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Myco-biorefinery approaches for food waste valorization: Present Status and Future Prospects

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Abstract

Increases in population and urbanization leads to generation of a large amount of food waste (FW) and its effective waste management is a major concern. But putrescible nature and high moisture content is a major limiting factor for cost effective FW valorization. Bioconversion of FW for the production of value added products is an eco-friendly and economically viable strategy for addressing these issues. Targeting on production of multiple products will solve these issues to greater extent. This article provides an overview of bioconversion of FW to different value added products.

Keywords: Biorefinery; waste valorization; food waste; fungi; bioconversion.

1. Introduction

Food waste (FW) in solid forms has been generated throughout the entire food life cycle, from the agricultural production process to the distribution of processed foods and even to their consumption in the market (Nayak and Bhushan, 2019). Most FW originates from the beverage manufacturing industry, the dairy processing industry, and the processing of fruits and vegetables (Nayak and Bhushan, 2019). Among these wastes, dairy industry wastes/byproducts being fat and lactose-rich waste, as well as having a short shelf life and being easily contaminated are crucial problems regarding their waste management (Sar et al., 2021). Although, meat poultry, fish and vegetable oil production facilities generate relatively less waste than previous industries, their waste treatment is more critical given the content of these wastes. Considering that approximately 1.3 billion tons of edible FW is leftover annually, recycling FW to the biorefinery will contribute both economically and socially (Qin et al., 2021).

There is a need to perform potential valorization methods regarding the contents of food waste. Due to the valuable compounds (antioxidants, polyphenols, anthocyanins, and etc.) of fruits and vegetables, the wastes are potential raw material sources for various sectors such as pharmacology and food (Campos et al., 2020; El Barnossi et al., 2021; Kumar et al., 2017). On the other hand, considering the excellent contents of FW (carbohydrates, proteins, fats, minerals and vitamins), they are a potential source of substrates for microbial production processes (Awasthi et al., 2022a). Although, bacteria and yeasts are generally used in microbial production processes, and filamentous fungi are robust producers for biometabolite production regarding their wide range of enzyme production capabilities (Sar et al., 2021). Integration of FW to biorefinery to produce of value-added products such as organic acids, enzymes, single-cell proteins, ethanol, and biopolymers will contribute to both waste treatment/valorization and bioeconomy with microbial processes (Lakshmi et al., 2021). Moreover, some FW (especially fruits and vegetables) contribute to the bioeconomy by obtaining both environmental and edible biomaterials such as biofilms (Gustafsson et al., 2019).

To produce fungi-based value-added metabolites, an effective biorefinery approach (i), sustainable circular economy (ii), techno-economic profitability (iii), and social and ethical appropriate are required. This study aimed to examine various types of food waste sources and their evaluation targets. For this purpose, how FW can be evaluated in fungi-based bioproduction processes has been extensively discussed. In addition, potential biorefinery systems, circular bioeconomy processes, techno-economic studies and social/ethical aspects of FW in the evaluation of valuable products are discussed in detail.

2. Sources and targets of food waste valorization

Food wastes constitute the majority of waste around the world and the amount of waste has been increasing day by day. Although, solid types of food products such as fruits and vegetables constitute a significant amount of food waste, processed food and food industry wastes are more important regarding their chemical compositions. Various types of fruit and vegetable wastes may be released during agricultural activities and food industry processes. Fruits and vegetables such as apples, citrus fruits (oranges, lemons, tangerines, etc.), bananas, grapes, mangoes, pineapples, pomegranates, root vegetables (potatoes, carrots, and beets), tomatoes, cabbage and bean varieties constitute a significant part of the worldwide waste. These wastes can be unprocessed or fresh types as well as contaminated or processed products. In addition, some parts of the fruits (seeds, stems, peels, and etc.) that are released after processing cannot be consumed due to their physiological properties and are a natural waste source. For example, fruits such as avocado, mango and pineapple consist of approximately 10-20% seeds and 10-25% peel (Sagar et al., 2018), while pomegranate peels constitute 30-40% of the total fruit (Balaban et al., 2021). Moreover, some fruits (e.g., apples and grapes) are overused for various purposes (production of wine, cider, vinegar, molasses, and fruit juice) and naturally generate excessive amounts of waste. In some cases, over-produced fruits are not suitable for sale for fresh consumption (unacceptable color, shape, maturity, lesions, and etc.) is the main reason for waste (Løvdal et al., 2019). In addition, to the cultivation and production of tea and coffee plants, which are widely consumed all over the world, spent coffee grounds and tea leaf residues are also potential FW on a domestic scale or an industrial level (Gammoudi et al., 2021; Sermyagina et al., 2021).

With the use of fruits and vegetables in food processing industries, various types of waste/by-products are released, depending on the content of the raw material used and the type of process. The global dairy processing industries are potential waste generators and are responsible for the excessive release of cheese whey, as well as the generation of some lactose- and fat-rich wastes (Awasthi et al., 2022a; Sar et al., 2021). In some specific regions producing palm (Indonesia, Malaysia) and olive cultivations (Mediterranean Region), unwanted, oily and high COD-containing wastes (palm oil mill effluent and olive oil mill wastewater) are formed after the processing of these products (Rakhmania et al., 2022). Similarly, fat- and protein-rich fish processing side-streams are also important pollutant substrates having high COD in some territories where the fishing industry is developed (Sar et al., 2020). In addition, to fat-rich wastes, the sugar industry (sugar beet, sugar cane, potatoes, cassava) also releases FW containing a high percentage of carbohydrates (starch-based) such as molasses, and potatoes (Drosg et al., 2021; Mustafa et al., 2020). Since these sugar-rich wastes are also edible by-products, they are appropriate raw material sources for mainly ethanol and single cell oil/protein productions (Arshad et al., 2019; Ben Atitallah et al., 2019; Lakshmidevi et al., 2021; Sar et al., 2022). Food products (pastries, butcher, poultry, fishery products, fruits and vegetables, dairy products, and ready meals) that remain unconsumed and/or expired in the market are also potential sources of food waste (Brancoli et al., 2017).

The food industry by-products (whey, molasses, starches, fresh fruits and vegetables etc.) can be used for edible bioproducts such as single cell protein or lactic acid production, while the wastes (contaminated, expired or spoiled) can be used in some processes like anaerobic digestion (Sar et al., 2021; Awasthi et al., 2022b). Although, FW are generally used for purposes such as biogas production or wastewater treatment for the disposal of them, it is possible to obtain various microbial products by consuming these wastes/byproducts through the enzyme production abilities of microorganisms. The valorization of FW can be achieved by the recovery of nutrients and the production of energy/metabolites from food waste via the 4R framework (reduction, recovery, recycle and reuse) in waste management with circular bioeconomy (Figure 1) (Ferreira et al., 2021; Yu et al., 2021). Fruits and vegetables are rich in valuable compounds such as phenolic compounds, pectin, oils and fatty acids, etc. These valuable compounds can be recovered by various methods such as supercritical-CO_2 or solvent/solvent extractions (Balaban et al., 2021; Coelho et al., 2018; Roselló-Soto et al., 2019). These extracts, rich in bioactive components, can be used for medicine, pharmacology/cosmetic and food purposes thanks to their anti-inflammatory, antimicrobial and antioxidant properties. In the recycling process of solid and liquid wastes from the food processing industry, the wastes can be evaluated either as biofertilizers or the fermentation of microorganisms can be carried out to obtain bioproducts (Awasthi et al., 2022d). Recently, the existence of fungal strains capable of producing various hydrolytic enzymes has been needed to accelerate the process of obtaining biofertilizer from food waste. Liquid and solid biofertilizers can be obtained by the cultivation of fungal species such as *Aspergillus* in food waste (Ma et al., 2020). By incubating industrial organic wastes with fungal strains, it is possible to obtain biofertilizer as well as biogas production (Du et al., 2018; Hadidi et al., 2021). Moreover, various value-added microbial products (Figure 2) such as organic acids, enzymes, biopolymers, ethanol, and single-cell protein can be obtained from FW by using fungal strains (Yukesh Kannah et al., 2020). In addition, the total COD and solid levels of FW containing nutrients can also be reduced by the cultivation of fungal strains concomitantly microbial productions. Thus, wastes from food processing industries can be valorized by integrating the industrial wastes to fungal production processes (Ibarruri and Hernández, 2019; Marzo et al., 2019; Sar et al., 2020; Sar et al., 2022).

Recycling is considered the conversion of food waste into secondary raw materials by biotechnological processes, while reuse refers to the use again of food stuffs as food. Environmentally-friendly materials (biomaterials and 3D objects) were successfully obtained by using apple pomace (Gustafsson et al., 2019). Similarly, salmon skin gelatin was also evaluated for 3D food-printing to obtain biomaterials (Carvajal-Mena et al., 2022). Thus, new food production has been generated to improve 3D food matrix by using food printing techniques and thus food valorization has been also achieved (Carvajal-Mena et al., 2022; Gustafsson et al., 2019; Duan et al., 2021).

3. Value-added products from food waste

Regarding unremitting global population growth, an increasing demand for food supply has led to environmental concerns and over-exploitation of natural resources. Moreover, increasing agricultural and food industries' wastes that is related to the human food supply requires precise waste management practices such as anaerobic digestion, activated sludge treatment, composting, or even conversion of FW to novel products (Ebikade et al., 2020; Uçkun Kıran et al., 2015). In general, FW include different types such as manufacturing wastes (fish, meat, vegetable, fruits, milk, and wine processing wastes), municipal solid waste (MSW), wholesale waste, foodservice waste, and household waste (Figure 3). Although, liquid and solid forms of these FW contain a high amount of moisture and organic content (carbohydrates, lipids, and proteins) that causes environmental issues, these properties make them appropriate choices to be used as frequent and inexpensive substrates for the production of numerous value-added products with economic advantages through minimization of water and energy consumption (Battista et al., 2020) (Fig. 1). Traditionally, FW are frequently used as low-cost animal feed or fertilizer; however, many profitable products can be obtained from FW, including organic acids, volatile fatty acids (VFAs), bioplastics, biofuels, enzymes, natural fibers, single-cell protein (SCP), etc. through biorefinery-based and sustainable approaches (Battista et al., 2020; Capanoglu et al., 2022; Esteban and Ladero, 2018; Khatami et al., 2021).

