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Integrated Technologies for Food Waste Valorization: A Sustainable Approach toward a Circular Bioeconomy

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ABSTRACT

Food waste is a significant global problem with far-reaching environmental and social impacts. The inefficient processing accelerates the ecological degradation and enhances the greenhouse gas emissions, which urges the development of advanced bioprocessing strategies. Food waste is an abundant and inexpensive feedstock for biorefineries because of its rich content of carbohydrates, proteins, lipids and minerals, which enables the generation of high-value products and the realization of the vision of a circular bioeconomy. Given the rising demand for energy and the need to reduce dependence on fossil fuels, recent research has increasingly employed genetic recombination and synthetic biology to improve the production of biofuels, bioplastics and bioactive compounds, overcoming critical bottlenecks in existing biorefinery systems. This review underlines the synergistic role of biorefineries and omics technologies in accelerating resource recovery and curbing waste generation, while providing perspectives on future directions for organic feedstock valorization.

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Introduction

Changing patterns in global food consumption have led to the expansion of agriculture. While agricultural intensification offers a potential solution to hunger, it also results in the generation of substantial waste. Throughout the food supply chain, food waste (FW) is produced, posing significant challenges to food security [1]. Immense FW generation poses a great risk on waste management system, resulting climate change, contributing to greenhouse gas emission and exacerbating the health of ecosystem and environment and subsequently causes loss of biodiversity. FW generation starts from farming production, followed by handling products, harvesting, storing, processing and consumption. Unavoidable FW are generated because of lack of proper storage and transportation, inefficient processing of preparation and consumption [2]. Additionally, inedible food parts include spoiled or contaminated food, posing health risk, if consumed. However, unavoidable FW cannot be completely omitted, thus efforts are essential to minimize its negative impact. Effective waste management is crucial for achieving sustainable development goal (SDG) 12, which promotes responsible consumption and production. It aims to halve food waste and significantly reduce food loss by the year 2030 [3]. Composting and anaerobic digestion (AD) are among the most efficient technologies for FW valorization. These processes yield nutrient-rich end products compost and bio-digestate which significantly reduce the reliance on synthetic fertilizers in agriculture. The efficiency of the waste biomass conversion faces several challenges and need to be optimized, hence new technologies (e.g., biorefinery) should be integrated to transform inedible FW into valorized resources like biogas and bio-energy production [4]. In this context, integrated biorefinery gains much attention for efficient waste management, addressing the shortcomings of biological techniques. Due to its availability, high nutrient density, and organic composition, FW is increasingly recognized as a low-cost and versatile substrate for the production of renewable energy and bio-based products, including biohydrogen, biodiesel, biomethane, and fertilizers [5]. Smart approaches are playing pivotal role in waste reduction system, addressing zero waste leakage. The underlying mechanisms of FW valorization depend largely on the physicochemical nature of the waste. Therefore, exploring the diversity of microbial communities represents a feasible and strategic step toward optimizing FW valorization. Omics technologies like genomics, transcriptomics and proteomics are efficient technologies for identifying the microorganisms used for waste conversion, thereby constructing selective microbial consortia for improvement of the conversion technologies and make it acceptable in globally [6]. In addition, biotechnological advanced techniques are employed to improve the efficiency of waste transformation technology. Recombinant technology and synthetic biology are potentially active to reframe the robust strain to increase the FW valorization sustainability [7]. This review delves into modern strategies for enhancing FW valorization, offering comprehensive insights into innovative solutions that tackle key limitations in FW management. It also discusses current challenges and presents forward-looking recommendations for sustainable improvement.

Food Waste Generation and Challenges

FW comprises a wide range of materials including discarded vegetables and fruits, expired and processed food products, inedible scraps, domestic kitchen waste, and agricultural residues [8]. Its composition is highly heterogeneous, primarily consisting of proteins, carbohydrates, and lipids. Physicochemical properties of FW vary significantly, with moisture content ranging between 74-90%, volatile solids constituting 80-97% of total solids, and carbon-to-nitrogen ratios fluctuating from 14.7 to 36.4. Furthermore, FW is enriched with macronutrients such as potassium, nitrogen, and phosphorus, essential for plant growth and photosynthesis [9]. Waste is generated throughout the food supply chain including stages like manufacturing, storage, handling, distribution, and packaging and is influenced by numerous factors such as excessive inventory, poor infrastructure, lack of technological advancement, insufficient logistics, limited skills, and unavailability of markets [10].

According to the United Nations Environment Programme (UNEP), approximately 931 million tonnes of FW were generated globally in 2019. In India alone, household FW accounts to 50 kg per capita annually, with the majority originating from fruits and vegetables, including peels, cores, and damaged produce. Fruit and vegetable processing industries in the U.S., India, and China generate substantial waste approximately 15 million tonnes, 1.81 million tonnes, and 32 million tonnes per year, respectively [11]. India, ranking second in global fruit and vegetable production, contributes 10% of total fruits and 14% of total vegetables, with an annual output of around 243 million tonnes [12]. Sub-sectors such as canning, pulping, freezing, dehydration, and concentration production contribute significant quantities of non-edible by-products like peels, seeds, pomace, and skins. These residues are rich in beneficial compounds such as polyphenols, carotenoids, fibers, vitamins, and enzymes, and constituted 10-60% of the original produce mass [13, 14]. Poor waste management practices often result in the loss of these nutrient-rich materials and contribute to environmental pollution.

