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A comprehensive review on upscaling of food waste into value added products towards a circular economy: Holistic approaches and life cycle assessments

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ABSTRACT

Background: Food waste (FW) generation is a global issue that affects the environment, society, and economy. The conventional methods of FW management lead to the generation of toxic leachate and greenhouse gases, high energy consumptions, and the lack of high-value products development. Therefore, more sustainable approaches to FW treatment are needed. The discarded FW is a valuable feedstock for biobased conversions owing to its carbon content and nutrients. Therefore, in addition to producing bioenergy, efforts have been made to convert FW into bioproducts with high economic value.

Scope and approach: This review aims to explore various approaches for effectively utilising FW, including various FW types, different strategies, and value-added products generated under various circumstances. Furthermore, techno-economic assessment and life cycle studies of FW management are discussed.

Key findings and conclusions: It is anticipated that FW conversion will become more sophisticated in the near future to generate a broad spectrum of biobased products. This will be accomplished through obtaining a better understanding of FW valorisation methods with a focus on the potential uses. In addition to the reduction of FW produced, bio-based products generation offers a safer alternative to synthetic substances that are hazardous to the ecosystem and human health.

1. Introduction

Demand for energy continues to rise worldwide due to a deficiency in the energy supply to fulfil the requirements (Sherwood, 2020). This pushed humanity towards clean, renewable alternatives to ensure an uninterrupted energy supply. A developing concept of biorefinery in waste management intends to convert various waste materials into energy, biofuels, chemicals, and biomaterials through efficient and environmentally friendly methods. Recently, the idea of a bio-refinery fosters the collaboration between scientists and researchers from various fields towards a bio-based industrial sector to increase the profitability and utility of renewable waste (Dung, Sen, Chen, Kumar, & Lin, 2014). Indeed, the concept of a circular economy is perfectly adapted for the long-term sustainability of waste valorisation. It serves as the appropriate prod essential for attracting the attention of society and financial investors. The reutilization of pre-existing spent resources is the core concept of renewable and restorative approaches. This has been suggested to increase their value, minimise the amount of waste produced, and complete the loops. Technical, economic, and sociological modifications are required to facilitate the implementation of a circular economy in waste management. Waste can be used as a potential substrate or feedstock for bio-based fuels, polymers and chemical synthesis. This would decrease the necessity to trade-in fossil-based raw materials (Pour & Makkawi, 2021). The utilisation of indigenous feedstock will also result in the implementation of novel procedures, which might boost the yield of renewable bioproducts and create new job possibilities. Food waste (FW) has been identified as a potential source causing various challenges in waste management throughout the world (Pour & Makkawi, 2021).

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1.1. FW: source of generation and management strategies

FW refers to the remains of uneaten food and the inedible parts of food disposed of during various stages, including production, processing, retailing, and consumption (Devi et al., 2023; Rajesh Banu et al., 2020). It is generated by households, canteens, restaurants, markets, processing plants, agriculture, and supply chains. According to the UNEP Food Waste Index Report (2021), around 931 million t of FW were generated in 2019, which is estimated to be around 17% of total global food production, with the major contribution by households (61%), followed by food service (26%) and retail (13%), as detailed in Fig. 1.

The regions with higher population densities and living standards generate larger quantities of FW (Pour & Makkawi, 2021). Indeed, it has been estimated that per capita FW is 107 kg/year in developed countries and 56 kg/year in developing countries, since higher living standards on one hand involve higher quality and aesthetic standards of food products, requiring more ingredients, on the other hand increase the quantity of food that is disposed instead of be donated (Thi, Kumar, & Lin, 2015).

Considering FAO statistics (2021), the highest food loss from post-harvest to distribution in 2016 can be attributed to Central and Southern Asia (more than 20%), followed by Northern America and Europe (more than 15%).

FW makes up 30–45% of municipal solid waste and primarily consists of carbohydrates, proteins, lipids, amino acids, and various other substances (Pour & Makkawi, 2021). Its composition is highly heterogeneous since it is affected by regional differences in diet and food preparation methods (Kim et al., 2021). It is composed of perishable substances, that make complex its collection, transportation, and storage due to leachate and odour production as well as rapid decomposition, representing a source of water, air, and soil pollution. The most common treatments for final disposal are (Mohanty et al., 2022) landfilling and incineration which emits harmful gases and chemicals to the environment.

Therefore, to decrease the environmental impact of FW management and to promote an approach based on circular economy, treatments aimed at generating value-added bioproducts have to be implemented. Considering the current economic context, the most attractive applications appear to be biofuels ($200–400/t biomass) and animal feed ($70–200/t biomass) production rather than power generation ($60–150/t biomass), although the interest in the generation of biodegradable polymers, organic acids, and enzymes ($1000/t biomass) is increasing (Sharma, Bano, et al., 2022). The current status of FW upscaling strategies and products along with techno-economic assessment and life cycle studies in FW management are hereby discussed in this review. The objective of this review is to outline the current status on essentials transformation of FW into high-value products. The problem of FW generation and justifications for its usage as a useful resource or feedstock are discussed initially. Then, biobased products produced from FW, and information on each approach are addressed. Finally, challenges, opportunities and future scope for FW management are discussed.

2. Upscaling of FW

Various methods involved in the management of FW are detailed in Fig. 2. Landfilling and incineration are the most common disposal methods for food waste. Despite they are simple and cost-effective, they release high emissions of greenhouse gases, and thus a significant environmental impact in terms of global warming. In this scenario, improved handling of foodstuffs at the various levels of the food industry and restaurants will undoubtedly contribute to reduce the overall amount of generated FW. Various methods have been developed for the utilisation of food wastes. So far, FW has been valued through traditional methods such as (i) composting, (ii) producing livestock feed, and (iii) the generation of biogas. Modern valorisation techniques are necessary for the effective synthesis of liquid biofuels and various bioproducts from food waste. The various upscaling methods of food waste (Fig. 2) are discussed in the following.

2.1. Bioplastics

According to Rudin and Choi (2013), bioplastics is a generalised term for polymeric materials derived from biomass. It may, however, only apply to compostable or biodegradable materials. As a result, the emergence of biomaterials for food packaging and biomedical applications has increased interest in plastic derivatives made from biomass. Since the costs of producing bioplastics is high, manufactured bioplastics are still not as affordable as conventional plastics. The method for extracting bioplastic components from food waste are discussed in the following.

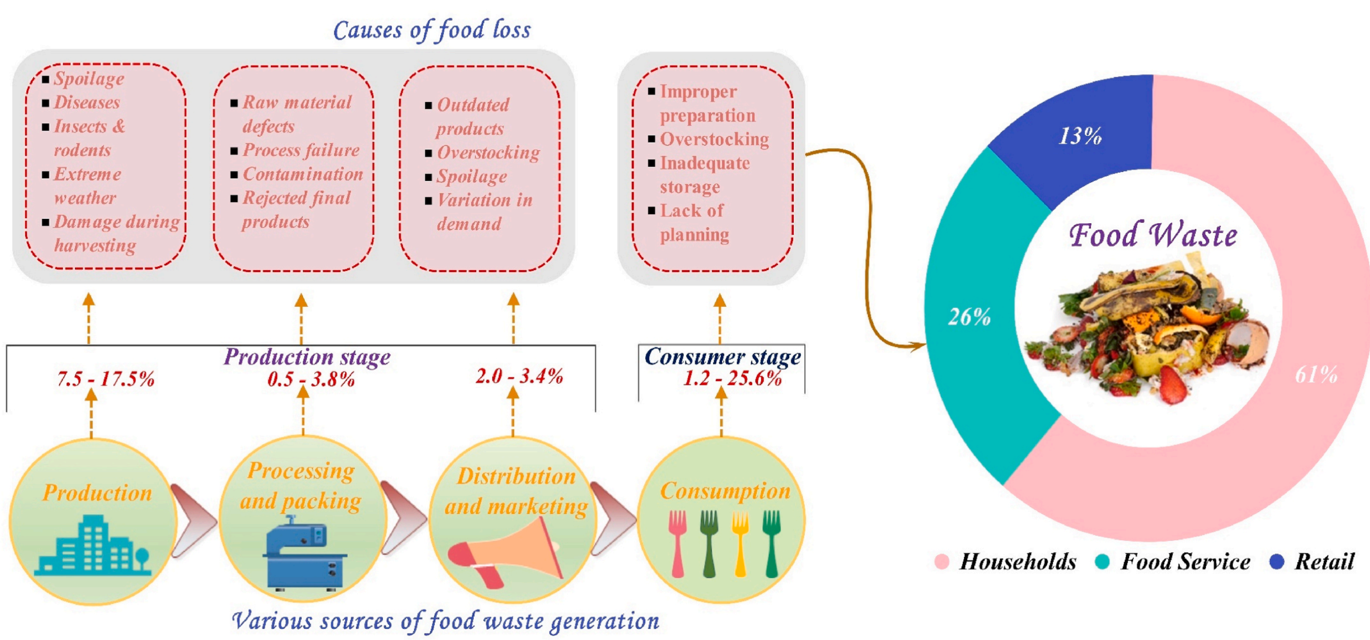

Fig. 1. Sources and generation of food waste from various sector (UNEP, 2021).

