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Integrated biorefineries for repurposing of food wastes into value-added products

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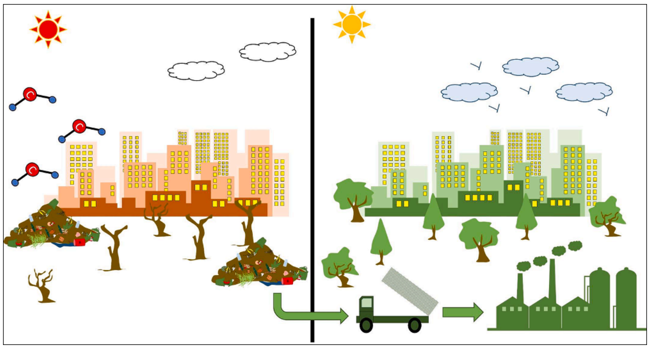
HIGHLIGHTS

- Food wastes (FW), rich in biomolecules, is a potential feedstock for biorefineries.
- Recycling and reuse of FW leads to pathway towards circular bioeconomy.
- Microbes are promising biocatalysts to turn FW into wealth.
- Valorisation of FW will result in reduced waste and carbon neutral society.

GRAPHICAL ABSTRACT



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ABSTRACT

Food waste (FW) generated through various scenarios from farm to fork causes serious environmental problems when either incinerated or disposed inappropriately. The presence of significant amounts of carbohydrates, proteins, and lipids enable FW to serve as sustainable and renewable feedstock for the biorefineries. Implementation of multiple substrates and product biorefinery as a platform could pursue an immense potential of reducing costs for bio-based process and improving its commercial viability. The review focuses on conversion of

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surplus FW into range of value-added products including biosurfactants, biopolymers, diols, and bioenergy. The review includes in-depth description of various types of FW, their chemical and nutrient compositions, current valorization techniques and regulations. Further, it describes limitations of FW as feedstock for biorefineries. In the end, review discuss future scope to provide a clear path for sustainable and net-zero carbon biorefineries.

1. Introduction

Food, a necessity to the living creatures on this planet, however, a large fraction of manufactured food is lost or wasted and does not reach to consumer due to several reasons. As per the definition, food waste (FW) is the unconsumed, discarded or lost edible mass during different stages of food supply chain including production and storage of raw material, industrial processing, and municipal waste disposal containing food passed the expiry date and unconsumed food coming from households, restaurants, supermarkets, and various catering services (Fig. 1). Approximately, 30 % of the food generated is lost during various stages of supply chain and a large part if it ends as the municipal solid waste (Kumar and Longhurst, 2018). As per the 2021-World Economic Forum reports, 931 million tonnes of FW is generated per year, wherein households generate 61 %, 26 % come from food services, and 13 % from retail. With current rate of waste generation it is expected that global waste could reach 3.40 billion tonnes by 2030 (Moza et al., 2022). It is estimated that globally-one third of food produced for human consumption is wasted annually, which accounts for 1.3 billion tonnes of food wasted worldwide. As per 2021 – World economic forum, about 9.3 million tonnes of FW was generated in 2019 alone, with major proportion coming from households (61 %) followed by food service industry (26 %). There are several types of FW including unconsumed food, unavoidable food supply chain waste, organic waste from kitchen, starch rich waste, fruit and vegetable waste, dairy waste, oil waste etc. The traditional routes for eliminating FW are landfilling, compositing and incineration, which cause environmental problems and health issues (Ouadi et al., 2019; Schmidt et al., 2018). Landfill and composting approaches release huge quantities of CO_2 into the atmosphere and have fewer economic benefits (Kumar and Longhurst, 2018). In the developed world, FW has been treated through anaerobic digestion (AD) to eliminate waste and curb the carbon emission, therefore, there has been significant increase in the number of AD plant in last decade. However, AD does not harness full potential of FW and has a low environmental