Cereals, the vital dietary staples due to their high content of carbohydrates, proteins, fats, and B-complex and E vitamins reached a production volume of 2,769 million tonnes globally in 2020, projected to rise by 0.7% [15]. Cereal processing employs dry and wet milling techniques, producing by-products such as bran, husk, straw, and germ [16]. Rice processing generates around 30% by-product mass comprising of 20% husk, 8% bran, and 2% germ. While straw has applications in biofuel and fertilizer production, it is often burned or left to decompose, which negatively impacts the environment [17]. Rice husk has historically been used for thatching, mat-making, and broom production, and more recently in fertilizer and brick manufacturing [18]. Malting of cereals like barley, corn, and wheat, used in beverage and vinegar production, generates nutrient-dense spent grain, rich in fibers, vitamins, phenolic compounds, and phytoestrogens [19]. In addition, dairy waste primarily results from cleaning, heating, cooling, and cheese production. The wastewater volume may be triple that of the processed milk, with whey constituting 85-90% of milk containing over half the nutrients and exhibiting high COD (chemical oxygen demand) and BOD (biological oxygen demand) values [20].

Meat processing generates by-products such as bones, skin, organs, and blood-rich wastewater, comprising over 50% of animal body weight. In Asia, edible pig by-products reached 625 million tonnes in 2004, nearly half the global total [21]. Seafood waste includes scales, shells, and skeletons, yielding 6-8 million tonnes annually. These materials are rich in proteins, calcium, and chitin, and when improperly disposed via landfill or incineration, can result in eutrophication and public health risks.

Inappropriate disposal practices such as incineration and landfilling release harmful pollutants like greenhouse gases, particulates, and toxic substances, leading to degradation of air and water quality. Globally, FW accounts for 8-10% of anthropogenic greenhouse gas emissions. Its average annual carbon footprint stands at 3.30 gigatons CO_2-equivalent (6% of global emissions), rising to 4.40 gigatons (8%) when expanded metrics are considered [22]. To address these critical concerns, implementing effective valorization strategies is essential. Reducing food waste and by-products is key to achieving the UN's 2030 SDG. The EU's Waste Framework Directive (2008) sets progressive reduction targets of 55% by 2025, 60% by 2030, and 65% by 2035 [23].

Food Waste to Wealth: A Concept of Circular Bioeconomy

The bioeconomy has recognized the potential of food waste as a source of energy. Therefore, its vast quantity can be integrated into the circular bioeconomy through three key strategies: reduce, reuse, and recycle. The untapped potential of FW can be harnessed through biorefinery processes that utilize various biochemical and microbial pathways such as fermentation, acidogenesis, methanogenesis, solventogenesis, photosynthesis, oleaginous conversion, and bio-electrogenesis [24]. These processes facilitate the transformation of FW into a wide array of valuable products, including biogas (methane), biofuels (CH_4, biodiesel, biohythane, hydrogen), bioelectricity, biomass, animal feed, biopolymers, biofertilizers, and platform chemicals like bioethanol, carboxylic acids, biobutanol, and fermentable sugars [25]. FW is a promising source for the production of energy, biofuels, and bioactive compounds. Its diverse composition and physicochemical properties such as porosity, surface area, and the presence of functional groups, enable effective adsorption of environmental pollutants. Organic constituents like lipids and proteins enhance FW's ability to trap dyes, heavy metals, and other contaminants. Fruit and vegetable waste, in particular, offers unique adsorption capabilities. For example, citrus peels, which are naturally rich in pectin, can chelate metal ions and efficiently remove heavy metals such as cadmium (Cd) and lead (Pb) from wastewater. Likewise, bread waste, with its high starch content and porous structure, has been shown to remove up to 75% of oils and organic pollutants from wastewater [25]. Spent coffee grounds, which contain active compounds like polyphenols and caffeine, also exhibit strong adsorption capacity, removing approximately 70% of Pb and 65% of chromium (Cr) from polluted water, highlighting their potential as low-cost bio-adsorbents [26]. Thus, redirecting the FW from landfilling to utilization as bio-adsorbent, approaching circular bioeconomy followed by zero waste leakage. To align with circular economy principles (Figure 1), it is essential to convert FW into valuable products such as chemicals and fuels, minimizing losses from the initial stages.