3.1.Organic acids

Organic acids are commonly employed in various industries and produced chemically and biologically. Microbial fermentation is the most frequent method for organic acids production from FW and agricultural residues. The most remarkable organic acids include acetic acid, butyric acid, caproic acid, citric acid, formic acid, fumaric acid, lactic acid, levulinic acid, oxalic acid, propionic acid, succinic acid, valeric acid, and vanillic acid (Esteban and Ladero, 2018). Among these acids, citric acid, which is recognized as a GRAS (generally recognized as safe) organic tricarboxylic acid and broadly used in food and pharmaceutical industries, can be produced through solid-state fermentation (SSF) by *Aspergillus niger* when grown on FW, especially fruit wastes such as citrus wastes, apple pomace, peanut shells, banana peels, pineapple waste, and date waste (Uçkun Kıran et al., 2015). However, submerged fermentation (SmF) is more common process for citric acid production (Esteban and Ladero, 2018).

Lactic acid (in the form of L(+) isomer) is considered a significant preservative, flavoring, emulsifying, and pH buffering agent in the food industry, and it is applicable in pharmaceutical, chemical, textile and leather industries that can be produced through lactose, glucose, or sucrose fermentation by lactic acid bacteria (LAB) (Esteban and Ladero, 2018; Uçkun Kıran et al., 2015). Other products resulting from sugar fermentation include ethanol, acetic acid, propionic acid, and 2, 3-butanediol, which are valuable materials employed as initial substrates for other chemicals and polymers production. Moreover, lactic acid can serve as an initial block for the industrial production of acrylic acid, pyruvic acid, propylene glycol, 2,3-pentandione, and polylactic acid (PLA). LABS such as *Aerococcus, Carnobacterium, Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Streptococcus* and *Tetragenococcus* are responsible for lactose fermentation; however, the main industrial producer genus for lactic acid production is *Lactobacillus* (Tsapekos et al., 2020). Food wastes such as cheese whey, grape stalks remaining during the winery, cafeteria and kitchen wastes, sugar cane baggage, and mango peel are considered potential sources for lactic acid production. In general, lactic acid fermentation needs nitrogen sources that by employing FW as substrate, this economic bottleneck can be resolved and makes the fermentation more feasible. However, some types of FW that include lignocellulosic materials should be pretreated by using physicochemical, chemical, or biological pretreatment approaches (Uçkun Kıran et al., 2015). For example, grape stalks and its pomace (marc) have a lignocellulosic structure that is pretreated to release pentoses and hexoses. The hydrolysate obtained from pretreated grape stalks and pomace can be fermented to lactic acid, bioethanol and even biosurfactant (Nanni et al., 2021). In a recent study, sophorolipids were produced by growing *Starmerella bombicola,* which is a non-pathogenic yeast species on pretreated restaurant food waste (Kaur et al., 2019). Moreover, these FW are a suitable source for aromatic organic acids such as ferulic acid, gallic acid, and *p*-coumaric acid. These acids can act as antioxidants which are applicable in pharmaceutical, food industry, and cosmetics (Begum and Srivalli, 2019).

In addition to lactic acid, succinic acid has a growing market because of its importance to resins and coating agents industries. As well, succinic acid is a green substitute for petrochemical intermediates which are used for adipic acid, tetrahydrofuran, and 1, 4-butanediol (Esteban and Ladero, 2018; Uçkun Kıran et al., 2015). It can be produced by anaerobic bacterial genera such as *Anaerobiospirillum*, *Actinobacillus*, *Basfia*, *Mannheimia* or recombinant strains of *Escherichia coli* when grow on bread hydrolysate, wheat hydrolysate, restaurant wastes, released glucose of FW, bakery wastes, corn stover, molasses, and cheese whey (Esteban and Ladero, 2018; Kwan et al., 2015; Arun et al., 2022). Comprehensively, organic acids can be produced by specific pure cultures, artificially mixed cultures, or natural microbial communities. The latter has no pure and mixed cultures drawbacks and can be employed for organic acids production without providing aseptic conditions. However, the final product of acidogenesis by natural microbial communities is a mixture of various organic acids that requires exclusive downstream processes. Moreover, the composition of FW may influence the profile of produced organic acids. For example, acidogenic fermentation of glucose mainly results in butyric acid production followed by propionic acid and acetic acid while glycerol fermentation mostly produces propionic acid. Furthermore, presence of high content of lipids in FW inhibits the acidogenic fermentation of carbohydrates. Protein hydrolysis is known as a rate-limiting process during acidogenic fermentation; however, acetic acid is the most pertinent product of this hydrolysis process (Battista et al., 2020).

3.2. Polyhydroxyalkanoates (PHAs)

Various microorganisms are able to store carbon and energy under nutrition deficiency conditions in intracellular granules called PHAs (Battista et al., 2020; Tarrahi et al., 2020). PHAs are classified as aliphatic polyesters in which repeating units in PHAs are hydroxy acids (HO-R-COOH). Based on the OH group position regarding the COOH end group, α, β, and ω-hydroxyacids are categorized (Uçkun Kıran et al., 2015). The biodegradability and biocompatibility features of PHAs make them a suitable choice to replace petroleum-based plastics in medicine, pharmaceutical, agriculture, food packaging, etc. (Nielsen et al., 2017). The most significant PHAs comprise poly(β-hydroxybutyrate) (PHB), 3-hydroxy-2-methylbutyrate (3H2MB), poly (hydroxybutyrate-co-hydroxyvalerate) (PHBV), polyhydroxyvaleric acid (PHV), 3-hydroxy-2-methylvalerate (3H2MV), and PLA (Esteban and Ladero, 2018; Otoni et al., 2021; Uçkun Kıran et al., 2015). PHB is a rigid thermoplastic that can be blended with other PHAs to improve its features, while PHBV is a crystalline thermal polymer that shows similarity to polypropylene. Additionally, PLA is an aliphatic crystalline thermoplastic that can be produced from starch. Sugar-containing FW such as potato starch, cotton seed hulls, beet molasses, cassava starch, winey wastes, corn stalks, carrot processing waste, and sugarcane press mud are appropriate sources for PLA production (Nanni et al., 2021; Uçkun Kıran et al., 2015).

However, high production costs have limited PHAs usage and commercialization. Many efforts have been made to reduce PHAs production costs through improving microbial strains, optimizing the fermentation process, finding affordable substrates and refining the downstream process for recovery of PHAs. The main cost of the PHAs production (up to 50%) is related to carbon substrate. Hence, it is reasonable to produce PHAs from low-priced carbon sources such as agricultural residues, FW, and food-processing wastes, including whey, corn liquor, date syrup, starch, legume wastes, spent coffee grounds, citrus wastes, sugar beet juice, sugarcane bagasse, avocado seed, waste oils, peanut husk, molasses, etc. (Nielsen et al., 2017; Otoni et al., 2021). In Table 1, various FW used for the microbial production of PHAs is listed. In a study conducted by Wang et al. (2020), food waste effluent containing VFAs has been used for PHAs production by a halotolerant *Bacillus cereus.* This acidogenic substrate is a promising feedstock for PHAs production as it results in 0.4 g/L PHAs from effluent in comparison to 0.34 g/L obtained from pure VFAs. Besides, *Bacillus megaterium* ATCC 14945 is able to utilize acidogenic FW for PHAs accumulation (Vu et al., 2021). However, some FW have a complicated structure that cannot be used directly by PHAs-producing microorganisms and should be undergone different pretreatments. These substrates can be utilized by pure cultures and mixed microbial cultures, but the yield of PHAs in mixed cultures (less than 65%) is lower than pure cultures (80%) (Nielsen et al., 2017).

3.3. Biofuels

Food wastes can be converted into liquid or gaseous fuels through biological, chemical and thermo-chemical processes. Biological approaches include dark fermentation (DF) and anaerobic digestion (AD), which convert FW into hydrogen and biogas (CH_4, CO_2, and H_2S) (Mohanty et al., 2022; Qu et al., 2021). Based on the thermo-chemical processes, many different final products may be produced. For example, during gasification, syngas (a mixture of CO_2, CO, CH_4, and H_2) is produced under limited oxidizing conditions, while pyrolysis of FW in the absence of oxygen results in solid char and liquid tar (Huang et al., 2020; Jeevahan et al., 2021). Citrus wastes, sugarcane bagasse, banana and pineapple peels, coconut sells, etc. have been gasified to form gaseous biofuels such as hydrogen and syngas (Jeevahan et al., 2021). Besides gaseous fuels, liquid biofuels such as bioethanol and biodiesel are biologically produced from various feedstocks including FW such as pastry and restaurant wastes which contain a large amount of lipid. Recently, Xia et al. (2016) showed that pea vine waste could be an exciting feedstock for bio-oil and biochar production due to its high organic content. Moreover, waste cooking oils, animal fats, and chicken skin are considered potential raw materials for bio-oil production. Bio-oils have a wide range of edible and non-edible applications, such as serving as lubricants (Esteban and Ladero, 2018).