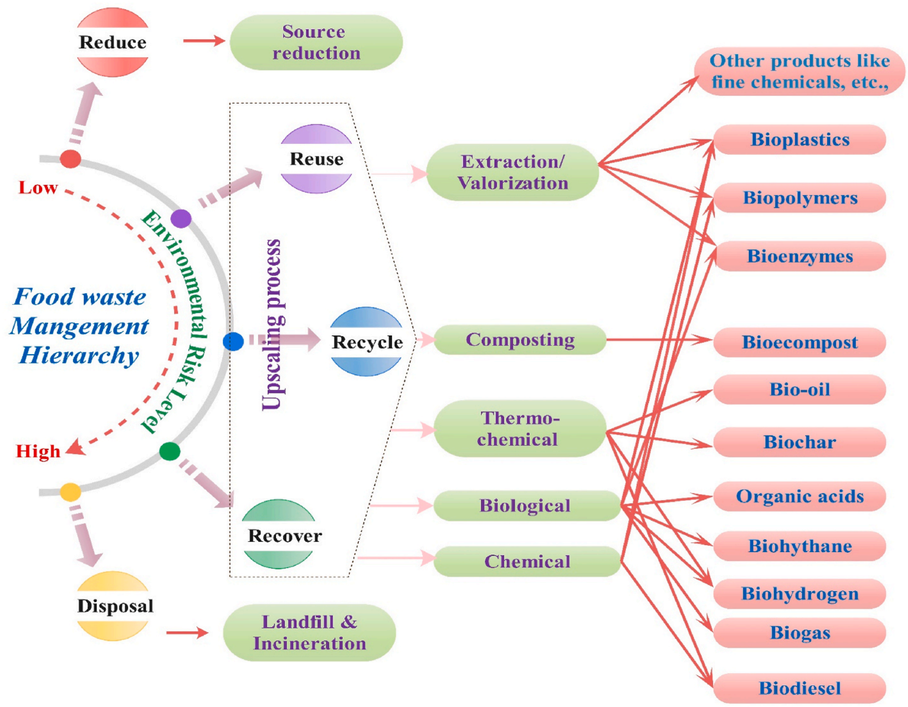

Fig. 2. Food waste management and upscaling process for biofuels and value-added products generation.

2.1.1. *Direct extraction*

In direct extraction processes, bioplastics are taken from a naturally formed biopolymer of biomass like starch and cellulose (Banu & Sharmila, 2023). The most significant kind of bioplastic is starch. It has been proven that main energy reserves of crops are typically defined as starch, the substance that generates and retains in their stems, leaves, potato tubers, shoots, seeds, and rhizomes. The largest source of starch is corn, but it can also be found in potatoes, wheat, rice, sorghum and barley. Both commercial and dietary uses have been made of it. It is possible to extract polysaccharide from rice, cassava, and soybeans. This is typically caused by elevated levels of amylopectin which can alter the long-term stability of amylase that affects the tensile strength and flexibility of bioplastics. Thermoplastic starch (TPS) is often used as a substitute for polystyrene. It is a film made of starch that is widely used as a coating material in food products. Natural starch has a limited applications and is further modified through its combination with plasticizers like glycerol, urea, sorbitol, or glycerine under conditions of increased temperatures and shear forces to improve the polymers plasticity and thermoplastic properties, resulting in the thermoplastic polymer, thermoplastic starch (Bangar, Whiteside, Ashogbon, & Kumar, 2021).

It is possible to create cellulose using a variety of dietary wastes. The pomace of the fruit contains significant amounts of cellulose, hemicelluloses, pectin, and starch, making it a suitable carbon source for fermentation. According to sources, cucumber pomace has a high cellulose level (8.13%), compared to tomato and apple pomace's low cellulose contents (8.60% and 8.81%, respectively). Cellulose was also removed from the rice husk by employing NaOH and neutralising it with HCl (Vigneswari et al., 2021). A sustainable source of chitin can be found in the shells of animals including lobsters, crabs, prawns, and others. Chitosan, a substance that has undergone a deacetylation process, is produced by treating chitin with alkali. Chitosan is a widely available N-acetyl-D-glucosamine and D-glucosamine copolymer with a (1,4)-bond. The abundance of easily available enzymes that can trigger hydrolysis makes the enzymatic breakdown more likely. Chitosan is therefore a suitable choice for food packaging.

2.1.2. *Extracted from biologically derived monomers*

Polyesters with a biodegradable framework are known as PHAs. The most typical PHA is P(3HB), also referred to as poly(3-hydroxybutyrate). PHAs are alternatives made from volatile fatty acids, glucose, glycerol, lactic acid, etc. that are favourable to the environment. *Bacillus, Pseudomonas, Citrobacter, Enterobacter, Escherichia,* and *Klebsiella* are extremely eminent microbes producing PHA (Atiwesh, Mikhael, Parrish, Banoub, & Le, 2021). It was shown that the enzymatically hydrolyzed corn stover produced 9.71 g/L of PHAs without any detoxification. Wheat straw, wood hydrolysate and bagasse were employed as substrates by *Ralstonia* and *Burkholderia* species for the fermentation-based synthesis of PHA. It generated PHAs at 65%, 72%, and 51.4%. *C. necator* and *P. citronellolis* were raised in fermentable sugar-containing apple pulp waste and produced 48% PHB and 52% PHA, respectively (Díaz-Vela, Totosaus, & Pérez-Chabela, 2015). The recently identified strain *Bacillus* sp. produces the highest PHB of 64.7 %, under ideal production circumstances. Consequently, the development of various genetic and metabolic engineering types has fundamentally altered how recombinant microorganisms are utilised to generate bioplastics. Only two-thirds of the energy is required to create conventional polymers polylactic acid (PLA). Furthermore, it has been scientifically demonstrated that the biodegradation of PLA bioplastics does not result in a net increase in carbon dioxide gas. Notably, 70% fewer greenhouse gases are released when PLA degrades in landfills. Other studies show that using PLA bioplastics made from maize instead of conventional plastic can reduce greenhouse gas emissions by 25% (Sharmila, Kavitha, Obulisamy, & Banu, 2020).

2.2. *Bio-enzymes*

Amylases, cellulases, and xylanases can be produced using starch-rich food waste streams generated through the production of maize, rice, and potato products. These significant industrial enzymes are used to manufacture biofuels, paper & pulp, textiles, and food (Martínez Sabajanes, Yáñez, Alonso, & Parajó, 2012). A solid-state fermentation of inexpensive substrates is being investigated to get high-activity enzymes for industrial demands.

2.2.1. Amylase

Due to its ability to hydrolyze the chain of starch polymer into glucose, maltotriose, and maltose, amylase is frequently used as a pretreatment for organic and agro-industrial by-products during industrial utilisation to enhance yields. After 72 h of fermentation, large quantities of amylase have been produced using kitchen waste as substrate through microbial solid-state fermentation (Pramanik, Suja, Zain, & Pramanik, 2019). Glucoamylase was produced in commercially acceptable amounts using rice flakes, manufacturing waste left over after producing rice-based food products. Using humidified bread waste as feedstock, fungi fermentation also produced significant quantities of amylase throughout a 120 h fermentation period. The synthesis of amylase through submerged fermentation of agricultural and industrial waste was investigated (Sharma, Bano, et al., 2022). Mixing carbon-rich farm waste with starchy kitchen food wastes like potato peels enhanced the amylase activity.

2.2.2. Cellulase

Manufacturing food, textiles, fuel, animal feed, chemicals, pharmaceuticals, and waste management all involve cellulases. Solid-state fermentation is based on fungi that make use of waste paper and inexpensive soybean hulls as supports (Salomão et al., 2019). At 96 h into the fermentation process, the activities of the three cellulase enzymes, endoglucanase, exoglucanase, and glucosidase were examined. Results showed that compared to wastepaper, the activity of all three enzymes was greater on soybean hulls. Streptomyces species create cellulase using carbon-rich fruit waste as a substrate (Ferdeș et al., 2020). The strongest enzymes were discovered to be produced at a pH of 5 and a temperature of 40 °C.

2.2.3. Protease

Protease is a different kind of enzyme frequently employed in the food and pharmaceutical industries, which is effective in hydrolyzing proteins (Nayak, Pal, & Pal, 2015). One of the most common foods wasted worldwide in bakeries, retail stores, and consumer houses is bread, which is consumed in many nations. *Rhizopus* sp. was used in a fungal-based solid-state fermentation process to produce significant levels of protease (2400 U/g). With a yield of 80.3 U/g of bread, a commercial system for producing protease in 1 L packed bed bioreactors was investigated. The observed protease production was significantly higher than lab-scale Petri dish studies. Pectinase, a digestive enzyme that breaks down pectin, is used to clarify the fibres found in fermented tea, coffee, and fruit juice. Owing to its liquefaction and maceration properties, pectinase is crucial in the raw materials processing of food and agriculture industries. In a solid-state fermentation setting, citrus waste was investigated as a substrate for synthesizing pectinase using yeast extracts. Hazelnut shell hydrolysate was employed as a carbon source in another bacterial fermentation technique to produce high yields of pectinase at neutral pH. Because of its capacity to hydrolyze xylan, the resin of plant, xylanase is another family of enzymes that is frequently utilised in the pulp processing of paper industry. In a 24 h incubation period, grape pomace was used to make xylanase producing significant levels of enzyme (Dessie et al., 2018). Solid-state fermentation was employed to create endoglucanase and xylanase from simulated food waste based on an average American diet as recorded by the USDA. Under optimal circumstances, a 6-day timeframe resulted in a 213.47 10.66 U/g ds yield of xylanase.

2.3. Nutrient sources

Some discarded foodstuffs are employed to produce certain food items such as cereal bars or cookies. Agricultural wastes from the industrial sector are employed to create flour-based foods (Agapios, Andreas, Marinos, Katerina, & Antonis, 2020). The usage of particular wastes improves the nutritional content of some foods. For instance, the protein content of a *tortilla* was increased by adding defatted soybean powder. The amino acid and protein content in spaghetti has also increased using soy flour. King palm flour was used to make gluten-free cookies and cookies rich in dietary fibre and some minerals such as potassium, calcium or magnesium. The core of pineapple was blended with some other ingredients; for instance, extracts of soybean and broken rice has been used to make a brand-new cereal bar which is low in calories and rich in protein, dietary fibre, and minerals. Di Salvo et al. (2023) employed flour of pineapple peel to enhance the physicochemical characteristics of cooked sausages which did not find pineapple peel flour to be greater than cactus pear peel flour despite their great findings. It lessens oxidative rancidity and aids in the water retention of sausages. Also, the skin of mango is a good source of dietary fibre. Pasta, baked goods, dairy products, and extruded foods can all be made with mango peel flour. These food products are all very significant in the world food market. The use of these extracts in the food industry to enhance food quality offers up new opportunities for the extraction of numerous compounds from accumulating food wastes and byproducts (Moraes et al., 2014). Some wastes are rich in concentrations of minerals that are essential to health and can enhance the nutritional qualities of current foods, such as protein or fibre content. A novel byproduct from the manufacture of olive oil called Patè Olive Cake (POC) was recently released. Many food waste and byproducts have a good probability of being utilised to make various kinds of foods with enhanced nutritional qualities.