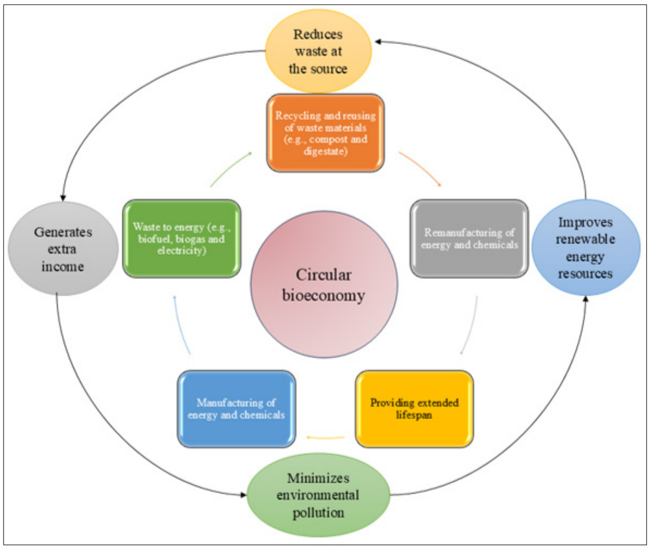

Figure 1: Circular Bioeconomy Framework for Food Waste Valorization

Food Waste Valorization Via an Integrated Biorefinery Approach

The integrated biorefinery framework utilizes a network of complementary techniques including AD, enzymatic hydrolysis, fermentation, and microbial transformation to recover bioenergy, biochemicals, and biomaterials from various food waste sources (Figure 2) [23]. By harnessing the synergistic potential of these processes, biorefineries promote efficient resource utilization, advance circular bioeconomy objectives, and contribute to sustainable waste management solutions. This process must be recognized to reduce the waste generation in each step of food processing. It begins with extraction of high value-added compounds like proteins, oils, vitamins, sugars, waxes, antioxidant compounds, fragrance compounds etc from FW through several extraction recovery technologies. However, the major portion of FW is redirected to the bioreactor or treated with AD and composting for generation of bioethanol, biogas and biofertilizers respectively [27]. Moreover, oil rich FW could be used as raw materials for the recovery of chemically pure compounds through chemical conversion. These oil-based feedstock could be employed for the synthesis of biofuels, stabilizers, surfactants, fatty amines, plasticizers, soaps, lubricants and dicarboxylic acids. Platform chemicals can be subsequently converted into high value-added chemicals and biopolymers through clean and green technologies [28]. Besides the value addition into waste, FW based biorefinery expedite nation's economy and can complement fossil-based refinery to a certain extent. This approach addresses the climate change issues and improves food security. Overall, biorefinery promotes collaboration among researchers, farmers, stakeholders, economics, industries, society and ultimately strengthens nation's economy. Incorporation of biorefinery into bioeconomy explores regeneration, restoration and reuse of existing waste materials to intact the circular-based economy, enable closing the loop, and ensure the technical, financial and societal transformations [26]. In near future, FW biorefinery can able to achieve sustainability in environment with zero waste leakage. FW management hierarchy begins from collection, processing, and transportation preventing food loss and waste (Figure 2).

Pretreatment of Food Waste

Due to heterogenous nature of FW, pretreatment of this organic feedstock is essential. Pretreatment is the crucial step in FW biorefinery, offering substantial contribution to circular bioeconomy. Thus, adequate pretreatment is essential to utilize the full potential of FW by focusing the accessibility of microorganisms to FW. Currently used pretreatment technologies are physical, chemical, physicochemical and biological. Physical pretreatment techniques (freezing, extrusion, microwave, pyrolysis and milling) are used to increase surface area, thereby enhancing the accessibility to microbes [29]. However, the process is cost-competitive. Further, inhibitors are released during the process, obstructing the process efficiency. In addition, chemical (acid/alkaline) pretreatment may cause environmental deterioration and it is also not cost effective. Integrating the pretreatment techniques with AD enhances biofuel generation and chemicals in return. For instance, methane with high potential was recovered from AD with prior chemical pretreatment. However, chemical pretreatment leads to obstruct the digestion process by producing inhibitors like phenolics and furans subsequently inhibit biological activity and lowers methane productivity [23]. Overcoming biorefinery challenges is essential for efficiently producing high-value products from FW while minimizing costs. Biological transformation of FW has significant advantages over chemical (hydrolysis, oxidation, supercritical fluid extraction, solvent extraction etc.) and physical treatment (milling, extrusion, freezing, microwave and pyrolysis). Furthermore, biological transformation is cost-effective and safe [30].

Food Waste Processing through Diverse Approaches

Moreover, biorefinery process involves network of technologies such as solid-state fermentation, in which proteins and carbohydrates are split into amino acids and monosaccharides respectively. Lizardi and Hernández-Martínez reported that a number of microorganisms are employed to produce bioactive compounds [31]. For example, *Aspergillus* or *Penicillium* are used for antibiotics production, *Mortierella* for biodiesel production, *Rhizopus* for bioactive compounds and similarly, *Bacillus* used for biosurfactants and yeast for bioethanol generation.

Submerged fermentations rely on biological enzymatic hydrolysis, facilitating the breakdown of food waste components. Studies have shown starch conversion rates reaching approximately 90%, yielding 143 g/L of glucose, 1.8 g/L of amino acids, and 1.69 g/L of phosphate in the final product. This method enhances resource recovery and promotes efficient biochemical transformation [30]. Selo et al. highlighted that ethanol and organic acid production can be achieved cost-effectively through FW treatment fermentation biorefinery [32]. Their study emphasizes how fermentation-based approaches enhance resource recovery while minimizing waste disposal costs. Composting and AD are valuable techniques in the biorefinery process, where microbes act as decomposers, breaking down the total biomass of FW into value-added products. In composting, microorganisms convert organic matter into nutrient-rich compost, which improves soil quality. In AD, microbes digest food waste in oxygen-free conditions, producing biogas (a renewable energy source) and digestate (a nutrient-rich byproduct) [33]. Later on, by using integration of fermentation and AD technology Demichelis et al. yielded 0.33 g lactic acid/g FW followed by 0.9 Nm3 biogas/KgVs in FW. This approach enhances FW valorization by extracting valuable biochemicals and generating renewable energy, making the process more efficient and sustainable. Thus, by integrating these technologies, it is possible to achieve industrial-scale production of both chemicals and energy, ensuring that the caloric content of FW is effectively utilized across multiple valuable products. This approach enhances resource efficiency and promotes sustainable waste valorization. Furthermore, biorefinery process is significantly contributed in the coproduction of different valuable products like biogas, ethanol and hydrogen through fermentation while recovering volatile fatty acids production simultaneously [34]. Lipid recovery plays a crucial role in biorefinery systems, where FW is separated into two distinct phases. In the solid phase, oils and fats are extracted and utilized for biodiesel production. Meanwhile, the liquid phase retains essential nutrients that are further processed through fermentation, enabling the production of various bio-based compounds [30]. Although the lipid fraction's composition makes it suitable for biodiesel production, meeting the European biodiesel standard EN 14214, its high free fatty acid content necessitates a two-step process, including an acid pre-esterification step. Studies have reported biodiesel yields exceeding 90%, though challenges such as low oxidation stability (4 hours, below the 6-hour minimum threshold set by EN 14214) persist due to the presence of polyunsaturated fatty acids [35]. Because of the amphiphilic nature of lipids, the Soxhlet method combined with organic solvents is the most commonly used extraction approach. Barik and Paul studied how exposure time and food waste/solvent ratio (using 2:1 methanol/chloroform) influenced extraction efficiency in household FW, reporting a peak lipid yield of 57.8% after 120 minutes. Innovations in nutrient extraction technologies have led to the adoption of ultrasound and cold plasma (CP) methods, replacing traditional solvent-based or thermal treatments [36]. These advancements reduce environmental impact and costs, while improving efficiency in macro- and micro-molecule separation, extraction, purification, and isolation. Additionally, CP serves as a low-temperature decontamination and sterilization technique, utilizing ultraviolet radiation, while also controlling FW odor and enzyme activity [37]. In contrast, ultrasound enhances extraction processes for phenols, sugars, pigments, and organic acids, supporting nanoencapsulation and fibre degradation in food waste treatment.