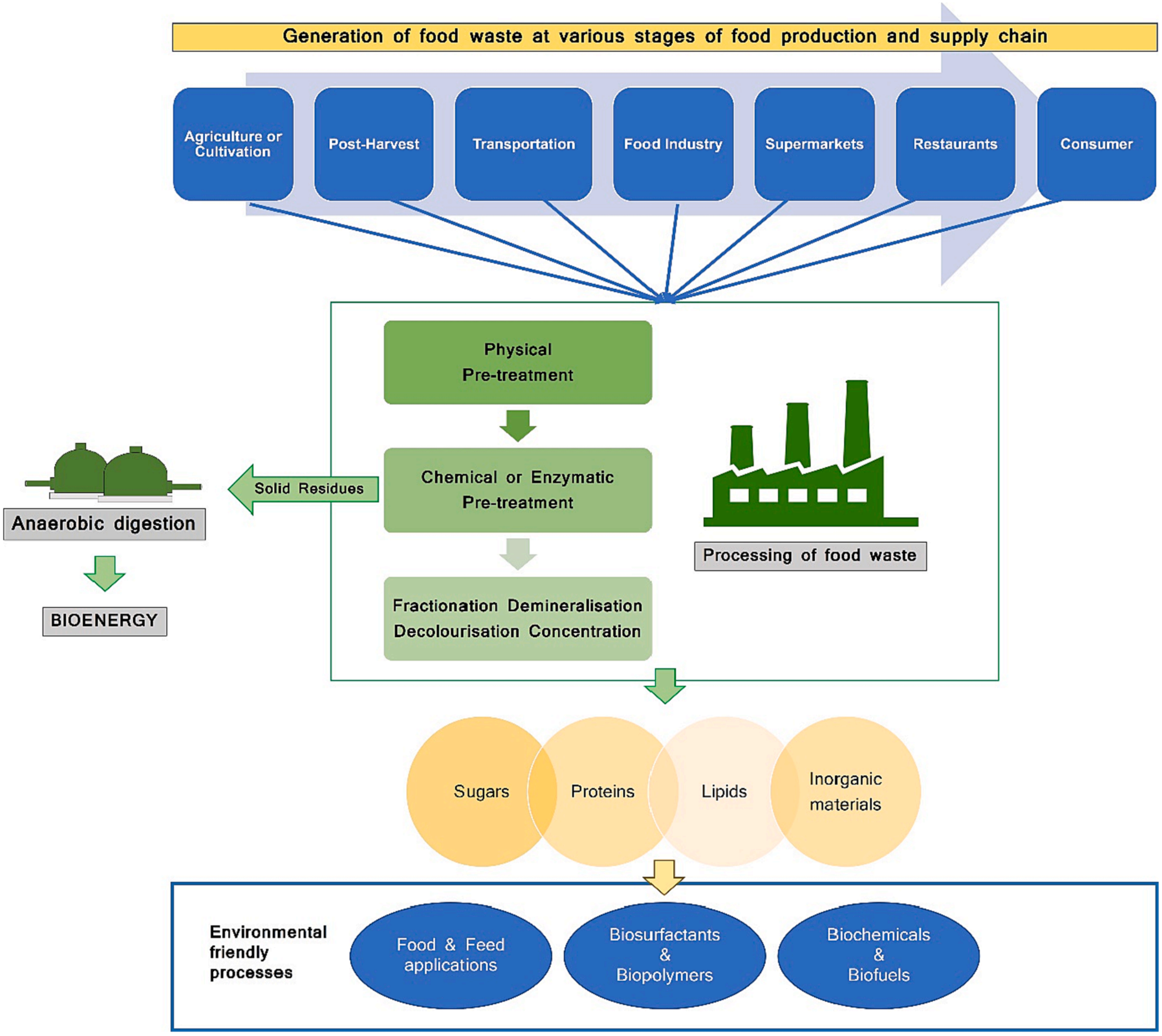

Fig. 1. Illustration of food waste generated at various stages of food production and supply, with emphasis on circular economy aspect of generating value-added products through integrated biorefinery approaches.

profile (Brancoli et al. 2020; Narisetty et al. 2021a). According to the biorefinery principle (Task 42), Circular Economy EU policies, and Sustainable Development Goals of Agenda 2030, the use of FW should be prioritised for production of high value chemicals over the formation of compost and bioenergy (Task-42-Biobased-Chemicals-value-added-products-from-biorefineries.pdf (ieabioenergy.com) (Teigiserova et al., 2020). Further, according to Bastidas-Oyanedel and Schmidt, 2018, fermentative production of chemicals followed by AD generates much more revenue. For example, lactic acid fermentation followed by AD leads to a revenue of $94/ton compared to $19/ton food waste with AD alone (Bastidas-Oyanedel and Schmidt, 2018; Cox et al. 2022).

