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Minimizing hazardous impact of food waste in a circular economy – Advances in resource recovery through green strategies

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ABSTRACT

Recent trends in food waste and its management have increasingly started to focus on treating it as a reusable resource. The hazardous impact of food waste such as the release of greenhouse gases, deterioration of water quality and contamination of land areas are a major threat posed by food waste. Under the circular economy principles, food waste can be used as a sustainable supply of high-value energy, fuel, and nutrients through green techniques such as anaerobic digestion, co-digestion, composting, enzymatic treatment, ultrasonic, hydrothermal carbonization. Recent advances made in anaerobic co-digestion are helping in tackling dual or even multiple waste streams at once with better product yields. Integrated approaches that employ pre-processing the food waste to remove obstacles such as volatile fractions, oils and other inhibitory components from the feedstock to enhance their bioconversion to reduce sugars. Research efforts are also progressing in optimizing the operational parameters such as temperature, pressure, pH and residence time to enhance further the output of products such as methane, hydrogen and other platform chemicals such as lactic acid, succinic acid and formic acid. This review brings together some of the recent progress made in the green strategies towards food waste valorization.

1. Introduction

Food life cycle is the end-to-end process of 'Farm to Fork' i.e., from the farms where it is sown, grown, and harvested or the aqueous systems from where it is fished to consumers i.e., humans and animals. Its supply chain follows the sequence of handling, storage, processing, distribution and finally consumption. At every step in this life cycle, there are opportunities for loss and waste creation. Nearly one-thirds of the total food produced amounting to 1.3 billion tons is wasted annually across the globe, which could feed nearly half of the global population (FAO, 2015; Srivastava et al., 2021). The economic value of this waste is estimated at approximately USD 680 billion. The efficiency of food production has been estimated at 50% i.e., approximately 1.6 billion tons of food raw material is lost or never utilized (Zuckerman, 2020).

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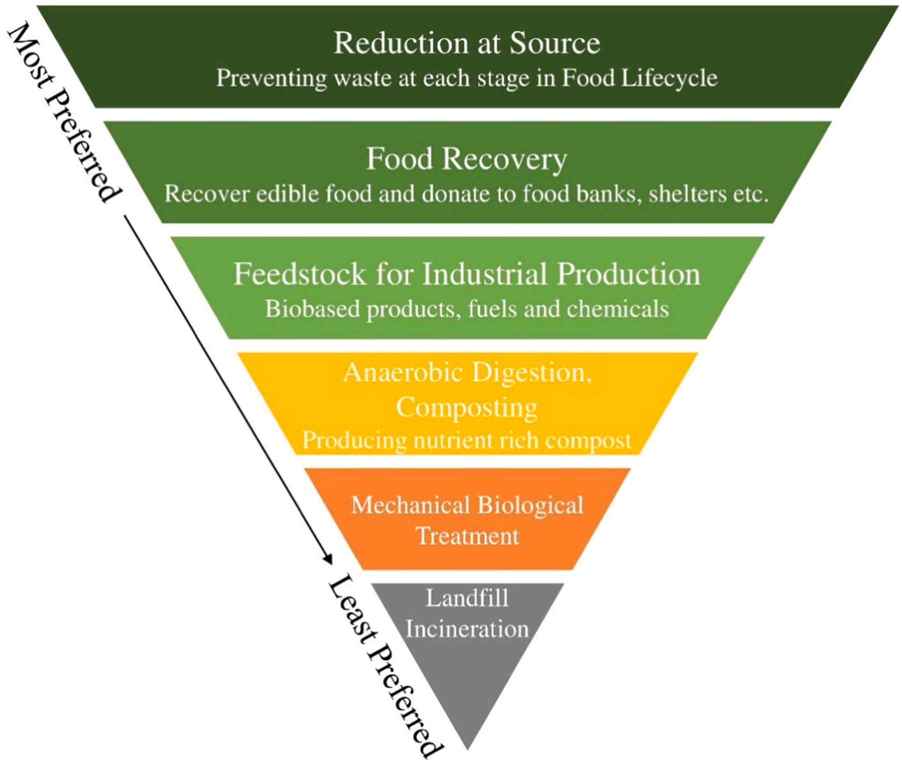

Fig. 1. Food waste recovery hierarchy modelled on the circular economy perspective.

According to a report published by the Boston Consulting Group (BCG), rate of food wastage (lost or thrown away) will rise to nearly 2.1 billion tons per annum by 2030 (BCG, 2018). It has been observed that developed nations tend to waste more food, while 842 million people in economically weaker nations are experiencing hunger problems. Xu et al. (2018) reported that food waste in developed countries ranges from 100 to 170 kg per capita per annum, which is more than double to that generated in developing countries. In the absence of regulatory policies, it was estimated that food waste in the EU would rise from 89 million tonnes per annum to approximately 126 million tonnes by 2020 (Xu et al., 2018). Oxfam estimated that COVID-19 pandemic has worsened the hunger crisis and by 2020 end mortality associated with pandemic induced hunger situation would be approximately 12,000 deaths per day (Oxfam, 2020). Wastage of food essentially results in a waste of public and private resources, and subsequently implies untapped potential in terms of tackling world poverty and hunger. Realizing this the United Nations adopted sustainable consumption and production as one of the goals in their 17 Sustainable Development Goals (SDGs) (UN, 2015).

It is of utmost importance that food waste be avoided and mitigated along every step in the life cycle by all the concerned parties, be it in processing, supply, or sales. However, households can also be a significant contributor towards food waste, which requires different strategies to tackle the problem at the consumption side. Hence, it is imperative to develop proper management strategies and policies to handle food waste at the end of their life cycle to avoid its hazardous impact on the environment and society. The high transportation costs of waste and limited landfill disposal sites have further drawn attention towards efficiently utilizing food waste by sustainable green processes (Lee et al., 2020). One of the ways to this is by adoption of a circular economy that advocates the recycle and reuse of seemingly waste materials as the feedstock for production of other materials, chemicals, and products (Lee et al., 2020) (Fig. 1). Taking sustainability and greenness into account, biobased techniques such as composting, anaerobic digestion (AD) (Oldfield et al., 2016), co-digestion (Gao et al., 2020), hydrothermal carbonization (Idowu et al., 2017), enzymatic pretreatment (Yin et al., 2016), ultrasonic pretreatment (Li et al., 2019a, 2019b) etc. can be beneficial routes to convert food waste into renewable energy, fertilizers, source of nutrients. This provides potential economic benefits such as, reduced expenditure on disposal, landfills and transportation of waste and creation of additional revenue streams from power, heat, biofuels, compost fertilizer and other products.

Carbohydrates, proteins, and lipids are the major constituents of food waste and their ratio varies widely depending on the food source (Kwan et al., 2016; 2018; Iris et al., 2018). Since the major fraction of food waste is organic matter, it can be utilized as a sustainable and renewable resource to produce biofuels, platform chemicals and other biobased materials (Lin et al., 2014). For instance, heterotrophic microalgae can be grown on food waste hydrolysates which are rich in nutrients beneficial for microalgae growth (Pleissner et al., 2013), hydroxymethylfurfural (HMF) can be derived by biobased conversion of hydrolysate produced form food waste hydrolysis (Iris et al., 2018). The hydrolysis of starch to glucose is an important step in the release of nutrients from food waste, as this often forms the first step towards the bioconversion of food waste into biofuels and chemicals (Li et al., 2019a, 2019b).