Furthermore, synergies exist between various methodologies, such as the electro-fermentation bioprocess, a hybrid approach combining fermentation with microbial electrochemical systems. This method addresses industrial-scale challenges, such as thermodynamic limitations, by using electrodes to lower activation energy, improving the catalytic efficiency of fermentation [30]. Studies show that this technique effectively extracts higher amounts of volatile fatty acids (VFA) from FW [38]. Implementing these cutting-edge technologies like ultrasound, microwave, and microbial processes within biorefineries enable the conversion of FW into bioactive substances, effectively tackling economic and environmental issues. However, there is limited prior research supporting the market benefits of food waste-derived value-added products. Furthermore, by focusing purification strategies at different stages of waste processing a mixture of value-added products can be recovered. This strategy will minimize the cost spent in downstream processing. For instance, ethanol production is found less concentration in fermentation technology, whereas development of the coupling of the fermentation and recovery technology (membrane pervaporation and gas stripping) can improve the ethanol yield and economy [39]. Sterilization remains a major challenge in waste valorization, particularly due to the heterogeneous composition of FW. The sterilization process can lead to sugar degradation, reducing the availability of fermentable sugars and making biofuel production less cost-effective [40]. An alternative to sterilization involves adjusting the solution's pH to highly acidic levels (pH 4), which promotes spontaneous ethanolic fermentation by yeast. This approach is commonly observed in wine production, where grape juice fermentation is facilitated by the model yeast *Saccharomyces cerevisiae*, eliminating the need for extensive sterilization while maintaining microbial control [39].

Hydrothermal treatment is a preferred method for waste processing, particularly over AD, as microbes used in waste valorization often struggle to survive in extreme conditions. To address this, highly resilient microbial strains should be employed to enhance bioconversion efficiency [41]. The end product obtained from this process is known as hydrochar, which serves as an efficient adsorbent and a valuable carbon source for soil microbes. Additionally, torrefaction is recognized as an effective waste conversion technique, but its high energy demand makes it economically challenging. To mitigate this, hybrid approaches such as torrefaction-pyrolysis and AD-torrefaction offer promising solutions for optimizing operational parameters, improving biomass valorization, and refining product characterization [42].

To further boost biofuel production, microbial growth in bioreactors can be enhanced by co-processing FW with other organic waste, including agricultural residues, livestock waste, and municipal waste. Furthermore, to support a circular bio-economy, a multichannel approach can be adopted, where effluent from bioprocessing is combined with the solid fraction for microbial degradation via anaerobic composting, leading to biogas production. This not only reduces industrial waste disposal burdens but also generates an additional revenue stream for processing facilities. Studies indicate that membrane technology is an effective large-scale solution for reducing production costs. For instance, Aydin et al. (2018) utilized membrane separation techniques for recovering VFAs from food waste [43]. Integrating this technology into AD systems enables continuous recovery of essential compounds while efficiently removing unwanted substances, such as in anaerobic membrane bioreactors [44].

Connecting membranes to bioreactors facilitates effective liquid-phase separation, allowing for analysis of bioactive compounds or reuse by mixing with solid substrates to enhance microbial activity. Another advantage of membrane technology is its ability to adjust the dilution of digested feedstock, optimizing biogas yield. By retaining solids, including slow-growing microbes and undigested substrates, it ensures faster and more uniform degradation, ultimately improving biogas production rates and effluent quality [44, 45]. However, membrane fouling poses a challenge in membrane technology applications. While biogas sparging is commonly used to minimize fouling, it comes with energy consumption concerns and an increase in production costs. Additionally, the profitability of these processes is significantly impacted by transportation and electricity costs. To optimize resource efficiency, these challenges must be thoroughly analysed and addressed, ensuring a more comprehensive evaluation of food waste losses in biorefinery systems [46]. Table 1 enlists several FW valorization techniques along with their corresponding product recovery outcomes.

