upcycle food by-products

EAE uses specific enzymes to break down the complex vegetable matrix, using enzymes like cellulases, pectinases, or proteases, which facilitates the recovery of compounds of interest that are trapped within. This technology is particularly valued for its specificity, as the enzymes can be selected based on the by-product composition, but also for its efficiency and the ability to operate under mild conditions, which help preserve sensitive compounds. During the enzymatic breakdown of complex carbohydrates (e.g. hemicellulose), oligosaccharides can be formed (Vilas-Franquesa et al., 2023) and some could have prebiotic activity.

FAE can be applied to agro-industrial by-products to solubilize and extract material from the inside of the vegetable cell or from the cell wall in a similar way as EAE, using the enzymatic activity of microorganisms (Bélafi-Bakó, 2007). During their growth, microorganisms produce enzymes that break down complex polymers present in the by-product, and use the outcoming products as sources of carbon and nitrogen. Additionally, fermentation can change the nutritional and functional properties of the by-product, which could improve digestibility or increase the bioavailability of nutrients and can be used to generate new flavors (Khubber et al., 2022; Sabater et al., 2020; Sadh et al., 2018). FAE can be applied following two main strategies: as submerged (SmF) or solid-state fermentation (SSF). SSF uses less water to achieve the same objective, which is beneficial in the upcycling of agro-industrial by-products, as they are mostly insoluble with low water content (Cerda-Cejudo et al., 2023).

The application of either EAE or FAE can be challenging because most agro-industrial by-products have strong cell walls, limiting the accessibility of enzymes and microorganisms to the substrates. FAE is negatively affected by the physical intactness of the substrates as this technological approach often requires an adequate amount of readily available carbohydrates during the first hours of fermentation. Some pretreatment strategies could be applied to overcome this accessibility issue, such as a short heat treatment or mild mechanical treatments. It is also useful to pasteurize or sterilize the product, reducing any potential cross-contamination. The application of FAE is generally cheaper than EAE, however, it takes substantially more time: even when using concentrated starter cultures, the microorganisms take days to efficiently metabolize the substrate (as it is not its preferred choice). Conversely, EAE is heavily dependent on the use of commercial enzymes, making this technology more costly, yet highly efficient and reproducible.

2.2. Building the tool

The FBBW (Fig. 1) was built by scrutinizing the successful applications of EAE and FAE to different by-products available in the literature. The wheel gathers published research from the most produced fruits, vegetables, crops, and cereals, such as sugarcane, coffee, rice, bananas, or potatoes. The wheel focuses on the use of recent research publications, showing the current research direction. To construct the wheel, three main groups of agro-industrial products were selected, namely fruits, vegetables, and crops and cereals (grouped for the sake of clarity). Further sub-categorization was done considering the individual product (e.g. orange, chicory, wheat, etc.).

From each of the subgroups, the most relevant by-products from their production process were identified. The wheel was constructed by considering all the vegetable, fruit, and crop commodities that produce higher amounts of by-products, on which interesting bio-based upcycling strategies have been investigated. The wheel does not include products of minor production or products of local/regional interest. The proximate composition of the by-product was considered when available, otherwise educated guesses were done considering the composition of the starting material. The latest papers on EAE or FAE applications on each specific by-product were taken into account and summarized in tables. We did not consider waste waters, solvents, or other liquid waste streams derived from cleaning, washing, or extraction processes: the focus was kept on the use of (formerly) insoluble by-products. All the articles used to construct the wheel were derived from lab-stage explorations, except when indicated otherwise. The lactic acid bacteria genera were standardized according to the recent taxonomy (Zheng et al., 2020).

2.3. How to read the wheel

The ultimate goal of the wheel is to understand what can be done by a specific by-product; what type of compounds can be extracted and what type of FAE or EAE can be used according to (1) related available literature and (2) the proven effectiveness of the process. The FBBW (Fig. 1) consists of different layers, conveyed into a round shape that should be read from the inside out. The inner circle contains the greater categorization of the by-product, which helps the user look for the

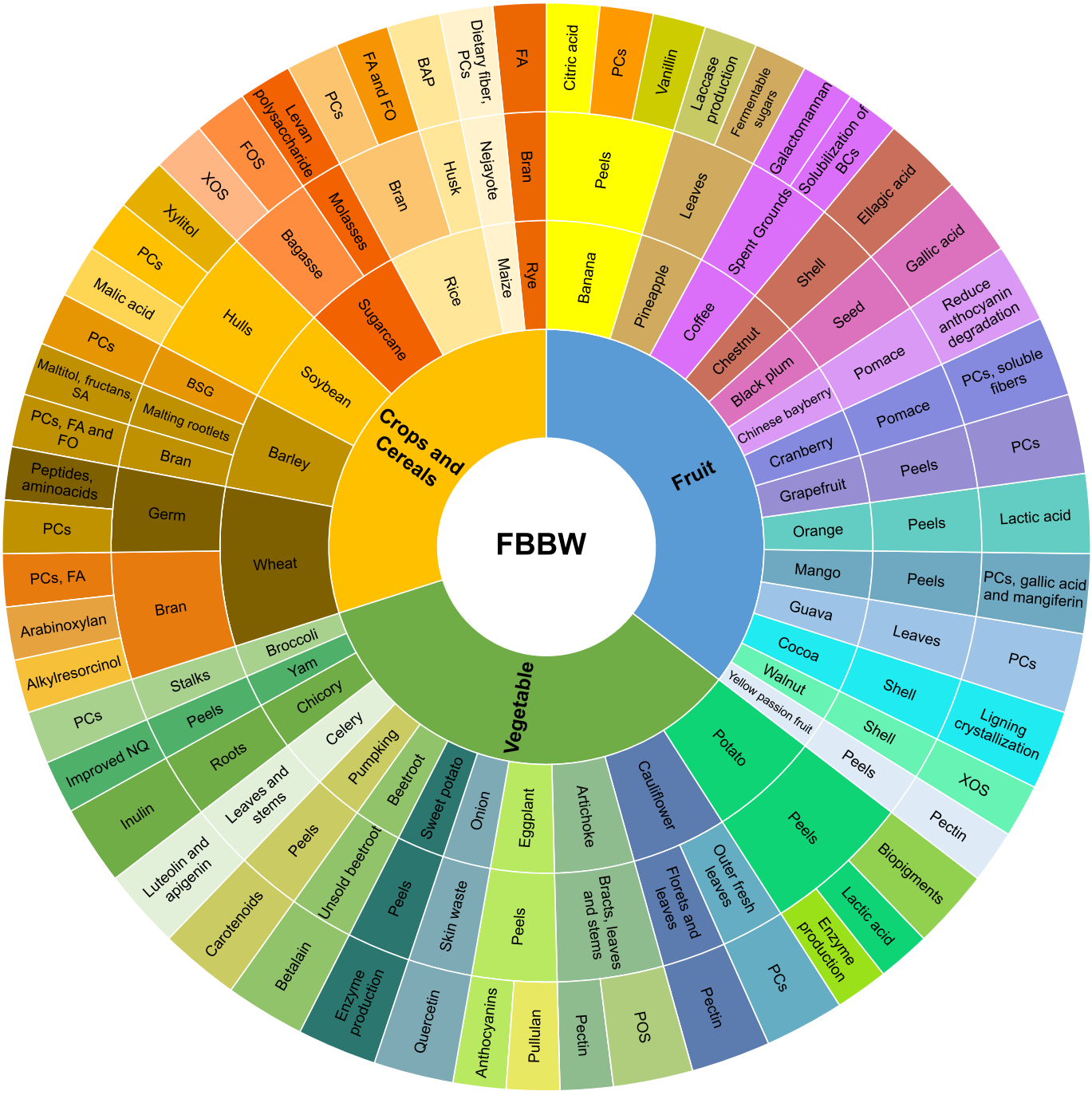

Fig. 1. The Food By-product Bioprocess Wheel (FBBW). Circle contents from inside out: (1) major classification, (2) agro-industrial product, (3) by-product investigated for upcycling strategies using EAE and FAE, (3) targeted compounds or objective of the EAE or FAE. PCs: phenolic compounds, FA: ferulic acid, XOS: xylooligosaccharides, POS: pectin oligosaccharides, FO: feruloyl oligosaccharides, SA: structuring agents, BAP: biologically active peptides.

bigger picture and (after that) narrow it down. The reader can see what has been done with products categorized as major crops, cereals, fruits, and vegetables. The second circle highlights the product that has been studied for upcycling purposes (e.g. rice), followed by the third circle, which shows which by-products have been studied for EAE or FAE (e.g. rice bran), separating in two boxes in case they are more than one (e.g. rice bran, rice husk). The last circle features the targeted compounds (e.g. pectin, quercetin) or the final objective of the extraction process (e.g. enzyme production). Supplementary Fig. 1 shows the reader how to read the FBBW.

The FBBW is complemented with three tables (one per product category) containing details about each of the processes highlighted in the wheel, providing the reader with useful information about the process parameters, pretreatments, and outcomes. In the next paragraphs, a summary of the most relevant literature on EAE and FAE applications to each by-product is reported.