Food by-products and waste are becoming more and more interesting to recycle and upgrade as it can help the food industrial growth, increase commercial outputs, and prevent waste from being mismanaged. To guarantee consumer safety and suitability, integrating these products into the food chain necessitates a careful assessment of the manufacturing and recycling procedures. The potential value and safety of food by-products are endangered due to the lack of specific legislation. An in-depth understanding for the efficacy and safety of by-products can be obtained through incorporating studies on contaminants, microbiology, and physicochemical processes. Also, cytotoxicity and mutagenic activity can be assessed through in-vitro analysis.

2.4. Various innovative bioproducts

The idea of a biorefinery reduces FW management challenges by offering a logistical method of producing useful fine chemicals such as aromatic compounds, pigments, antibiotics, essential oils, etc., The FW can function as a reservoir of flavours and fragrances. Physiological, enzymatic, and fermentation processes can produce aromatic compounds from FW in the form of ketones, alcohols, hydrocarbons, aldehydes, acids, lactones, or esters. Vegetable and cereal waste undergoes microbial change, producing fragrance compounds utilised in the pharmaceutical, food, cosmetic, and detergent industries. Some esters, including isoamyl acetate (which has a banana, pear, and fruity aroma), ethyl esters (which has an apple, fruity, sweetish, floral, and aniseed aroma), and phenyl ethyl acetate (which has a rose and honey aroma), are made from the leftover orange peel utilising aqueous fermentation process with *Saccharomyces cerevisiae* (Mahato, Sharma, & Cho, 2019). The microbe *Ceratocystis fimbriata* produces ethyl butyrate, which has a pineapple flavour, when it ferments apple pomace within a solid condition. The primary fragrance existing in a citrus family that can be derived from its waste is limonene terpene. Orange peel distillation produces *limonene terpenes*. A higher concentration of limonene and menthol terpenes is produced by the microbial fermentation of olive mill waste by *Rhizopus oryzae* and *Candida tropicalis*. Terpene may be obtained from leftovers of all known species of carrot. Additionally, the medicinally beneficial leaves of sages can be utilised to produce *camphor terpenes*. While the cassava bagasse has a fruity aroma, the unsaturated lactones 6-phenyl pyrole (6-PP) produced by the fermentation of sugarcane bagasse have a coconut-like aroma. The ketone molecules, which have a fruity or musty smell, are produced by the metabolism of glucose, citrate, and lipids. Acetoin and diacetyl are two ketones that have a buttery fragrance. Ketones such as heptanone, 2-octanone, 2-nonanone, and undecanone are produced by the enzymatic hydrolysis of fish waste and have been utilised as a seafood flavour (Dinesh, Chauhan, & Chakma, 2018).

The use of bio-pigments in the production of foodstuffs, colours, cosmetics, and medications has been increasing substantially. This bio-pigment produced from FW is considered safe because it contains no cancer-causing or toxic substances and is readily degradable in nature. Using *Serratia marcescens MBB05*, prodigiosin pigment was produced for about 560.04 mg/mL concentration from leftover peanut powder (Cudjoe, Chen, & Zhu, 2022). The monascus pigments are a secondary metabolite that were mostly formed by fermentation process and consist of the colours yellow (*monascin* and *ankaflavin*), orange (*rubropunctatin* and *monascorubin*), and red (*rubropunctamine* and *monascorubramine*). This kind of pigment is frequently used in food as a flavouring, colour, and preservation. The amount of chlorophyll pigment produced by using ultrasonic aided solvent extraction approaches in yellowish-green and reddish-green bell peppers is 380.00 g/g and 807.89 g/g, respectively (Neha, Prasanna Kumar Ramesh, & Remya, 2022). Consumable, hygienic, cosmetic, and leather goods all include this safe chlorophyll pigment, as well as inks, candles, resins, and some types of leather.

Today, antibiotic resistance sickness is being brought on by excessive antibiotic use without a valid prescription. As a result, various studies were being done on creating antibiotics. Additionally, the method of extracting antibiotics from food waste was environmentally beneficial. The Penicillium species of *chrysogenum* and *notatum* were isolated from the rotten orange waste (Rajendran & Han, 2022a, 2022b). Additionally, *A. chrysogenum C10* produces 428–3200 g/g of cephalosporin C from the bagasse of sugarcane. The substances found in FW include cephalosporins: soy oil (40 g/L), corn steep liquor (330 mg/L), and beetroot malosses (180 mg/L). Erythromycin is produced in 735.65 g/g of beetroot sugar root (Bernstad & la Cour Jansen, 2012). Tetracycline is produced by the bacteria *Streptomyces rimosus*, *S. vendagensis*, and *S. speibonae* during the solid-state fermentation of groundnut shell, sweet potato wastes, cassava peels, and cocoyam peel.

Fish oil, peel oil, and seed oil are the most widely used types of oil in most industries. Additionally, these oils have prominent uses within the pharmaceutical, medical, and food sectors. Essential oil (1.57 %) and pectin (25 %) were sequentially extracted from fruit wastes (orange peel) using microwave irradiation. Lemon peel was used to extract essential oil and lemon pigment using a microwave (Khoo, Lim, & Tan, 2010). According to gas chromatography with a flame ionisation detector, the main components of lemon essential oil were about 65% limonene, 14% -pinene, and 10% -terpinene, while ultra-high performance liquid chromatography revealed that the lemon pigment contains roughly 4.7% eriocitrin, 7.3% diosmin, and 2.65% hesperidin. Due to the wide range of FWs, the content and chemistry of the wastes, the chemistry of the bioactive compounds, and the extraction conditions and/or parameters, there are no standard protocols for the extraction of bioactive compounds. Therefore, for an effective circular bioeconomy, it is essential to create more effective and efficient extraction procedures for specific bioactive chemicals from specific FW.

2.5. Bio-compost

According to Cerda et al. (2018), composting is an ecologically conscious process that turns food scraps into bio-fertilizer (compost) using a sequence of biological reactions. Composting has many benefits when used as a waste management startegy, including fewer landfills (which reduces greenhouse gas emissions and groundwater contamination), efficiency, sustainability, and high-value bio-fertilizer production, which enhances soil properties. Controlling the process variables and the waste material characteristics is necessary for producing high-quality compost (Ayilara, Olanrewaju, Babalola, & Odeyemi, 2020). A significant concentration of non-biodegradable components would adversely impair the process, causing the production of foul odours and yielding poor-quality compost.

The moisture content and low pH of FW make its solitary composting unfavourable for the environment. Composting of co-substrate of FW with other agricultural leftovers offers various benefits and prevents these drawbacks. Rice husk, straw, and sawdust are examples of agricultural leftovers with significant lignocellulosic content but little water content. In addition, the FW and agricultural wastes co-composting acts as a bulking agent and speeds up the breakdown of the lignocellulosic component.

2.6. Biofuels

Biofuels from FW can be classified as second-generation or advanced biofuels. Deriving from waste material, they play an important role in the food versus fuel debate. Depending on their properties, biofuels from FW can be produced through biological, thermochemical, and chemical processes, eventually after suitable pretreatments of the biomass feedstock (Fokaides, Christoforou, López-García, & Garcia-Garcia, 2023). The main available processes and their products are shown in Fig. 3.

2.6.1. Biological processes

The most common biological process is anaerobic digestion (AD), which consists in the degradation of the organic-biodegradable waste, including FW, in four steps, hydrolysis, acidogenesis, acetogenesis, and methanogenesis, carried out by different classes of bacteria. The by-products of this process are **biogas**, a valuable energy source, and digestate that can be used as soil additive. The biogas is a combustible gaseous mixture mainly composed of methane (40–75%) and carbon dioxide (25–60%) (Emmanuel, Nganyira, & Shao, 2022), thus with an interesting lower heating value that make it suitable to be used as a fuel for electrical and/or thermal energy production. Microbial activity and consequently biogas production are affected by different operating parameters. Depending on temperature, AD can be carried out at psychrophilic, mesophilic (between 20 and 40 °C, typically 35 °C), and thermophilic (up to 65 °C, normally 45 °C) conditions (Kothari, Pandey, Kumar, Tyagi, & Tyagi, 2014). Thermophilic conditions present different advantages, such as a higher growth rate of methanogenic bacteria, a lower retention time, improvement of pathogens destruction, and enhancement of digestibility and degradability of solid substrates, whereas mesophilic process is more stable and lower

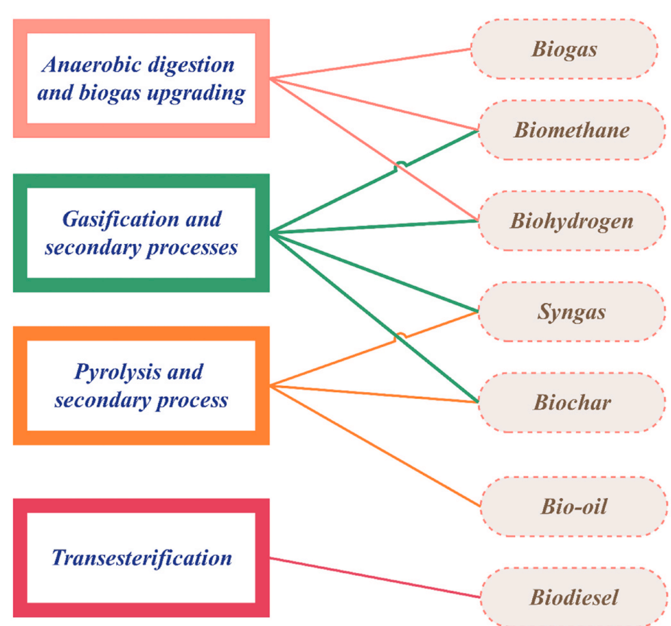

Fig. 3. Main processes for biofuels production.

energy-demanding.

Biogas production is also influenced by pH. Its regulation is fundamental since in the first steps bacteria produce organic acids, thus an acidic pH is preferable, whereas the operation of methanogenic microorganisms is improved at a higher pH. Also the organic loading rate (OLR) affects biogas production since it influences the methane yield. OLR is the amount of dry organic solids fed into the digester per unit time and unit volume of digester. Higher OLRs increase methane production, but organic overload could cause acid accumulation and thus problems to the microbial communities responsible for methanogenesis step (Liu et al., 2023; Pramanik et al., 2019). As an example, analysing biogas production from FW collected in a university canteen, the effect of OLR was tested, finding that its increase promotes the accumulation of hydrogen due to the inhibition of hydrolysis and methanogen bacteria (Zhang et al., 2022). To make the process stable and increase its performance, C/N ratio has to be checked since anaerobic bacteria need a proper balance of nutrients to grow and keep their environment stable. However, the ideal proportion is complicated to be defined since it depends on different factors, i. e, the substrate type, chemical composition, and biodegradability; at the same time, it cannot be too high because the nitrogen is rapidly consumed by methanogenic bacteria or too low since high concentration of ammonia is harmful to the methanogenic bacteria (Maria et al., 2023).