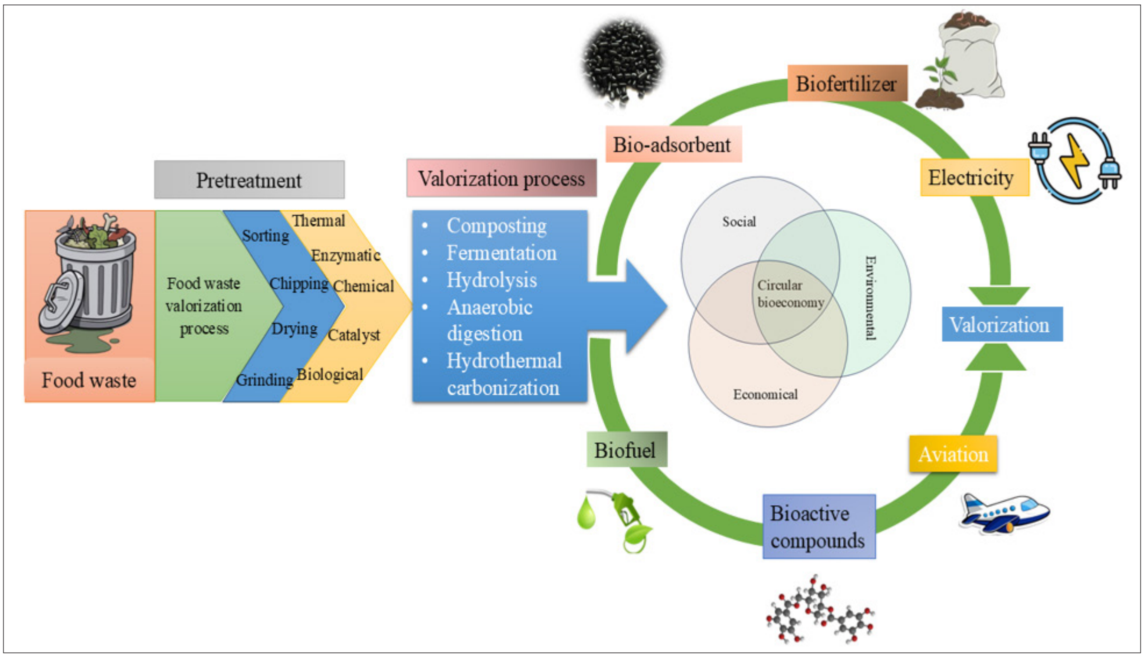

Figure 2: Valorization of Food Waste through Several Bioprocessing Techniques

Table 1: Valorization of Food Waste through Different Advanced Processes

Food waste	Valorization process	Product obtained	References
Orange peel waste	Freezing and thawing	Lactic acid and acetic acid	[23].
Food waste	Dark fermentation	Hydrogen	[47].
Mango peel	Ultrasound assisted extraction	Pectin and phenolic compounds	[48].
Fruit and vegetable waste	Acidogenesis and methanogenesis	Volatile fatty acids and biohydrogen	[49].
Food waste	Dark fermentation and mesophilic anaerobic digestion	Biomethane	[50].
Grape marc	Microwave assisted extraction	Flavanols	[23].
Bread waste	Solid state fermentation	Bioethanol	[39].
Food waste	Anaerobic digestion	Biogas	[39].
Potato peel	Subcritical water extraction	Gallic acid, vanillic acid and caffeic acid	51].
Mung bean waste	Ultrasound assisted extraction	Catechin, gallic acid and vitexin	[50].
Meat industry waste	Homogenizer assisted extraction	Meat protein	[50].
Kitchen waste	Dark fermentation and anaerobic digestion	Biohythane	[52].
Pastry and cake waste	Hydrolysis and fermentation	Succinic acid	[23].
Tomato peel waste	Ultrasound assisted extraction	Pectin	[50].
Coffee husk	Solid state fermentation	Volatile compounds (ethyl butyrate, ethanol, acetaldehyde, ethyl butyrate)	[25].
Rice bran oil	Submerged fermentation	Vanillin and vanillic acid	[25].
Custard apple seeds	Ultrasound assisted extraction	Oil, protein	[50].
Food waste	Hydrothermal carbonization	Hydrochar	[42].

Key Challenges in Biorefinery Development and Food Waste Processing

The basic hurdle in FW biorefinery system is the FW composition and its physicochemical properties. It is difficult to achieve desirable product through biotechnological process. FW with high moisture level (> 80%) creates anaerobiosis and impeding the oxygen uptake through microbes, leading to hamper decomposition rate [53]. In case of fermentation, use of biocatalysis in production of renewable by products is cost-competitive. Further, variation in pH and temperature hinder the enzymatic activity and optimization of biological process becomes essential [23]. Excess N-content in FW can impede the acceleration of decomposition by promoting ammonia production with low microbial activity. On the other hand, low N-level causes prolong the digestion period of carbohydrate substances [21]. The particle size of FW is a critical factor in biorefinery processing, influencing degradation efficiency and overall system performance. Larger particles slow down microbial activity and enzymatic breakdown, reducing conversion rates. Conversely, smaller particles can lead to compaction, restricting airflow and microbial access, which negatively impacts fermentation and AD processes [21]. Moreover, kitchen waste contains high quantity of salt and oil which can directly or indirectly affect the metabolic rate of microorganisms, influencing the recovery of volatile compounds during fermentation [54]. The presence of heavy metals such as Cd, Pb, and Zn can inhibit the synthesis of key enzymes, including amylase, cellulase, and urease, negatively impacting nutrient transport and membrane function [55]. Additionally, iron plays a crucial role in hydrogen fermentative production, as it is essential for the oxidation of pyruvate to acetyl-CoA [56]. Studies have also highlighted the influence of divalent and monovalent metals on α-amylase activity during ethanol fermentation in yeast, showing that K, Mg, and Ca enhance activation, while heavy metals cause inactivation [30]. Furthermore, storage and management practices significantly affect the moisture content of FW. For example, switching from plastic bags to paper bags can result in a 25% reduction in FW weight due to water evaporation [30]. Environmental conditions, such as temperature fluctuations and natural evaporation, can further alter nutrient concentration and the heating value of FW. To unlock the full potential of FW valorization in biorefineries, it is essential to address these obstacles through strategic innovations, supportive policies, and technological advancements.