3.3.1. Ethanol

Second-generation ethanol is produced from non-edible resources such as lignocellulosic materials and FW. Currently, cereal crops residues, tomato processing waste, olive pruning, grape processing waste (grape stalks, lees, and pomace), banana peel, mango waste, corn stalk, pineapple waste, cassava pulp, cane molasses, papaya waste, kitchen garbage, etc. are commonly used as substrates for bioethanol production by *Saccharomyces cerevisiae*, *Trichoderma reesei*, and *A. niger*; although, these substrates should be pretreated to increase accessibility of fermentable sugars (Nanni et al., 2021; Panahi et al., 2022). Recently, cheese whey was subjected to be used for bioethanol production; however, the high concentrations of lactose and proteins present in the whey do not allow it to be a competitive substitute for the cane (Chavan et al., 2022). Despite the high cost of current technology for the production of second-generation bioethanol, the utilization of free agri-food wastes for energy production affects the regional economy positively and mitigates the environmental problems caused by these wastes. On the other hand, by overcoming bioethanol production obstacles through the development of effective, robust, and inexpensive enzymes and microbial strains, improvement of the fermentation process, and practical implementation of the 3-R strategy (recycling, reduction and reuse), the current technology can be upgraded (Yan et al., 2020; Narisetty et al., 2022).

3.3.2. Hydrogen (It is added by me. If it is not required you can remove it.)

Hydrogen is receiving increasing interest as a future green fuel due to remarkable advantages such as carbon-free nature, high energy content (2.75 times higher than common fossil fuels), and clean combustion product (H_2O) (Jeevahan et al., 2021). At present, it is traditionally produced from natural gas, ammonia and methane reforming, heavy oils and even electrolysis. But low-cost wastes can be sustainable substitutes for hydrogen production through photo-fermentation, DF, and thermo-chemical processes, reducing the dependency of the production process on fossil fuels. Among these processes, DF of wastes is a promising feasible approach in which no external light and energy sources are necessary. The FW from tofu, potato, milk, and sugar industries are considered suitable feedstocks for biohydrogen production. However, FW composition, microbial community structure, temperature, operating conditions, retention time, loading rate, etc. may affect hydrogen yield (Chavan et al., 2022; Harirchi et al., 2022).

3.4.Enzymes

Progress in biotechnology and biochemistry increases the demand for more effective and robust enzymes for industrial applications. The most commonly used enzymes in different industries include amylases, insulinases, proteases, pectinases, lipases, cellulases, lignin and manganese peroxidases, laccases, and xylanases. Inclusively, high production costs of enzymes may restrict their usage; therefore, it is an essential priority to reduce the total costs of enzymes production and make them affordable for the industry. One of the essential ways to reduce total costs of enzymes production refers to the use of inexpensive carbon, nitrogen and energy sources for the growth of enzyme-producing microbes such as *Rhizopus*, *Trichoderma*, *Aspergillus*, and

Bacillus. Enzymes production by these microorganisms can be carried out through SSF and SmF. In SSF process, enzymes production is carried out with lower water and energy consumption compared to SmF. Moreover, despite SmF, less volume of effluent is produced during SSF. One of the substantial advantages of SSF is related to the usage of low-cost wastes as initial substrate for enzymes production (Chilakamarry et al., 2022). Food wastes such as bakery and restaurant wastes, potato peels, soy fibers, tannery solid wastes, tomato pomace, chicken feather, apple pomace, wheat bran, cotton wastes, rice straw, corn wastes, ground nut, oil cakes of coconut, sugarcane bagasse, and mustard are affordable and nutrient-rich substrates for enzymes production via SSF because practical procedures of this method are almost straight forward (Tuly et al., 2022). However, the production of each commercial enzyme necessitates various operating conditions, specific substrates, and downstream processing that should be optimized for higher enzyme production. In comparison to agricultural residues, FW are more preferable as they contain a higher amount of nutritional supplements; therefore, it is not necessary to add any extra nutritional supplements during enzyme production (Uçkun Kıran et al., 2015). Some examples of enzymes produced from FW are shown in Table 2.

3.5.Bio-compost

Food wastes, due to their high moisture and biodegradable organic contents, can be subjected to a natural aerobic process in which thermophilic microorganisms break down organic materials and produce bio-compost (Rashid and Shahzad, 2021). This material is an appropriate substitute for mineral fertilizers. Vermicomposting is the same as the traditional composting process; expect that earthworms are used during the processing to improve the final bio-compost properties (Pour and Makkawi, 2021). Based on the aeration way and storing conditions, there are three common approaches for composting: a) aerated piles, b) passive piles, and c) in-vessel, which in the latter environmental conditions are optimally kept to increase aerobic deterioration of the wastes. Composting is an affordable but out-fashioned degradation process of the wastes as it has some drawbacks such as GHGs (Greenhouse gases) emissions, releasing of volatile organic and inorganic compounds, and irritating odor emission. However, controlling environmental parameters and optimizing process conditions can mitigate process problems to produce highly effective and enriched bio-composts (Cerda et al., 2018; Jeevahan et al., 2021).

3.6.Myco-food, feed and protein

Food wastes are appropriate sources for SCP production, farm animal feeds, edible mushroom cultivation, myco-proteins (fungal proteins), and functional peptides due to their nutritional values. Moreover, fungal-treated FW and agricultural residues have no hazardous risk to be used as functional feeds (Pourbayramian et al., 2021; Wong et al., 2016). In general, fungi can break down recalcitrant materials and release more nutrients that result in improved digestibility and trace elements availability in animal feeds. For example, wheat straw fermented with edible *Pleurotus ostreatus* (oyster mushroom) showed a considerable decrease in lignin, cellulose, and hemicellulose contents by 37.48 %, 37.86 %, and 45.00 %, respectively, after 30 days while it contended high crude protein (5.08%) (Shrivastava et al., 2011). In addition to mushroom cultivation, SCP production of *S. cerevisiae* through SmF was performed on vegetable and fruit peels (Gervasi et al., 2018). For instance, Mondal et al. (2012) demonstrated that the crude protein extracted from 100 g of cucumber peels as the substrate for *S. cerevisiae* growth was 53.4%. Moreover, cheese whey has been used for edible mushroom cultivation and SCP production of different yeast species such as *Candida bovina*, *Kluyveromyces lactis*, and *Kluyveromyces fragilis* as animal feed. Additionally, food wastes such as peanut cakes, wheat bran, bakery and restaurant wastes, soybean cakes, and corn meal are recently used for fish feed pellets formulation and insect larvae used as animal feed (Ojha et al., 2020; Wong et al., 2016).

3.7.Other products

It is known that FW are valuable sources for various novel products. For instance, sea FW containing crabs, lobsters, or shrimps are convenient sources for the production of chitosan, a copolymer of *N*-acetylglucosamine and glucosamine, which has a wide range of applications in agriculture, wastewater treatment, medicine, pharmaceutical, winemaking, packaging industry, protein recovery from whey, etc. (Al-Tayyar et al., 2020; Esteban and Ladero,2018; Gupta et al., 2022). Moreover, limonene, a fragrance compound, which can be extracted from orange peels, has cosmetic and pharmaceutical applications (Bacanlı et al., 2018). Another example refers to tannins which are obtained from agri-food wastes such as grape pomace. Tannins are phenolic materials used in wood industry as adhesives or in pharmaceutical industry as antidiabetic, anti-inflammatory, and antimicrobial agent (Fraga-Corral et al., 2021). Other examples of value-added products can be referred to as bioactive compounds like immune-modulators, anti-viral and antibacterial compounds, antioxidants, pigments, hormones, anti-tumors, carotenoids, polyunsaturated fatty acids (PUFAs), and vitamins (Čolović et al., 2019; Lai et al., 2022; Wang et al., 2022). Winery and live wastes, berries, citrus, and tropical fruits residues, tomato peels, spent green tea, and spent coffee grounds are some examples of FW for antioxidant production (Čolović et al., 2019). Recently, a wide range of agri-food wastes with high carbohydrate content (fruit peels, corn root, rice husk, potato and tomato peels, lettuce, onion, bean, and bakery wastes such as biscuit, bread, rice noodle, and risotto) have been valorized to levulinic acid, furfural, 5-hydroxylmethyl furfural (HMF), and formic acid. Formic and levulinic acids were produced in the presence of sulfuric acid and γ-valerolactone at high temperature (130 °C). Formate is considered a platform chemical that broadly employed in pharmaceutical, dyeing, and leather industries. Moreover, it has a great potential to be used as a hydrogen carrier in various applications (Ebikade et al., 2020; Yao et al., 2020). Another commodity chemical produced from FW is 2-methylidenebutanedioic acid (itaconic acid), that is widely used as an additive or building block in resins, detergents, dye, and lubricants industries. At present, itaconic acid is biologically produced, and *Aspergillus terreus* is the main producing microbe (Narisetty et al., 2021). Newly, the waste cooked rice was considered a valuable food waste for maltobionic acid production through a genetically engineered strain of *Pseudomonas taetrolens*. This aldonic acid is extensively used in pharmaceuticals, food, cosmetics, etc. and exhibits antimicrobial, chelating, antioxidant, and moisturizing features (Oh et al., 2022).

In addition to novel products from FW, sometimes these wastes can be valorized directly. For instance, cheese whey contains lactose, proteins, vitamins, and essential minerals such as calcium, sulfur, and phosphorus that make it applicable to be used as an animal feed additive or supplement. Approximately 9 kg of cheese whey (95% water) is produced per 1 kg formed cheese; therefore, ultrafiltration (UF) of whey results in protein concentrate and lactose-rich permeate as the latter is an appropriate substrate for microbial oil production, especially γ-linolenic acid. Furthermore, due to the low pH value of cheese whey, it can be employed for alkaline soils to decrease the pH value to the favorite levels. However, the application of cheese whey as a soil fertilizer requires precise regulations to avoid potential damages to soils structure (Chavan et al., 2022). Other examples can be referred to as spent coffee grounds, spent grains, sawdust, coconut fibers, or tea particles that are employed as bio-sorbents or bio-carriers due to their particular properties such as high porosity, presence of functional groups, biocompatibility, and high surface area.