While some of the biobased techniques have proven to be effective in the valorization of food waste, most techniques suffer from the drawbacks of being complex, costly, leaving post-processing residue, and large setup requirement. Thus, there has been a recent push from the research community to develop integrated solutions that bring together energy and resource recovery, at a lower price, smaller footprint and minimum remains. This review provides an insight into some of the advances made in food waste treatment technologies that try to address the emerging demands in the circular economy context. An extensive literature survey was performed taking into consideration peer-reviewed papers published in the last five years or so. Web of Science and Elsevier were used as the databases for this survey as it has one of the highest indexed information on peer-reviewed journals. The search terms used for paper search included: (food waste/municipal solid waste/agro-industrial waste) AND (treatment OR valorization OR valorisation OR pretreatment) AND (Anaerobic Digestion OR co-digestion OR enzymatic OR ultrasonic OR sonification OR Hydrothermal Carbonization OR HTC). Few additional reports from reputed organizations were also considered to strengthen the arguments and to substantiate the implementations of pilot/large-scale plants. This time span (2015–2021) was chosen as the focus for the search term to derive conclusions from most current knowledge around the treatment methodologies selected for this review. Overlaps in the results from Web of Science and Elsevier were manually removed. The relevancy of the selected articles was manually judged based on the following criterion: (a) Focus on studies that dealt with the treatment of both household and industrial food waste (b) research that estimated the environmental Life Cycle Assessment (LCA) of food waste (c) studies that focused on resource recovery and energy generation and (d) co-treatment of food waste with other waste streams to enhance the overall process efficiency. Also, importance was laid on the articles that provided conclusive data associated with the treatment methodologies under discussion. This curation process yielded a total of 114 articles and reports which were considered in this review.

2. Environmental hazards of food waste

Apart from the fact that food waste results in mismanagement of resources (including fertilizers, water, and energy) involved in the production of food that did not fulfil its purpose, it also negatively impacts the environment through the release of greenhouse gases (GHGs) on its degradation, contaminates aqueous systems through seepage and runoff and acts as potential health hazard by serving as a breeding ground of various pathogens. This section provides a short summary of the hazardous impact of food waste on the environment and society.

2.1. GHG emissions and climate change

The primary GHGs contributing to climate change due to global warming include methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) and are generated at every stage of food production, consumption and disposal: conversion of forest land into agriculture releasing carbon that was sequestered in the biomass; livestock, manures and slurries; burning fossil fuels for energy, operation of farm equipment; producing and usage of fertilizers; general heating of premises and farms; food processing, refrigeration and transportation. Further, the disposal of food waste in landfills releases further gases to the atmosphere. It is estimated that the supply chain associated with food waste contributes to nearly 6.8% of global emissions (World Bank, 2016). Spurred by the UN SDGs, UK has set a goal to reduce their GHG emissions by 40% by 2030, including strategies to reduce food waste (EC, 2014). Each tonne of food waste placed into an anaerobic digestion setup can save approximately 580 kg CO_2 equivalent while producing biogas that can serve as a fuel in many applications (EMAF, 2013).

2.2. Impact on water footprint

Water is one of the most important ingredients for sustenance of animals and plants. In the absence of adequate rainfall, groundwater, aquifers, rivers, and lakes form important sources of water for irrigation purposes. Both, the growth of food in farms and the wastage of food impacts the amount and quality of water available in a region through groundwater seepage and runoff. FAO (2013) estimated that the amount of blue water used in the production of food that ends up as waste is nearly 250 billion litres, amounting to more than 1.5 times the volume of Dead Sea. It has been estimated that changing the cropping pattern itself could reduce blue and green water demand. For instance, Schyns and Hoekstra (2014) were able to reduce water footprint of 12 crops by 67% by strategically relocating their cropping grounds. In another study, by modifying the cropping patterns, Davis et al. (2017a, b) were able to demonstrate the reduction of blue-green water consumption for 11 crops by 5% in the US, and for 14 crops globally by 12–14%.

Utilization of fertilizers and pesticides and their subsequent runoff adversely impact the quality of groundwater as well as surface water (Chai et al., 2021). While the leachate from landfills and dumpsites contaminates the surface as well as groundwater. Another source of pollution is from the production plants that process food materials and then dump the sewage sludge into water bodies and nearby landfill sites. The food-based processing plants utilize water in most of their steps. For instance, water is extensively used in washing raw materials and peeled products, blanching, reducing size, cooling and cooking of processed items and finally sanitation. This results in a wastewater stream which often contains significant quantities of processing chemicals and pesticides (Karas et al., 2016a). Fungicides are also used in huge amounts in the fruit-packaging process to prevent fruits from going bad during storage (Łozowicka et al., 2016; Karas et al., 2016a, 2016b), which adds to the chemical content of the wastewater stream as the fruits and vegetables are washed before being processed further (Ponce-Robles et al., 2017).

2.3. Landfill and dumpsites

While there have been efforts to adopt circular economy for the reuse of food waste, nearly 50% of waste still ends up in landfill sites with economically weaker countries dumping 13–33% of waste in open areas (World Bank, 2020). These dumping sites for food and other organic waste act as the perfect breeding grounds for harmful parasites which can enter human population causing gastrointestinal diseases (UNEP, 2015). These dumping sites attract birds, flies, mosquitoes, vermin, and other communicable disease carriers, exposing health risks to humans by entering the food chain (ISWA, 2015). In many developing nations, it is a common practice to let dairy, poultry, and other farm animals to feed off from the food waste dumpsites, resulting in disease causing bacteria and other parasites to enter humans.

3. Enhanced valorization strategies

The food waste management strategies prioritise prevention at the highest level, followed by reuse, recycle and the least preferred option as landfills or incineration. Biowastes generated from food industries are rich in fats, lipids and carbohydrates which can be metabolized by bacteria processing enzymes like proteases, carbohydrases, and lipases (Kumar et al., 2014). The biobased valorization strategies form a key component of the recycle strategy and many methods have been used to convert food waste into useful materials, products, and bioenergy. Out of all the methods biobased techniques are most feasible, reliable, and cost-effective. This section will detail out the state of the art of existing biobased food waste management techniques and progress made in new techniques that aim to improve upon the efficiency of waste recycling on the parameters of complexity, setup size and cost.