Cutting-Edge Innovations and Synthetic Biology Application

Synthetic biology and genetic engineering have notable potential to transform the organic feedstock to value-added by products by optimizing the biorefinery process. In addition, system biology explores genomics, transcriptomics, proteomics and metabolomics to provide valuable information which will help to modify the gene information rapidly [7].

Enzymatic Treatment of Food Waste

Enzyme engineering is another attractive technology which will catalyse the FW processing. Catalytic enzymes are highly efficient, tolerant to high temperature and pH and functionally active to produce precious products like pigments, sugars, biosurfactants, lipids, biofuels, bioactive compounds etc. Enzymatic pretreatment also plays a crucial role in methane production. further, enzymatic pretreatment technologies do not need any harmful chemicals and high temperature/pressure [50]. Nevertheless, it is time-consuming. Several enzymes are employed to degrade FW. They are amylase, protease, palatase, cellulase, laccase, hemicellulose, xylanases, carbohydrases, xylanases and α-glucosidases, offering advantages for hydrolyzing complex organic substances into simple molecules [57]. Zhang et al. demonstrated that enzymatic processing of FW increased synthesis of butanol from 0.1 to 1.5 g/L, indicating acceleration of FW decomposition [58]. Carbohydrate is the major component in FW approximately contains 35.5-69% of total stream. Starch is the abundant form of carbohydrates found from household kitchen and restaurants. Starch hydrolysis can be carried out by amylase and glucoamylase. Li et al. reported that starch hydrolysis with 0.1% glucoamylase released 69.8 g/L of glucose from FW. Similarly, 120 g/L of glucose was released from FW by addition of 10 U/g of amylase and 120 U/g of glucoamylase [59]. FW hydrolysis with amylase and glucoamylase, resulting reduction of 52% VSS (volatile suspended solid) [60]. Additionally, cellulose and hemicellulose present in FW can be broken down by cellulase and hemicellulase. Moon et al. compared glucose yields from FW pretreated with cellulase, hemicellulase, amylase, and a combination of these enzymes [61]. The mixed carbohydrase treatment produced the highest glucose yield at 0.46 g/g, outperforming amylase alone (0.41 g/g) and the combined cellulase and hemicellulase treatment (0.35 g/g). Additionally, proteolytic enzymes like trypsin have been employed to hydrolyse protein waste from sources such as dairy, grains, oilseeds, and eggs, yielding valuable compounds including polymer precursors [62]. Similarly, FW comprises of a huge number of eggs, fish, meats and chickens, accounting to 3.9-21.9% of total FW [63]. To access protein hydrolysates, protease enzyme application is quite feasible. Protease hydrolyse proteins into free amino acids. For example, FW treated with 150 U/g of protease released 3 g/L of free amino acids at 55 ^{o}C and pH range of 4.5 for 24 h. Microbes can utilize free amino acids as nitrogen source for their growth and development [64]. Further, effective hydrolysis of proteins by protease releases ammonia, thereby causing acidification in FW matrix and neutralize the pH [65]. Therefore, protease pretreatment is essential for recovery of bioenergy from FW. In addition, FW containing high lipid content, ranging from 22.8% to 31.45%, serves as an excellent substrate for biodiesel production. According to Xu et al., the biomethane yield from lipids reaches 1.014 m^3/kg VS, significantly surpassing that of carbohydrates (0.74 m^3/kg VS) and proteins (0.37 m^3/kg VS). However, lipid hydrolysis is relatively inefficient compared to other FW components, making enzymatic pretreatment a crucial step [66]. Lipase-based pretreatment has proven effective, with optimal conditions for biomethane recovery identified at 40 ^{o}C and pH 7.4-7.6 over a 24-hour period [67]. For example, lipase-mediated hydrolysis of vegetable oil, animal fat, and floatable grease shortened reaction time by 10-40 days and enhanced biomethane production by 26.9% to 157.7% [68]. Enzymatic treatment of the lipid-rich fraction of FW can generate high-value products such as biodiesel, surfactants, and lubricants. Lipase-catalysed esterification of cooking oil waste and sardine oil has demonstrated successful biodiesel production. In one approach, a hybrid biocatalyst was created by immobilizing lipase from *Pseudomonas fluorescens* onto mesoporous sodium and calcium-based supports. When applied to waste processing oils, this system achieved a 90% yield of fatty acid ethyl esters (FAEEs) at 37 °C and 180 rpm, which were subsequently converted into biodiesel through transesterification [50]. Thus, enzymatic treatment of the organic feedstock is useful in biorefinery system while making material recovery.

Metabolic Engineering and Synthetic Biology

Recombinant technology plays a significant role in FW biotransformation, where desired genetic material is introduced into a host organism to enhance its performance [69]. This approach improves biocatalytic efficiency, enabling the conversion of FW into valuable bio-products such as biofuels, organic acids, and enzymes. For instance, agro-industrial waste utilization is the production of catechol and adipic acid from glucose derived from agro-industrial waste using recombinant *Escherichia coli* [70]. Similarly, the genetic engineering of *Saccharomyces* sp. enabled the conversion of glucose and xylose present in lignocellulosic waste into bioethanol, representing a significant advancement in transforming low-value substrates into high-value products [71]. Similarly, citrus fruit waste serves as a valuable resource for producing ethanol, fibres, essential oils, carotenoids, cellulose, and bioactive compounds such as hesperidin and hesperetin, known for their anti-inflammatory and anticarcinogenic properties [72].