3. Fruit by-products

The main by-products resulting from fruit processing include peels,

pomace, shells, seeds, and leaves, each having a very different nutritional and phytochemical composition. Peels and pomace generate more interest in the application of FAE due to their high presence of monomeric sugars and other carbohydrates, whereas seeds, shells, and leaves offer a biotechnological challenge. It should be noted that the external sections of the fruit, such as the peels, shells, or husks, may contain high levels of pesticides. This poses a challenge for their upcycling. However, some researchers are exploring ways to upcycle fruit waste extracts to decrease the presence of specific pesticides, like diazinon and parathion (Hussain et al., 2022).

3.1. Pomace

Pomace, a frequent by-product in fruit and juice processing, is generated in substantial quantities annually. It has a high moisture content of around 70–75% and is rich in pectin/hemicellulose dietary fibers. These fibers can be easily solubilized by depolymerization producing bioactive oligosaccharides (Wilkowska et al., 2019). Furthermore, the sugar concentration is generally higher compared to other by-products from the fruit processing industry, which facilitates bacteria/fungi growth and therefore stimulates the application of FAE. Fruit pomaces are also a good source of different phytochemical components, featuring a high concentration of bioactive compounds, including PCs but also carotenoids, tocopherols, and different fatty acids.

Currently, large amounts of berry pomace are still discarded or used for composting or animal feed. Nevertheless, some studies have shown its potential application as a functional ingredient after FAE or EAE: some studies selected as described below are summarized in Table 1. Zhu et al. (2022) observed that mixed liquid fermentation on Chinese bayberry pomace could produce a new beverage with improved quality by slowing down the degradation of the anthocyanins and promoting the conversion of flavonoids into flavonol aglycones. Jagelaviciute et al. (2022) showed that enzymatically treated cranberry pomace has a different composition and technological properties depending on the enzyme used for hydrolysis and can be used in various novel food products. *Trametes versicolor* has also been used to upcycle grape pomace to mycelial biomass and produce highly antioxidant intracellular polysaccharides (Kachrimanidou et al., 2023), which are usually derived from the uptake of sugars by the fungi.

3.2. Leaves

Leaves are mainly a by-product of fruit harvesting, and the volume can be very variable depending on the fruit. The leaves are interesting because they contain high amounts of PC, most of which have been linked to a specific health effect. Although they have almost no sugars, upcycling of leaves by EAE and FAE has been tried and the findings of some papers are summarized in Table 1.

Wang et al. (2019) showed that raspberry (*Rubus idaeus* L.) leaves harbor interesting PCs that can be extracted, especially ellagic acid. They observed that acid and EAE increase the concentration of ellagic acid by 156.1-folds when compared to conventional methanolic extraction. The extract had strong antioxidant activities and inhibitory potential to α-glucosidase. Wang et al. (2018) applied fermentation with *Monascus anka* and *Saccharomyces cerevisiae* with hydrolyzation by complex enzymes to the guava leaves, observing an increase of the total phenolics, flavonoids, quercetin, and kaempferol content by 2.1, 2.0, 13.0 and 6.8 times, respectively, when compared to the unfermented.

In the pineapple industry, residues from its harvest represent 80 % of the total mass of the plant since only the fruits are readily consumed. In Mexico, 875.830 tons of pineapple fruits are produced, which roughly represents 4 million tons of leaves. Commonly, these are incinerated or left to decompose in open fields, generating serious environmental problems. Pineapple leaf residues present a high holocellulose content (62.17% w/w) (Aili Hamzah et al., 2021). Chablé-Villacis et al. (2021) proposed the SSF of pineapple leaves by *Trametes hirsuta* for lignocellulosic enzyme production and to obtain fermentable sugars, claiming it to be a sustainable and affordable process.

A common setback for the use of leaves is their composition, which includes a greater presence of lignin. Sometimes adequate pretreatments can be used to facilitate the access of enzymes and microorganisms to the carbohydrates of interest.

3.3. Seeds

Seeds can differ in composition as well as in size and the structure of the coating layers. Some seeds contain a high amount of starch (e.g. mango), some others contain a great quantity of oil (e.g. avocado), while others are considerably small (e.g. raspberry) and some display high concentrations of cyanogenic glucosides (e.g. peach). It is thus impossible to give a general overview of their utilization. Yet, due to these differences, bioprocessing technologies could be a good choice for their upcycling due to their versatility as highlighted in some studies reported in Table 1.

A clear example is mango seed, presenting high starch content. This seed is enveloped in a layer (seed coat) of high lignin content. Fermentation of mango seed by *Aspergillus niger* can be a good strategy to release antioxidant compounds, especially PCs (Torres-León et al., 2019). In fact, the release of PCs (i.e. gallic acid) from other fruit seeds (e.g. black plum, apple) by the use of *A. niger* has also been reported (Saeed et al., 2020). However, the upcycling of mango seed into a functional product (i.e. flour) is then thwarted by the use of a non-food-grade fungus.

Wang et al. (2019) showed that raspberry (*Rubus idaeus* L.) seeds are potential substrates to produce PC. They showed that by acid and EAE, the concentration of ellagic acid in the extract was 101.8 times higher when compared to methanol extraction. The extract also had inhibitory effects on α-glucosidase activity, as claimed in the leaf extract.

The upcycling of fruit seeds through EAE or FAE has received little attention thus far. It could be interesting to explore the use of FAE with food-grade fungi for the upcycling of starchy seeds – such as mango seeds – or the use of EAE for the upcycling of other seeds with higher lignocellulosic material.

3.4. Peels

Fruit peels are by-products primarily of juice production, or from conventional peeling. In either case, the process results in peels with pulp attached as it is not 100% efficient. Compositionally, this by-product is similar to pomace, as it contains a high amount of water (around 70%) and simple carbohydrates, offering another opportunity to use FAE for their upcycling.

Orange and mango peels have been recently fermented by lactic acid bacteria (LAB). Different species of LAB were employed to produce lactic acid from orange peels. Ricci et al. (2019) demonstrated that *Lacticaseibacillus casei* 2246 was the most efficient strain, reaching the highest concentration of lactic acid (209.65 g/kg) and yield (0.88 g/g). Orange peels represented a suitable raw material for FAE processing employing LAB. A recent study sought to upcycle mango peels through a sequential process involving EAE and FAE, employing *Lactiplantibacillus plantarum* and *Bifidobacterium animalis*. The findings suggest that this method of sequential processing could be used to extract phenolic aglycones and oligosaccharides from mango peels (Vilas-Franquesa et al., 2024).

Banana peels, which correspond to about 30–40% of the whole fruit, have been exploited for the production of citric acid through fermentation by *A.niger* (Monrroy et al., 2019). In this work, Monrroy and colleagues observed that the pH is the most important factor determining the efficiency of the production of citric acid (maximum production of 29 g/kg, Table 1). Islam et al. (2024), used EAE to produce extracts and achieved high antioxidant activity measured by DPPH (81.59%) and ABTS (88.25%), and α-glucosidase inhibitory activity (74.67%). Among different enzymes, Viscozyme L was found to be more

Table 1
Recent publications on the application of EAE and FAE on fruit by-products.