Thoroughly, food wastes contain trace elements, sugars, lipids, amino acids, and different salts, etc., which are usual compounds for microbial growth and cultivation, and particularly microalgae (Chong et al., 2021; Jeevahan et al., 2021). This property of the FW provides a fascinating concept to modify various FW as microbial culture media to produce a defined compound (Jeevahan et al., 2021). For example, culture media containing corn starch, litchi extract, haricot extract, and pineapple juice are used for bacterial cellulose production by *Komagataeibacter xylinus* which is known as the best producing species for bacterial cellulose (Esteban and Ladero, 2018). Along with value-added products obtained from FW, electricity can be generated through bioconversion of FW organic materials in microbial fuel cells (MFCs). This technology can work under ambient temperature with high efficiency in comparison to other conventional technologies. Though, FW characteristics such as organic matter content, moisture, inhibitors, and pH, etc. and may affect the economic and efficiency of MFCs.

4. Biorefinery approaches for management of food processing waste

The circular biorefinery approach focused on the management and valorisation of bioresources towards intention of multiple bio-based products through industrial symbiosis collaboration by utilizing waste streams, recycling co-products and by-products and generating energy to boost the process with less environmental impact (Vlachokostas et al., 2021; Liu et al., 2021). In this context, the integration of multiple bioprocesses for production of industrial interest primary and secondary end-products could bring economic and environmental benefits, improving process efficiency, capex and opex of the process, resource recovery and waste upcycling with the objective to obtain a broad range of different bio-products, while sustainability in promoted (Kalmykova et al., 2018; Solarte-Toro et al., 2021). Renewable bioresources such as non-edible lignocellulosic biomasses are recognized as agri-food residues like straw, corn stover, cobs, and spent grains as well as vegetable and fruit bagasse, stems, cores, shells, seed and peels, have gained enormous attention as new raw-materials to produce biofuels and biochemicals, and many other high value compounds (Esparza et al., 2020). Since these food residues/by-products are highlighted as rich bioresources of value compounds e.g., organic acids, lipids, proteins, simple sugars and complex carbohydrates (cellulose, hemicellulose and lignin polymer), which can be isolated and extracted to later be applied as ingredients or substrates for different industrial purposes (Bhatia et al., 2020; Gómez-García et al., 2021a).

Particularly, fruit processing industries are recognized as one of the main actors that produce great quantities of lignocellulosic by-products, including stems, seeds and peels (among others) without any remarkable application (Campos et al., 2020). In this regard, several studies have been developed different strategies to manage food waste and by-products under biorefinery and bioeconomy contexts (Patel et al., 2019; Awasthi et al., 2022e). These by-products could be and should be valorized as soon as they are generated within the industrial processing chain due to their high produced amount and high-water content (up to 80%), which can promote the growth of microorganisms and therefore lead to spoilage and wastage. In this regard, fruit by-products have been treated under sustainable fractionation processes, avoiding the use of toxic chemical/solvents as well as expensive and sophisticated equipment in order to obtain multiple fractions (Ribeiro et al., 2020; Gómez-García et al., 2021). Such fractions present similar characteristics and compounds only differing in their concentrations (Figure 1). On one hand, a fraction rich in water (up to 90%), which also contain simple sugars and proteins among other in less extend (lipids and organic acids). Additionally, protein recovery can be performed in this rich water fraction by applying a green protein precipitation method, which represents a simple scale-up process, rapid technique for protein separation and does not use toxic chemicals (Gómez-García et al., 2021b). In this way, two fractions can be obtained, one rich in sugars and other rich in protein. On the other hand, a fiber rich fraction is generated with high content of cellulose and hemicellulose and in less amount lignin, starch or pectin (depending on the fruit). All the obtained fractions could be dried in order to reduce their volume but also to increase their stability and self-life.

Microbial fermentative process, which have gained research and industrial interest for obtaining multiple value-added byproducts can be applied after the sequential fractionation process of fruit by-products (Mancini and Raggi, 2021). Filamentous fungi are used in organic acid, enzymes and phenolic antioxidants production, bioethanol industry, food industries and pharmaceutical industry (Torres-Leon et al., 2019). For example, the liquid fraction can be used on a fresh weight as culture medium and the dry fibre rich fraction as support-substrate for liquid and solid-state fermentations, respectively. These fermentation processes can use several fungal strains such as *Aspergillus, Trichoderma, Penicillium, Rhizopus* and *Neurospora* (among others) to break down complex carbohydrates into simple sugars (pentose and hexose) due to their ability to produce hydrolytic enzymes, including cellulases, hemicelluloses, xylanases and lacases (Shah and Patel, 2017; Gómez-García et al., 2018; García-Galindo et al., 2019). The resulted simple sugars can be then fermented by yeast to biodiesel or bioethanol production. The integration of dark and anaerobic fermentation for biohydrogen, volatile fatty acid (VFA: acetic, butyric and propionic acids), polyhydroxyalkanoates (PHA) and methane production could be applied to exploit carbohydrate, protein and lipid portions of the waste by different bacteria consortiums (Mancini and Raggi, 2021; Harirchi et al., 2022). Therefore, the simultaneous production of enzymes, biofuels and biopolymers could make an integrative cost–effective and eco-friendly process when lignocellulosic by-products are used as carbon and nutrient sources. However, more evaluations and optimizations are needed to exploit completely the food waste as adequate substrate for microbial growth to produce cost-effective biocatalyst (enzymes), biochemicals (biopolymers), bioenergy (biohydrogen and biomethane) to make the processes more profitable and sustainable (Jain et al., 2022. Chatterjee and Mohan, 2022; Karimi and Taherzadeh, 2022).

5. Circular economy approaches

5.1. Techno-economic evaluation

Fungal biorefinery provides the opportunity for a sustainable circular economy. Various products could be obtained via fungal biorefinery including mycoprotein, alcohols, and organic acids. However, from an industrial perspective, the economic feasibility plays a pivotal role for its scale-up, commercialization, and expansion. The industrial feasibility can be verified using techno-economic analysis. Ethanol was the main product of various fungal biorefineries presented in the literature (Table 3). This was due to the lignocellulosic revolution which focused on ethanol as key liquid fuel. Various byproducts could be obtained alongside ethanol including DDGS, corn oil, Xylo-oligosaccharides (Awasthi et al., 2022c), pectin, electricity, heat, and CO_2 (Gerrior et al., 2022; Gomes et al., 2021; Manhongo et al., 2021; Wang et al., 2022). Bioethanol from lignocelluloses satisfies the demand in the transportation sector, simultaneously, valorizes the waste generated from agriculture, effectively. However, the ethanol production cost was high, when compared with sugar-rich first-generation ethanol. This was due to the low-bulk density, higher transportation cost, pretreatment and enzymes cost associated with it.

The capital expenditure of an ethanol-based fungi biorefinery varied between 5.01 t/h to 47.91 Mt/h, depending on scale, and the type of byproducts produced (Gomes et al., 2021; Kurambhatti et al., 2021). The production cost of such plants varied between 1-4 \$/gal. When compared with first generation ethanol plants, the CAPEX was 21.92% to 90.6% higher (Gerrior et al., 2022; Nazemi et al., 2021). Reducing the CAPEX and OPEX directly enhances the profitability of the process. Purification of ethanol was an energy-intensive process, which used evaporator to remove the water from ethanol and the byproduct of DDGS was obtained. Instead of DDGS, anaerobic digestion of leftovers after fermentation can result in an energy-rich compound of methane, which can reduce the energy dependency on the plant. Replacing the evaporator with anaerobic digestion reduces the CAPEX by 15.35% (from 147.9M$ to 125.2M$). This intern reduced the natural gas dependency from 347 GJ/h to 68 GJ/h (Gerrior et al., 2022). Furthermore, post to anaerobic digestion, the digestate can be used to produce struvite (natural fertilizer) which increased the revenue by 4% (when compared with evaporator system). This system provides a scope for a sustainable circular economy concept wherein the fertilizer can be used for the cultivation of crops which can be used to produce fuel and products including fertilizer.

New enhancements were attempted to improve the financial viability on the fungal biorefinery systems. This includes converting the carbon dioxide produced from the fermentation to convert it to additional ethanol via electrolysis. The carbon dioxide was reduced to carbon monoxide, while the water was split to hydrogen and oxygen. This process combines electrolysis with gas fermentation to produce additional ethanol. By adopting this way, 45% higher ethanol could be produced. However, the additional CAPEX required was 6.07 M$/t of ethanol produced (Huang et al., 2020). There were three key parameters that affect the industrial feasibility of ethanol production, which includes energy efficiency of electrolyser, cost of electricity and carbon dioxide conversion efficiency. The increasing cost of lignocelluloses over time challenges the profitability of ethanol. The usage of feedstock residues can help to overcome the above bottleneck for instance the cost of eucalyptus wood was 50$/t while that of eucalyptus wood residue from pulping industry was 15$/t, thereby reducing the feedstock cost by 70% (Iglesias et al., 2021; Pighinelli et al., 2018). In a similar case, when eucalyptus wood from pulp industry was used for ethanol production, it was not economically attractive (Gomes et al., 2021). To counter feasibility, whey liquid was added to the fermentation. This process increased the ethanol productivity by 50%, however NPV was negative. Next, an engineering approach of extracting xylo-oligosaccharides in the hydrolysis liquor was carried out as it was an expensive chemical (50,000 $/t). Nonetheless, the economic viability increased only when the energy optimization was placed alongside higher-grade products. Identically, producing pepsin and other phenolic compounds alongside ethanol increased the economic feasibility of processing mango waste (Manhongo et al., 2021). This shows that for a fungal-biorefinery to be self-sustainable optimization of product, co-products, and energy was necessary.