AD performance can be increased by separating the acidification stage, which is usually operated at low hydraulic retention time and low pH, and the methanogenesis phase, run at comparatively higher hydraulic retention time and pH (6.0–8.0). Indeed, two-stage AD guarantees to these processes their specific operation conditions improving the global performance: compared to a single stage process, the energy yield of by-products, the removal efficiency of COD and volatile solids, the specific biogas production and biomethane yield may increase.

Biogas production can be also improved through the co-digestion with other biomasses. Co-digestion with sludge from wastewater treatment is extensively investigated since FW allows improving the energy and nutrient recovery compared to mono-digestion. Indeed, testing FW from a canteen and a fruit and vegetable wholesale market, it was experimentally demonstrated that co-digestion increases the process performance and biogas production compared to mono-digestion of sewage sludge (Cabbai, De Bortoli, & Goi, 2016), due to the enhancement of biodegradation connected to the higher C/N ratio and a better balance of nutrients. Another experimental analysis of co-digestion of food leftovers from canteens and expired food products with sewage sludge confirmed that FW increases the methane yield of biogas compared to raw sludge mono-digestion, highlighting that this effect increases with the percentage of FW used as a co-substrate (Koch, Plabst, Schmidt, Helmreich, & Drewes, 2016). Considering specific sources of FW, sewage sludge can become the responsible for the process improvement. As an example, co-digestion with sewage sludge increased methane content of biogas produced from citrus peels (Martínez et al., 2018).

FW has been also employed in co-digestion with livestock manure, finding different trends. Assessing the effect of the C/N ratio, an optimum ratio between FW and cattle manure was identified with a methane yield increase of 41.1% (Koch et al., 2016). With specific types of FW the performance of the AD can significantly decrease, making co-digestion particularly important. As an example, it was experimentally proven that pig slaughterhouse wastes increase methane production when they are co-digested with tomato industry waste due to improvement in the biodegradability of the substrate. Similarly, cow dung slurry was observed to increase biomethane production as well as process stability and performance if co-digested with rice wastewater. Indeed, due to the imbalanced C/N ratio, high ORL and biodegradability, mono digestion of rice wastewater is difficult to be carried out. Several studies highlighted that also co-digestion with algae may improve energy recovery from FW. Indeed, co-digestion with algae increased up to double methane yield compared to mono-digestion (Khanthong, Kadam, Kim, & Park, 2023). The enhancement effect is influenced by the ratio between the two substrates.

During the last decades, a great effort has been made in the field of biogas upgrading for **biomethane** production. Biogas upgrading consists in the removal of CO_2 to obtain a fuel with a heating value similar to that of natural gas. The upgrading also allows reducing the corrosion properties and, if coupled with CO_2 capture, contributing to decrease global warming from greenhouse effects and atmospheric pollution. Considering the available literature, biomethane produced from FW is mainly used for electricity and heat generation as well as vehicle fuel (Devi et al., 2023). The main technologies used for biogas upgrading are:

- physical scrubbing, known also as solvent scrubbing, based on the adsorption of carbon dioxide from raw biogas by a solvent (the most common is water) in an absorption column at high pressure, due to its higher solubility compared to methane;
- chemical scrubbing that uses water solutions of amines and their acid–base neutralization reaction with acid gas, generally CO_2, that is absorbed in the liquid phase. Then the saturated solution is regenerated by heating;
- membrane separation that exploits the different molecular size and affinity of the different biogas components to remove CO_2;
- pressure swing adsorption, based on the selective adsorption of CO_2 on the surface of an adsorbent material. The process is carried out at high pressure and low temperature and after the CO_2 separation the system is depressurized to atmospheric pressure, to release low adsorbing gases;
- cryogenic separation, in which the different condensation temperature between carbon dioxide and methane is exploited to separate at a very low temperature pure methane in gaseous state.

A comparison among these technologies is proposed in Table 1. Considering the pertinent literature (Nguyen, Ta, Lin, Chu, & Ta, 2022), all the available techniques are employed for the upgrading of biogas from FW although emergent technologies, such as cryogenic process are

Table 1
Summary of advantages and disadvantages of biogas upgrading technologies.

Method	Advantages	Disadvantages
Physical scrubbing	Mature, efficient and widespread technology due to its simplicity, low costs, absence of harmful substances, high methane purity	Needing for pre-treatment and off-gas post-treatment, large space requirement, clogging and corrosion, high requirement of freshwater and needing for wastewater treatment (in case of water used as solvent)
Chemical scrubbing	High methane purity, low methane losses, low space requirement	High investment costs, high thermal energy demand for regeneration, use of harmful substances, corrosion, treatment of chemical by-products, needing for pre-treatment
Membrane separation	Environmentally friendly technique, low investment and operating costs, simple equipment, operation without the production of harmful secondary waste, low space requirement, high scale-up flexibility	Needing for pre-treatment and off-gas post-treatment, high losses, energy demand
Pressure swing adsorption	High energy efficiency, low operational and installation costs, highly compact equipment, and easy operation	High investment and operation cost, high methane losses, extensive process control required
Cryogenic process	high purities but also with minimal methane losses	High investment and operating cost, high energy demand energy, needing for pre-treatment

employed at experimental scale rather than in commercial systems. FW is also considered a promising source for **biohydrogen** production, through:

- biophotolysis, in which hydrogen of water is captured through solar or artificial light energy via photosynthesis, employing various photosensitive microorganisms, generally algae, as biochemical conversion devices;
- photofermentation that is an anoxic process found in photosynthetic bacteria mainly in purple nonsulfur photosynthetic bacteria where organic compounds are degraded and form hydrogen and carbon dioxide in light;
- dark fermentation, which is carried out by obligate and facultative anaerobes, capable of using energy-rich hydrogen molecules to produce energy, in the absence of light and oxygen;
- the hybridization of these last two processes, to convert the products from dark fermentation to hydrogen through photo-fermentation.

Considering FW, the dark fermentation appears to be the most common process to be applied, since it does not need external energy and light and is suitable to process different streams (Aslam et al., 2018). The difference between conventional AD and photo- or dark fermentation is that this second class of processes is based on the enhancement of hydrolysis and the overcome of the methanogen barrier to avoid further conversion of hydrogen to methane, by introducing a methane inhibitor or by modifying the operating conditions of the reactor, including retention time, pH, and volatile solid content (Habashy, Ong, Abdel-dayem, Al-Sakkari, & Rene, 2021). Pretreatments may further improve hydrogen production. The most common techniques are:

- physical pretreatments, including milling, chipping, screwing, extrusion, pressure homogenization, or by using different types of radiation such as gamma rays, electron beams, microwaves and ultrasounds, and thermal pretreatments, which enhance the liquification of FW and thus the efficiency of the bioprocess (Rajesh Banu et al., 2020);
- microwave irradiation, in which the dielectric polarization leads to the colliding of ions, thereby degrades the lignocellulosic components, effectively increasing the hydrogen production (Zhang, Cui, et al., 2021);
- thermo-chemical processes, such as hydrothermal carbonization that due to high temperature under subcritical conditions weakens the H-bonding of water, releases the inhibition of the long-chain fatty acids resulting from the excess lipids and enhances bio-hydrogen production potential (Li et al., 2014).

Biohydrogen production is affected by different operating conditions, especially (Yasin, Mumtaz, Hassan, & Abd Rahman, 2013):

- pH that has to be controlled to increase the activity of hydrogen-producing bacteria and limit that of hydrogen-consuming bacteria especially methanogens; indeed, no biohydrogen production was reported at pH lower than 4.0 or above 8.0;
- temperature that should be kept between 50 and 60 °C, since thermophilic conditions enhance hydrogen production.

As for biogas, co-digestion with other substrates can increase biohydrogen production. Indeed, co-digestion with sewage sludge may improve the balance of C/N ratio, increasing biohydrogen production (Zhou, Elbeshbishy, & Nakhla, 2013).

As mentioned before, a further strategy consists in separating AD into two stages to simultaneously enhance the hydrolysis/acidogenesis and methanogenesis phases and to maximize biohydrogen and biomethane production, respectively (Cheng et al., 2016). Indeed, the bacteria responsible for hydrolysis and acidification convert the organic matter into volatile fatty acids at a rate higher than that at which methanogens convert the volatile fatty acids into CH_4; this accumulation of volatile fatty acids can inhibit methanogenesis and lead to AD failure (Pour & Makkawi, 2021).

Bio-hydrogen and bio-methane can be used separately or mixed together to obtain **biohythane** (5–10% H_2, 30–40% CO_2, 50–65% CH_4), characterized by a combustion efficiency and an emission performance higher than natural gas (Nathao, Sirisukpoka, & Pisutpaisal, 2013). Beyond the energy and environmental benefits, using biohythane does not require particular storage system or any major modifications in the engines commonly employed for the combustion of compressed natural gas. However, further research is necessary to upscale biohythane production and achieve widespread utilisation. Indeed, biohythane production requires a two-stage reactor and thus additional energy to heat up the reactors, higher investment costs and complexity of operation. As mentioned for AD, operating parameters such as temperature, pH, ORL, as well as pretreatments and co-digestion can enhance biohythane production. Regarding the pretreatments:

- implementing low-cost pre-aeration was found to positively affect the acidogenic process and the formation of metabolites, inhibiting methanogens and promoting the production of H_2 and other acidogenic metabolites (Sarkar & Venkata Mohan, 2017);
- hydrothermal pretreatment, as for biohydrogen, was observed to improve the solubilization of organic components, promoting fermentation performance and thus the global energy conversion efficiency (Ding et al., 2017).