Product	By-product	Microorganisms/enzyme	Objective	Process parameters	Required pretreatment	Outcomes	Reference
Pineapple	Leaf	Enzymatic hydrolysis (cellulases) + SSF with *Trametes hirsuta*	Bioconversion into fermentable sugars and production of laccase	27 and 35 °C for 21 days, in the dark	None	The greater delignification rate (28%) at 35 °C. The highest level of laccase activity was obtained at 27 °C. 580 mg/g hydrolyzed biomass and saccharification of the holocellulose, in the first 12h (0.35 g L^{-1} h)	Chablé-Villacis et al. (2021)
Apple, guava, tamarind, black plum and watermelon	Seeds	SSF with *Aspergillus. oryzae*	Production of tannase and gallic acid	30 °C, 96 h incubation period, and pH 5.5.	None	Black plum seed gave the highest activity of 34.40 U/g for tannase and 16.66 mg/g for gallic acid	(Arshad et al., 2021)
Grapefruit	Peel	Cellulase	Extraction of bound phenolics	8% enzyme dosage, 60 °C for 2 h	Microwave-assisted extraction, at 600 W, 85 °C	Release of insoluble bound phenolic compounds (148.856 ± 0.620 GAE mg/100 g) and high content of gallic acid (42.50 ± 3.21 μg/g DW), ferulic acid (18.46 ± 1.65 μg/g DW) and protocatechuic acid (6.16 ± 0.72 μg/g DW).	(Peng et al., 2021)
Orange	Peel	*Lactiplantibacillus plantarum* 285, *Lacticaseibacillus rhamnosus* 1019, *Lacticaseibacillus casei* 2246, and *Lacticaseibacillus paracasei* 4186	Production of lactic acid	The SSF was carried out for 5 days with a concentration of 7 log CFU/g	Orange residues were cut into pieces, dried for 5 days in an oven at 40 °C, and milled. The sample was sterilized in an autoclave (20 min, 121C, 1.2 atm) and the pH adjusted to 5 or 6.5	*L. casei* 2246 reached the highest concentration of lactic acid (209.65 g/Kg) and yield (0.88 g/g)	Ricci et al. (2019)
Mango	Peel	Viscozyme L, Pectinex XXL, Celluclast, Pectinex XXL *Lactiplantibacillus plantarum*, *Bifidobacterium animalis* spp lactis	Solubilization of phenolic compounds, production of antioxidant dietary fibers, and recovery of gallic acid and mangiferin aglycones	Enzymatic treatment for 2 h at 50 °C Bacterial inoculation 10%, stock solution: log 7 CFU/ml for 48 h at 37 °C	2% sodium carbonate to reduce the bacterial load	Viscozyme increased galacturonic and glucuronic acids (308.96 and 12.97 mg/100 ml higher than control, respectively), Pectinex solubilized oligosaccharides (5.3% more than control). Pectinex and *B. animalis* increase the recovery of gallic acid aglycone by 17-fold over the control. Either bacteria increased the recovery of mangiferin aglycone by 60 %	Vilas-Franquesa et al. (2024)
Guava	Leaves	SSF with *Monascus anka* and *Saccharomyces cerevisiae* Enzymatic hydrolysis cellulase, xylanase, hemicellulose, β-glucosidase	Solubilization of phenolic compounds	Incubation at 28 °C for 8 days under 45% relative humidity. After SSF, 2% enzymes were added and incubated for 12 h at 50 °C. The enzymes were inactivated for 20 min at 80 °C	The substrate of guava leaves was steam-sterilized at 121 °C for 15 min	156.1-fold increase of ellagic acid when compared to conventional methanolic extraction	Wang et al. (2018)
Yellow passion fruit	Peel	30 U/ml protopectinase	Pectin extraction	Temperature 37 °C, Time 45 min, pH 3	None	The yield of pectin 26% and galacturonic acid 85.4%	Vasco-Correa and Zapata Zapata (2017)
Cranberry	Pomace	Enzymatic hydrolysis (Viscozyme® L and Pectinex® Ultra Tropical, Celluclast 1.5 L)	Increase the soluble fibers, total phenolic compounds and assess the prebiotic activity	Substrate: water 1:10 ratio; 50 °C with shaking (200 rpm)	None	Increased soluble dietary fiber in samples hydrolyzed with Celluclast® 1.5L. 10.9% and 13.1% higher content of total phenolic compounds were obtained using Viscozyme® L and Pectinex® Ultra Tropical respectively than the control.	Jagelaviciute et al. (2022)

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Table 1 (*continued*)

Product	By-product	Microorganisms/enzyme	Objective	Process parameters	Required pretreatment	Outcomes	Reference
Chinese bayberry	Pomace	Mixed fermentation: *Saccharomyces cerevisiae, Streptococcus thermophilus, Lactobacillus delbrueckii* subsp. *bulgaricus, Bifidobacterium longum, Bifidobacterium breve, Bifidobacterium lactis, Bifidobacterium infantis, Bifidobacterium adolescentis, Lactobacillus acidophilus, Lacticaseibacillus rhamnosus, Limosilactobacillus reuteri, Lactiplantibacillus plantarum, Lacticaseibacillus casei;* Enzymes: cellulase, hemicellulose, and pectinase	Slow down the degradation of anthocyanins and make a beverage having a better quality	inoculation with 0.2% and 0.1% (w/w) of yeast (w/w) at 25 °C for 24 h/6 days 1.0% cellulase, 0.5% hemicellulose, and 0.6% pectinase	Before fermentation, the mixture was ultrasonically sterilized for 30 min	The type of phenolic acid did not change, but the content increased (gallic acid: 185.68 ± 0.54 vs 12.84 ± 0.04 and protocatechuic acid: 89.03 ± 0.08 vs 29.72 ± 0.06)	Zhu et al. (2022)
Black plum	Seed	SSF with *Aspergillus niger*	Production of gallic acid	Substrate water ratio of 1:3, 72 h of incubation, pH 5, and temperature 30 °C	None	High yield of gallic acid i.e. 13.31 mg/g of substrate	Saeed, Baig, et al. (2021)
Banana	peel	*A.niger*	Production of citric acid	30 °C, 150 rpm for eight days, Ph 1.4, Inoculum loading 20 mg	None	29 g kg− 1 citric acid	Monrroy et al. (2019)
Banana	peel	*E. hormaechei*	Biotransformation of ferulic acid to vanillin	30 °C, pH 5, 130 rpm for 32 hm, OD of inoculum of 0.6	Banana peel powder has been mixed with 60 mL of NaOH solution (prepared by adding 2 M NaOH, 30% ethanol, 15% ammonia, or water). The ferulic acid-rich fraction was isolated by adding 60 ml ethyl acetate thrice to the solution. All the ferulic acid precipitates were collected and concentrated by a rotary vacuum evaporator	3.8 ± 0.14 g/L bioconverted from 7 g/L of ferulic acid	Saeed, Baig, et al. (2021)
Banana	peel	Viscozyme	Phenolic compounds	1.0% enzyme concentration, 9 h extraction time, 55 °C extraction temperature, and the solute-liquid ratio 1:25.	None	TPC 25.37 mg GAE/g DM, TFC 13.99 mg QE/g DM, 81.59% (DPPH) and 88.25% (ABTS) scavenging ability, and 74.67% of α-glucosidase inhibitory activity.	Islam et al. (2023)
Cocoa	Shell	*P.roquesforti*	Hydrolysis and crystallization of lignin	10^7 conidia/g of cocoa bean shell and the fermentations carried out at 27 °C for 7 days, medium humidity adjusted to 50%	None	An increase of 36.6% in the crystallinity index	Lessa et al., 2023
Coffee	Spent grounds	Viscozyme and Celluclast	Solubilize bioactive compounds	Viscozyme L and Celluclast 1.5L concentrations were 66.0 and 33.6 μL/g of SCG, 4.91 and 55 °C, 14 h	Microwave-assisted extraction	The total soluble matter increased almost 8 folds. Insoluble fiber were hydrolysis into monosaccharides (up to 17 g/100g), soluble melanoidins were up to 72 mg/g, and caffeic acid up to 2.22 mg/g.	Montemurro et al. (2024)
Coffee	Spent grounds	Viscoflow + *L.rhamnosus*	Solubilize bioactive compounds	Viscoflow 0.1% w/w and 0.8% v/w of the liquid protease with 5% of *L. rhamnosus* (ATCC® 7469™) for 24 h, at 37 °C, with shuffling, pH 5	None	Polyphenols increased for 67% (227.3 ± 3.3 mg GAE/g dm extract), reducing sugars 57% (277.9 ± 7.6 mg glucose/g dm extract), and α-amino nitrogen 80% (161.2 ± 9.8 mg/100 g dm extract),	Milić et al., 2023

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Table 1 (*continued*)

Product	By-product	Microorganisms/enzyme	Objective	Process parameters	Required pretreatment	Outcomes	Reference
						and the chlorogenic acid content doubled, while the caffeine reduced for 38% compared to the SCG control	
Coffee	Spent grounds	endo-mannanase from *Trichoderma reesei*	Galactomannan (GalM)	endo-mannanase (20 U/g galactomannans) at 50 °C using 50 mM citrate buffer (pH 4.8) and shaken at 150 rpm for 48 h.	Treatment at 140 °C, 50 min	50.1% of GalM in pretreated SCG was converted into free GalM in enzymatic hydrolyzate.	Gu et al. (2020)
Chestnut	Shell: inner pellicle and peel	SSF with *Aspergillus japonicus* ZGM4	Ellagic acid extraction	10^7 spores/mL, 5 gr of chestnut shell sample and incubated at 30 °C up to 7 days.	None	6-fold increment of ellagic acid compared to the unfermented chestnut shell.	Gulsunoglu-Konuskan et al. (2021)
Walnut	Shell	Endo-1,4-β-xylanase	Xylooligosaccharides	40 °C in continuously homogenized reaction mixtures.	Homogenization, pectin extraction, delignification, and alkaline extraction to recover hemicellulose	Total xylan conversion of 81.8% of recovered xylose	(Cebin et al., 2021)

Only the most recent published articles were selected. Research articles related to the use of waste waters, solvents, or other liquid waste streams derived from cleaning, washing, or extraction processes were not included. The focus remained on the extraction of bioactive compounds or the production of useful compounds (i.e. lactic acid) from (formerly) insoluble material. DW: dry weight, SSF: solid-state fermentation, GAE: gallic acid equivalents, SCG: spent coffee grounds, TPC: total phenolic compounds, TFC: total flavonoid compounds, QE: quercetin equivalents, CFU: colony forming units.

effective compared to cellulase, and pectinase.

3.5. Shells and hulls

Hulls are the soft part that surrounds the shells, whereas the shells are the hard cover found in most nuts. The upcycling of shells by EAE or FAE is very challenging as they consist of dead cells that have heavily lignified walls with high cellulose content (60–80%), also known as sclerenchyma tissue (Carrillo-López & Yahia, 2019). Nevertheless, these by-products are a rich source of valuable beneficial components that can be upcycled into functional ingredients, as now they are only used for fuel production or animal feed (Alvarez-Parrilla et al., 2018).