Third generation feedstock such a micro- and macro- alga provides an exciting opportunity for a fungal biorefinery system. Algae were known for pigments, alginates, protein, and fertilizer. When ethanol production was combined to it, a perfect platform for fungal-biorefinery exists to the plethora of products that could be obtained. However, the commercializing them has a long road ahead in-terms of higher yields, easier downstream processing, and energy optimization. Table 4 shows the products beyond ethanol from a fungal biorefinery system. Important products obtained from a fungal biorefinery system include citric acid, glutamic acid, succinic acid, furfural, and butanol. The production of higher-grade products was obtained from a biorefinery system, the probability of financial viability increases. The feasibility was affected by feedstock cost, pretreatment and the price of the product produced. For instance, producing glutamic acid was financially attractive, when compared with citric acid, though the CAPEX of the former was on the higher side (Özüdoğru et al., 2019). This was due to the product cost, where glutamic acid was sold at 3265 $/t, while citric acid cost 680 $/t (Özüdoğru et al., 2019). Likewise, the choice of feedstock determines the net present value (NPV) of producing a product. Producing succinic acid from grape pomace, grape stalks, and wines lees also helped in eradication of feedstock cost as wine making industries spend a minimum of $35/t for solid waste disposal which can be used to transport the feedstocks to biorefinery system. The above biorefinery yielded an NPV of $M39.4 and $M439.4 respectively, when the maximum and minimum market price of the co-products produced (grape-seed oil, crude phenolic extract, calcium tartate and crude tannin extract) were considered (Figure 4) (Ioannidou et al., 2022).

Trade-off was one of the criticalities in the feasibility of a biorefinery system. Higher product yield, energy consumption vs. profitability was one of the classical trade-offs. In certain scenarios, higher product yield must be compromised with the additional energy consumption. For example, consuming sugarcane bagasse for steam and electricity production improved the viability, when compared with producing itaconic acid (Nieder-Heitmann et al., 2018). In this case, the cost of raw material affected this trade-off to produce energy than the higher-value product of itaconic acid. Similarly, class of co-products produced states the profitability. A higher-value product with lower energy consumption would yield more return than vice-versa. Producing acetone and ethyl glycerol than acetone and ethanol as a co-product alongside butanol yielded bigger return on investment (ROI) in an Acetone-Butanol-Ethanol (ABE) fermentation. The ROI of the former process was 37% while the later had 8% lower ROI (Meramo-Hurtado et al., 2021). Similarly, the choice of favoring a pathway in a biorefinery also affects its profitability. Furfural was a common by-product in ethanol fermentation along with electricity generation. The profitability of such a process was usually competitive. However, the profitability reversed when furfural was produced as a main product alongside ethanol and electricity (Manhongo et al., 2021).

5.2. Social and ethical aspects

5.2.1. Social aspects

While awareness of the negative consequences of food loss and food waste is growing, this awareness does not necessarily cover all types of food. By the example of bread, a British study found that the amount of bread wasted at the individual level is perceived to be insignificant by consumers and some are under the impression that bread waste does not have a significant environmental impact (WRAP et al., 2011). Yet, a Swedish study found that 80 500 tons of bread are wasted each year and an estimated 30 000 tons (37% of the total bread waste and 8kg per person per year) are generated at the household level which is more than is wasted at the retail level. Given the amount of food loss and food waste, it is important to encourage individuals to engage in food waste prevention. One way of preventing food waste that can be done at the household level is fungal-fermentation of carbohydrate-rich leftovers in SSF to produce new food products from the biomass which can then be fried, grilled or cooked in any other way. Part of this can be to i) share instructions about how carbohydrate-rich leftovers, such as bread, can be fermented using fungi, or ii) to communicate the benefits of choosing products that are derived through fermentation of surplus resources.

To achieve wider awareness and motivate individuals to engage with fungi-based products that used rescued substrates, it is important to encourage individuals to find motives that are perceived as valuable enough to trigger engagement with such products or perhaps to inspire individuals to fungal-ferment themselves. Encouraging such reflections about such motives is a key action because motives and perceived meaning are the most influential triggers for behavioral change. Every individual holds unique perspectives and values. Motives to ferment leftover food may thus vary across individuals. Motives that may be perceived as valuable and trigger engagement may be of diverse nature such as socio-symbolic (e.g., being part of a societal movement), concrete (e.g., producing one's own food while also avoiding negative consequences of food loss and waste) or personal (e.g., satisfaction from re-using food instead of throwing it away). Nutritional benefits, which are the results of enzyme production during fungal growth (Rousta et al., 2021), may also be perceived as valuable and trigger engagement in fermentation or with food products derived from rescued substrates.

5.2.2. Ethical aspects

The global population is expected to grow to 9.8 billion by 2050 (UN, 2017). This increase will go hand in hand with even greater demand for resources in food production to provide humans with nutritious diets. Simultaneously, roughly one third of food produced for human consumption ends up as waste. Food loss not only results in unnecessary environmental implications such as CO_2 emissions and loss of ecological and economic value for farmers and consumers. But food loss is also linked to ethical concerns as millions of humans are undernourished and/or suffers from chronic hunger. There is an only limited amount of food that is rich in nutritious and protein-rich in some parts of the world. Disregarding other important micronutrients and focusing on protein alone, this results in more than one billion people being unable to meet daily protein requirements (Godfray et al., 2010). Moreover, because the global distribution of food is uneven, demands for sustainable, affordable and accessible high-quality food are raised. Filamentous fungi generally grow on substrates that contain sources of carbon and nitrogen, such as, for example, rice, legumes, bread, grains and cereals (Gmoser et al., 2020; Hong and Kim, 2020). Filamentous fungi can covert sources of carbohydrates into a fungal biomass that is rich is many macro- and micronutrients, including proteins, dietary fibers, fat, vitamins and minerals, and that are essential for human health (Alberti et al., 2017).

Fungal fermentation can so provide individuals with opportunities to provide for themselves without having to rely as much on supply chains and well-stocked grocery store shelves. This can be especially important when access to protein- and nutrient dense food is difficult, because fermentation may enable individuals to convert cheaper carbohydrate-rich food into nutritious and protein-rich fungal biomass. Because fungal-fermentation in SSF requires relatively little amounts of water, it may be a constructive approach not only to lessen FW and food loss but also in the fight against hunger, and (protein-) malnutrition in famine-stricken areas. Another ethical dimension in this context centers around the involvement of human subjects in future research on fungi-based food that is based on rescued substrates, including tasting studies. Ethical review requirements will vary depending on legislation where the research takes place. In the European Union, as an example, some fungal species may be considered novel by the European Union's Commission for Food Safety (EC, 2021) which may lead to ethical review requirements in certain member states.

6. Conclusion

Bioconversion of food waste to value added products have several economic and environmental benefits. It will address two major societal issues – production of a value-added product as well as waste management. Targeting production of multiple products will reduce the overall process economics. Several fungal species serve as a potential candidate for effective bioconversion for producing multiple products. One of the major challenges is the heterogeneous nature of food waste as well as the higher moisture content. Using mixed cultures or natural microbial communities for the production of multiple value added products, most of these challenges can be addressed to a greater extent. Various fungal fermentation approaches could be implemented for waste food valorization and this will enhance the resource utilization and also address the environmental issues.

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.

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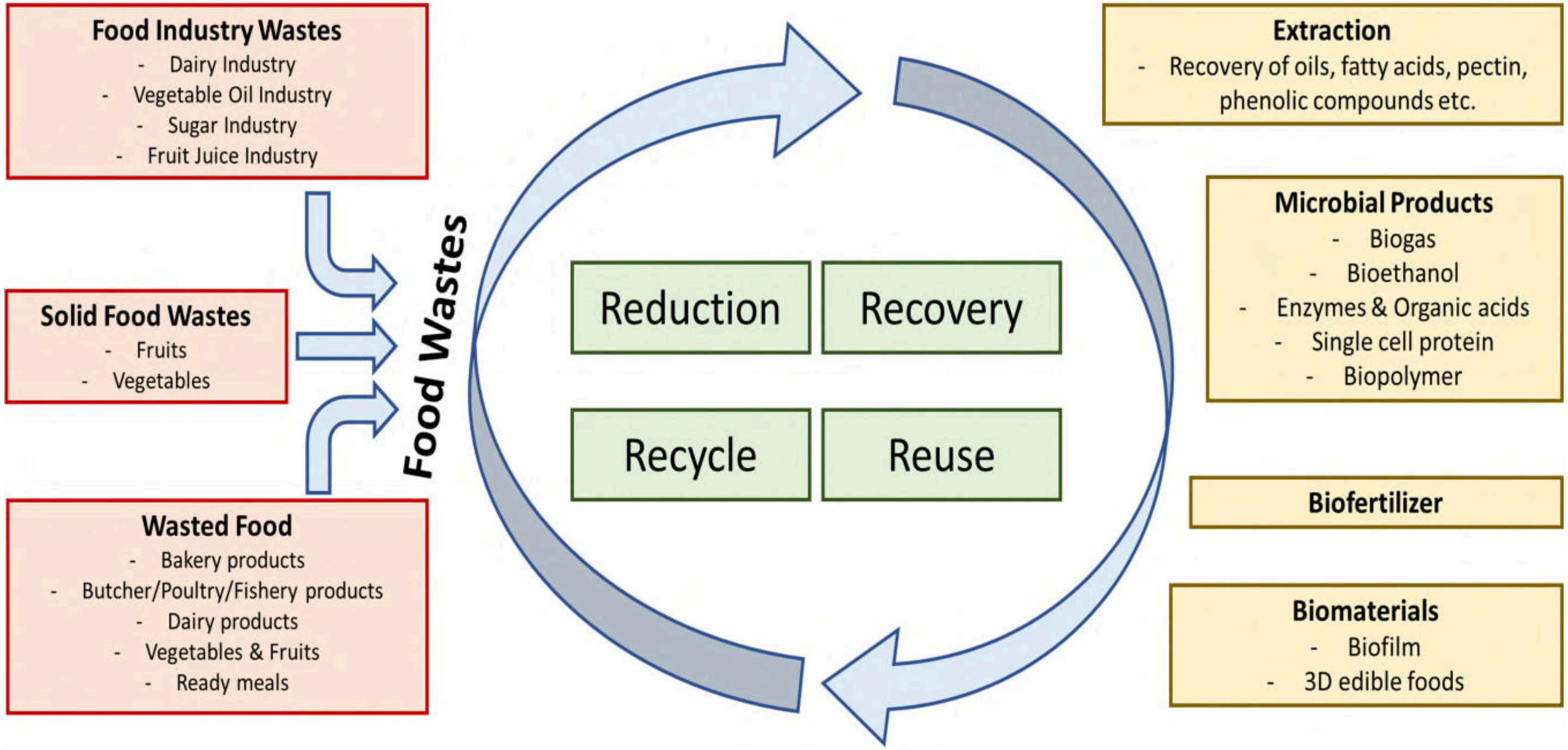