Additionally, Gassara et al. highlighted that brewery waste and apple pomace can serve as effective substrates for the cultivation of *Phanerochaete chrysosporium*, a white-rot fungus renowned for its lignin-degrading capabilities [73]. These agro-industrial byproducts were found to stimulate the production of key ligninolytic enzymes specifically laccases, manganese peroxidase, and lignin peroxidase which are instrumental in breaking down the complex lignin polymer. This enzymatic activity plays a pivotal role in enhancing lignin degradation, thereby facilitating the bioconversion of lignocellulosic biomass into valuable end-products. While synthetic biology significantly improves biorefinery efficiency, several challenges remain that must be addressed for optimal performance [7]. These include pretreatment complexities, sterilization requirements, agitation and aeration control, pH and temperature optimization, and efficient product recovery. Overcoming these hurdles through advanced bioprocess engineering, improved microbial strains, and innovative reactor designs is essential for enhancing biorefinery sustainability and scalability. Developing a robust microbial strain capable of enduring harsh environmental conditions while efficiently degrading diverse waste types is crucial. Additionally, to reduce downstream processing costs and uphold the principles of a circular bioeconomy, prioritizing highly efficient microbes that can utilize all available carbon sources and generate target products with minimal toxic byproducts is essential [39]. DNA fingerprinting and bioinformatic analysis have been spectacularly revealing metabolic pathways and enzymatic variations. This approach enables to optimize the process parameters and efficiently produce biofuel from the platforms like higher carbon consumption efficiency, carbon flux redirection, manipulation of cellular energetics, prolonged existence in an adverse environment and obtaining of final products from culture broth by mitigating the cell toxicity (caused by inhibitors produced during the process), and produces single desired end product [39]. Genetic engineering and gene editing tools like TALEN, ZFN, TAL and CRISPR-Cas9 can explore the hidden mechanism and principle behind processing of waste substances by microbes. Understanding their role, it is easier to achieve their adaptability in various range of waste substrates. For instance, *Bacillus* sp., *Ralstonia* sp., *Cupriavidus* sp., have substantially exhibited better PHB (Poly-hydroxy butyrate) production by using FW as substrate [39]. However, their waste processing still remains challenged due to heterogenous composition of FW. Nogueira et al. exhibited that overexpression of glucose transporter in *Neurosporo crasssa* (a lignocellulolytic fungi), improved bioethanol production from lignocellulosic biomass [74]. Additionally, as discussed above, CRISPR-Cas9 (gene editing tool) can be efficiently used to manipulate the gene encoding special by-products. For example, ATCC1015 genes in *A. niger* involved in by-product formation were knocked down and fumarate reductase and C4-dicarboxylate transporter were overexpressed for the enhancement of succinic acid production by using nutrients from sugar beet molasses and wheat straw hydrolysate [39]. Table 2 elucidates several genetic manipulated microbes used for efficient FW valorization. Therefore, advancements in synthetic biology and microbial engineering could help overcome these limitations, enabling more efficient waste valorization in bioplastic manufacturing.

Table 2: Engineered Microbes used in Food Waste Valorization Processes

Engineered microbes	Food waste substrate	Product yield	Process of valorization	Reference(s)
S. cerevisiae	Cheese whey and corn cob	>50 g/L ethanol was obtained	Fermentation	[75].
Yarrowia lipolytica	Glucose rich hydrolysates	Succinic acid (71.6 g/L)	Fed batch fermentation	[76].
A. niger (metabolic modification)	Food waste	Citric acid	Submerged fermentation technique	[77].
A. *niger* (overexpression of glucose transporter MstC, pfkApkiA and hxk A)	Food waste	Malic acid	Submerged fermentation	[78].
A. *niger* (Gene editing technique based on Cre-loxP system for the deletion or insertion of genes)	Food waste	Organic acid and enzyme production	Fermentation	[79].
E. coli	Soyabean oil	Bioplastic	Fed-batch fermentation	[80].
Yarrowia lipolytica	Fatty feedstock	Aroma production	Solid state fermentation	[81].
A. niger	Sugar beet molasses and wheat straw hydrolysate	Succinic acid	Fermentation	[39].

Integration of Multi-Omics Approaches for Assessing Food Waste Management

Recent breakthroughs in omics technologies including metagenomics, transcriptomics, proteomics, and metabolomics have opened up exciting possibilities for creating high-throughput systems to uncover previously uncultivable microorganisms, novel genes, and metabolic pathways linked to biogas production from various biomass sources [82]. These multi-omics tools offer powerful methods for tracking gene activity, metabolite levels, and protein expression within microbial communities, and could serve as indicators of how well FW management could be achieved (Table 3). Metagenomics unfolds the diversity of microbial communities in a given sample of FW, based on DNA isolation and amplification. However, it fails to provide accurate information about microbes' physiological mechanisms. Thus, meta-transcriptomics and meta-proteomics are implemented to analyse the genes, enzymes and proteins which being expressed by microbial communities [6]. However, despite the promise of transcriptomic, proteomic, and metabolomic techniques, there's still a need for a unified and targeted framework specifically tailored to managing food waste. Many researchers have honed in on transcriptomic-based bioprocess engineering in biogas production, as transcriptomics investigates an organism's full RNA output. Through transcriptomic analysis, key microbial players can be identified based on their relevant genes and metabolites. For example, *Clostridia* sp. has emerged as major hydrolytic agent in the initial stages of biomass breakdown, as shown by transcriptomic studies

[27]. While meta-transcriptomics provides valuable insights into actively transcribing genes within microbial communities, its effectiveness is limited by the inherent instability and degradation of mRNA. This often results in incomplete gene expression data and an inaccurate reflection of protein translation processes. Thus, scientists switch to meta-proteomics as a viable approach for investigating the protein and enzyme expression profiles of the waste microbiome [6].