Recent studies have focused on the upcycling of pistachio by-products through EAE. Pistachios feature a testa covered by a soft lignified shell, a hard-woody shell, and an exterior hull that varies in color from green to red depending on how ripe the fruit is. Hesam et al. (2021) produced valuable prebiotic xylooligosaccharides (XOS) containing xylotriose (0.818 mg/ml) and xylobiose (1.86 mg/ml) from pistachio shell by EAE of xylan with commercial endoxylanases (Table 1).

Other recent publications focus on the upcycling of chestnut processing residues. In this case, the bur and shell are the two main by-products of chestnut processing. In contrast to the shell, which is extracted during the peeling process in factories and is typically used for the production of biofuel, the bur (spiny and sharp green envelope) resulting from fruit harvesting typically remains on the field. An inner pellicle and an outer, tougher peel make up the two layers that make up the bur. The lignocellulosic shell may be a practical and affordable source of natural antioxidants. According to Gulsunoglu-Konuskan et al. (2021), the chestnut shell is a potential raw material to produce ellagic acid through FAE by *Aspergillus japonicus* ZGM4 which can increase up to 6-fold its concentration and increase its solubilization.

Cocoa shells are also highly produced during roasting and winnowing of cocoa beans. The rich amount of lignocellulosic residues in cocoa shells makes it also a challenging substrate for solid-state fermentation to obtain value-added products. Nevertheless, Lessa et al. (2023) showed that SSF by *P. roqueforti* was able to hydrolyze lignocellulose, changing the crystallinity of the residue, existing functional groups, and higher porosity. Although this does not directly contribute to the effective extraction of compounds (e.g. PC), it could be used as pretreatment.

3.6. Spent grounds

Global coffee production leads to the production of 8–15 MTn of spent coffee grounds (SCG) annually (Horgan, Floyd, Mundaca, & Crisol-Martínez, 2023). Montemurro and colleagues recently demonstrated how EAE in combination with microwave-assisted extraction (MAE) can be used to upcycle SCG. The total soluble matter increased almost 8 folds due to high insoluble fiber hydrolysis into monosaccharides (up to 17 g/100g), soluble melanoidins (up to 72 mg/g), and caffeic acid (up to 2.22 mg/g). Milić et al. (2023) proposed an innovative biotransformation process of spent coffee grounds using a cocktail of enzymes and *Lactobacillus rhamnosus*. This process increased the content of chlorogenic acid, total polyphenols, and free amino acids, while the amount of caffeine was reduced by 38% in comparison to the non-fermented SCG, deriving a product desirable to be incorporated as an additive in food (Table 1).

4. Vegetable by-products

Vegetables are commonly defined as parts of plants – other than fruit – that are used for human consumption. The consumed parts vary widely, from leaves to roots, stems, or inflorescences. Due to the high variety of plant parts that are considered vegetables and their contrasting nutritional composition, the nature of by-products derived from

Table 2
Recent publications on the application of EAE and FAE on vegetable by-products.

Product	By-product	Microorganism/Enzyme	Objective	Process parameters	Required pretreatment	Outcome	Reference
Cauliflower	Florets and leaves	Protease (Promod), neutrase, cellulase (Cellulyve)	Pectin extraction	4h at 50 °C in acetate buffer (pH5.5)	None	Extraction of high methylated and acetylated pectin (contributes to emulsion stability by preventing pectin aggregation)	Zykwinska et al. (2009)
Cauliflower	Outer fresh leaves	EAE with Viscozyme L from *Aspergillus aculeatus* (120 fungal beta-glucanase U/ml) and Rapidase from *Aspergillus niger* and *Trichoderma longibrachiatum*.	Extraction of PCs	Optimization sequential process. Best extraction conditions at 0.2% ratio (enzyme/cauliflower outer leaves, w/w), 35 °C, pH 4.	Cutting to pieces of 2 × 5 cm, 3 min mixing using kitchen homogenizer	2.5-fold higher recovery of PCs when using Viscozyme or Rapidase after 12h of incubation when compared to control	Huynh et al. (2014)
Broccoli and Cauliflower	Stalks	Spontaneous fermentation	Phytochemical profile	6% brine solution at ratio 1:4 (v/w) with fresh stalks for 3 weeks at RT	Washing with warm water (45 °C)	Reduction of total phenolic compounds after fermentation of the stalks	Bekhit et al. (2013)
Artichoke	Blanched external bracts, leaves and stems	Celluclast®1.5L	Pectin production	Factorial design with different artichoke by-product concentration (2–7% w/w), enzyme dose (2.2–13.3 U/g) and extraction time (6–24 h), under orbital shaker conditions (200 rpm) at 50 °C and pH 5	Particle size reduced to ≤ 500 μm	Best pectin extraction (176 mg pectin/g DM) at 6.5% powder concentration (w/w), 10.1 U/g of enzymatic activity and 27.2 h.	Sabater et al. (2018)
Artichoke	Blanched external bracts, leaves and stems	Pectinex®Ultra-Olio (202.6 U/g), Glucanex®200 G (189.2 U/g), Pentopan®Mono-BG (161.5 U/g), and cellulase from *A. niger* (263.7 U/g)	Pectic oligosaccharides (POS) extraction	0.05 M acetate buffer (pH 5.0), 0.54–6.75 U/ml of enzyme at 2% (w/v), 50 °C, 750 rpm, 0.5-1-4 h	Preliminary enzymatic treatment with Celluclast®1.5L of artichoke by-product powder (Particle size reduced to ≤ 500 μm) concentration 6.5%, enzyme dose 10.1 U/g, 48 h	Greatest amount of POS using cellulase (310.6 mg/g pectin), molecular weight of 6–14 kDa.	Sabater et al. (2019)
Eggplant	Peels	Cellulase (100,000 carboxymethylcellulose U/g)	Anthocyanins, phenolics extraction	Box-Behnken design, best extraction conditions at 60 °C, 5% concentration enzyme/substrate, 4.5h.	None	Recovery of total anthocyanins up to 585.30 mg Cyanidin-3-glucoside/L and TPC up to 3060 mg GAE/L	(Amulya & ul Islam, 2023)
Eggplant	Peels	Enzymatic hydrolysis by Viscozyme® L and fermentation by *Aureobasidium pullulans*	Pullulan production	EAE: pH 5 50 °C for 24h, FAE: 5% inoculum (v/v), 28 °C, pH 5.5 up to 10 days	Pectin and phenolic extraction in a first heating step (90 °C, 90min and liquid/solid ratio 40 ml/g).	Up to 16.8 g/L of pullulan production after 7 days of fermentation	Kazemi et al. (2019)
Beetroot	Unsold beetroot	Pectinase (polygalacturonase and pectin lyase activity), cellulase, xylanase	Betalain extraction	pH 5.5, 25–45 °C, 20–300 min, different enzyme combination	None	Optimal conditions extracting around 15 mg betalain/ml	Lombardelli et al. (2021)
Yam	Peels	*Saccharomyces cerevisiae*	Develop an added value ingredient	27 °C, 96h, SSF	Washing, drying (60 °C/12h), sieving, sterilization (121 °C/15min)	5.18% increase in true protein, 0.43% increase in crude fiber, 0.4% increase in fat content in the fermented peels	Aruna et al. (2017)
Potato	Peels	*Aspergillus niger*	Production of carboxymethyl cellulase (CMCase), filter paperase (FPase) and xylanase	Central Composite Design on time, best production conditions for CMCase at 82.88 h, 51.48 % water content and 29.46 °C; for FPase at 80.62 h, 50.19 % water content and 30 °C; for xylanase at 81.92 h, 50.72 %	Sterilization (121 °C/15min)	Higher activity observed for CMCase at 24 U/L, FPase at 15 U/L and xylanase at 24 U/L.	Dos Santos et al. (2012)

(*continued on next page*)

Table 2 (*continued*)