FW is organic and biodegradable in nature and typically composed of carbohydrates (30–60 %) (starch, cellulose, lignin and pectin), proteins (5–10 %) and lipid (10–40 %) molecules (Uçkun Kıran et al., 2015). The presence of all these macromolecules or their hydrolyzed products in significant amounts not only facilitates microbial growth but also conducive for accumulation of metabolites from cell factories. These nutrients can be recovered, concentrated, and transformed into high value products and it has been found that FW transformation into to chemical building blocks is more profitable than conventional processing methods. Further, recycling FW into valuable chemicals will directly contributes to the transition from current fossil-based economies to a bioeconomy and reduced waste society (Cox et al. 2022; Narisetty et al. 2022a; 2022b). Henceforth, upgrading the FW utilization towards the collective biobased product synthesis such as biosurfactants, biopolymers, diols, bioenergy, food, and feed ingredients in the biorefinery framework will not only effectively manage FW but also result in development of low biomanufacturing technologies and strengthen the bioeconomy sector (Naresh Kumar et al., 2022).

Despite all these advantages and continuously growing market demand of the bio-based products, various approaches have been confined to the laboratory scale either due to complexity in the upstream or downstream processes like cost of the substrate, suitable host, and separation and purification procedures. The current review focuses on conversion of surplus FW as potential feedstock into range of value-added products including biosurfactants, biopolymers, diols, and bioenergy production. The review includes in-depth description of various types of FW, their chemical and nutrient compositions, current valorization techniques and regulations. Further, it describes challenges and limitations of FW as feedstock for biorefineries. In the end, review discuss future scope to provide a clear path for sustainable and net-zero carbon biorefineries.

2. Food waste composition and nutrient profile

Being heterogenous in nature, it is essential to understand the composition and the nutrient profile of FW before evaluating its potential as a feed or substrate for bio-based processes (Carmona-Cabello et al., 2018). While the moisture content in FW ranges between 52.1 % and 73.9 %, the remaining 27 % to 47 % majorly comprises organic fractions and minimal trace elements (Carmona-Cabello et al., 2020). It is imperative to deal with water content present in FW as high moisture content may (i) adversely affect downstream processing of FW (ii) result in loss of >74 % nutrients (Gunaratnam et al., 2005; Kim and Dale, 2015) (iii) drive contamination and auto-hydrolytic processes (Tran et al., 2017) (iv) decrease the calorific value of raw materials (Tran et al., 2017) (v) accelerate the process of FW biodegradation (Carmona-Cabello et al., 2020). Different methodologies are employed such as speed vacuum drying, thermal evaporation to reduce the moisture content (Carmona-Cabello et al., 2020). The resultant dry organic matter is then processed to value added products. The dry matter obtained is rich in following: (i) 14–20 % Carbohydrates, (ii) 7.2–11.8 % lipids, (iii) 4.6–11.4 %, proteins, and (iv) 1.3–2.6 % inorganic material, including ash content. Carbohydrates constitutes the chief component of FW, making it a suitable substrate for fermentation-based products such as bioethanol, bioplastics, and microbial oil production. The carbon source in FW is present in various forms including reducing sugars, simple sugars, fibre, and starch, amongst which starch constitutes the dominant component (24.1 % w/w) (Carmona-Cabello et al., 2020; Pirani and Arafat, 2016). The FW rich in biomolecules, is a potential feedstock for biorefineries. The simple carbohydrates obtained from such FW can be easily assimilated by microorganisms and has been reported for bioethanol production, anaerobic digestion, and lipid accumulation (Carmona-Cabello et al., 2018; Kumar et al., 1998). Overall, compositional knowledge constitutes an indispensable deciding factor for FW processing and valorisation.

Lipids constitute the second highest constituent of FW after carbohydrates and can go up to 28.1 % w/w, of total dry biomass (Carmona-Cabello et al., 2020). Various foods like meat, fish, dairy products, and oily sauces are the major sources of lipid enriched FW (Pirani & Arafat, 2016). The information of fatty acid chain length and extent of saturation in fatty acid are critical factor for selecting valorisation of FW rich in lipids. The fatty acid composition of the FW differs on the source, type of food, etc, but the range of fatty acid methyl esters (FAME) was found to be similar to the fractions in vegetable oils, with 36.39 – 41.57 % w/w oleic acid (C18:1), and 21.37–38.63 % w/w linolenic acid (C18:2). The lipid fractions from the FW can be used in bio-diesel production and manufacturing bio-lubricants (Carmona-Cabello et al., 2018). Proteins extracted from FW demonstrate big potential in the biotech industry especially animal and pet foods, nutraceuticals, cosmetics, and pharmaceutical industry demanding protein-based compounds such as chitosan, collagen, keratin, or elastin. Furthermore, protein-based FW can be used as rich sources of nitrogen in microbial fermentation (Carmona-Cabello et al., 2020).