Figure 1. Obtaining value-added products by valorization of various types of food wastes.

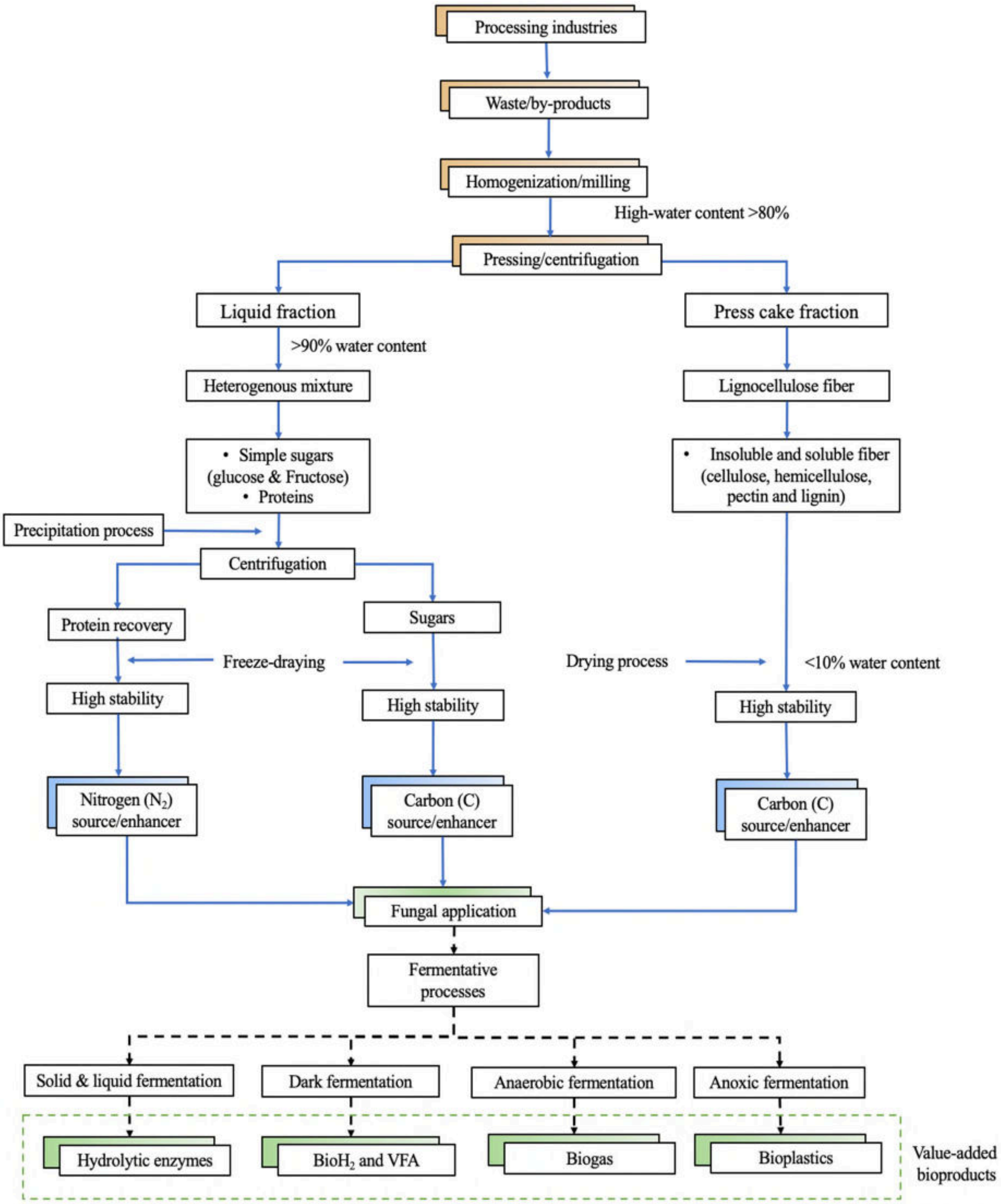


Figure 2. Biorefinery approach on fruit by-product to obtain multiple fractions and their application as carbon source in different fermentative processes.

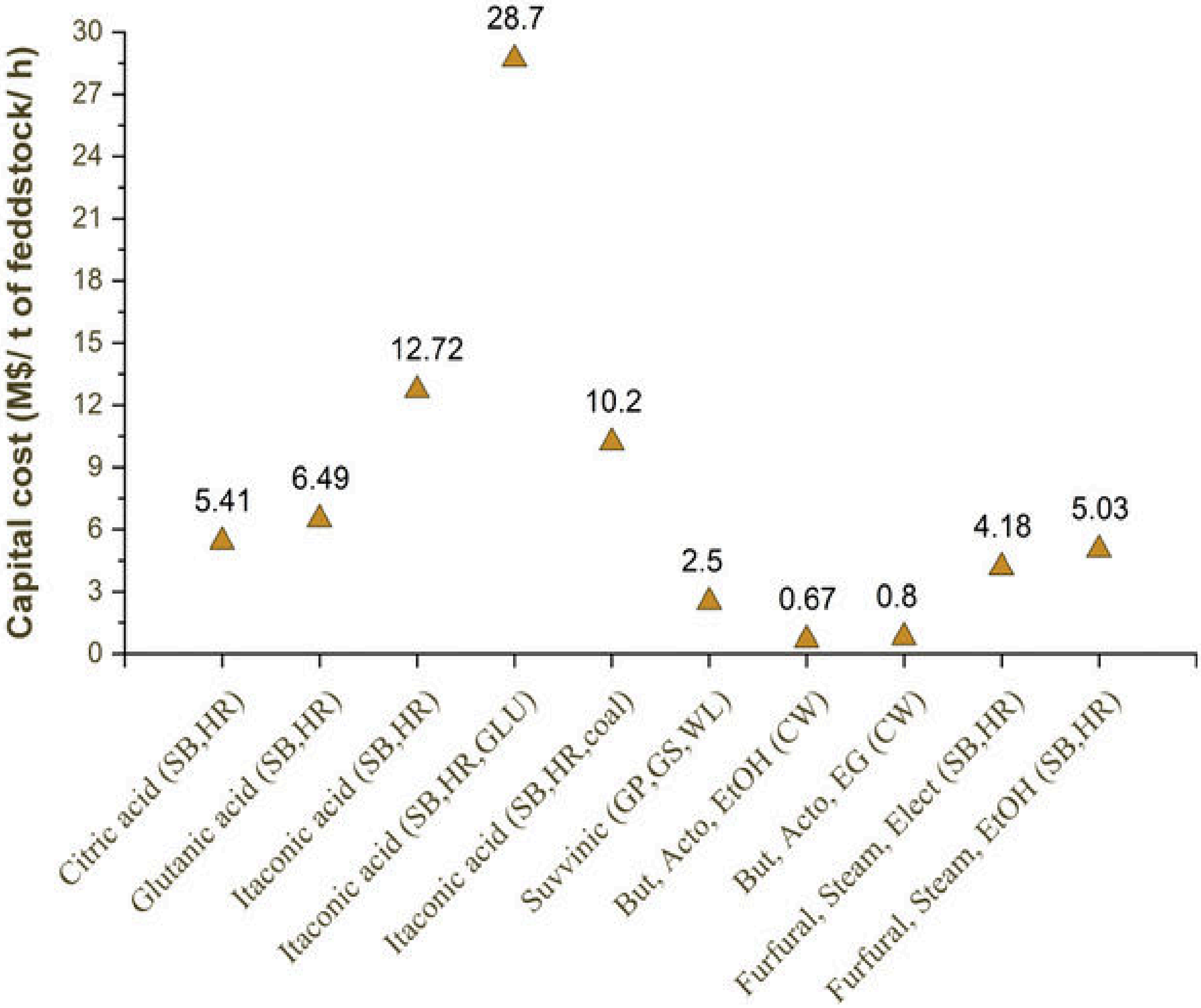


Figure 3. Capital cost of biorefinery system that produces other than ethanol as primary product SB – Sugarcane Bagasse, HR – Harvesting residue, GLU – Glucose, GP – Grape pomace, GS – grape stacks, WL – Wine lees, BUT – Butanol, Acto – Acetone, EtOH – Ethanol, EG – Ethylene glycerol, Elect – Electricity.