Product	By-product	Microorganism/Enzyme	Objective	Process parameters	Required pretreatment	Outcome	Reference
				water content and 28.85 °C.			
Potato	Peels	*Rhizopus oryzae*	Production of lactic acid	Potato peel waste rate of 8 %, 1–2 mm particle size, enriched liquid medium, inoculation at 10^5 spores/ml, 35 °C, 150 rpm, 96, 144 or 192 h.	Drying of potato peel waste at 75 °C until constant weight, blending and sieved	Highest lactic acid production of 0.039 g/g of potato peel waste	Ozer Uyar and Uyar (2023)
Potato	Peels	*Pseudomonas aeruginosa* BK25H	Production of pyocyanin and 1-hydroxyphenazine	Concentration of 15 g potato peels/L, 24h, 37 °C, shaking (rpm not disclosed in lab flasks), pH 7.8. Addition of NaCl as side-treatment.	Homogenization at 1200 W using a kitchen blender, sterilization by autoclaving.	Using potato peels with the addition of NaCl the recovery of biopigments was approximately 10 times higher than without NaCl. The analysis was performed spectrophotometrically and no quantitative data was provided.	Pantelic et al. (2023)
Sweet potato	Peels	*Aspergillus niger*	Production of α-amylase	Central Composite Design, best production conditions at 6 days, pH 6.5 and 2% substrate concentration	Drying (60 °C/24-48h) and milling (35 mesh)	Highest α-amylase activity of 214.28 U/ml	Pereira et al. (2017)
Onion	Skin waste	Cellulase, pectinase and xylanase	Quercetin extraction	1% substrate (w/v), phosphate buffer pH 4.8, 180 rpm, 48h and 45 °C	Lyophilization	1.59-fold increase in quercetin extraction after enzymatic treatment	Choi et al. (2015)
Celery	Leaves and stems	Cellulase (>1000 U/mg) and pectinase (1.41 U/mg)	Extraction of luteolin and apigenin by sequential application of ultrasounds and EAE	Resuspension of 10 g of powder to 75 ml of enzyme solution (both enzyme solutions at 0.4 mg/ml). Ultrasonication at 80 W for 30 min, 25 °C. EAE: pH 3 for luteolin and pH 5.5 for apigenin, 33 °C, 24h, intermittent stirring.	Air-dried celery stems and leaves, crushing with mortar and pestle to obtain fine powder.	Up to 25 mg/g of luteolin and 40 mg/g of apigenin after pectinase and ultrasonic treatment.	Zhang et al. (2011)

Only the most recent published articles were selected. Research articles related to the use of waste waters, solvents, or other liquid waste streams derived from cleaning, washing, or extraction processes were not included. The focus remained on the extraction of bioactive compounds or the production of useful compounds (i.e. lactic acid) from (formerly) insoluble material. PCs: phenolic compounds, DM: dry matter, GAE: gallic acid equivalents, TPC: total phenolic compounds, SSF: solid-state fermentation, EAE: enzymatic-assisted extraction, FAE: fermentation-assisted extraction.

their processing differs greatly. In this section, the most recent upcycling strategies of vegetable by-products using FAE and EAE are discussed, and the relevant papers are summarized in Table 2.

4.1. Leaves

Leaves can be edible, like that of spinach or rocket, or non-edible, like that of artichoke. Leaves – edible or not – have a considerably high amount of moisture content, generally above 90%, the rest being mainly dietary fiber, some proteins, and ash (U.S. Department of Agriculture, 2023). In addition, they contain high concentrations of PCs and chlorophyll. The low readily available carbon source and the high concentration of PCs make very challenging the application of FAE and EAE. Edible leaves can be juiced, leaving behind a fiber-rich leaf pomace. Nevertheless, the most voluminous by-products are the left-overs from the initial processing of vegetables.

Some authors already have shown in the past that EAE of PCs from cauliflower leaves is possible (Huynh et al., 2014). In addition, the EAE of pectin from artichoke bracts and leaves has been recently optimized by Sabater et al. (2018). EAE of pectin was also attempted on cauliflower leaves in the past (Zykwinska et al., 2009). Sabater et al. (2019) further studied the subsequent production of pectic oligosaccharides (POS) using pectin-lyase enzymes. These works demonstrate that using EAE could be a good alternative for the recovery of PCs and oligosaccharides from bracts and leaves.

4.2. Stems and stalks

The stems are part of the plants usually sustaining the whole plant weight. The most researched stems are those that can be eaten, including but not limited to celery and asparagus, both having fiber as their main carbon source (U.S. Department of Agriculture, 2023). It has been reported that celery by-products (e.g. leaves) contain high amounts of sugars (5.9% sucrose) and could be a good source of mannitol (Rupérez & Toledano, 2003), luteolin and apigenin (Zhang et al., 2011). Furthermore, asparagus has been identified as a good source of fructans (up to 12.5% on a fresh weight basis (Viera-Alcaide et al., 2022),). Fructans are fructose and glucose-based polymers that are stored in the vacuoles of plant cells, whereas luteolin and apigenin are PCs generally bound to the plant cell wall polysaccharides (Rocchetti et al., 2022). During asparagus processing, part of the stem is cut and thrown away, missing the chance of upcycling this valuable by-product.

The only studied technology for the upcycling of stem by-products is EAE. Zhang et al. (2011) studied the EAE extraction of luteolin and

apigenin from a mixture of celery stems and leaves. This approach yielded favorable results, hinting at the potential extension of this technique to other analogous products like asparagus, or vegetables with similar phenolic compositions, such as artichokes.

Stalks are generally considered more robust, thicker stems, like the ones from broccoli or cauliflower. The upcycling of cauliflower and broccoli stalks had been attempted by FAE using spontaneous fermentation (Bekhit et al., 2013). This research explored the fermentation of stalks cut to pieces and quantified the PCs of the fermented solid material. The authors reported a notable drop in the concentration of PCs from the raw solid material (Bekhit et al., 2013) while disregarding any change in the PCs concentration in the aqueous phase, which was likely increased. However, when selecting appropriate bacteria, FAE is possible on these matrices and could be used to increase the solubilization of bioactive compounds. In fact, LAB fermentation of broccoli puree interestingly increased the contents of glucoraphanin, glucoiberin, and progotrin (glucosinolates), and a considerable increase in 10 major PCs found in this matrix (Ye et al., 2019). Although the authors focused on broccoli florets – the edible part of broccoli – the results are promising for the application of the same technology to broccoli stalks.

4.3. Roots

Roots are the parts of the plants that do not receive light and thus they do not contain chlorophyll. In some cases, the roots are highly nutritious and cultivated (e.g. potato, carrot), yet in most cases, the root biomass is generally discarded or left in the field. The processing of roots is tedious as they come with a lot of soil debris. Some roots have been the focus of many studies such as chicory roots. There is a great variety of chicory plants, most of them giving out highly nutritional thick roots. In fact, chicory roots are inulin-rich by-products (i.e. 30% of the total carbohydrate content), which makes them an interesting candidate for upcycling strategies (both EAE and FAE). The EAE of inulin from chicory roots has been done by using an enzymatic cocktail from *Xanthomonas oryzae* (Pradal et al., 2016). Inulin has become a commodity that can be used in many fields besides food ingredients: from the production of cosmetics to the production of antimicrobial solutions (Häkkinen et al., 2022).

4.4. Peels

After harvesting, further processing of vegetable products often includes peeling. There are great differences in peel composition depending on the processed vegetable, from high starch content (e.g. potato, sweet potato) to high lignocellulosic material (e.g. pumpkin). The interesting part about upcycling vegetable peel by-products is that, like what happens with fruits, they can contain parts of the flesh and therefore relevant quantities of fermentable carbohydrates, which could be advantageous for the application of FAE.

Sugar or starch-rich tubers are the most upcycled peels within all the vegetable by-products. Presenting high moisture content (≈85%), potato peels contain about 10% of carbohydrates with some traces of protein (≈2%) (Joshi et al., 2020). The carbohydrate concentration can reach values of about 20% of fresh products (i.e. sweet potato, (Wang et al., 2016). Due to the high readily available carbohydrate concentration, potato, and sweet potato peels have been extensively used for the production of cellulolytic enzymes or, more specifically, α-amylase production (Dos Santos et al., 2012; Pereira et al., 2017). More recently, potato peels and pomace have been used as substrates to produce biopigments. For instance, Chen et al. (2021) produced biopigments from potato pomace (a by-product from starch production primarily consisting of peels) through a SSF by *Monascus purpureus*, whereas Pantelic et al. (2023) produced pyocyanin and 1-hydroxyphenazine after fermentation of potato peels by *Pseudomonas aeruginosa* BK25H. Yam peels have alternatively been used for protein production after SSF by *S. cerevisiae* (Aruna et al., 2017). In addition to biomass production and enzyme synthesis via fermentation, peels rich in starch and sugars hold significance as primary resources for biogas production. This highlights that the value of these by-products is the abundant carbohydrate content rather than specific bioactive compounds.

The processing of onions can also give out their outer layer as a by-product. Compositionally, these by-products contain lower amounts of carbohydrates, but they are still a relevant source (raw onions contain approximately 10% of carbohydrates (U.S. Department of Agriculture, 2023)). Differing from starchy roots, onions have great quantities of PC, quercetin being one of the most relevant (Choi et al., 2015). In that vein, the high concentration of PCs can limit the implementation of FAE. In fact, onion skin waste has been upcycled exclusively through EAE in the past, showing promising results for the recovery of quercetin (Choi et al., 2015).

Eggplant peels have been used for the production of pullulan, a maltotriose-composed polymer, by fermenting them with *Aureobasidium pullulans*, a fungus known for its high production of exopolysaccharides (Kazemi et al., 2019). The same fungus has been used in pumpkin peel hydrolysate, yet the production of exopolysaccharide was five times lower compared to eggplant (Akdeniz Oktay et al., 2022). Eggplant peels are also a good source of anthocyanins, which give them the classic purple color, making them a target for extraction. EAE has been applied for this purpose, showing interesting results (Amulya & ul Islam, 2023).