3.1. Advanced anaerobic digestion of food waste

Anaerobic digestion is considered to be economical and environment-friendly technique and has been used extensively as the prime method to valorize food waste into useful products (Maroušek et al., 2019). It is a multi-step process comprising methods such as acetogenesis, acidogenesis, hydrolysis and methanogenesis (Patel et al., 2021) and involves different bacteria having a wide range of metabolic activities to produce value added products (Kumar et al., 2014). Patel et al., 2016, 2017 reported anaerobic digestion process to be a cost-effective process for production of methanol by methanotrophs which in turn produces value added products. Dahiya et al. (2018) estimated the conversion efficacy of anaerobic digestion at around 50% and found that nearly 350 L of CH_4 could be produced, by utilizing 1 kg of chemical oxygen demand, which could release ~14 kJ of energy that

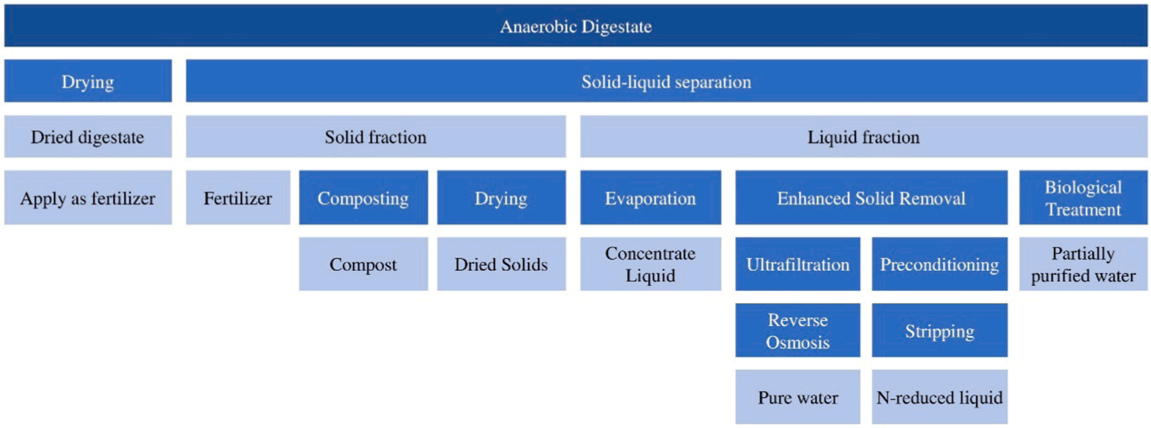

Fig. 2. Anaerobic digestate recycle and reuse pathways.

Table 1
Globally operated anaerobic digestor plant sites with capacity and cost.

Plant Site	City/Country	Year	Utilization	Capacity (Tonnes/year)	Capital Cost (in USD)	References
Skrzatusz	Wielkopoiska, Poland	2012	Heat and Electricity (CHP)	33,600	6,200,000	Fab Biogas (2012a, 2012b, 2012c)
Boleszyn	Mazury, Poland	2012	Heat and Electricity	43,900	6,200,000	Fab Biogas (2012a, 2012b, 2012c)
Ganser Umwelt	Munich, Germany	1997	Electricity	30,500	3,600,000	Bin2Grid (2016a, 2016b)
Finsterwalkder Umwelttechnik	Bernau, Germany	2000	Electricity	6000	1,700,000	Bin2Grid (2016a, 2016b)
AVA	Augsburg, Germany	2013	Biomethane to grid	55,000	20,000,000	Bin2Grid (2016a, 2016b)
Biokraft	Hartberg, Austria	2004	Heat and Electricity	7,000	2,400,000	Bin2Grid (2016a, 2016b)
Grossfurtner	St. Martin, Austria	2003	Heat and Electricity	10,000	2,100,000	Fab Biogas (2012a, 2012b, 2012c)
UW-Oshkosh Urban dry digester, Oshkosh	Wisconsin, USA	2011	Heat and Electricity	10,000	4,700,000	American Biogas Council (2016)
Harvest Energy Garde,	Lake Buena Vista, Florida, USA	2014	Heat and Electricity	130,000	30,000,000	American Biogas Council (2014)
Elgen fruit juices, Grabouw	Western Cape, South Africa	2013	Heat and Electricity	20,000	1,600,000	Green Cape (2017)
New Horizons Energy	Athlone, Capetown	2017	Biomethane	200,000	30,000,000	Green Cape (2017)

can generate 3.9 kWh electricity. But it has also been reported that the continuous thermophilic process of anaerobic digestion on food waste poses several technical and economic drawbacks (Xu et al., 2018). It has been found that the presence of large quantities of volatile fatty acids in conjunction with available nitrogen reduces buffer capacity, causes foaming and overall makes the process instable (Xu et al., 2018). Food waste is generally rich in fats and oils that provide additional energy to anaerobic biota, thus escalating biogas outputs (Wiater and Horysz, 2017). Anaerobic digestion of excessive content lipids and proteins at higher temperature and pH has also been found to release higher amounts of sulfide and ammonia it which inhibits the overall digestion process (Hecht and Griehl, 2009). This places food waste feedstock in the category of energy-rich, biodegradable, but irrepressible (Zhang et al., 2014). The process parameters and operational conditions can be tuned by adding other agricultural waste streams such as straw and maize silage to food waste (Hijazi et al., 2016). But these added waste components degrade at a slow rate, prolonging the hydraulic retention times, reducing economic performance, and impact the overall process stability (Kovacova et al., 2019; Udell et al., 2019).

The major outputs from anaerobic digestion process are biogas and nutrient rich digestate. The primary components in biogas are CH_4, CO_2 with some amounts of H_2, CO and H_2S. The proportion of the CH_4 and CO_2 present in the released biogas varies widely depending upon the food waste composition and source as well as the operational parameter of the plant. In general, the CH_4 concentration ranges from 60% to 65% (Woon et al., 2016; Di Maria et al., 2016). On an average, the biogas production volume in anaerobic digestors ranges from 350 to 750 Nm^3/Mg VS (Di Maria et al., 2016). The second component is digestate, which is a stable material that can either be used as-is or separated into its liquid and solid components (Fig. 2) to be used further (Nayal et al., 2016; Evangelisti et al., 2017). The as-is digestate has been utilized extensively as soil amendment or fertilizer, while the separated fractions can be reutilized within the processing plant for other purposes (Nayal et al., 2016). While the digestate may replace commercially available fertilizers, its usage is permitted for crop fertilization under various legislations in many countries such as Italy and UK (Evangelisti et al., 2017). Few of the commercially deployed anaerobic digestor plants across the globe have been mentioned in Table 1. While they have been under operation for many years and rely on traditional method of digestion, there are several advances that have been made in recent years to find new methods that can enhance their performance.

A point to note is that digestion of food waste anaerobically is seriously hampered by the high biodegradability of its components and low C/N ratio (Jabeen et al., 2015). A way to tackle this to deploy a co-digestion system by mixing different substrates such as cellulosic waste, sludge, wastewater etc. with food waste to balance the C/N ratio. Another emerging trend has been the application of microalgae and macroalgae to raise the C/N ratio adding buffer capacity to create a stable pH which usually declines due to the hydrolysis of food waste. Capson-Tojo et al. (2017) studied anaerobic co-digestion using a batch dry system at various inoculum-to-substrate ratio loads to investigate the impact of initial substrate loading on its performance. They found methane production to kick off at an inoculum-to-substrate ratio of 4:1. Food waste co-digestion with rice husk performed by Jabeen et al. (2015) indicated that the system became stable at an organic loading rate (OLR) of 5–6 kg-VS/m^3d with 82% volatile solid (VS) removal.

Microalgae has also emerged as an interesting substrate for the co-digestion of food waste and is being studied extensively (Du et al., 2019; Zhen et al., 2016; Kim and Kang, 2015). Admixing algal biomass and raw sludge with food waste in 1:1:1 ratio increased the C/N ratio to 7 and displayed significant improvement in the performance of anaerobic digestion systems in the production of methane (Kim and Kang, 2015). By mixing *Spirulina platensis* as a co-substrate with sludge and food waste, Du et al. (2019) achieved an improvement in methane production in the range of 5–15%. Anaerobic digestion of *Scenedesmus* sp. and *Chlorella* sp. with food waste increased the methane production by nearly 5 times to 639.8 ± 1.3 mL/g VS_{added}. Addition of appropriate substrates in the co-digestion of food waste can significantly improve the methane production due to the synergistic impact of moisture regulation, nutrient balance, and remediation of toxic chemicals in the digestate (Du et al., 2019; Capson-Tojo et al., 2017; Zhen et al., 2016).