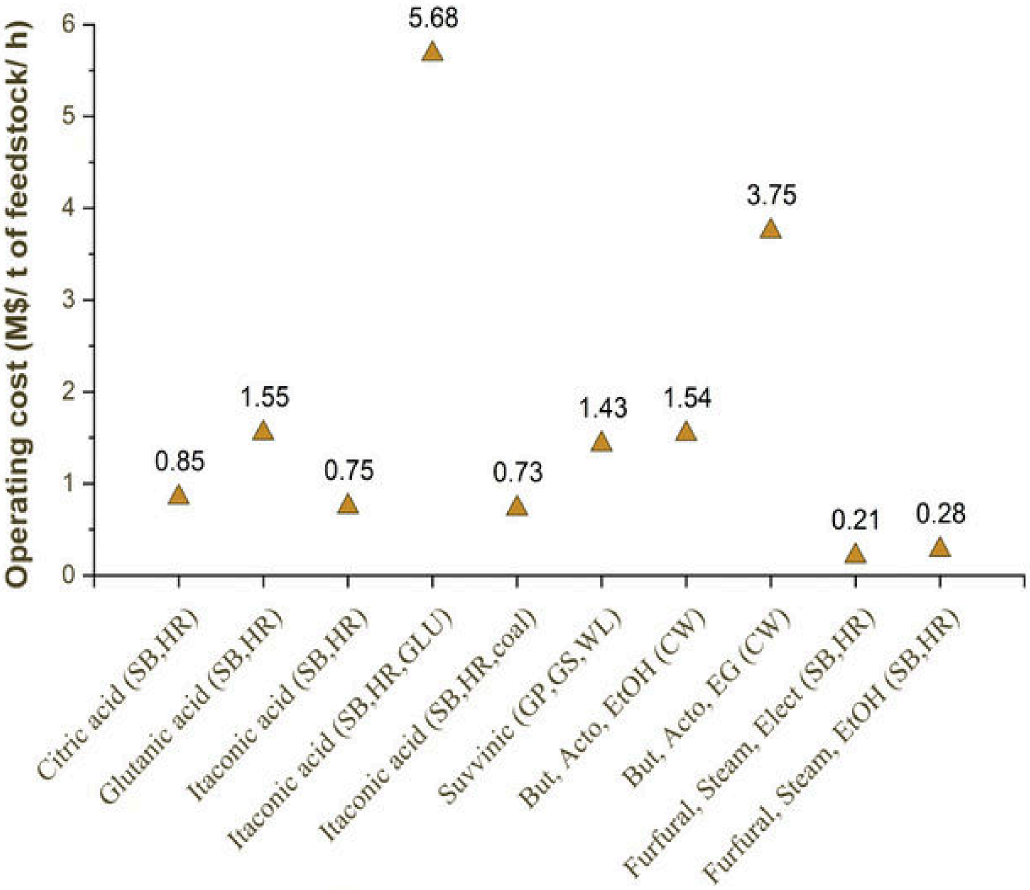


Figure 4. Total operating cost of biorefinery system that produces other than ethanol as primary product.

Table 1. Various microorganisms producing PHAs from different food wastes.

Microorganism	Substrate	PHA Type	Reference
Cupriavidus necator	Waste frying oils	PHB	(Benesova et al., 2017)
	Extracted oil from date seeds		(Yousuf and Winterburn, 2017)
Halomonas sp. YLGW01	High-fructose corn syrup (HFCS)		(Park et al., 2021)
Bacillus aryabhattai T34-N4	Cassava pulp and oil palm trunk starch		(Bomrungnok et al., 2020)
Azohydromonas lata DSM 1123	Cane sugar industrial products		(Wisuthiphaet and Napathorn, 2016)
Bacillus sp.	Sugarcane bagasse		(Getachew and Woldesenbet, 2016)
Bacillus megaterium	Cheese whey permeate	PHBV	(Suhazsini et al., 2020)
Haloferax mediterranei	Ricotta cheese exhausted whey		(Raho et al., 2020)
Ralsthonia eutropha	Pineapple peels		(Vega-Castro et al., 2016)
Lactobacillus spp.	Distillers Dried Grains with Solubles	PLA	(Mohd Zaini, 2018)
Rhizopus sp. MK-96–1196	Corncob		(Zhang et al., 2015)
Lactobacillus paracasei	Food waste		(Hu et al., 2017)
Pedioccocus acidilactici ZY271	Wheat straw		(He et al., 2022)

Table 2. Some recent examples of agri-food wastes feedstocks for microbial enzymes production.

Agri-food waste	Microorganism	Produced enzyme	Reference
Tea residues	*Trametes versicolor*	Laccase	(Xu et al., 2020)
Corn liquor	*Phlebia brevispora*		(Prigioni et al., 2018)
Wheat straw	*Ganoderma lucidium*		(Gupta and Jana, 2018)
Pomegranate peels	*Bacillus subtilis*	Protease	(Al-Abdalall and Al-Khaldi, 2016)
And iroba oil cake	*Aspergillus ibericus* MUM 03.49	Lipase	(Oliveira et al., 2017)
Sesame oilcake			
Rapeseed cake	*Penicillium camemberti*		(Boratyński et al., 2018)
Olive oil cake	*Bacillus licheniformis*		(Sahoo et al., 2018)
Jojoba oil cake	*Aspergillus niger* NRRL-599		(Abd El Aal et al., 2019)
Distillers Dried Grains with Solubles	*Trichoderma reesei*	Xylanase	(Cekmecelioglu and Demirci, 2020)
Rice bran	*Aspergillus niger* IBT-7	Pectinase	(Abdullah et al., 2018)
Food and kitchen waste	*Bacillus sonorensis* MPTD1		(Sindhu et al., 2020)
Soy flour	*Trichoderma atroviride* G79/11	Cellulase	(Oszust et al., 2017)
Potato peels	*Bacillus subtilis* K-18	Amylase	(Mushtaq et al., 2017)
Wheat bran	*Talaromyces thermophilus*	β-Glucosidase	(Mallek-Fakhfakh et al., 2017)

Table 3. Economics of fungal biorefinery with ethanol as a main product.

Feedstock	**Feed rate**	**Fungi type**	**Pre-Treatment**	**Main Product**	**Main Product yield**	**Co-Product**	**Co-Product yield**	**Capital Cost**	**Operating Cost**	**Payback Period**	**NPV**	**IRR**	**Reference**
Corn grain	111.13 t/h	Yeast	Dry milling and fibre separation	Ethanol		DDGS, Hi-Pro and Fibre with syrup Corn oil, and CO_2		$147.9 million	18.68 million				(Gerrior et al., 2022)
Corn grain	111.13 t/h	Yeast	Dry milling and fibre separation	Ethanol		DDGS, Hi-Pro and Fibre with syrup Corn oil, Struvite, Chlorella sorokiniana cultivation, methane, and CO_2		$125.2 million	22.58 million				(Gerrior et al., 2022)
Corn grain	18.95 t/h	*Saccharomyces cerevisiae*	Dry milling	Ethanol		DDGS, Corn oil, CO_2		$127 – 242 million	$1.066 - 3.56/gal ethanol				(Huang et al., 2020)
Corn grain	47.91 Mt/h	*Saccharomyces cerevisiae*	Dry milling	Ethanol	40.1 million gallon / year	DDGS, Corn oil,	149374 MT/y and 5953.7 MT/yr.	$87 million	77.66 million				(Kurambhatti et al., 2021)
Corn grain and whey powder	47.91 Mt/h	Genetically engineered *Saccharomyces cerevisiae*	Dry milling	Ethanol	40.1 million gallon / year	DDGS, Corn oil, 2′ -fucosyl lactose enriched DDGS	169.96 MT/yr, 5953.7 MT/yr, and 3048 MT/yr	$119 million	100.11 million				(Kurambhatti et al., 2021)

Corn grain and whey liquid	47.91 Mt/h	Genetically engineered *Saccharomyces cerevisiae*	Dry milling	Ethanol	40.1 million gallon / year	DDGS, Corn oil, 2′ -fucosyl lactose enriched DDGS	169.96 MT/yr, 5953.7 MT/yr, and 3048 MT/yr	$130 million	94.66 million			(Kurambhatti et al., 2021)
Bagasse (70%) and harvest residues (30%)	65 t/h	CelluX™4	Steam explosion technology	Ethanol	95.69 %	Steam and electricity		$294 million	18.12 million		8.26 – 10.18 %	(Ntimbani et al., 2021)
Rice straw	83.3 t/h	*Saccharomyces cerevisiae* CRD51	dilute acid (sulphuric acid) pre-treatment	Ethanol	0.166 g/g of rice straw for solid loading to 25% (w/w)	Electricity	50,237 kWh	$321 million	$1.36 /gal ethanol			(Yu et al., 2022)
Rice straw	83.3 t/h	*Saccharomyces cerevisiae* CRD51	Densifying with calcium hydroxide	Ethanol	0.228 g/g of rice straw for solid loading to 25% (w/w)	Electricity	61,583 kWh	$391 million	$1.75 /gal ethanol			(Yu et al., 2022)
Sugarcane bagasse	41.76 t/h	Yeast	Low-moisture anhydrous ammonia	Ethanol	24.58 million gallon / year	Electricity		$33.78 million				(da Conceição Trindade Bezerra e Oliveira and