Additionally, the upcycling of pumpkin or carrot peels is interesting due to their substantial carotenoid content. FAE (as precision fermentation) using *Blakeslea trispora* has been recently applied to carrot peel powder mixed with orange and papaya peels, observing high production of β-carotene after 72 h of fermentation (Kaur et al., 2019). Although there is no recent published data on the recovery of carotenoids from pumpkin peels by EAE or FAE, carotenoid extraction of pumpkin flesh has been recently optimized using cellulose and pectinase, achieving recovery yields up to 61.75% under the best conditions (Sharma & Sogi, 2022). Fructooligosaccharides (FOS) have also been produced from carrot peels through SSF by *A. niger* (Guerra et al., 2023). This technique benefits from the production of β-fructofuranosidase by *A. niger* and other fungi, which can interchange fructose residues from different molecules to produce FOS. Guerra et al. (2023) obtained the highest β-fructofuranosidase production after 3 days at 30 °C (90.82 U/mL), and other authors are exploring the production of FOS from other food by-products (see section 5.6.).

5. Crops and cereals by-products

Crops represent the most significant food sources for human consumption worldwide with a production of more than 2.5 billion tons annually (FAO, 2023). Sugarcane, wheat, maize, rice, soy, and barley are the most significant crops on a worldwide scale, whereas sorghum, millet, oat, and rye are highly produced cereals. Regrettably, more than 30% of this production becomes waste due to losses during agricultural production and processing operations in milling and other processes within the cereal-based goods industries, representing 12.9% of total food waste (Fărcaș et al., 2022). Besides the losses during agricultural management and primary processing, the two main by-products of the milling industries for flour production are bran and germ. The primary rationale behind the removal of germ and bran is their adverse effects on the processing properties of flour, despite their abundance of vitamins, minerals, and dietary fiber (Verni et al., 2019). Considering the similarity in composition among different by-products from the same crop/cereal, the subsections were divided according to the crop/cereal type, and all the studies are summarized in Table 3.

5.1. Rice

Rice (*Oryza sativa*) serves as the primary dietary staple in Asia and Africa. The cultivation of rice annually results in the generation of substantial amounts of straw, husks (approximately 20% of the rice

Table 3
Recent publications on the application of EAE and FAE on crops and cereal by-products.

Product	By-product	Microorganism/ Enzyme	Objective	Process parameters	Required pretreatment	Outcome	Reference
Rice	Rice-starch by-product	*Lacticaseibacillus rhamnosus*, *Lactiplantibacillus plantarum*	Production of bioactive peptides	rice-starch by-product supplemented with sugar and minerals at 37 °C for 72 h	None	Production of antioxidant, antihypertensive, anti-tyrosinase anti-inflammatory and anti-aging peptides	Babini et al. (2020)
Rice	Defatted bran	*Trichoderma viride*	Bounded phenolics	water content 66.57%, inoculum of $10^{5.19}$ spores/g dry weight, fermentation at 28 °C for 100 h, pH 4.23.	Separation of insoluble dietary fiber from defatted rice bran	Release of ferulic acid, p-coumaric acid, and organic acids, and increase in antioxidant, α-amylase, and α-glucosidase inhibitory activities	Xie et al. (2021)
Rice	Bran	Neutrase	Release of feruloyl oligosaccharides and ferulic acid	Enzymatic extrusion at the moisture content of 30% and screw speed of 50 rpm	None	Increase of feruloyl oligosaccharides and ferulic acid	Deng et al. (2023)
Rice	Bran	*Aspergillus oryzae*	Release of total phenolic content	Fermentation at 25 °C for 4 days	Soaking of rice bran powder	Increase the total phenolic content (mainly gallic acid and ascorbic acid) and antioxidant potential	Punia et al. (2020)
Barley	Brew Spent Grain	*Aspergillus niger* enzymatic cocktail	Release of sugar	Incubation at 40 °C, 270 rpm for 100 h	Preparation of enzymatic cocktail from BSG fermentation in bioreactor	Increase the total phenolic content (mainly gallic acid and ascorbic acid) and antioxidant potential	Paz et al. (2019)
Barley	Bran	Neutrase	Release of feruloyl oligosaccharides and ferulic acid	Enzymatic extrusion at the moisture content of 30% and screw speed of 50 rpm	None	Increase of feruloyl oligosaccharides and ferulic acid	Deng et al. (2023)
Barley	Malting rootlets	*Lactiplantibacillus plantarum*, *Lactobacillus amylovorus*, *Weissella cibaria*, *Leuconostoc citreum* and *Limosilactobacillus reuteri*	Increase of functional potential of barley rootlets	Fermentation at 30 °C for 4 days	Heating at 90 °C for 30 min and sugar addition (5% w/v)	Conversion of fructose into mannitol, increase in fructan content, and modulation of oil and water binding capacities	Neylon et al. (2023)
Barley	Bran	*Aspergillus oryzae*	Release of total phenolic content	Fermentation at 25 °C for 7 days	Soaking of barley bran powder	Increase the total phenolic content (mainly gallic acid, ascorbic acid, and catechin) and antioxidant potential	Bangar et al. (2022)
Wheat	Bran	*Lacticaseibacillus rhamnosus*	Increase of functional properties to obtain a functional ingredient	Inoculum of 10^7 CFU/mL and incubation at 37 °C for 48 h	None	Increase of phenolics and antioxidant properties of wheat bran, increase in arabinoxylans (3 folds)	Spaggiari et al. (2020)
Wheat	Bran	*Enterococcus faecalis*	Production of an extract with high functional value	10% of inoculation rate at final moisture content of 60%, fermentation at 37 °C for 36 h	None	Increase in phenols, flavonoids, and alkylresorcinols contents, as well as the antioxidant and free radical scavenging activities, Ferulic acid in concentration 5.5-fold higher.	Mao et al. (2020)
Wheat	Germ	*Lactiplantibacillus plantarum*	Production of an extract with high functional value	Fermentation at 37 °C for 2 days pH 6	None	Release of total phenolic content, dimethoxy benzoquinone, and increase of antioxidant activity. Increase of peptides and gamma-aminobutyric acid concentrations	Bayat et al. (2022)
Wheat	Germ	Alcalase	Production of protein hydrolysate with high functional properties and structuring potential	Protein hydrolysate in water bath at 50 °C, speed of 200 rpm, enzyme rate 1% (of	Production of protein isolates hydrolysate	High free amino acids with high essential amino acids concentration and high	Ghelich et al. (2022)

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Table 3 (*continued*)

Product	By-product	Microorganism/ Enzyme	Objective	Process parameters	Required pretreatment	Outcome	Reference
				the hydrolysate protein), 30 min		solubility, foaming, and emulsifying properties	
Rye	Bran	Viscozyme L	Ferulic acid production	Incubation at 44 °C and 100 rpm	None	Releasing 369.3 mg of ferulic acid per 100 g of rye bran	Radenkovs et al. (2021)
Maize		*Lactiplantibacillus plantarum* and *Weissella confusa*	Production of functional ingredient	Inoculum of 10^7 CFU/g. Fermentations at 30 °C for 24 h.	None	Release of free amino acids and peptides, increase of antioxidant activity, phytic acid degradation and lipase activity decrease.	Pontonio et al. (2019)
Maize	Cooked maize by-product (nejayote)	*Pleurotus ostreatus*	Production of functional ingredient	Inoculum with 3% w/w, fermentation at 25 °C for 3 days	Preparation of nejayote from tortillas preparation	Increase of 325% in phenolic and 2 folds in the antioxidant capacity. Increase of 45% of soluble dietary fiber	Acosta-Estrada et al. (2019)
Sugarcane	Bagasse	*Aspergillus oryzae*	Production of fructooligosaccharides (FOS)	SSF, tray reactors, 5 g of substrate supplemented with mead, pH 4.5, moisture content 70%, inoculation at 2×10^7spores/g, 30 °C, 36 h. Obtention of extract after SSF.	Washing with distilled water, drying at 60 °C, dehydration at 60 °C for 3 days and milling to obtain a particle size <0.5 cm.	Maximum FOS production at 12 h of fermentation (7.64 g/L of extract).	De la Rosa et al. (2020)
Sugarcane	Bagasse	Endoxylanase from *Aspergillus flavus*	Production of xylooligosaccharides (XOS)	Enzymatic hydrolysis of xylan extracted from sugarcane bagasse at 50 °C, mild shaking (50 rpm), 5–120 IU of enzyme activity, xylan concentration at 0.5% (w/v), reaction time 16, 24 and 48 h.	Chopping, washing with hot distilled water, oven drying at 60 °C for 24 h, and sieved to a uniform size of <4 mm. Delignification pretreatment using different reagents (sodium hypochlorite, sodium chlorite, aqueous ammonia, H_2O_2-Hac). Endoxylanase produced by *A. flavus* MG-7 was first purified and concentrated (ammonium sulfate fractionation) followed by dialysis for 8 h. Enzyme preparation was lyophilized. Both processes were optimized	Maximum reducing sugar content (947.49 mg/g of xylan) produced at 100 IU concentration, 24 h and 2% xylan concentration (w/v). XOS produced consisted of xylotetrose (69.75%, w/w), xylobiose (13.17%, w/w), and xylotriose (8.37%, w/w).	Gupta et al. (2022)
Sugarcane	Molasses	*Halomonas* sp.	Production of levan	300 mL of culture media, 1% inoculum (v/v) grown overnight, orbital shaker incubators at 180 rpm and 37 °C, up to 210 h of fermentation.	Use of sugar beet molasses and starch molasses were clarified (5000 *g*, 15 min), pH adjusted to 7, followed by sulfuric acid, activated carbon, and tricalcium phosphate pretreatment. Subsequent sterilization 121 °C for 2 min.	Higher biomass and levan concentrations after 210 h of fermentation (6.09 g dried cell weight and 12.4 g levan/L of extract, respectively).	Küçükaşik et al. (2011)
Soybean	Hulls	Recombinant strains of *Saccharomyces cerevisiae*	Xylitol production	Two oxygenation conditions were tested: anaerobic conditions (50 mL of hydrolysates in 250 mL Erlenmeyer flasks sealed with silicone stoppers), and aerobic conditions (150 mL of	Mixture of oat and soybean hulls (1:1) hydrolyzed by acid pretreatment (concentrated sulfuric acid, heat treatment 40 min at 121 °C, 1:10 (w/v)), followed by enzymatic hydrolysis by	Final xylitol concentration of 8.17 g/L under oxygen limitation	Cortivo et al. (2018)