Using a two-stage biological membrane setup under high pressure, Li et al. (2017a, b) demonstrated the impact of pressure on the methane quality and yield, achieving best methane output at 0.3 MPa pressure. Another two-phase anaerobic digestion method developed by Wu et al. (2016) used a two-reactor setup with the first reactor operating at an unregulated pH 4.0, prominently yielding lactate, and then degrading the effluent in an upflow anaerobic sludge blanket (UASB) reactor to produce methane. In another three-stage system developed by Wu et al. (2015a, b) each step in the digestion of the food waste viz. saccharification, fermentation, and methane formation, was conducted in separate containers. This system enhanced the food waste decomposition rate by 27.5%, reduced operational energy requirement by 51.8%, and increased total energy output by 17.6%. Another three-stage anaerobic digestion system developed by Zhang et al. (2017a, 2017b, 2017c) deployed three independent chambers for hydrolysis, acidification, and methanogenesis. This system was able to enhance the methane output anywhere between 24% and 54% when compared against single-stage or two-stage anaerobic digestion systems. These processes have demonstrated the superior performance of the three-stage and two-stage systems making them excellent candidates for practical application to reduce overall cost of the digestion process with enhanced energy efficiency and increased energy outputs.

Anaerobic digestion brings forward many advantages towards achieving environmental sustainability goals. Energy generated from the plants can be used either to supplement the energy demands of the processing plant or the surplus can be fed back into the grid bringing down the overall cost of operations for the plant. The biogas generated can supply the local demands for natural gas and the heat generated can be rerouted into the plant for central heating purposes. The utilization of the biogas generated through anaerobic digestion is an excellent route for the reduction of greenhouse gases. The reutilization of organic matter and nutrients in the digestate of anaerobic digestate returns them into the soil thus contributing to sustainable utilization of soil and replenishing essential nutrients.

3.1.1. Environmental assessment of anaerobic digestion for energy recovery

Anaerobic digestion is the major technique behind the food waste-based biogas plants. These biogas systems comprise different systems that are mainly associated with (i) pretreatment of food waste, (ii) production of biogas (iii) management of digested substrate (iv) biogas conversion into energy (v) Energy utilization (Jin et al., 2015). Thus, sub-system level life cycle assessment (LCA) is necessary to ensure the environmental sustainability of the energy plant. Several different modes for the utilization of biogas were established worldwide for linking the production of biogas with agriculture. Chen et al. (2012) reported about South China adopting a six-component biogas system (SIOBS) with fruit cultivation, pig breeding, growing vegetables, cropping and agricultural processing, and anaerobic digester for efficient and cost-effective utilization of biogas. They further carried out the environmental and energy assessment of a SIOBS in China focussing majorly on production of energy. Their major goals were set up to bring forward the environmental and energy performance for widespread usage of biogas and its digestate at household level through different pathways. They observed that GHG emissions reduction can be achieved through utilization of biogas and its digestate in energy production.

Franchetti et al. (2013) performed LCA to compare the energy, economic and environmental implications related to food waste disposal treatment by various options: (i) landfill disposal, (ii) single stage anaerobic digestion (iii) two-stage anaerobic digestion system involving pretreatment with ultrasound, (iv) hydrogenesis (acidogenic and thermophilic (v) stabilisation of long-term food waste digestion. Their study reported that scenarios iii, iv and v presented better environmental and economical performance compared to landfilling. They observed scenario iii to be most efficient system for GHG emissions and cost. However, this scenario generated lower amount of energy as compared to scenario iv. Their LCA study concluded that organic waste to energy systems is less preferrable than landfilling due to GHG emissions, cost, and energy. Chen et al. (2015) studied about the co-digestion of dairy manure with food waste and concluded that co-digestion poses less environmental problems than the control system (anaerobic digestion) with respect to eutrophication, global warming and smog thus, considering it a good option for mitigation of environmental impact. The food waste management system and its working strategy was validated by Chiu et al. (2016) in Macau through assessment of energy and environmental aspects of co-digestion, incineration, and anaerobic digestion of sewage sludge and food waste. The reported co-digestion to be the most preferred option in Macau for wastes treatment as it generates the highest energy and lowest environmental issue. Mondello et al. (2017) investigated different scenarios for treatment and disposal of food waste fractions taking options such as anaerobic digestion, composting, landfilling and incineration into consideration. They observed the anaerobic digestion showed lowest environmental impact while, incineration and landfilling were environmentally harmful techniques. In UK and Italy, the environmental impacts related to different methods of converting biomethane produced by anaerobic digestion of FW into heat and power for consumption into housing communities. They observed technologies like micro gas turbine, stirling engine and fuel cells and found fuel cells to be the most environmentally friendly technique. Despite several environmental advantages anaerobic digestion systems still act as problematic as they cause heavy vehicle traffic and release aerosols and odours thus, affecting human and environment health (Righi et al., 2013). These challenges could be overcome by focusing on building smaller facilities rather than medium, large and centralized ones. An LCA of anaerobic digestion by Righi et al. (2013) to study these challenges for co-digestion of food waste with sewage sludge (dewatered) in small scale plants demonstrated co-digestion as a beneficial option for food waste treatment as opposed to direct composting and landfilling.

3.2. Integrated approaches for food waste valorization

While food waste poses advantages as a feedstock for biomethane and fertilizer production, the presence of recalcitrant organic compounds and its complex composition, makes its direct aerobic or anaerobic digestion inefficient (Ma et al., 2018). Due to the low hydrolysis efficiency of the VS in food waste, it is estimated that only about 40–60% anaerobic bioconversion to methane takes place (Zhang et al., 2014). This has led to a slew of developments in the utilization of various pretreatment methods such as mechanical extrusion, biological, chemical, thermal and ultrasonic to maximize the hydrolysis efficiency VS in food waste before being subjected to anaerobic or aerobic digestion (Ravindran and Jaiswal, 2016). The aim of such integrated processes is to achieve zero solid waste discharges i.e., fully utilizing the food waste stream to produce various products. While the current food waste

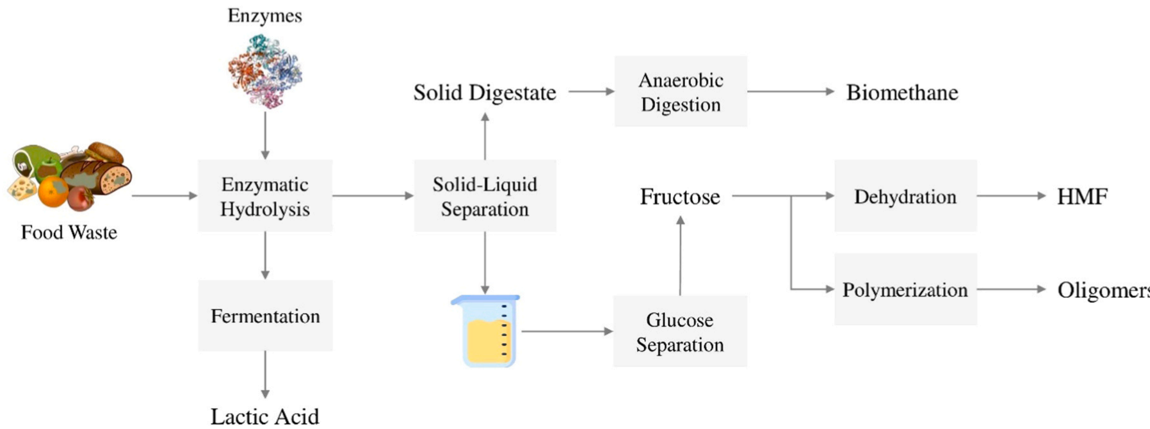

Fig. 3. An integrated multi-step enzymatic valorization of food waste. This process enables the maximum utilization of the food waste, separating the outputs of every stage into various fractions and utilizing multiple valorization techniques to convert them into products such as biomethane, HMF and other polymers.