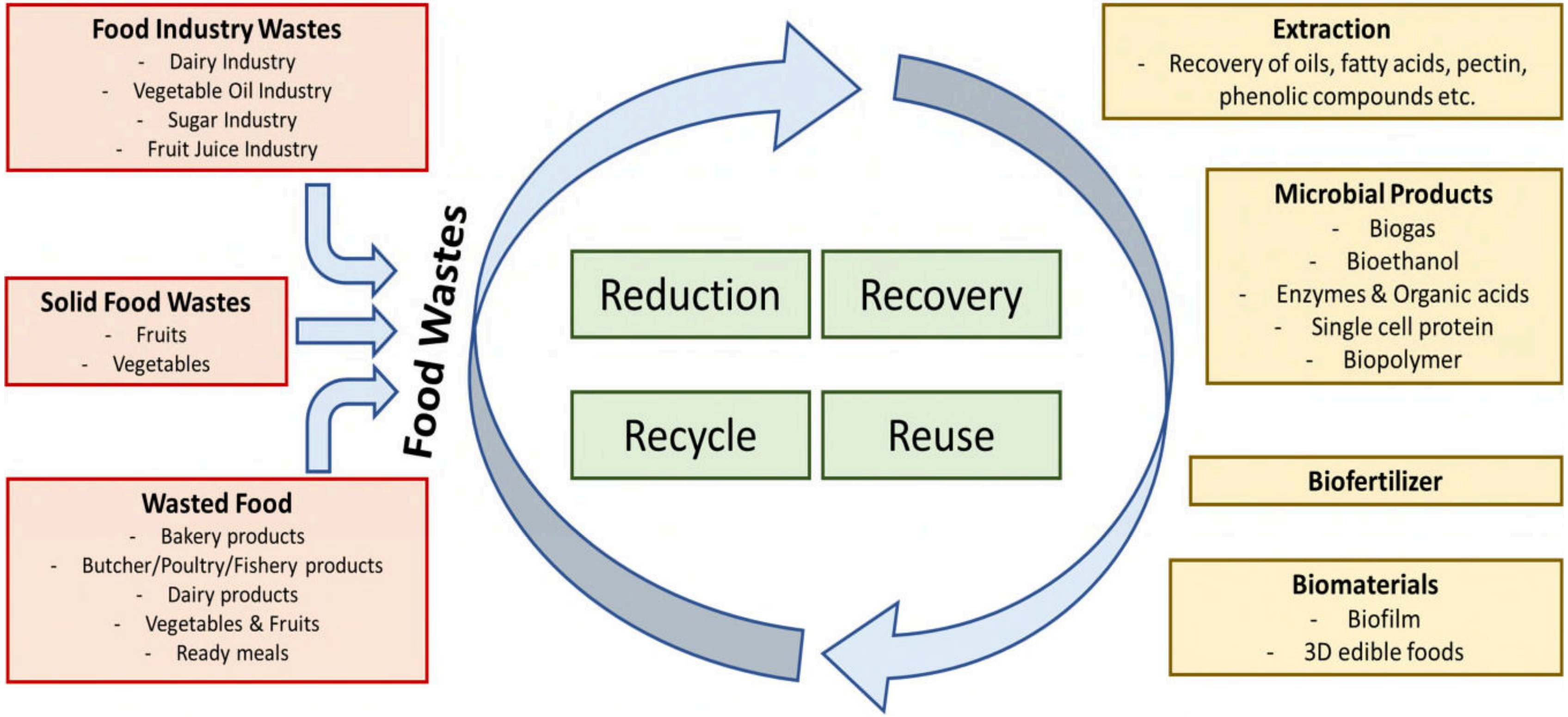
													Rosentrater, 2021)
Eucalyptus wood residues and cheese whey	5.01 t/h	*Saccharomyces cerevisiae*	Milling	Ethanol	93.03 g/L	Xylooligosaccharides	0.923 g/L	$11.38 million	$5.69 million	2.84 years	$18.94 million	24.1 %	(Gomes et al., 2021)
Eucalyptus wood residues and cheese whey	5.3 t/h	*Saccharomyces cerevisiae*	Milling	Ethanol	93.03 g/L	Electricity and Heat	5778 kWh	$8.16 million	$4.06 million	8.31 years	$-2.78 million	1.95 %	(Gomes et al., 2021)
Eucalyptus wood residues and cheese whey	7.07 t/h	*Saccharomyces cerevisiae*	Milling	Ethanol	93.03 g/L	Xylooligosaccharides, electricity and Heat	0.923 g/L	$13.44 million	$5.45 million	2.91 years	$23.3 million	23.3 %	(Gomes et al., 2021)
Eucalyptus wood residues and cheese whey powder	8.97 t/h	*Saccharomyces cerevisiae*	Milling	Ethanol	93.03 g/L	Xylooligosaccharides, electricity and Heat	0.923 g/L	$13.99 million	$7.38 million	4.67 years	$7.43 million	13.4 %	(Gomes et al., 2021)
Nizimuddinia zanardini	6.25 t/h	*Escherichia coli*	Soaked in hot water	Ethanol		Electricity		$261.7 million	$57.3 million				(Nazemi et al., 2021)
Nizimuddinia zanardini	6.25 t/h	*Zymomonas mobilis*	Soaked in hot water	Ethanol		Sodium alginate, mannitol, protein, fertilizer, and bioenergy		$522.5 million	$100.2 million				(Nazemi et al., 2021)

Mango waste	62.5 t/h	*Saccharomyces cerevisiae*	Shredding and milling	Ethanol	Electricity and steam	$77.1 million	$11.2 Million				(Manhongo et al., 2021)
Mango waste	62.5 t/h	*Saccharomyces cerevisiae*	Shredding and milling	Ethanol	Pectin, electricity, and steam	$85.2 million	$11 Million		$239 million	45.3 %	(Manhongo et al., 2021)
Mango waste		*Saccharomyces cerevisiae*	Shredding and milling	Ethanol	Pectin, polyphenol, electricity, and steam	$87.5 million	$12.2 Million		$311 million	53.6 %	(Manhongo et al., 2021)

Table 4. Economics of fungal biorefineries beyond ethanol as a main product.

Feedstock	Feed rate	Fungi type	Pre-Treatment	Main Product	Main Product yield	Co-Product	Co-Product yield	Capital Cost	Operating Cost	NPV	IRR	Reference
Bagasse and harvesting residues	65 t/h	*Candida oleophila* ATCC 20177	Dilute acid	Citric acid (oxalic acid)	14.9 t/h	Electricity	8 MWh	$351.59 million	$55.5 million	$-273.2 million	NA	(Özüdoğru et al., 2019)
Bagasse and harvesting residues	65 t/h	*Brevibacterium divaricatum* NRRL 8–231	Dilute acid	Glutamic acid	12.6 t/h	Electricity	11.4 MWh	$421.93 million	$100.9 million	$866.5 million	31.2%	(Özüdoğru et al., 2019)
Bagasse and harvesting residues	29.9 t/h	*Aspergillus terreus* DSM 23081	Dilute acid	Itaconic acid	5.6 t/h	Electricity	5.8 MWh	$380.2 million	$22.37 Million		9.7%	(Nieder-Heitmann et al., 2018)
Bagasse and harvesting residues and Glucose	10 t/h	*Aspergillus terreus* DSM 23081		Itaconic acid	25.1 t/h	Electricity	42.1 MWh	$287.0 million	$ 56.81 million			(Nieder-Heitmann et al., 2018)
Bagasse and harvesting residues and coal	65 t/h	*Aspergillus terreus* DSM 23081	Dilute acid	Itaconic acid	12.2 t/h	Electricity	5.1 MWh	$662.9 million	$ 47.77 million			(Nieder-Heitmann et al., 2018)
Grape pomaces, grape stalks, and wine lees	101.8 t/h	*Actinobacillus succinogenes*	Dilute aqueous sodium hydroxide	Succinic acid	0.79 g/L h 30,250 t/y	Grape-seed oil, Crude phenolic extract, Calcium tartrate and Crude tannin extract	3,763 t/y, 1,982 t/y, and 60,332 t/y	$254.7 million	$145.6 Million	$39.4 – 439.4 million		(Ioannidou et al., 2022)

Waste from Cassava (Manihot esculenta)	320.83 t/h	*Clostridium acetobutylicum*	Dilute (sulphuric) acid treatment	Butanol	63%	Acetone and ethanol	32% and 1.4%	$214.76 million	$493.41 million	$908.74 million	29.11 %	(Meramo-Hurtado et al., 2021)
Waste from Cassava (Manihot esculenta)	320.83 t/h	*Clostridium acetobutylicum*	Steam explosion technology	Butanol		Acetone and ethylene glycol		$269.87 million	$1203.42 million	$879.03 million	37.76 %	(Meramo-Hurtado et al., 2021)
Bagasse (70%) and harvest residues (30%)	65 t/h	CelluX™4	Steam explosion technology	Furfural		Steam and electricity		$272 million	$13.7 million		9.91 – 12.92 %	(Ntimbani et al., 2021)
Bagasse (70%) and harvest residues (30%)	65 t/h	CelluX™4	Steam explosion technology	Furfural		Ethanol		$327 million	$18.37 million		10.3 – 12.78 %	(Ntimbani et al., 2021)



Graphical Abstract

Highlights

1. Various types of food wastes are generated from agricultural production to consumption reviewed.

2. Food wastes can be valorized by recovery, recycling and reusing.

3. Food wastes can be integrated to myco-biorefinery to obtain valuable products.

4. Food waste bioconversion helps waste management and value addition.

Myco-biorefinery approaches for food waste valorization: Present status and future prospects

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