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Table 3 (*continued*)

Product	By-product	Microorganism/ Enzyme	Objective	Process parameters	Required pretreatment	Outcome	Reference
				hydrolysates in 500 mL Erlenmeyer flasks sealed with oxygen-permeable cotton balls). All cultivations at 28 °C and 180 rpm of agitation.	Celluclast (0.1 M sodium citrate buffer at pH 4.8, 50 °C, 120 rpm in orbital shaker, 1:20 (w/v), 10, 15 and 20 FPU/g solids) and concentrated by vacuum at 60 °C, pH adjusted to 5.5 by 1 M NaOH		
Soybean	Hulls	*Aspergillus oryzae*	Extraction of phenolic compounds	SSF: 1 g of soybean hulls mixed with 10 mL of saline solution, 30 °C for 2, 5, 7 days. After fermentation, 10 mL of distilled water was added and filtered. Enzymatic treatment with α-amylase as positive control (pH 6, 90 U/mL, 10:1 solvent: solute ratio, 135 min, agitation 100 rpm, 30 °C).	Milling at 28,000 rpm and sieved to particle size between 0.21 and 2 mm, sterilization by autoclaving.	Higher recovery of phenolic compounds at 5 days of fermentation (~0.25 g GAE/100 g soybean hulls). Commercial α-amylase achieved a recovery of 0.102 g GAE/100 g soybean hulls.	Cabezudo et al. (2021).
Soybean	Hulls	*Aureobasidium pullulans*	Polymalic acid production	50 mL of medium containing 60–100 g/L of total sugar from the hulls hydrolyzation supplemented with corn steep liquor at 10 g/L as nitrogen source. Inoculation at 10% (v/v, magnitude of inoculum not disclosed), 25 °C rotary shaker 220 rpm for 4–7 days. Scale-up to 2 L production volume, same parameters except agitation changed to 600 rpm and aeration at 1 vvm.	Hydrolizate produced by acid treatment (0.1 M HCL at 121 °C, 15 psig, 30 min) and enzymatic process (Cellulase cocktail Ctec2, other information not provided), and concentrated in a rotary evaporator.	Malic acid produced at 0.5 g/L*h and a final yield of 0.4 g/g.	Cheng et al. (2017)

Only the most recent published articles were selected. Research articles related to the use of waste waters, solvents, or other liquid waste streams derived from cleaning, washing, or extraction processes were not included. The focus remained on the extraction of bioactive compounds or the production of useful compounds (i.e. lactic acid) from (formerly) insoluble material. BSG: brewer spent grain, GAE: gallic acid equivalents.

grain), and rice bran (approximately 6% of the rice grain) (Barcelos et al., 2020; Goodman, 2020). The composition of rice husks consists of cellulose, hemicellulose, lignin, silica, and several minor components. This compositional profile makes these by-products suitable for FAE not only by fungi but also by LAB. Additionally, rice bran is known to include PC, such as ferulic and p-coumaric acids which can be released by EAE. Therefore, several studies were performed by using purified and/or commercial enzymes to obtain oligosaccharides with prebiotic potential or PCs (e.g. ferulic, p-coumaric acid, vanillic and p-hydroxybenzoic acid) and peptides with potential antioxidant activity (Barcelos et al., 2020; Tlais et al., 2020). Recently, (Deng et al., 2023) optimized an enzymatic extrusion process to obtain high feruloyl oligosaccharides (more than 5% of bran dry weight) and ferulic acid by using neutral protease. When looking at the potential FAE application, the fermentation by *Trichoderma viride* released bound phenolics from defatted rice bran by SSF in higher concentration (up to 5.55 mg GAE/g dry weight) than alkaline hydrolysis in terms of ferulic acid, p-coumaric acid, and organic acids thus increasing antioxidant, α-amylase, and α-glucosidase inhibitory activities (Xie et al., 2021). Another fungal culture of *Aspergillus oryzae* was used in SSF to increase the total phenolic content of the same matrix (mainly gallic acid and ascorbic acid in concentration up to 23.3 and 12.7 μg/g, respectively) after 4 days (Punia et al., 2020). Similarly, *Aspergillus awamori* was compared to *Aspergillus oryzae* finding that the first one was able to increase the phenolic acids of black rice bran up to 2735.7 μg/g and the antioxidant activity evaluated by DPPH assay up to 22.90 TE/g. Moreover, the tyrosinase inhibition activity increased after FAE, reaching tyrosine values of approximately 30% by using either fungi (Shin et al., 2019). Cellulose and hemicellulose degradation of rice chaff was obtained through the combined fermentation by *Thermobifida fusca* and *Ureibacillus thermosphaericus* allowing the production of reducing sugars (Nakamura & Kurosawa, 2020). Although protein fraction is not the most abundant in rice by-products, the set-up of fermentation by *Lacticaseibacillus rhamnosus* and *Lactiplantibacillus plantarum* led to the release of different peptides with significant biological value including antioxidant, anti-hypertensive, anti-tyrosinase, anti-inflammatory and anti-aging effects (Babini et al., 2020). The functional properties of fermented rice by-products were also exploited by Moon and Chang (2021) after obtaining a 20% bran slurry.

The fermentation of the slurry increased the cholesterol binding (up to 68%) and antimicrobial activities against foodborne pathogenic bacteria and food spoilage fungi. This was due to the combination of the selected bacteria strain properties and the bran compounds released during the process.

5.2. Barley

Barley (*Hordeum vulgare*) is a prominent crop used for both human consumption and animal feed. Pearl barley, the grain without its husk, constitutes the most important form in which barley is marketed. It is milled or grounded and subsequently included in cereal-based formulations (e.g. bakery products) or consumed as porridge. Additionally, barley is primarily employed in the beer production process, and after malting, it yields a significant quantity of brewer's spent grains (BSG). Pearling by-products are characterized by high concentrations of tocols and β-glucans, found approximately at concentrations of 70 mg/kg and 40 g/kg of dry weight, respectively (Arvanitoyannis & Tserkezou, 2008).

BSG has been successfully used in the production of different nutrients, including oligosaccharides, β-glucans, and proteins, by using both EAE and FAE (Table 3, Puligundla & Mok, 2021). Paz et al. (2019) compared the effect of the enzymatic cocktail from *Aspergillus niger* obtained by SSF of BSG against commercial enzymatic cocktails in the production of sugars from BSG. Barley malting rootlets are another by-product derived from the beer industry. They are separated from barley malt considering the strong bitter taste, but are rich in fiber, protein, and minerals, being also a natural source of enzymes and antioxidants. FAE by 5 different LAB was used to increase the functional potential in terms of conversion of fructose into mannitol, increase in fructan content, and modulation of oil and water binding capacities (Neylon et al., 2023). Moreover, the fermentation of barley bran by *Aspergillus oryzae* for 7 days increased the concentration of the soluble PCs including gallic acid, which increased by more than 30-fold compared to the unfermented bran (Bangar et al., 2022).

5.3. Wheat

In the process of traditional wheat milling, a significant portion of the endosperm is pulverized into wheat flour. Consequently, bran, together with the aleurone layer and residual endosperm, is transformed into a by-product during the milling process. Arabinoxylans and β-glucans are the predominant polysaccharides found while phenolic acids are usually trapped in the fiber network (Pontonio et al., 2023). On the other hand, wheat germ is considered the most nutritionally dense portion of the wheat grain with a global production of around 25 million tons per year, containing amino acids, polyunsaturated fatty acids, minerals, vitamins B and E, dietary fiber, as well as phytochemicals such as flavonoids and phytosterols (Khosroshahi & Razavi, 2023).