The mineralization process of FW is understood by studying the composition of ash content containing metal fraction. Ash and trace elements are found in organic samples. Ashes comprise of 4.5 % w/w for all FW samples based on gravimetric analysis. Highest values were reported from FDR and IR comprising 5.3 % and 4.6 % respectively while GR and UCC reported to show below average results (Carmona-Cabello et al., 2020). Minerals present in FW samples have been classified into three concentration levels namely trace elements, ultra-trace elements and main elements (Belitz et al., 2009). Minerals like Na, K, Ca, and Mg constitutes the major fraction at an average concentration of 0.32 %, 0.26 %, 0.11 %, and 0.03 % w/w, of the total FW, respectively. Trace element fraction comprises of Zn, Mn, and Fe at concentrations 0.008 %, 0.004 %, and 0.02 % w/w, respectively. Finally, the third category is the ultra-trace elements comprises of Cu, Ni and As at 0.0009, 0.0002 and 0.0001 % w/w, respectively (Schmidt et al., 2014). Estimates report that 0.06 kg of potassium and 0.03 kg of magnesium is required to synthesize 1 kg of biodiesel from microalgae, *Auxenochlorella protothecoides*. Hence the presence of detectable levels of Mg, Fe, Cu, Zn, and Mn in the FW could assist in the production of biodiesel (Bohutskyi et al., 2014). Fe and Ca help stabilize bioprocessing operation in anaerobic digestions. Furthermore, Fe possesses a critical role in redox reactions owing to its electron transfer properties (Kaur et al., 2019a). In a valorisation process, mineral nutrient bio-accessibility must be factored by considering the reduced solubility of metals with substances such as oxalates, phytates, fibres and tannins.

3. Food waste regulations and current management techniques

In modern times, FW is considered a valuable source for nutraceuticals, supplements, plant-based medicines, cosmetics, and many more high value retail-based products generating sales, revenue and mode of income and employment for many (Djilas et al., 2009; Schieber et al., 2001). Although FW are rich in starch, due to diverse cuisines and rich organic and inorganic compositions, FW is considered as a second-generation feedstock, the studies conducted by Food and Agriculture Organization (FAO) indicated that a third of globally manufactured food is lost or wasted in the supply chain (from Farm to Fork) equivalent to 1.3 billion tonnes/year (Gustavsson et al., 2011). To mitigate this loss, enormous emphasis is laid on the recycling, recovery and reconditioning of FW to convert it into value-added products viz., bio-pigments, food supplements, emulsifiers, colourants, essential and edible oils, biofuels, bio-fertilizers, bio-preservatives and single cell protein (Laufenberg et al., 2003). Various conventional and advanced techniques like mechanical pressing, foam mat drying, electro-osmotic dewatering, acid or alkali treatment, or enzymatic hydrolysis are in place for pretreatment or extraction of value-added compounds from FW (Galanakis, 2012). FW including peels, albedos, pomaces from berries, cheese, whey etc, upon processing by emerging as well as established recovery technologies, have demonstrated to be great sources for extracting high value products like pectin, phenols, proteins etc (Fig. 2). It was observed that maximum recovery of phenol was obtained from olive mill wastewater whereas minimum was observed in mango peel waste. On the other hand, peel waste was found to be a major source for pectin recovery. Therefore, FW should be segregated and managed appropriately with the goal of maximum recovery. It is utmost important to control FW at its source in the supply chain in an ideal FW management system (Närvänen et al., 2020). Developed countries have established ingenious and innovative solutions to track, record, monitor and manage FW to reduce, reuse and recycle FW efficiently. For this, several waste management's practices viz., composting, sanitary landfills, incineration etc are adopted and accordingly benchmarks are set for other nations to follow. Significant efforts are made to manage FW by laying down regulations relevant to FW management, for example United Kingdom has rationalised the plan for effective waste management by running a campaign for consumers to encourage people to make smart decisions on purchasing, food management, and consumption. In December 2018, a reform was proposed by England to implement an elaborate waste management strategy, which involves: (i) planning to ameliorate recycling by ensuring consistency in collections, (ii) working with business and local authorities, (iii) taxation on recycled plastic packaging with less than 30 % recycled content, (iv) extending responsibility for packaging regime, etc. The UK government is aligning to the EU's circular economy with the goal to achieve a 65 % municipal recycling (WRAP, 2020). Astonishingly, US spends $218 billion USD on tackling the food waste generated per annum, Fig. 3 explains the amount of food waste generated per capita (per person) and the revenue loss in billion USD per annum in countries like US, Australia, Europe, India, and China. US has implemented state and federal laws to reduce FW with an aim to protect natural resources, feed the hungry and create economic opportunity. In EU, majority of the cost is incurred in managing with household FW followed by waste from retail businesses (Fig. 4) (Stenmarck et al., 2016). Households and processing together account for 72 percent of EU food waste that amounts to 64 million tonnes approximately. Various law enforcement strategies like zero food waste act 2021, EU Green Deal, EU farm to Fork strategy (Garske et al., 2020), EU Circular Economy Action plan, Zero Waste Scotland, Sustainable Development Goal 12.3, India's compulsory food waste reduction bill 2018, and China's Clear your plate campaign is directly or indirectly addressing the reduction of food waste.