Proteomics, on the other hand, involves a detailed study of the full protein repertoire of an organism, while meta-proteomics expands this to examine all proteins produced by complex microbial ecosystems in a specific environment at a given time. By understanding the proteome of microbes that able to degrade agro-food waste, creating a promising approach to identify the key enzymes responsible for the degradation of complex substrates. For instance, proteomic analysis of fungal species can reveal the presence of lignin-degrading enzymes which can easily solubilize the lignocellulosic waste into fermentable sugar molecules [83]. Proteomics study encompasses mass spectrometry and 2D gel electrophoresis techniques to characterize the peptides generated under different fermentation conditions, demonstrating the proteolysis potential of lactic acid bacteria, enhancing bioavailability of nutritional profiles and offering sustainable option as food ingredients [84]. Metabolomics provides substantial information about various metabolites of microbes in a specific FW sample, reflecting the physicochemical characteristics as well as biological condition of particular environment. Several techniques are involved in elucidating metabolomics including liquid chromatography and gas chromatography [50]. Furthermore, mass spectroscopy and nuclear magnetic resonance are used to identify the chemical molecules in waste sample. Data obtained from the metabolomics could be analysed through bioinformatics or chemo-informatics software by using various algorithms [6]. Only limited studies have explored the metabolomic profiling of FW for the production of value-added products like vinegar and wine, specifically using pineapple pulp and peel as substrates. These studies have employed advanced analytical techniques such as gas chromatography–mass spectrometry (GC-MS) and ultra-high performance liquid chromatography (UHPLC) coupled with quadrupole time-of-flight tandem mass spectrometry (UHPLC-QTOF-MS) to characterize the resulting biochemical composition [8]. Integrating omics datasets offers a comprehensive framework for analyzing processes involved in waste valorization, thereby supporting the advancement of efficient biotechnological solutions. For instance, through omics-based insights, metabolomic analysis has revealed microbial genes of *Zopfiella* and *Fusarium* in compost derived from vineyard pruning waste, indicating their potential role in plant disease suppression. Furthermore, integrating genomics with metabolomics can enable researchers to unravel the underlying mechanisms by which compost contributes to disease control [85].

However, several obstacles hinder the widespread adoption of omics technologies. Chief among them is the high operational cost, which presents a substantial barrier. Additionally, the challenge of consolidating data from diverse omics platforms highlights the need for robust computational tools and standardized formats to enable effective data integration. Bridging the gap between foundational research and practical deployment requires active collaboration among scientists, industry professionals, and policy makers. Such partnerships are vital to translating omics-derived insights into scalable and economically viable applications. Despite this promise, scalability remains a concern due to the technical complexity and specialized equipment needed for high-throughput analysis, which further contributes to increased expenses. Moreover, the financial feasibility of omics-driven valorization strategies is shaped by extended research and development timelines, as well as the imperative for rigorous validation prior to commercialization [86].

Table 3: Major Omics Approach used for Food Waste Management

Technologies used	Omics approaches	Description	Reference
Whole genome sequencing (WGS), next generation sequencing (NGS), molecular markers (AFLP, SNP and SSR)	Genomics	Reveals DNA sequences that comprise genome structure and function, contributing phylogenetic analysis of microbial community	[50].
RNA sequencing, reverse transcription PCR (RT-PCR) and microarrays	Transcriptomics	Helps to study about the active gene expression	[87].
Liquid chromatography-Mass spectrometry MALDI-TOF, 2D gel electrophoresis	Proteomics	Study of the structure and function of proteins and peptides in a given sample	[88].
GC/LC-MS, NMR	Metabolomics	Study of the molecules/ metabolites of low molecular weight involved in metabolism in microbial community	[89].

Challenges and Recommendations

Modern techniques like omics and biorefinery can improve FW valorization by converting FW into biofuels and bioenergy. However, several challenges may hinder the sustainable FW valorization. Such problems are associated with scaling up of the procedures associated with FW collecting costs, choosing of appropriate techniques, optimization of system, requirement of skilled personnel, chemical characterization and process efficiency [90]. Omics is playing spectacular role in FW valorization, nevertheless the phenotypic alteration in the stream of FW cannot be elucidated through genomics. Thus, separate analysis of transcriptomics and proteomics need to validate the results. Further, bioinformatics elucidates the comparative analysis of finding results and the existing data available in the database conversely, certain research gaps are still existed, which needs to be addressed. Recent advancements in smart technologies such as AI, the IoT, and ML could further enhance resource recovery efficiency while minimizing waste generation [91,92].

Conclusion

FW possesses significant potential to address challenges related to non-renewable energy. Valorization of FW presents a sustainable solution that aligns with the objectives of the SDG. Integrating biorefinery systems within the food supply chain enables the efficient utilization of FW and maximizes resource recovery. In addition, omics technologies including metagenomics, metatranscriptomics, metaproteomics, and metabolomics provide comprehensive insights into microbial communities, facilitating the identification and enhancement of robust strains for effective waste degradation. To fully unlock the potential of these valorization technologies, it is imperative to establish vigorous policies, a supportive regulatory framework, economic feasibility, and active stakeholder engagement. Through a future oriented lens, AI-powered FW management emerges as a cornerstone of the circular economy by improving energy efficiency, extending product lifespans, and enabling data-driven decision-making processes. Ultimately, the integration of AI and omics approaches could offer a transformative pathway for minimizing FW across all stages of the supply chain.

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