Also, the use of recirculated temperature-phased AD, in which two digesters are operated in series with thermophilic conditions in the first stage and mesophilic conditions in the second one, was investigated to identify the optimal recirculation ratio to obtain stable H_2 production in biohythane (Qin et al., 2019). Specific FWs may also be used as enzyme supplier as investigated with pineapple waste used to enhance the hydrolysis of swine manure in a newly-developed single-stage anaerobic fermentation system for biohythane production. A hydrogen concentration in the range of 23.6–60.5% was obtained depending on the operating conditions (Nguyen et al., 2022).

Several experimental campaigns were carried out to investigate AD in terms of:

- biochemical methane potential (BMP), which represents the maximum amount of methane that can be produced by AD of a specific substrate;
- biohydrogen production;
- biohythane generation.

Some examples are shown in Table 2.

2.6.2. Thermo-chemical processes

Thermo-chemical processes, such as pyrolysis and gasification, can effectively convert the high volatile content of FW into energy. However, the high moisture content and the amount of ash can greatly impact the kinetics of the reactions involved in these processes (Murugesan, Raja, Dutta, Moses, & Anandharamakrishnan, 2022).

Gasification transforms carbonaceous materials derived from biomass into different gaseous components, including H_2, CO, CO_2, CH_4, C_2H_6, at high temperatures (700–1000 °C) and under partial oxygen conditions. The resulting gas, known as syngas, can be utilised directly or after upgrading for energy generation, or to produce chemicals. Gasification also produces char, a solid residue characterized by high carbon content, heating value, and energy densification that can be employed as fuel, amendment in agriculture, or adsorbent material, and other undesired products such as tar. As shown in Table 3, gasification can be classified depending on the gasification agent and the reactor configuration.

Several studies demonstrated that a higher temperature greatly

Table 2
Some examples of BMP, biohydrogen and biohythane production, with indication of source of FW, country, yields, eventual pre-treatment and/or co-substrate.

Anaerobic digestion of FW: biomethane potential

Source	Country	BMP	References
Kitchen waste of a university refectory		393 - 543 $NmL_{CH4}\ g_{VS,\ added}^{-1}$	Okoro- Shekwaga et al. (2020)
Plate waste and kitchen wastes of a university refectory		Up to 544.6 $NmL_{CH4}\ g_{VS}^{-1}$	Okoro- Shekwaga et al. (2020)
Kitchen waste of a university canteen	Ireland	314 - 467 $L_{CH4}\ kg_{VS,\ added}^{-1}$	Browne and Murphy (2013)
FW of a University canteen co-digested with garden waste	Portugal	276.8 ± 15.4 L kg^{-1} of COD added	Abreu, Tavares, Alves, Cavaleiro, and Pereira (2019)
FW of a campus canteen	China	270.9 mL g_{VS}^{-1}	Cheng et al. (2016)
FW of a University canteen	China	443, 535, 423 mL g_{VS}^{-1} at different fermentation types in acidogenic phase	Chen et al. (2015)
Cranberry & manure	USA	231 ± 33 mL g_{VS}^{-1}	Lisboa & Lansing. (2013)
Chicken & manure		452 ± 15 mL g_{VS}^{-1}	
Meatball & manure		421 ± 27 mL g_{VS}^{-1}	
Ice-cream & manure		125 ± 48 mL g_{VS}^{-1}	
Food mixture & manure		413 ± 16 mL g_{VS}^{-1}	
Animal FW	Denmark	572 mL g_{VS}^{-1}	Naroznova, Møller, and Scheutz (2016)
Vegetable FW		425 mL g_{VS}^{-1}	
Vegetation waste		504 mL g_{VS}^{-1}	
Animal kitchen waste	Japan	500 mL g_{VS}^{-1}	Kobayashi, Xu, Li, and Inamori (2012)
Vegetable kitchen waste		400 mL g_{VS}^{-1}	
Other kitchen waste		410 mL g_{VS}^{-1}	
Cereal waste		380 mL g_{VS}^{-1}	
Tea and coffee dregs		300 mL g_{VS}^{-1}	
Uneaten animal kitchen waste		590 mL g_{VS}^{-1}	
Uneaten vegetable kitchen waste		520 mL g_{VS}^{-1}	
Vegetation waste		340 mL g_{VS}^{-1}	

Anaerobic digestion of FW: biohydrogen yield

Source	Country	Eventual pretreatment	**Biohydrogen yield**	**References**
FW taken from a university canteen	Portugal		160 $mL_{H2}\ g_{VS}^{-1}$	Alavi-Borazjani, Capela, and Tarelho (2019)
Kitchen waste from a dining hall	China	Hydrothermal	Up to 81.27 $mL_{H2}\ g_{VS}^{-1}$	[23]
Catering waste (Red onion, tomato, lettuce, spring onion, pepper, pasta, lemon peel)	UK		1.87 $L_{H2}\ kg^{-1}$	Redwood, Orozco, Majewski, and Macaskie (2012)
Catering waste (Onion, pea, potato, carrot, courgette)			0.93 $L_{H2}\ kg^{-1}$	
Catering waste (Rice, pasta (cooked).)			5.99 $L_{H2}\ kg^{-1}$	
Wholesalers waste mango	UK		2.65 $L_{H2}\ kg^{-1}$	Redwood et al. (2012)
Wholesalers waste Asian pear			3.32 $L_{H2}\ kg^{-1}$	
Wholesalers waste avocado			0.52 $L_{H2}\ kg^{-1}$	
Brewers spent grain			1.07 $L_{H2}\ kg^{-1}$	
FW	Canada	Thermal pre-treatment	4.2 ± 0.32 $L_{H2}\ L^{-1}$	Zhou et al. (2013)
FW and primary sludge			0.7–5.2 $L_{H2}\ L^{-1}$ (at different mixing ratio)	
FW and waste activated sludge			0.2–6.2 $L_{H2}\ L^{-1}$ (at different mixing ratio)	
FW, primary and waste activated sludge			3.3–6.8 $L_{H2}\ L^{-1}$ (at different mixing ratio)	
FW and sewage sludge	China		60.7–174.6 $mL_{H2}\ g_{VS}^{-1}$ (at different mixing ratio)	Cheng et al. (2016)

Anaerobic digestion of FW: biohydrogen and biomethane yield in biohythane

Source	Eventual pretreatment	Biohydrogen yield	Biomethane yield	References
FW		49 $mL_{H2}\ g_{VS}^{-1}$	426 $mL_{CH4}\ g_{VS}^{-1}$	Qin et al. (2019)
FW (synthetic preparation)		115 $mL_{H2}\ g_{VS}^{-1}$	334 $mL_{CH4}\ g_{VS}^{-1}$	Yeshanew, Frunzo, Pirozzi, Lens, and Esposito (2016)
Pineapple waste and swine manure		1.8–50.2 $mL_{H2}\ g_{COD}^{-1}$	28.5–40.4 $mL_{CH4}\ g_{COD}^{-1}$	Nguyen et al. (2022)
FW, from a dining hall		0.31 ± 0.04 $m^3_{H2}\ kg_{VS}$	0.21 ± 0.02 $m^3_{H2}\ kg_{VS}$	Han & Shin. (2004)
FW from restaurants		0.065 0.546 $m^3_{H2}\ kg_{VS}^{-1}$	0.546 $m^3_{CH4}\ kg_{VS}^{-1}$	Wang & Zhao. (2009)
FW from restaurants	Hydrothermal pretreatment (140 °C, 20 min)	43.0 $mL_{H2}\ g_{VS}^{-1}$	511.6 $mL_{CH4}\ g_{VS}^{-1}$	Ding et al. (2019)
FW		53.5 $mL_{H2}\ g_{VS}^{-1}$ (mesophilic conditions)	276.5 $mL_{CH4}\ g_{VS}^{-1}$ (thermophilic conditions)	Ghimire et al. (2022)
		37.6 $mL_{H2}\ g_{VS}^{-1}$ (mesophilic conditions)	307.5 $mL_{CH4}\ g_{VS}^{-1}$ (thermophilic conditions)	

enhances the syngas overall quality, due to the advancement of (Sajid et al., 2022):

- the Boudouard reaction, which is responsible for the conversion of CO_2 to CO;
- the steam methane reforming reaction, where H_2, CO, and a relatively small amount of CO_2 are produced;

Table 3
Main characteristics of gasification process.

Gasifying agent Sajid et al. (2022) Wang et al. (2023)	Using air as a gasifying medium is generally preferred because it is cheap and readily available, but the high amount of nitrogen significantly affects the composition and heating value of the syngas. Employing oxygen would increase reaction rates and temperatures, leading to greater thermal efficiency. However, purifying oxygen is an expensive process that would negatively affect the economic feasibility of the process. Steam as a gasification medium enhances the calorific value of the syngas produced and the conversion rate of carbon. Moreover, it is widely recognized as the optimal gasification agent for generating syngas with a high hydrogen content. Nevertheless, it suffers from inadequate economic viability.
Reactor design Akbarian et al. (2022)	The **fluidized bed** biomass gasifier is a mature technology, based on the concept of fluidization, where the inert bed material and fuel behave like fluid. These gasifiers are characterized by good heat transfer properties and can effectively address the challenges of varied fuel quality. The temperature of the reactor is determined by the melting point of the bed material and usually a catalyst is required to achieve the gasification reaction. Fluidized bed gasifiers have a high carbon conversion efficiency and there are two forms based on the bed height and degree of fluidization: bubbling and circulation fluidized bed reactors. **Entrained flow** gasifiers require high pressures and temperatures to operate successfully. They can handle a wide range of raw materials. These gasifiers generate gas with minimal tar due to their intense reaction conditions and use a quench cooler to ensure the gas exits at a reasonable temperature. However, they suffer from low energy efficiency and high initial investment costs due to the substantial heat input needed to achieve higher ignition status. **Fixed bed** gasifiers are the simplest type and include a fuel feeding device, a cylindrical vessel, a gas outlet, and an ash collecting unit. These gasifiers usually have gas cleaning and cooling systems that involve wet scrubbing, dry filtering, and cyclones. They are typically made of concrete or steel, operating at low gas velocities and achieving a high carbon conversion rate. These gasifiers are mainly used for small-scale heat and electricity generation. Depending on the flow of the fuel and the gasifying agent, fixed bed can be classified as downdraft, updraft, and cross-draft.

- the water-gas reaction, in which CO and water vapor form CO_2 and H_2;
- the secondary cracking of tar.