Canada possesses an efficient food policy blueprint for sustainable and healthier food system targeted to aim for ending hunger and promoting healthier and sustainable lifestyle (Abdulla et al., 2013). The FW initiatives launched by the Canadian government is very innovative and extremely appreciable. They launched 'FW reduction challenge' competition where the government is working with talented and innovative human capital to resolve FW issue. Canada is committed to work along the UN sustainable development goal 12.3, that has set target to decrease food wastage along the production and supply chain by half that includes post-harvest losses by 2030 (de Visser-Amundson, 2020). Similarly, the Australian government has also aligned its goal with UN sustainability development goal 12.3. The government has implemented the Australia National FW strategy wherein the emphasis is given on the value of wasted food products and in identifying opportunities for achieving greatest benefits in creating circular economy. The Australian government has set up an action plan by: (i) establishing stop FW program, (ii) developing the Australian food pact voluntary agreement for industry. It brings food supply chains together to identify opportunities to extract benefits from FW thereby increasing productivity, (iii) digressing more food to the food rescue division to redistribute surplus food to the needy ones, (iv) bolstering for educational campaigns for reducing FW and the negative impacts associated with wastage of food (Pearson et al., 2010). The overall purpose of FW management is to strategize and formulate innovation plans in waste treatment to create value from FW to save billions of dollars, thereby effectively contributing to the growth of national economy. Overall, the While this firmly demonstrates how critically FW problem is dealt in Australia, it is very evident from the data illustrated in the bar graph representing the expenses incurred to manage FW. Thus, there is a dire need to develop

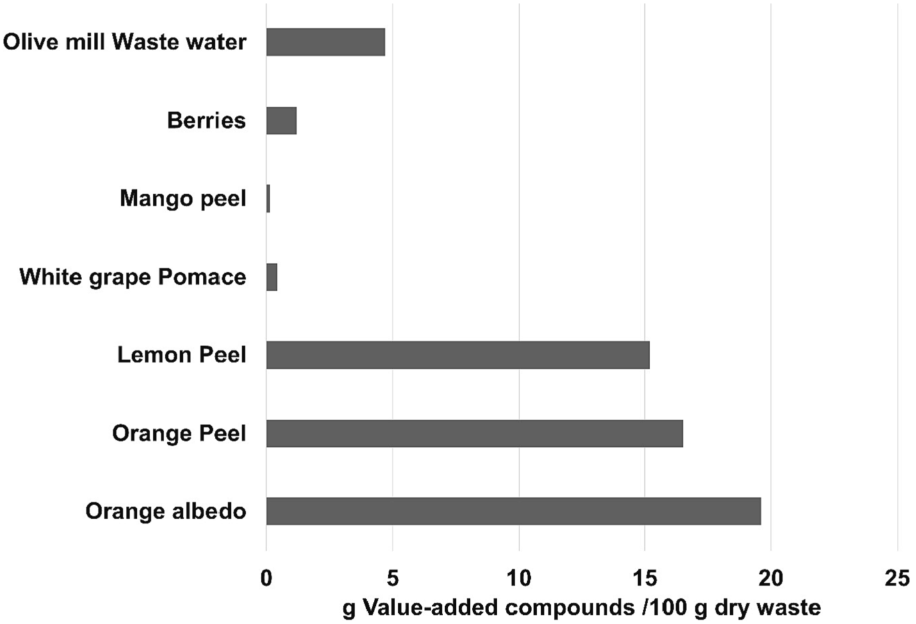

Fig. 2. Graphical representation of grams of value-added compounds like phenols, pectin, etc can be obtained per 100 g of various FW.