Table 2
Enzymatic pretreatment of food waste to produce value-added products.

Enzyme	Dose of Enzyme (concentration)	pH	Temperature	Duration of Hydrolysis	Other conditions	Hydrolysis Resultant	References
Lipase	0.67–1%	7.0	40–50 °C	24 h	–	42.7 g/L of Long chain fatty acids	Meng et al. (2017)
	1%	7.4–7.6	40 °C	24 h	–	12.5 g/L total fatty acids	Meng et al. (2015)
Carbohydrase	Amyloglucosidase- 72 U/g and α-Amylase-18 U/g	5.5	55 °C	–	100 rpm	45.3 g/L of reducing sugar	Li et al. (2017c)
	32 U/g-glucoamylase and 32 U/g-α-amylase	–	55 °C	8 h	–	52% reduction in volatile solids	Zhang et al.(2020)
	Glucoamylase-120 U/g, α-amylase-10 U/g	4.5	55 °C	24 h	1:1- Solid to Liquid ratio	120 g/L of glucose	Sun et al. (2014)
	Cellulases and β-glucosidase in the ratio: 5:1	5	50 °C	8 h	9:11- Solid to liquid ratio	–	Matsakas et al. (2014)
	Concentration of glucoamylase 0.1%	–	50 °C	18 h	150 rpm	69.8 g/L of Glucose	Li et al. (2019a, 2019b)
Protease	0.25% concentration of protease	4.5	59 °C	24 h		1.92 g/L of free amino acids	Demichelis et al. (2017)
	150 U/g of protease load	4.5	55 °C	24 h	1:1- Solid to Liquid ratio	3 g/L of free amino acids	Sun et al. (2014)
	0.4% concentration of protease	4.5	50 °C	24 h	150 rpm	39% reduction in volatile suspended solids	Moon and Song (2011)

management techniques do not warrant such an outcome, there is a growing demand for innovative integrated biological processes that can concurrently recover nutrients (e.g., macronutrients such as nitrogen, potassium, phosphorus as well as trace nutrients such as magnesium, sodium and calcium) and produce energy (e.g., methane, biogas and bioenergy).

3.2.1. *Enzymatic pretreatment with anaerobic digestion*

Enzymatic pretreatment of food waste is a green technique which does not require highly specialized setup and does not result in secondary pollution (Meng et al., 2017). Yin et al. (2016), utilized a fungal mash grown from *Aspergillus awamori* to enzymatically hydrolyse food waste admixed with activated sludge before subjecting the mixture to anaerobic digestion. This process enhanced the biomethane yield by nearly 2.5 times over untreated activated sludge. In another experiment by Ma et al. (2017), ultra-fast enzymatic hydrolysis of food waste was performed for 8 h using a fungal mash followed by anaerobic digestion. Following a solid-liquid separation, the solid component was directly utilized as a fertilizer, whereas the liquid fraction was fed into anaerobic digestor to produce biomethane. This two-step process left no solid discharge at completion and 1 ton of food waste would yield biomethane to produce power equivalent of 210 kWh. A general approach to integrated enzymatic hydrolysis is demonstrated in Fig. 3, which brings together the idea of creating multi-step processes to enable higher biomethane production and also potentially lead to zero-solid discharge.

Demichelis et al. (2017) performed separate enzymatic hydrolysis and fermentation (SHF) of food waste using *Streptococcus* sp. to produce biogas (via anaerobic digestion of solid component) and lactic acid (via fermentation of liquid fraction). Biogas can be further used for methanol production using immobilized co-cultures of methanotrophs (Patel et al., 2018a, 2018b). In another experiment, Pleissner et al. (2017) used simultaneous saccharification and fermentation (SSF) on mixed food waste using *Streptococcus* sp. They found that an increase in solid-to-liquid ratio of food waste increased the lactic acid generation. Iris et al. (2018) conducted an experiment on the enzymatic hydrolysis of food and beverage waste to produce hydroxymethylfurfural (HMF) as the end-product. They used glucoamylase and sucrase as the enzymes to produce glucose, which underwent further isomerization into fructose and eventually converted into HMF. Addition of lipases has also been shown to be effective in removing floatable grease from food waste, thus enhancing its digestibility in the subsequent anaerobic digestion (Meng et al., 2017). Table 2 presents the use of different classes of enzymes such as carbohydrase, lipase, and protease for the pretreatment of food wastes to yield value added products and in the reduction of volatile suspended solids.

These approaches build upon circular economy principles and are beneficial to establish a biorefinery for food waste valorization into useful chemicals such as lactic acid and HMF. Combining enzymatic pretreatment with anaerobic digestion enhances the production of the end-products from anaerobic digestion. Immobilized enzymes can be used as a pretreatment method as they not only improve efficiency and stability (physiochemical and thermal), but also improve the environment-friendliness and cost-efficiency of the overall process when compared against traditionally used chemical pretreatments and catalysts. Higher thermal stability of the enzymes allows for their sustained performance in the anaerobic digestion stages, improving the process efficiency.

3.2.2. Ultrasonic pretreatment with enzymatic hydrolysis

Ultrasonic frequencies are sound waves that exceed 20 kHz in frequency and travel in a media as a series of compressions and rarefactions. These waves are responsible for releasing a huge amount of energy through cavitation, a process in which air bubbles expand and implode in the areas of rarefactions (Gonzalez-Fernandez et al., 2015). These "hot spots" have very high temperatures and pressure which makes ultrasonic pretreatment an attractive green method to break down the food waste into easily hydrolysable state thus making further enzymatic hydrolysis more efficient (Tang and Sivakumar, 2015). The impact of ultrasonic treatment on food waste can be observed through various chemical and physical parameters such as soluble chemical oxygen demand (Li et al., 2016), lignocellulosic content (Ravindran et al., 2017), cellulose crystallinity and degree of polymerisation (Ma et al., 2021), and surface area and particle size (Subhedar and Gogate, 2015), and few more.