Another important factor is the equivalence ratio (ER) that describes the air/biomass ratio in the gasification process. Higher ER values decrease the concentration of H_2 and CO and increase that of CO_2 in the gas and reduce the formation of tar (Wang, Gupta, Bei, Wan, & Sun, 2023). When steam is used as gasifying agent, the steam to biomass ratio influences the composition and consequently the energy content of the produced syngas. Indeed, as this parameter increases, the concentration of H_2 and CO_2 increases whereas that of CO and CH_4 decreases.

Pyrolysis refers to the thermal degradation of biomass in the absence of oxygen or other oxidizing agents. Various factors such as temperature, heating rate, pyrolysis time, raw materials, particle size, catalysts, and the flow rate of carrier gas affect the process. Biomass pyrolysis generates solid char, liquid bio-oil, and gaseous fuel, whose proportion depends on different parameters (Akbarian et al., 2022; Huang, Chiueh, & Lo, 2016):

- a lower process temperature (550–950 K) and an extended residence time (450–550 s) promote the production of char in the so-called slow or conventional pyrolysis;
- moderate temperatures (850–1250 K) and short residence times (0.5–10 s) maximize the production of liquid products in the fast pyrolysis;
- high processing temperatures (1050–1300 s) and short residence times (<0.5) encourage biomass conversion into gas.

Beyond traditional heating, where heat is transferred from the heating medium to biomass particles in fixed-bed reactors, fluidized bed reactors, or electric furnaces, pyrolysis can be carried out using microwave heating. Some details on these reactors are given in Table 4. Considering microwave co-pyrolysis of FW with other substrates, i.e. rice straw, it has been proven that characteristics of biochar can be improved including susceptors, such as biochar or $ZnCl_2$ (Mbugua Nyambura et al., 2023).

Considering the pertinent literature, it appears that:

- steam and supercritical water gasification aimed at bio-hydrogen production, with the eventual use of catalysts to enhance hydrogen generation, are becoming more and more attractive;
- pyrolysis of FW is mainly employed for bio-oil production.

Some examples are shown in Table 5.

2.6.3. Transesterification

Triglycerides from different feedstock, including fats from FW, can be converted into fatty acid methyl esters in the presence of alcohol (methanol or ethanol), through a process called transesterification, to produce biodiesel. Since lipidic wastes cause operational issues in AD, some specific substrates, such as waste vegetable oil or animal fats, represent a viable source for biodiesel production (Almutairi, Al-Hasawi, & Abomohra, 2021). Biodiesel is a promising biofuel due to its biodegradability, high calorific value, low sulphur content, lubrication ability, and high cetane number. However, the main limitation to its spread is represented by the high production costs, especially due to the feedstock supply. Therefore, using FW may be very attracting. However, FW contains 5–30% of lipids that have to be separated, i.e. by solvent extraction with high economic costs for the solvents and the generation

Table 4
Characteristics of main pyrolysis reactors.

Type of reactor	Operation	Advantages and/or disadvantages
Fixed-bed	Feedstocks are exposed to a heated medium or bed, where catalysts can be included if needed. As the feedstocks flow through the fixed bed, they decompose, forming pyrolysis products.	No need for back-mixing, easy design, suitability for fast pyrolysis to produce bio-oil. The efficiency may be low, limiting the use at large scale.
Fluidized bed	fluidization increases mixing and interaction leading to efficient heat transfer, uniform temperatures, improved reaction rates and higher yield of bio-oil.	High efficiency due to the higher heat transfer, increase of the yield of bio-oils and gases, as products.
Electric furnace	The heating source is a resistive heating wire.	Compact and easy to be operated, but with a low capacity that increases its use at lab-scale.
Microwave reactor	Microwave electromagnetic radiation used as heating source.	No contact, short reaction time, high heating rate, selectivity, energy efficiency, and reduced emission of pollutants.

Table 5
Some examples of thermo-chemical processes of FW, with indication of main products yields, the waste source and country as well as of the main operating conditions.

Gasification

Source	Country	Operating conditions	Hydrogen and/or methane yield	Ref.
FW of a University hostel		Supercritical water gasification carried out in a 300 ml volume batch reactor, using different additives	12.9 mol H_2 kg^{-1} and 1.5 mol CH_4 kg^{-1} with $NaHCO_3$ as additive	Koshariya et al. (2023)
FW taken from a university canteen	China	Supercritical water gasification carried out in a 10 ml autoclave reactor at temperature and pressure of 800 °C and 40 MPa, using different catalysts	38.29 mol H_2 kg^{-1} with K_2CO_3 as catalyst	Cao et al. (2022)
FW collected from university dining halls	India	Steam gasification of raw and torrefied FW carried out in a fixed bed downdraft gasifier	0.6 m^3 H_2 kg^{-1} (untorrified), 1.04 m^3 H_2 kg^{-1}, 1.66 m^3 H_2 kg^{-1} and 2.15 m^3 H_2 kg^{-1} (torrefaction at 230 °C, 260 °C and 290 °C)	Singh & Yadav. (2021)
FW collected from a University dining hall	Singapore	Biochar-assisted high-solid anaerobic digestion and subsequent steam gasification of the digestate in a lab-scale fixed-bed reactor	34.92 mol H_2 kg^{-1} (gasification), 126.7 mL CH_4 g_{VS}^{-1} (anaerobic digestion)	Zhang, Cui, et al. (2021)
FW (synthetic preparation)	China	Supercritical gasification carried out in a 250 ml batch reactor at different temperatures (400 °C–450 °C)	2.0 mol H_2 kg^{-1} (non-catalytic) 12.73 mol H_2 kg^{-1} (with NaOH as catalyst at reaction) both at temperature 450 °C and residence time 60 min	Su, Kanchanatip, et al. (2020)
FW collected in a treatment center	China	Hydrothermal carbonization in a 200 mL batch reactor (maximum temperature 600 °C and maximum pressure 35 MPa) and supercritical water gasification in the same reactor at different temperature (360 °C, 420 °C, and 480 °C) and residence times (15 min, 30 min, and 45 min) testing several alkali catalysts (NaOH, Na_2CO_3, KOH, and K_2CO_3)	Highest hydrogen yield: 1151.26 mmol H_2 L^{-1}, at temperature 480 °C and residence time 45 min with 5 wt% KOH as catalyst	Yan et al. (2022)
FW (synthetic preparation)		Supercritical water gasification in a 200 mL batch reactor at different reaction temperature (420–480 °C), residence time (30–75 min), feedstock concentration (5–15 wt%) testing three different food additives (NaCl, Na_2CO_3 and $NaHCO_3$)	Highest hydrogen yield: 10.37 mol H_2 kg^{-1} (Reaction temperature 480 °C, residence time 75 min, pressure 28 MPa with Na_2CO_3 used as additive)	Su, Kanchanatip, et al. (2020)

Pyrolysis

Source	Country	Operating conditions	Char, liquid and gas yield	Ref.
FW from the canteen, the dormitory areas, and the grocery store of a university	China	Pyrolysis carried out in a horizontal fixed bed reactor, at temperatures of 300, 400, and 500 °C, heating rate of 10, 20 and 30 °C/min and residence time of 5, 10, 20, 30 and 40 min	Optimal yield of bio-liquid of 37.52 wt% from pure FW (at 400 °C, 20 °C/min and 20 min)	Okopi et al. (2023)
FW produced by catering and households collected in a treatment plant	China	Pyrolysis carried out in a fixed-bed quartz reactor with an inner diameter of 60 mm, heated by a two-stage electronical furnace, reaction time of 30 min at temperatures of 400, 500, 600 and 700 °C	Maximum yields of bio-char (40.26%) and bio-oil (34.90%) obtained at 400 °C; maximum yield of gas (43.10%) at 700 °C	Qing et al. (2022)
FW provided by a treatment company	South Corea	Fast pyrolysis in a bubbling fluidized-bed reactor with silica sand used as the fluidizing bed material, reaction temperatures between 400 and 550 °C; torrefaction employed as pre-treatment	Highest liquid yield (39.54 wt%) at 450 °C	Ly et al. (2022)
Industrial FW and FW solid digestate	China	Pyrolysis carried out in a fixed bed reactor at temperatures of 500, 600, 700 and 800 °C, reaction time of 30 min	FW: gas yield from 47.2 to 67%, oil yield from 19.5% to 8.2%, char yield from 33.3% to 24.8%.	
FW solid digestate: gas yield from 36.3 to 48.8%, oil yield from 15.9 to 8.3%, char yield from 48.8 to 42.8%.				
Both substrates with temperatures ranging from 500 °C to 800 °C	Zhao et al. (2022)			
Cooked FW collected from dining halls of a University	India	Pyrolysis carried out in down-draft fixed bed reactor, heating rate of 10 °C/min, temperatures from 300 to 500 °C), test of 1 h	Oil yield of 31%, 45% and 41% at temperatures of 300, 400 and 500 °C	Modak et al. (2023)
–	–	Co-pyrolysis with polyethylene terephthalate (PET) carried out in a semi-continuous batch reactor, at various temperatures (250, 300, and 350 °C) and reaction times (30, 60, 90, and 120 min), heating rate of 30 °C/min.	Maximum yields of bio-oil and bio-char, 66 and 40, respectively, at 350 °C (strong influence of temperature and weak effect of the reaction time)	Amrullah, Farobie, Septarini, and Satrio (2022)
FW from local eateries and food stalls		Co-pyrolysis with plastics in a fixed-bed batch reactor at temperatures of 300, 350 and 400 °C	Highest yield of bio-oil (up to 29%) obtained at 400 °C	Lim, Tang, Chai, Yusup, and Lim (2022)

of volatile organic solvents such as hexane that are harmful to the environment (Karmee, Linardi, Lee, & Lin, 2015). For this reason, the most common FW used for biodiesel production is waste vegetable oil. Indeed, beyond the operational and economic aspect, biodiesel production from waste vegetable oil may significantly lower the environmental impact of this waste, whose incorrect disposal may damage the sewage system, and have a harmful impact on the aquatic ecosystem.

Beyond vegetable oils, animal fats from beef tallow, poultry fat, fish oils and yellow greases may be used for biodiesel production, obtaining a product with a higher cetane number compared to vegetable oils, due to the higher values of viscosity and saturated fatty acid. In general, biodiesel production is affected by different operating conditions, such as type of reactor, time, reaction temperature, oil to alcohol ratio, stirring speed (MonikaBanga & Pathak, 2023).