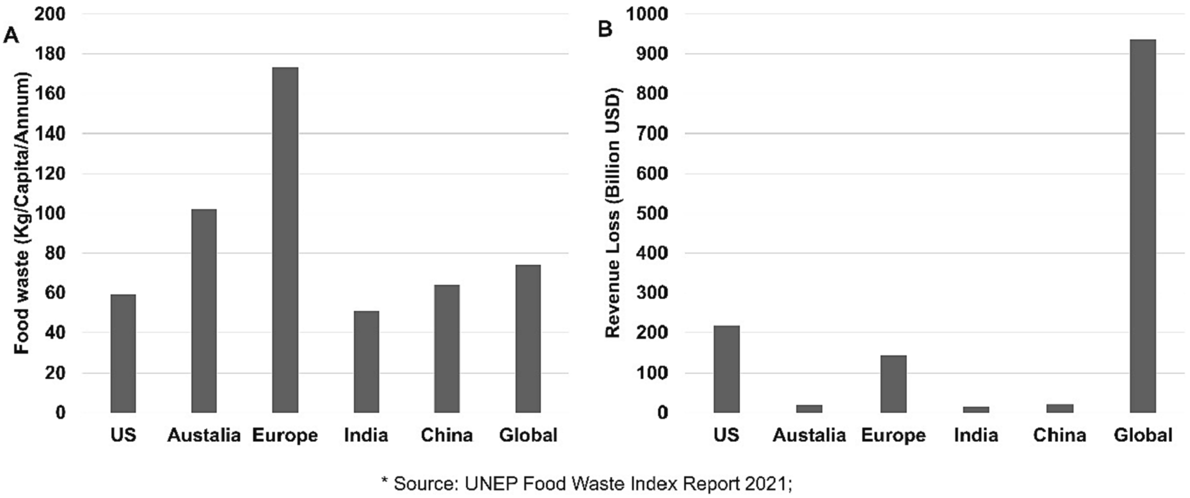

Fig. 3. Graphical representation of (A) FW available in major countries and globally and (B) cost incurred or revenue loss due to waste and management.

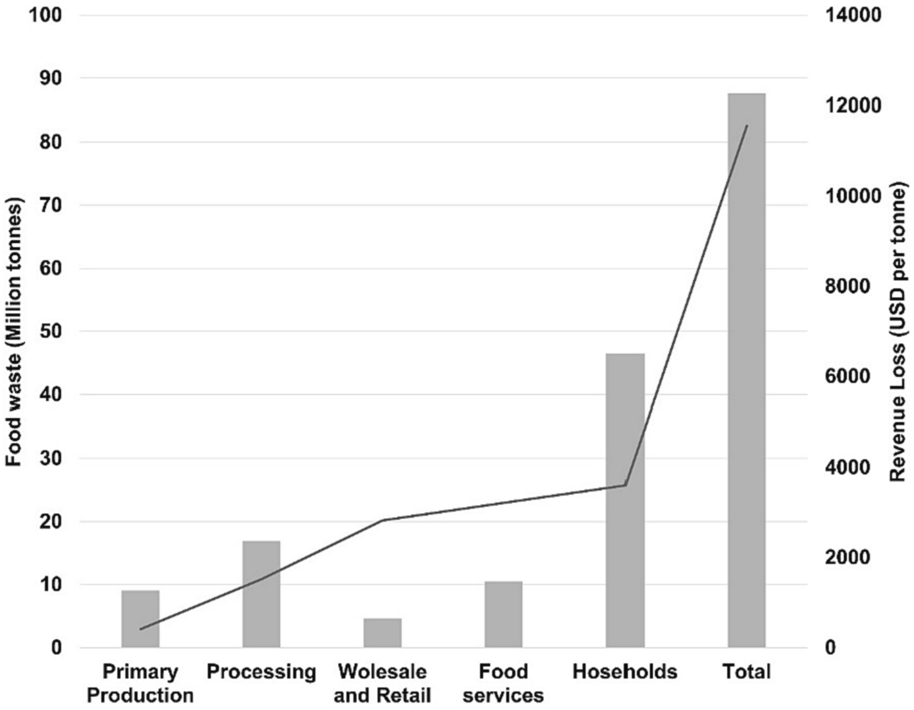

Fig. 4. Graphical representation of FW (Million tonnes) produced at different steps of supply chain from Farm to Fork in European Union and costs (USD per tonne) incurred due to this loss.

valorisation technologies to divert the FW generated for manufacturing high value products to receive economical gains (Fig. 3B). Additionally, recycling and reuse of FW leads to pathway towards circular bioeconomy.