Ma et al. (2021) subjected food waste to ultrasonic pretreatment followed by enzymatic hydrolysis to produce caproic acid. They observed that the volatile fatty acids (VFAs) were significantly reduced due to ultrasonic treatment thus enhancing the hydrothermal conversion of lactic acid into caproic acid by nearly two times as compared against untreated waste. They also observed that the fermentation of food waste into these acids was dominated by *Caproiciproducens* bacterium which played a major role in breaking down proteins and carbohydrates. In an analytical model developed by Suresh et al. (2020), it was demonstrated that ultrasonic treatment of potato waste prior to enzymatic hydrolysis enhanced the bioethanol yield of the overall process. On the other hand, Taheri et al. (2021) observed that exposing food waste to ultrasonic pretreatment did not result in significant release of free sugars, which could be due to the low cellulose degradation ~38% observed in their process. But, in an earlier experiment Jiang et al. (2015) observed an enhancement in the amount of reducing sugars formed (3.6–4.4 times), indicating that other factors such as VFA formation, dissolved COD and lipid concentration might significantly affect the final reducing sugar formation. In another integrated setup including ultrasonic treatment Li et al. (2019a, 2019b) observed a 10% increase in glucose yield of sonically treated kitchen food waste as well as a possible reduction in enzyme usage and reactor size by 50%.

Liu et al. (2018) observed the impact of food waste sonication on the production of VFAs and hydrogen production in biogas. They found that food waste particle size played an important role in the effect of sonication and reported larger food particles reacted better to sonication pretreatment thus allowing for better yields. They also reported a reduction of 50% in the time taken to produce the highest yield of biogas under optimized conditions when the food waste was pretreated using ultrasonic frequencies. The exposure time and energy density of the ultrasonic frequencies also impacts the biogas yield (Rasapoor et al., 2016). Even in pilot scale digestion setups ultrasonic pretreatment shows promising results, improving the quality and quantity of biogas generated in shorter time. Rasapoor et al. (2019) were able to achieve an increase of 80% in the biogas yield by pretreating the food waste with ultrasonic waves. Recovery of antioxidants from common bean (*Phaseolus vulgaris* L.) was shown to enhance by nearly seven times when compared against solvent based extraction (Yang et al., 2019). Similarly, ultrasonic-assisted extraction of oils from waste coffee grounds was shown to improve by 13.5% over conventional solvent extraction (Mofijur et al., 2020).

Table 3
Breakdown of nutrient composition in food waste digestate (WRAP, 2016).

pH	8.3
Nutrient	Content (kg/tonne of fresh waste)
Dry matter	3.3
Nitrogen	5.4
Potassium (K_2O)	1.9
Phosphorus (P_2O_5)	0.8
Calcium	1.2
Sulphur (SO_3)	0.62
Magnesium (MgO)	0.14

Overall, ultrasonic treatment can be a useful technology given its green nature and overall significant positive impact on the production of reducing sugars from food waste, which can then be successfully fermented into various useful chemicals. The utilization of ultrasonic-assisted pretreatment and extraction methods have proven to be more energy efficient, reduce the dependence on utilization of harmful chemicals for extraction and require less time to hydrolyze the food waste to produce biogas. These advantages position ultrasonic-assisted methods as environmentally and economically sustainable.

3.3. Hydrothermal carbonization for resource recovery

While the food waste may not be a feasible resource for direct application, they still contain a rather large quantity of underutilized nutrients that get wasted under the current waste management practices. The last decade has been an eventful period for the focus placed on thermal conversion of biomass waste into biofuels such as biochar, bio-oil, and biogas (Wang et al., 2018a). Hydrothermal carbonization (HTC) process is a potential green approach in the resource recovery for nutrients from food waste due to its high applicability to wet streams such as food waste (Wang et al., 2018b), sewage sludge (Wang et al., 2019), algal biomass (Park et al., 2018) etc. Additionally, the water present in the food waste serves as the reaction media, thus reducing the overall water consumption of the process (Saqib et al., 2019). HTC thermally converts the wet feedstock into value-added energy-dense hydrochar, chemicals and other nutrients (Leng et al., 2020).

HTC offers unique advantages over other thermal techniques such as pyrolysis and torrefaction, such as elimination of pre-drying step, accelerated reaction speed, moderate reaction settings and lower energy requirement (He et al., 2019). At comparatively lower pressure (2–10 MPa) and moderate temperature (180–350 °C) settings with processing times ranging from 0.5 h to several hours, food waste undergoes hydrolysis, dehydration, decarboxylation, aromatization, condensation & polymerization to yield solid hydrochar (Yao and Ma, 2018; Guo et al., 2015). These conditions also result in the formation of subcritical water with lower dielectric constant favouring the dissociation of biopolymers (Suárez et al., 2020). Economically speaking, the elimination of the pre-drying process significantly reduces the amount of energy required for the overall process, thus reducing the total cost of operations (Pauline and Joseph, 2020). The process efficiency of HTC is significantly higher when compared to traditional thermal techniques making it economically attractive (Shen, 2020). Additionally, HTC also significantly reduces the production of greenhouse gases during food waste valorization making it an overall green and sustainable technique (Wang et al., 2019).

To develop a suitable strategy for nutrient recovery from food waste which has undergone HTC, it is imperative to evaluate the fate of nutrients. Various studies have tried to evaluate the fate of nutrients such as nitrogen, phosphorus, and potassium for a range of waste streams (Idowu et al., 2017). An example of nutrient content in food waste digestate is presented in Table 3. But there is lack of uniformity in the results achieved thereof due to high dependence of HTC output i.e., hydrochar on feedstock properties and composition and, operational

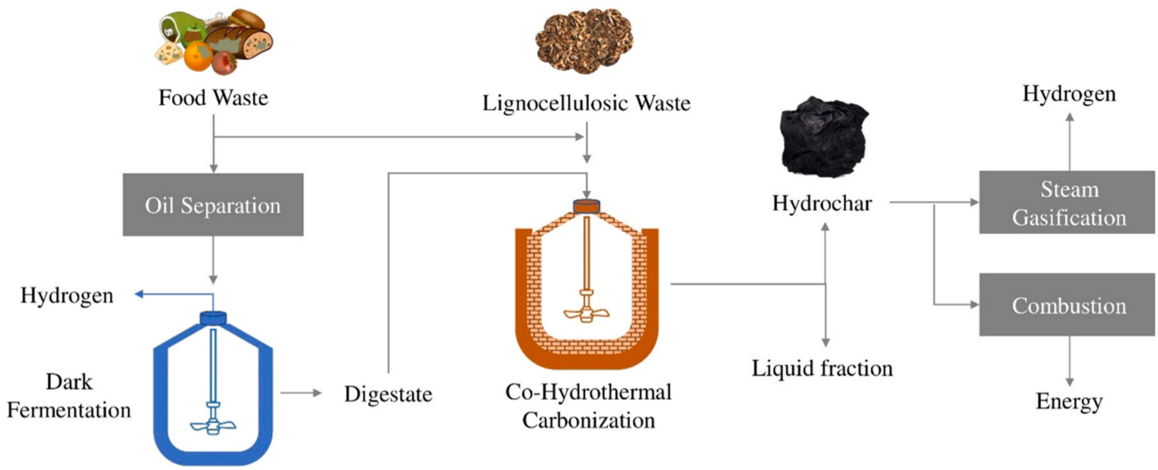

Fig. 4. A schematic overview of co-hydrothermal carbonization.

parameters thus making it difficult to define a generalized strategy for various feedstocks. Benavente et al. (2015) evaluated the fate of phosphorus and potassium in various food wastes (olive mill waste, canned artichokes and orange juice waste) and reported their values between 0% to 33% and 8–32% respectively. Other studies have estimated that nearly 70–90% of phosphorus present in the hydrochar can be recovered due to formation of crystalline compounds between phosphorus and other metals (Huang et al., 2018). The recovery of nitrogen from swine manure hydrochar was estimated by Lang et al. (2019) to be in the range of 52–64%. They also found that nitrogen recovery from hydrochar produced at high HTC temperature was lowered due to faster hydrolysis of organic substances. However, temperature had no impact on the presence of phosphorus which sustained a 20% level in the liquid fraction of the HTC process. Wang et al. (2017a) studied the impact of temperature and pH on the phosphorus content of hydrochar obtained by subjecting sludge to HTC between 200 and 260 °C and found that pH of feedwater impacted the distribution of phosphorus which ranged from 74% to 94%. Based on the findings of these studies it can be conclusively argued that nutrient content in hydrochar varies with feedstock type and reaction conditions.