Using catalysts contributes to decrease the residence time and enhances the production of biodiesel in terms of quantity and quality. Catalysts can be classified as:

- homogeneous, which can be alkali (i.e. potassium hydroxide, sodium hydroxide, and sodium methoxide compounds) and acid catalysts (i.

e. sulphuric acid, hydrochloric acid, phosphoric acid, and sulfonated acids). Alkali catalysts due to their higher efficiency, low cost and large availability are more commonly used than acid catalysts;
- heterogeneous, either alkali or acid, that are employed due to their low environmental impacts, no corrosion problems, reutilization potential, possibility to separate the catalyst from the reaction mixture;
- enzymatic, emerging due to their low environmental impact, possibility of operating in mild conditions, absence of soap formation and wastewater production, low energy demand;
- bifunctional, useful since they can act as acid and base in esterification reactions of free fatty acids and transesterification reactions of triglycerides.

FW has also been proposed for the synthesis of catalysts for transesterification. As an example, biochar obtained from waste citron has been used as catalyst to produce biodiesel from restaurant FW, with the advantage of reducing economic and environmental costs of the process compared to chemical catalysts.

Plasma technology, based on the application of an intense electric field with the formation of radicals that can replace the conventional chemical catalyst, is also suggested as promising for biodiesel production due to the short reaction time, the absence of glycerine formation and ease of biodiesel separation. Using plasma technology, the reactions on which the process is based are the same of conventional transesterification, with the difference that energetic electrons act as electrocatalyst and the reaction pathway requires less activation energy. Finally, it has to be mentioned that waste vegetable oil could be also directly used as a fuel in internal combustion engines, avoiding the transesterification process with a global lower environmental impact.

2.7. Organic acids

Among the fermentative products in the global market, organic acids represent the third largest category. Organic acid is an organic molecule with weak acidic characteristics that do not entirely dissociate in the presence of water which can be created through microbial activity (El-Qelish et al., 2020). Popular organic acids include acetic acid, lactic acid, and citric acid. Many different industries and processing units, including those involved in processing food, feed and nutrition industry, the pharmaceutical sector, oil and gas stimulation units, etc., use these organic acids. Microorganisms, specifically fungal and bacterial species, are employed commercially to produce organic acids. To make organic acids, bacteria including *Bacillus* sp., *Arthrobacter paraffinensis*, *Streptococcus thermophilus and Lactobacillus* sp., as well as fungi like *Yarrowia lipolytica*, *Aspergillus* sp., and related yeast species, are utilised. The bioprocessing of FW to derive organic acids is discussed below.

2.7.1. Acetic acid

Commercially, a periodic increment in the production of organic acids from the variety of FW generated from the canteen, kitchen, restaurants, etc., was observed. The most common method utilised for acid production is solid-state fermentation, which takes place in the absence of water and is a predominantly preferred method involved in converting various enzymes from wide FW varieties to organic acids and other intermediates. In the food processing industry, acetic acid, also referred to as vinegar, is a low-cost carboxylic acid generated using the remnant residual from anaerobic fermentation of substrates, but the demand for vinegar is still growing. According to Roda et al. (2017) pineapple waste, particularly peels, has a high sugar concentration, rendering it a unique source for wine and vinegar production. As a result, it enhances possible applications of employing pineapple waste for producing alcohol and acetic acid for making vinegar. The findings of this investigation showed that 30 days were needed for pineapple wine-based vinegar to produce an acidity level of 5% (w/v). The olive oil processing industry generates pomace and wastewater, which can yield phenol-enriched vinegar acidity of over 5.6%. A multistage membrane integrated hybrid process has been developed to commercially synthesize acetic acid from waste cheese whey (Nayak et al., 2015). According to reports, this procedure produces excellent acetic acid recoveries from multistage fermentation systems.

2.7.2. Citric acid

One of the most frequently utilised organic acids in numerous sectors is citric acid because of its numerous commercial applications. Additionally, it has been designated to be a GRAS (Generally Recognized As Safe) chemical. This significant organic acid can be generated in vast scale through the process of fermentation. Citric acid manufacturing unit may use fruit wastes like orange peel, sweet lime peel, banana peel, and pineapple peel as a substrate. More than 80% of the citric acid produced in the globe seems to be produced by submerged fermentation using the *Aspergillus Niger* which grown on media containing glucose or sucrose. Due to its unique physiological characteristics, this bacterium may produce large amounts of citric acid. Compared to the chemical approach, the anaerobic fermentation technique for producing citric acid reduces production costs by 50%, saving $5 per kg (Karaffa, L & Kubicek, 2019) Thus, it appears to be a commercially viable technique to reduce production costs and an environmentally sustainable waste management method to fulfil the demands of a growing global citric acid market. Citric acid has been fermented using a variety of substrates, including lignocellulosic biomass, waste bread, and fruit waste. About 278.5 g/kg citric acid was yielded by using dried pomegranate peels as a substrate over the course of 8 days at 25 °C and pH 8.0.

2.7.3. Succinic acid

Another type of acid, succinic acid, a dicarboxylic acid, plays a significant role and is used in producing a variety of goods with added value. Succinic acid is commonly made from maleic acid and anhydrides through paraffin oxidation, electrolytic reduction, or catalytic hydrogenation. It is also widely used as an artificial sweetener in manufacturing polybutylene succinate-terephthalate, polyester, coatings, pigments, and resins in the food and pharmaceutical industries. Waste peel of Citrus fruits produced from the fruit processing industry undergoes hydrolysis using dilute acid to produce essential oils and pectin, resulting in substantial succinic acid yields with no inhibitor formation. In a different study, residues from watermelon, potato, banana, pineapple, onion, orange, tomato, vegetables and fruits yielded 27.03 g/L succinic acid (Dessie et al., 2018). The production of succinic acid by biological organisms, such as *Escherichia coli* and *Actinobacillus succinogenes*, is distinguished by special traits such as osmotic pressure tolerance (caused by sugars and acids) (Ong, Fickers, & Lin, 2020). The greatest yield ever recorded for succinic acid fermentation from leftover bread was 47 g/L. *Actinobacillus succinogenes* was used to generate 24.8 and 31.7 g/L of succinic acid from cake and pastry scraps. *Actinobacillus succinogenes* was also used in an anaerobic procedure to produce succinic acid with a high yield (92%) from potato wastes.

2.7.4. Lactic acid

The carbon atom in lactic acid is asymmetric, making it a C3 carboxylic acid. This lactic acid is produced chemically, enzymatically, and by fermentation processes. In fact, biological fermentation processes account for 90% of all lactic acid production. Since *Lactobacillus* is abundantly present in nature and can multiply and develop quickly, it is utilised more frequently than *yeast, cyanobacteria,* or other microbes. The cost of the raw materials and the expenses of downstream separation and purification are still major problems in the of lactic acid fermentation. Agricultural waste, FW, and other inexpensive raw materials are commonly employed as a substrate for lactic acid production to minimise production expenses. In general, lactic acid bacteria are facultative or obligate anaerobes that may grow in various pH and temperature conditions. Batch fermentation of kitchen waste produces 4.5 g/L L-lactic acid by using *marine-animal-resource* (MAR) bacterial consortium. Without using exogenous enzymes or pretreatment, *Streptococcus* sp. fermented FW to produce lactic acid with a yield of 0.81 g/g. Reactors inoculated with fresh food waste produced substantially more lactic acid at a rate of 28.4 g/L along with methanogenic and anaerobic sludge. At pH 6.02, 35.37 °C, and 20% inoculum, the maximum organic acid content was 77 g/L, with LA accounting for 78% (Lian et al., 2022). Uncertainty exists over the ideal C/N ratio. The maximum LA concentration and yield were 48.4 g/L and 0.904 g/g total sugar was achieved at a C/N ratio of 23, while Cao, Zhang, Zheng, Lian, and Dong (2020) discovered that the maximum lactic acid yield was 44.3 mg COD/g VS added at a C/N ratio of 35. Many techniques have been devised for the removal and purification of lactic acid in fermenting liquor, including extraction, precipitation crystallisation, and membranes. The maximum concentration of LA was attained at a 14-day HRT and 2.14 g VS/L day OLR operational parameter, yielding 0.82 g LA/g CA and an overall concentration of 8.72 g COD/L. The LA production yield fell when the OLR was raised while the HRT was lowered.

2.7.5. Propionic acid

Propionic acid is a preservative that is mostly utilised in the food processing industry and is typically generated through expensive petrochemical processes. *Propionibacterium freudenreichii T82* wild strains were employed by Piwowarek, Lipińska, and Hać-Szymańczuk (2016) to manufacture propionic acid from pomace of apple, a common biomass from fruit waste. Within 120 h of the fermentation culture, fermentation of propionic-acetic acid uses pomace as the carbon source to generate a maximum value of 1.77 g/L of propionic acid concentration. Recently, in the research work of Zhang et al., 2023, *Aspergillus* spp.-derived fungal mash was proposed as green enzyme supplement to be used in FW valorisation. A complex enzyme isolated from *Aspergillus oryzae* was used to boost the quantity of propionic acid in VFAs produced during FW fermentation. The VFA concentration in the FW fermentation liquid reached 38.1 g COD/L at the complex enzyme dosage of 0.2 g/g VSS, with the fraction of propionic acid increasing to 42.7%.

3. Circular economical approaches for FW upscaling

3.1. Technoeconomic evaluation

When effectively managed, FW can be transformed into valuable products. To be economically feasible, the generation of multiple value added products rather than that of a single product from heterogeneous FWs should be promoted. However, the comparison among different processes is complex due to the limited studies on the techno-economical aspects of existing technologies, including material storage, handling and conversion facilities, especially at large-scale. AD is one the most common processes to manage FW, since it is a commercially available, energy efficient and environmentally-friendly technology, producing energy from biogas and amendment/fertilizer from digestate (Emmanuel et al., 2022). Regarding biogas, different techno-economic analyses indicate that its use as a car fuel appears to be one of the major future uses, whereas on-site or in the nearest industries, heat can be employed to maintain the temperature of the reactor (Nguyen et al., 2022). The upgrading to biomethane increases the economic attractiveness of biogas production compared to direct electricity production. However, due to the high investment costs of the upgrading technologies the economic profitability cannot be achieved without suitable subsidies or CO_2 trade.