Modern mathematical modelling on FW treatment operations involves retrofitting of FW treatment plants to make the entire operation profitable. For example, centralized management techniques utilizing single technology of AD (N = 1) has a fixed installation cost of 15 $M/year and the revenue generated is 1.5 $M/year. So, the payback period here itself is ten years. Now, comparing that to decentralized system adopting two technologies which are AD and rotating biological contactors (N = 2) retrofitted together costs 4.2 $M/year as installation cost bringing down the cost of distributed treatment by 33 % and payback period by 70 % to three years approximately. Similarly, double retrofitting in bioethanol plant has reported to generate an overall objective cost to negative 0.104 $M/year making the investment highly profitable (Mountraki et al., 2016). Finally, sustainability evaluation of a process against FWMA using pre-established criterion. In addition, other qualitative and quantitative parameters dictate the decision-making process. Qualitative parameters help in identifying the most appropriate FWMAs whereas quantitative parameters provide quantitative data about the properties of FW. Qualitative parameters include, (i) physical state, (ii) edibility, (iii) complexity, (iv) origin, (v) presence of animal product, (vi) packaging, (vii) treatment, (viii) stage of supply chain and (ix) packaging biodegradability. The attributes must be defined when considering FWMAs, for example, quantitative and qualitative estimation of volatile fatty acids is important while assessing AD of FW (Chang and Chen, 2010; Garcia-Garcia et al., 2017).

4. Biosurfactants production from food waste

Biosurfactants are a surface-active compound produced by microbial cell factories such as bacteria, fungi and yeast. It is a suitable replacement of chemical surfactants and correspondingly gaining vast popularity due to its striking features such as non-toxicity, biodegradability and effective over broad range of pH and temperature (Liu et al., 2018; Ribeiro et al., 2020). The market value of biosurfactants was ~ 1.8 billion USD in 2016 and has been forecasted to reach 2.8 billion USD by 2023 especially with 8 % gain in Rhamnolipid production (Singh et al., 2019).

Since late 19th century there is a huge market demand for the surfactants due to its unique molecular structure comprising of hydrophilic, hydrophobic moieties with diverse variation, and versatile characteristics. It is immensely used in the production of various chemical commodities related to environmental application, cosmetics, personal hygiene, industrial and pharmaceutical products (da Silva et al., 2021a) These surfactants are generally amphipathic in nature and tends to reduce surface tension of oil–water interface and enhances the miscibility of the water insoluble substance. The surfactants also acts as an emulsifier for water in oil and oil in water mixtures and can produce stable gels and foams (Naughton et al., 2019). Currently, the majority of surfactants are chemically manufactured using petroleum feedstock, which is economical in nature but may not be feasible in the long run due to the drastic depletion of crude oil reservoirs and surplus accumulation of greenhouse gases (GHG). To overcome this bottleneck, search for an alternative surfactant production method by the biological route has been initiated over last few decades, which exhibits superior structural and functional properties and ecologically safer (Geetha et al., 2018). Based on the molecular weight, biosurfactants can be broadly classified into two main categories. The lower molecular weight compounds are known as biosurfactant with molecular weight ranging from 0.5 kDa to 1.5 kDa. These molecules tend to lower the surface and interfacial tension and some of the examples are glycolipids (sophorolipids, rhamnolipids, trehalose lipids and mannosylerythritol lipids) lipopeptides (surfactin, fengycin) etc. The high molecular weight compounds range over 500 kDa and are known as bio emulsans, which stabilizes the oil-in-water emulsion such as lipopolysaccharides or lipoproteins and polymers of heteropolysaccharides (da Silva et al., 2021b; Twigg et al., 2021). The biological synthesis of surfactants and their yields are quantified based on emulsification index (EI) and can be calculated from Eq. (1).

$$EI = \frac{Heightofemulsionlayer \times 100}{Totalheightoftheliquid} \tag{1}$$

Microorganisms like bacteria (*Acinetobacter, Arthrobacter, Bacillus,*

Table 1
Summary of value-added products from food waste.