FAE by *L. rhamnosus* enhanced the levels of free PCs and antioxidant activity of wheat bran, in addition to increasing the solubilization of arabinoxylans by a factor of three (Spaggiari et al., 2020). Similarly, Mao et al. (2020) increased both antioxidant capacity and free radical scavenging capacity through FAE by *Enterococcus faecalis*, partly due to a substantial increase in the concentration of ferulic acid. Furthermore, high solubilization of dietary fiber content and the increase of amino acids were reported. Fermentation was also applied for the valorization of wheat germ resulting in an effective method for its stabilization, improving nutritional and functional values with its therapeutic potentials (for a review see Khosroshahi and Razavi (2023)). Recently, the optimal conditions for FAE by using *L. plantarum* were evaluated, obtaining extracts with great concentrations of PCs and 2,3-dimethyl-1, 4-benzoquinone, and high radical scavenging activity (Bayat et al., 2022). The characterization of the extracts included also the levels of peptides and gamma-aminobutyric acid (GABA) (20 g/kg) confirming the high value of the optimized process (Bayat et al., 2022). The quality of wheat germ fraction was also investigated by using EAE in the production of protein isolate. This protein isolate exhibited superior nutritional attributes, characterized by elevated levels of total free amino acids and essential amino acids. Additionally, it demonstrated enhanced structuring potential, as evidenced by improved solubility, emulsifying properties, and foaming properties, particularly when an endo-protease was utilized (Ghelich et al., 2022).

5.4. Rye

Rye production is comparatively lower than that of wheat. Furthermore, rye bran has received relatively limited attention in research, despite its potential as a valuable source of bioactive compounds such as benzoxazinoids, phenolic acids, and alkylresorcinols. The hydroxycinnamates found in rye bran, specifically ferulic acid, are structurally similar to those found in wheat and strongly bound to hemicellulose through ester bonds (Radenkovs et al., 2021). In recent extractions, EAE technology has been employed (Table 3). Notably, Viscozyme® L was utilized in an EAE lasting 48 h, resulting in the release of 369.3 mg of ferulic acid per 100 g of rye bran. This stands as the highest concentration achieved among rye, wheat, and oat bran when utilized as a lignocellulosic source (Radenkovs et al., 2021).

5.5. Maize

Maize bran typically comprises 60–70 g/kg after the milling process and, like other cereal brans, is considered a source of dietary fiber and natural dietary antioxidants. Maize germs derived from both dry and wet milling procedures are commonly employed in the food industry to extract edible oil (Barrera-Arellano et al., 2019). The improvement of maize by-product quality was evaluated by bacterial and fungal FAE. In detail, *L. plantarum* and *W. confusa* were used to ferment a germ and bran mix derived from raw and heat-treated maize milling by-products. The fermentation by these microorganisms increased the levels of free amino acids and peptides, along with the breakdown of phytic acid and an improvement in radical scavenging activity (Pontonio et al., 2019). *L. reuteri* and *L. plantarum* were used to increase the free PCs and antioxidant activity of maize bran (Akbari er al., 2023Fermentation by *Pleurotus ostreatus* increased PC, antioxidant capacity, and soluble dietary fiber contents after 3 days of fermentation of lime-cooked maize by-product (nejayote) (Acosta-Estrada et al., 2019). EAE was applied using a sequential treatment of xylanase and cellulase, in that order, thus allowing the release of xylo-oligosaccharides and glucose. The prebiotic-rich substrate obtained was then used to grow a probiotic strain of *Bacillus subtilis* (Yang et al., 2023).

5.6. Sugarcane

Sugarcane is another highly produced crop worldwide, reaching production rates of 1600 M Tn/year (Sarker et al., 2017). The process of extracting sugar from sugarcane results in significant by-products: approximately 280–300 kg of bagasse per ton of sugarcane, which is the fibrous material left after the sugarcane has been pressed for juice extraction; around 30 kg of press mud per ton of sugarcane, the solid waste collected after filtering out impurities; and about 40 kg of residual molasses per ton of sugarcane, a by-product remaining from the sugar crystallization process (Sarker et al., 2017). Sugarcane bagasse has been extensively investigated for biogas, bioethanol and enzyme production (e.g. cellulase, pectinase, pectate-lyase, laccase …), using either fungi or bacteria, and SmF or SSF. The production of enzymes from sugarcane has been reviewed and reported by Sarker et al. (2017). A novel, interesting strategy to upcycle sugarcane bagasse is to produce FOS or XOS, as it has important concentrations of hemicellulose (i.e. xylan) and cellulose. FOS production can be achieved through transfructosylating enzymes, as explained before (section 4.4.). De la Rosa et al. (2020) effectively upcycled sugarcane bagasse to FOS through SSF by *Aspergillus oryzae*, achieving a final concentration of 7.64 g FOS/L of extract

through SSF while using mead as a technological aid (Table 3). XOS production has been performed by xylan hydrolysis through endoxylanases from *A. flavus* (Gupta et al., 2022, Table 3), which could be extended to the use of the fungi directly in the sugarcane bagasse.

Press mud and molasses, rich in sugar and nitrogen, are frequently utilized in the production of hydrogen, bioethanol, or organic acids but they also serve as valuable resources for producing enzymes or microbiological media (Sarker et al., 2017). Molasses, in particular, is commonly employed as a raw material in the commercial production of yeast. The exploration of additional uses for these by-products is sometimes overlooked due to the commercial attractiveness of these established processes. Some authors attempted the production of levan polysaccharides through the fermentation of residual beet molasses by *Halomonas* sp., achieving 12.4 g of levan/L of extract (Küçükaşik et al., 2011) (Table 3).

5.7. Soybeans

Dehulling is one of the first steps in the primary processing of soybeans, which leaves the hulls as by-products. Approximately 20 M Tn of hulls are produced annually (Liu & Li, 2017). These hulls are composed primarily of fiber (including cellulose (up to 51%), hemicellulose (10–25%), lignin (1–4%) and pectin (4–8%)), with adequate amounts of protein (11–15%) (Liu & Li, 2017). Int terms of upcycling, recent research has used soybean hulls to produce xylitol (reaching 8.17 g/L under oxygen limitation conditions) through fermentation by recombinant strains of *Saccharomyces cerevisiae* (Cortivo et al., 2018), or to produce malic acid (up to 0.4 g/g of starting material) through fermentation by *Aureobasidium pullulans* (Cheng et al., 2017) (Table 2). In both cases, the starting hulls were hydrolyzed by using acid reagents and a subsequent enzymatic process to facilitate the release of fermentable sugars and the fermentation process. Another interesting research approach used soybean hulls as raw material for lipid production (47.9 mg lipid/g soybean hull), achieving a 3.3-fold increase when fermenting by *Mortierella isabellina* in SSF (Zhang & Hu, 2012). More than 80% of total fatty acids were C16 and C18, which difficult the upcycling of soybean hulls to functional ingredients through this strategy. SSF by *Aspergillus oryzae* has also been used as a technique to extract PCs from soybean hulls, achieving considerably higher recovery compared to a commercial solution of α-amylase (Cabezudo et al., 2021).

6. Conclusion, limitations, and recommendations

Food by-products are an inherent consequence of food production. As the global population increases, the need for food products increases, and the quantity and diversity of by-products subsequentially do too. To minimize their negative socio-economic and sustainable impact, food industries and researchers are compelled to upcycle food by-products to functional ingredients or products. Different strategies, such as the 2030 Agenda for Sustainable Development from the United Nations encourage and facilitate the implementation of these processes by laying out helpful guidelines. In that line, the use of visual, easy-to-interpret tools can be beneficial to achieve their implementation. In the present article, we developed a guiding tool (FBBW) in which we summarized the most fruitful enzymatic and/or fermentation processes to upcycle food by-products from some of the most consumed crops and cereals, vegetables, and fruits. Furthermore, the present article comprehensively revises the latest developments in the field of EAE and FAE from the same by-products, giving insight into which future research seems more promising. It would be worthwhile conceiving new wheels, encompassing other technologies available for food applications. These kinds of tools could streamline the transfer of technology from laboratory research to industrial implementation, spanning across numerous fields.

The development of these tools faces certain limitations. As we consider a technological transition towards industrializing the production of agro-industrial by-products, scalability becomes crucial. Much of the existing literature fails to address the scale-up of these processes, nor does it consider their life cycle assessments. Consequently, the technological readiness level of these processes remains at the laboratory scale. Future research should put more effort into scalability studies of the claimed findings, to ensure the lab research could be effectively translated into practical applications.

A significant volume of research is focused on the biotechnological upcycling of food by-products. Only a handful of approaches achieve the upcycling of the whole by-product, whereas the vast majority lead to the production of extracts rich in different bioactive compounds. While the latter approach provides valuable insights into potential upcycling strategies to various by-products, the ultimate objective should be the upcycling of the entire by-product. Such focus is crucial for minimizing the environmental footprint of food supply chains and should be implemented in future research efforts.

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Arnau Vilas-Franquesa: Conceptualization, Project administration, Investigation, Visualization, Writing – original draft, Writing – review & editing. Marco Montemurro: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. Melania Casertano: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. Vincenzo Fogliano: Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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