Beyond biomethane, the interest for bio-hydrogen production from FW is increasing, However, although the two-stage dark fermentation appears to be promising in efficiently converting FW to bio-hydrogen in both laboratory and pilot scales, it may be premature to assert its feasibility and cost-effectiveness in commercial-scale operations (Franchetti, 2013) Different costs have been estimated for bio-hydrogen from FW biogas, ranging from 3.2 \$/kg-H_2 (Zhao, Wang, Li, Yan, & Chen, 2022) to 27.13\$/kg-H_2 (Feiz et al., 2022) (considering the LHV of hydrogen and the average production cost of \$0.814/kWh). The scale of the plant significantly affects the economic profitability of bio-hydrogen production. As an example, the minimum selling price of bio-hydrogen has been found to be US\$ 26.3/kg with a capacity of 50 t/d of FW, with a decrease up to US\$ 6.2/kg, which is a cost comparable to that of fossil-based H_2, by increasing the plant capacity to 2000 t/d. Similarly, it has been shown that to obtain a reasonable unit production cost of hydrogen, estimated at US\$1.02/m^3, the plant has to operate at a capacity higher than 0.3 ton/day (Sharmila et al., 2020). Another aspect to be considered is the maximization of revenues through suitable valorisation of all the by-products, i.e. composting the undigested solids to obtain organic fertilizer. Finally, as for biomethane, policymakers need to establish financial systems to support the spread of biohydrogen production, since the financial needs for such infrastructures may exceed the stakeholders possibilities (Díaz-Vela et al., 2015). Differently from biomethane and biohydrogen, very limited literature is available about economics of biohythane (Yan et al., 2022).

Considering thermo-chemical treatments, they are energy-intensive and require advanced equipment and expensive investments. (Su, Cai, et al., 2020). Typically, the most affecting parameters on the production cost of gasification are raw materials, process utilities, maintenance and hazardous waste disposal. The costs connected to the utilities further increase when plasma gasification is considered since this process is characterized by high power and large cooling water consumption. Regarding pyrolysis, the economic feasibility increases when all the products, i.e. bio-oil and bio-char, are effectively used (Sharmila et al., 2020) and when the operating conditions improve their quality, i.e. by employing microwave pyrolysis rather than traditional heating pyrolysis. Similarly to the previous recovery routes, the economic attractiveness of biodiesel production from FW is significantly influenced by the facility-dependent cost, i.e. maintenance, depreciation, insurance, local taxes, and factory expense, raw material cost, and labor cost, as well as by the possibility of reusing all the by-products of the process (Agapios et al., 2020). Concerning material recovery, the available literature related to techno-economic analyses is very limited compared to biofuels production. In rural areas, FW is often improperly managed, and the only applied strategies appear to be recovery for animal feeding or compost production. Education and awareness campaigns to modify the current behavior of households (Pocol, Pinoteau, Amuza, Burlea-Schiopoiu, & Glogoveţan, 2020), as well as funding to reduce the high costs that cannot be mitigated through the economies of scale, should be implemented as strategies to improve management of FW in rural areas.

FW and beverage waste were used to produce sugar syrups finding that the process is economically self-sustainable with net profit generation and positive net present values. Regarding the production of organic acids, lactic acid was obtained from FW without sterilization, employing the indigenous microbial population (Peinemann, Demichelis, Fiore, & Pleissner, 2019). It was found that the process economically feasible, with a simple payback lower than 10 y, only at large plant size. In comparison to the production of methane, the profitability of converting FW to organic acids, such as lactic acid or butyric acid, can be raised by 5–16 times. Dark fermentation with butyric acid separation and purification yields has the highest profit at 296 USD/t VS (47 USD/t of FW). The importance of the economy of scale was highlighted also analyzing different valorisation pathways for several types of FW, i.e. extraction of lycopene and β-carotene from tomato wastes, extraction of three phenolic acids and three glycoalkaloids form potato waste, extraction of essential oils, pectin and phenolics from orange waste, and extraction of phenolic compounds from olives waste (Cristóbal, Caldeira, Corrado, & Sala, 2018).

Another addressed pathway is the production of thermoplastics, where the production cost is significantly affected by the operating costs, especially those of the chemicals employed in the processes. Focusing on PHAs, their production integrated with biofuels generation, was demonstrated to be economically feasible, especially at high solid loading and low solvent volumes (Rajendran & Han, 2022a, 2022b). Similarly, solvent usage was found to significantly affect poly (butylene succinate) production (Rajendran & Han, 2023).

3.2. Life cycle assessment

Life cycle assessment (LCA), a standardized method developed to quantify the potential impacts on the environment and human health associated with a product or a service, is commonly employed to compare different solutions for FW treatment (Di Salvo et al., 2023).

The majority of LCA studies on FW management focuses AD as processing strategy. It resulted the most convenient strategy, in terms of global warming impact, when compared to aerobic composting and incineration due to the possibility of energy self-supply by using the produced biogas and the CO_2 reduction connected to the use of the compost produced from the digestate material (Moraes et al., 2014). However, composting was identified as more environmentally friendly compared to incineration. AD has been recognized to be efficient also at small scale. More in detail, investigating the implementation of small-scale biogas plants in university campuses, it was demonstrated that the environmental consequences associated with FW management can be mitigated, especially if AD is integrated with pyrolysis for disposing of the digestate (Nathao et al., 2013). Such a strategy can be particularly valuable in countries where using digestate from FW as a soil fertilizer is forbidden. Regarding the use of digestate as fertilizer, energy recovery from FW rather than the production of compost to replace mineral fertilizers was indicated as more convenient from an environmental point of view, due to the high energy demand and off-gas emissions of combined AD-composting (Devi et al., 2023). However, at the same time, using biogas for energy generation, i.e. in a cogeneration plant, negatively impact carcinogenics, non-carcinogenics, and ozone depletion, highlighting the inevitable environmental consequences of energy production from biogas.

LCA was also used to compare different operation strategies of AD. More in detail, several emerging technologies of AD, namely two-stage AD system with ultrasound pretreating, two stage continuous combined thermophilic acidogenic hydrogenesis and mesophilic with recirculation of the digested sludge, long-term AD of FW stabilized by trace elements, were compared to the conventional single stage AD and landfilling, identifying the two-stage AD system with ultrasound pretreating as the more environmentally process (Mahato et al., 2019). Focusing on AD aimed at biomethane production, the lower climate impact, lower non-renewable primary energy use and significant nutrient recovery of such a biofuel compared to conventional fossil fuel were recognized, investigating plants with different scales and varying shares of treated FW, pointing out the importance of the efficiency of pretreatment, the energy system used for self-supply of the plant, and the digestate treatment to increase the overall performance of these systems (Dinesh et al., 2018). Other important parameters to reduce the environmental impact of AD are the correct source separation and the pretreatment rejection rate related to the removal of non-organic material incorrectly sorted with FW. Regarding bio-hythane production through co-digestion of FW and micro-algae, electricity production, CO_2 release in pressurized water, and energy recovery were identified as the processes characterized by the highest emissions (Okoro- Shekwaga, Turnell Suruagy, Ross, & Camargo- Valero, 2020).

Although different studies on FW processing based on lifecycle perspective can be found in the literature, the comparison between different alternatives appears to be difficult especially due to variations in system boundary settings, methodological choices, and to a lesser extent, differences in input data (Atiwesh et al., 2021).

4. Challenges and opportunities

Substantial accumulation of FW due to the world's expanding human population has prompted the quest for environmentally friendly methods of managing FW to address ecological problems. The process of biotransformation of FW into high-value-added bioproducts that are considered to be potentially appropriate for commercial application owing to its prospective significant economic benefits and ecological reliability demonstrated by the bioprocesses after optimisation (Aslam et al., 2018). A major barrier to the commercialization of the bioconversion of FW into profitable bioproducts is the initial investment cost for the extensive biorefineries experimental trials for optimal operating efficiency and the infrastructure (Murugesan et al., 2022; Sajid et al., 2022). A bioeconomy viewpoint emphasises the significance of recovery technology in determining product quality, together with hygienic issues that are crucial when dealing with certain materials like FW or contaminated waters (Lian et al., 2022). Furthermore, because there haven't been any actual biorefinery deployments, comprehensive economic studies are currently not available still. Apart from these challenges, the creation of efficient and affordable technology to extract these value-added compounds will greatly lessen the industry sector's economic and environmental impact. A value-added product offers people opportunities for creativity that allow them to participate in the business activities. This product manufacture opens up opportunities for income generation, which boosts employment across a variety of industries. Workers' creativity is used to produce appealing new items, good labelling, and attractive packaging. Suitable surplus food can be distributed to those in need through the right organisations, charities, etc. In addition, some of the startup companies are developed for marketing the FW waste derived bioproducts. RUBBLES ARE RUBIES is a UK based company which produces condiments from food waste example: spicy tomato relish produced from tomatoes which were too ripe or flawed to be sold in the production department, or a pear chutney produced from imperfect pears. Brooklyn-based yogurt company White Moustache produces probiotic tonic from a discarded liquid on making yogurt for producing whey. From the perspective of a biorefinery, the low cost of the FW feedstock could compensate for the high initial cost of establishing a biorefinery. Thus, the development of effective and economical technologies to extract these value-added compounds will significantly reduce the economic and environmental impact of industrial sector which in turn create more opportunities.

5. Conclusion and future perspective

This review illustrates the important potential of food waste as a resource for the creation of high added value products. The main aspect to be highlighted from both economic and environmental perspective is the integration of different processes and different waste streams to obtain multiple high added value products rather than a single product. However, due to the complex infrastructure required for practical implementation, economic barriers frequently impede the development and growing interest in the search for alternative approaches to food waste management. In consideration of this fact, cautious and highly organised investigation in biotechnology with provocative assumptions is needed to achieve the circular economy goal with optimised economic profits with the least amount of energy consumption and financial investment.

Credit authors statement

Simona Di Fraia: Writing – original draft, Review & editing. V. Godvin Sharmila: Writing – original draft, Review & editing, Conceptualization, Methodology. J. Rajesh Banu: Resources. Nicola Massarotti: Resources.

Data availability

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