While the application of higher temperature during the HTC of food waste does increase the possibility of ammonia formation, it has also shown to significantly improve the production of much stabler nitrogen forms such as quaternary nitrogen and pyridine in hydrochar (Zhuang et al., 2018; Wang et al., 2018b). Food waste is usually rich in protein content leading to the possibility of higher amination of nitrogen during HTC. Addition of a lignocellulosic waste stream to food waste can be of value as the HTC of the lignocellulosic components results in feedwater containing lactic, acetic and formic acids which can enhance the deamination of nitrogen (Kim et al., 2016). This was further explored by Wang et al. (2017a) who found that hydrolysis and denitrification of protein was enhanced due to the acidic feedwater, and at the same time hydrochar carbonization also improved. Addition of woody biomass waste to food waste during HTC has also been shown to produce hydrochar with improved mechanical strength (Wang et al., 2018a). Hence, there is merit in co-HTC of food waste with lignocellulosic waste. Idowu et al. (2017) demonstrated a nitrogen recovery in the range of 89–130% from solid and liquid phases of co-HTC of food waste with packaging materials. They also found that the liquid-phase of the HTC contained potassium and sodium (>75% of their initial value).

While nutrient recovery is an important aspect, majority application of HTC is in the production of hydrochar which is energy rich. But obtaining a high quality hydrochar is highly dependent on the operating conditions of the HTC process. Akarsu et al. (2019) optimized the subcritical water HTC of food waste and its digestate to produce hydrochar with properties similar to lignite. They subsequently subjected the hydrochar to steam gasification to produce hydrogen (57–59 mol H_2/kg hydrochar). HTC of food waste performed by Saqib et al. (2018) demonstrated that higher HTC temperature resulted in reduced activation energy. Additionally, reaction parameter such as residence time and temperature define the properties of the hydrochar such as heating value and fixed carbon content (Simsir et al., 2017). It has also been observed that temperature impacts the tensile strength of the hydrochar pellets produced. For instance, when HTC temperature was raised from 200 °C to 250 °C, the tensile strength of the hydrochar pellets was reduced which could be attributed to the carbonization of lignin resulting in lack of proper bonding (Wang et al., 2017b). This was also confirmed by Zhai et al. (2018), who presented that the high protein content and limited lignin content in food waste could not produce a hydrochar that had great mechanical strength as the pellet formation relied on weak bonding between the hydrochar microspheres. Addition of co-substrates such as molasses and woody waste has been shown to increase the mechanical strength of the pellets due to strong binding properties induced by their addition (Zhai et al., 2018).

Separating the oils from food waste creates a new stream to generate hydrogen from food waste, whereas the remaining digestate and food waste can undergo co-HTC with lignocellulosic waste which enhances the operational properties and valorization of food waste into biochar. The hydrochar can further be converted into hydrogen and energy.

An integrated approach towards leveraging HTC in conjunction with other technologies such as dark fermentation and steam gasification makes it an important technique towards scaling direct conversion of food waste into value-added products (Fig. 4). Additionally, the approach of co-HTC serves two purposes – act as a binding material due to introduction of lignin and solve the problem of solid waste management. The high carbon content of hydrochar and high calorific content similar to lignite make it an excellent alternative to solid fuel (Wang et al., 2018c).

The ability of HTC to act upon a wide range of food waste substrates without the need of a pre-drying step makes it an environmentally sustainable process. The process can occur at even lower temperatures (<350 °C) thus reducing the overall energy requirement of the process (Berge et al., 2015). HTC is an effective method to extract nutrients such as nitrogen, phosphorus and potassium from food wastes and food residues and reduces the need to acquire virgin nutrients from other sources such as fertilizers, thus reducing the overall energy requirements associated with food production. The energy density of the hydrochar generated from HTC has been found to be equivalent to coal, making it an environmentally friendly alternative to the fossil fuel (Pham et al., 2015; Wang et al., 2018c). An LCA analysis by Berge et al. (2015) on HTC-based hydrochar production and utilization in electricity production revealed that hydrochar-generated electricity was more

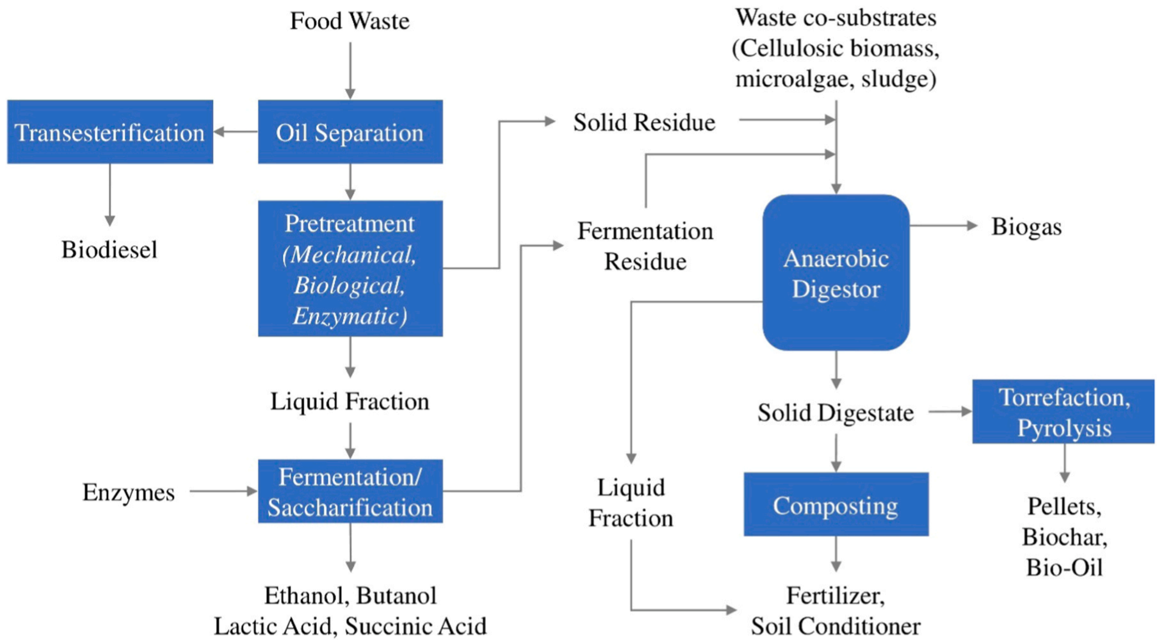

Fig. 5. Proposed setup to scale biorefinery for food waste valorization.

environment friendly as opposed to coal-based power generation. These results indicate that large-scale adoption of HTC on food waste and subsequent usage in power generation could be a feasible method to reduce dependence on fossil-fuel based energy.

4. Research gaps and future perspectives

The feasibility of using green and sustainable methods to transform food waste into valuable products and energy is backed up by the development of novel, green and sustainable techniques. However, the scale up of these techniques to industrial size is hampered by operational challenges such has high cost of food waste collection, chemical characterization and suitability of process. Moreover, the setup of biorefineries requires a high upfront cost as there are multiple considerations in the setup, design and optimization of operations. Apart from the setup and scale-up challenges, all the valorization techniques pose some challenges. For instance, the anaerobic digestion process is highly dependent on the appropriate growth of bacterial communities, and their degradation behaviour is driven by several factors, including substrate type, competition with native bacterial communities, OLR, operating pH and temperature. Tuning these operational parameters and maintaining degradation conditions varies largely with the food waste being treated. There is also a lack of understanding of the degradation pathways, hence tuning the degradation becomes tedious. Hence, research focus is required to unearth these interactions and metabolic pathways to better develop the pretreatment and valorization methods.

Any valorization technique that aims to convert food waste into valuable products needs to consider preservation of carbon in the feedstock. Thus, storage and pre-processing of waste feedstock has to be taken into account. One possible way to do that is to freeze the material or completely dry it before storage. An important aspect to consider in the resource recovery or bioconversion is considering pre-conditioning of the food waste using additional methods such as ultrasonic, microwave and other thermal treatments. These require further analysis as it has been observed that the outcome of these techniques varies depending on the composition of the feedstock. Integrated methodologies will be a definitive aid in improving the efficiency of processes such as anaerobic digestion and dark fermentation, as they enable better access to the organic components of the waste that undergo degradation by the microbial communities to release methane and hydrogen, respectively. Similarly, co-digestion of food waste although being a promising technique, is highly dependent on the substrate being added. While generalizations can be made that addition of lignocellulosic components and sludge does enhance the overall efficiency of the digestion process, it is imperative to test these techniques at pilot or medium scale to understand their economic applicability.

In majority of the biobased techniques microbial communities play a very important role in the degradation of food waste. There have not been many insights into the correlation between changes in indigenous microbiota of food waste and the release of carbohydrates in during the initial degradation of the food waste. This is important to study as the effect of these microbes determines the production of methane or hydrogen. Regulation of the microbial communities thus becomes a necessary part of the valorization process to enhance the production of methane and hydrogen (Srivastava et al., 2017). HTC technique is thus an important avenue that avoids the challenges of dealing with wet waste. But its dependence on the feedstock lignin content poses a significant challenge in producing pellets that can be directly used as fuel sources. This more research is required in co-HTC process that can appropriately produce energy-dense hydrochar. Another important point to consider is the tuning of operational parameters in the HTC process so as to achieve the desired characteristics on the hydrochar i.e., making it as energy dense as coal varieties. This requires further analysis of various types of food waste feedstock and the effect of other processes such as oil removal and pretreatment on the subsequent HTC process. Physical parameters such as feedstock particle size is important to improve product recovery through these techniques, as the process efficiency is largely dependent on the surface area of exposure. It has been observed that particle size of < 2 mm favours enhanced methane recovery, there is no clear understanding of the optimal particle size that improves hydrogen production.

One way to improve the efficiency of overall process of food waste valorization is to combine multiple techniques that improve upon different aspects of the valorization process. A biorefinery concept (Fig. 5) that combines enzymatic fermentation with anaerobic digestion has been proposed that aims at achieving zero-waste by breaking down each effluent from the previous step into multiple useful products. An important strategy to improve the economic feasibility of this setup is to co-locate the food waste processing plant with sewage treatment plants

Table 4
GHG emissions reduction by utilizing food waste to produce biogas.

Food waste-based feedstock source	Production of Biogas (m^3/wet tonne) (US Environmental Protection Agency, 2015)	Reduction in emissions of GHG used in heat (kg CO_2) (NFCC, 2016)	Reductions in emissions of GHG used in electricity (kg CO_2e) (International Energy Agency, 2017)	Reductions in emissions of GHG (CO_2) used in trucking (Joint Research Center, 2013)
Brewery waste	60–100	1919	1862	1896
Abbatoir waste	120–160	2034	1936	1995
Vegetables	50–80	1890	1844	1872
Potatoes	100–120	1976	1899	1946
Mixed Food from restaurants and supermarkets	75–140	1872	1896	1942
Cheese	˃600	2920	2499	2753
Bread	400–500	2631	2315	2506
Molasses	450–579	2756	2394	2612

or wastewater treatment facilities (Moreno-Garcia et al., 2017). An estimated 26.44 billion kWh of electrical power is possible to be derived by co-digesting food waste with sewage sludge (Ma et al., 2017a, 2017b). Additionally, each of the solid digestate and liquid fractions are rich in nutrients (nitrogen, potassium and phosphorus) thus making them an excellent candidate for direct application as soil amendments or for further treatments to extract these nutrients. These co-located systems can achieve economies of scale faster than independent plants due to shared facilities, equipment, and material which keeps the cost of setup and operations in check. However, the cost of collection, separation and categorization of food waste based on its composition must be considered while evaluating the circular economy objectives. In addition, the initial setup costs for trialling the co-located biorefineries and arriving at optimal operational conditions would be a challenge that needs to be looked at. But the clear advantages of setting up such biorefineries on the environment are evident from the reduction in GHG emissions that these systems can contribute towards (Table 4).

5. Conclusion

This review brings together an analysis of the newer biobased green strategies for food waste management. While the goal of achieving zero-waste discharge from food waste into the environment may seem difficult, the current technologies do give an opportunity towards creating such a system. Economically feasible and environmentally sustainable process setups will require further research as there are still wide gaps in bringing down the cost of operations for some of the advanced techniques. Most of the research has focused on exploring the potential of various biotechniques at the lab-scale towards zero-waste but scaling these to pilot or plant level operations needs more investment and efforts. Thus, there is a need to bring together concerted efforts from private and public enterprises to enable a paradigm shift in the field of food waste management. The integrated biobased refineries are a great way towards achieving this goal of concurrent resource recovery and energy generation. Exploring techniques that have been utilized in other biowaste management such as lignocellulosic biorefineries is another great way to enhance the food waste valorization industry.

CRediT authorship contribution statement

Zeba Usmani: Writing original draft, Data curation, Investigation, Formal analysis, Editing. **Minaxi Sharma:** Writing - review & editing, Data curation, Editing, Formal analysis. **Abhishek Kumar Awasthi:** Writing - review & editing, Data curation, Investigation. **Gauri Dutt Sharma:** Writing - review & editing, Data curation, Investigation, Editing. **Denise Cysneiros:** Visualization, Writing - review & editing. **S Chandra Nayak:** Visualization, Writing - review & editing. **Vijay Kumar Thakur:** Formal analysis, Visualization, Writing - review & editing. **Ravi Naidu:** Visualization, Writing - review & editing. **Ashok Pandey:** Visualization, Formal analysis, Writing - review & editing. **Vijai Kumar Gupta:** Conceptualization, Validation, Visualization, Investigation, Supervision, Reviewing.

Declaration of Competing Interest

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

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