Product	Substrate	Processing	Microorganism	Titers	Yield	Productivity	References
Biosurfactants							
Surfactins	Rice mill polishing residue	Liquefaction at 70 °C for 10 mins	*Bacillus subtilis* MTCC 2423	83.4 mg/L	4.2 mg/g	–	Gurjar & Sengupta, 2015
Mannosylerythritol	Cheese whey and Waste frying oil	No treatment	*Moesziomyces aphidis* 5535	13.1 g/L	–	1.3	Nascimento et al., 2022
			M. antarcticus 5048	13.9 g/L	–	1.4	
Iturin	FW	Co-culture with *B. subtilis* expressing amylase and lipase	*B. amyloliquefaciens* HM618	10.5 mg/L	–	–	Miao et al., 2022
Rhamnolipids	Waste cooking oil	No treatment	*Pseudomonas aeruginosa* P7815	16 g/L	0.23 g/g	0.06 g/L. h	Sharma et al., 2022
Sophorolipids	FW and Oleic acid	Enzymatic hydrolysis	*Starmerella bombicola* ATCC 22,214	115.2 g/L	0.33 g/g	1.25 g/L.h	Kaur et al., 2019b
Fengycin	KW	Co-culture with *Pichia pastoris* expressing amylase, glucosidase, and lipase	*B. amyloliquefaciens* HM618	21.2 mg/L	–	–	Wang et al., 2022
Biopolymers							
PHA	FW and acidogenic effluents from biohydrogen process	–	Microbial consortium	–	35.2 %	–	Reddy and Mohan, 2012
PHA	Volatile fatty acids from acidogenic fermentation of FW	–	Microbial consortium	–	7.6 % *	–	Moretto et al., 2020
PHB	Volatile fatty acids from acidogenic fermentation of FW	–	*B. megaterium* ATCC 14,945	–	8.6 %	–	Vu et al., 2021
PHB	Volatile fatty acids from acidogenic fermentation of KW	–	Cupriavidus necator CCGUG 52,238	–	84.5 %	–	Farah et al., 2011
PHB	Volatile fatty acids from acidogenic fermentation of FW	–	Cupriavidus necator ATCC 17,699	–	87 %	–	Hafuka et al., 2011
Bio-diols							
2,3-BDO	FW	No pretreatment	*B. licheniformis* YNP5-TSU	4.3 g/L	0.41 g/g	0.18 g/L.h	OHair et al., 2021
2,3-BDO	BW	Acid hydrolysis	*Enterobacter ludwigii*	135.4 g/L	0.42 g/g	1.41 g/L.h	Narisetty et al., 2022b
2,3-BDO	BW	Enzymatic hydrolysis	*Enterobacter ludwigii*	138.8 g/L	0.48 g/g	1.45 g/L.h	Narisetty et al., 2022b
2,3-BDO	Bakery waste	Enzymatic hydrolysis	*B. amyloliquefaciens*	103.9 g/L**	0.39 g/g	0.87 g/L.h	Maina et al., 2021

Biopolymer yields were calculated as % of cell dry weights; Diols yields are calculated based on glucose released from respective feedstock; *Yield calculated based on volatile solids; **Concentration of combined acetoin and BDO; PHA: Polyhydroxyalkanoate; PHB: Polyhydroxybutyrate; FW: Food waste; BW; Bread waste; KW: Kitchen waste.

Enterobacter, Halomonas, Pseudomonas, Rhodococcus), yeast (*Candida* and *Rhodotorula* sp.), and fungus (*Aspergillus* and *Penicillium* sp.,) are extensively used for biosurfactant production. Among the biosurfactant, glycolipid is extensively studied it is composed of saccharide units attached with aliphatic or hydroxy aliphatic acids and most of the chemical bonds will be ether or esters in nature (Shekhar et al., 2015). Rhamnolipids synthesized by *Pseudomonas aeruginosa* has been commercialized by Jeneil Biosurfactant company in USA for bioremediation as well as agronomical applications. Yeast species such as *Candida* sp., and *Rhodotorula* sp., are known to produce sophorolipids, while *Pseudozyma* yeasts produces mannosylerythritol lipids (Konishi et al., 2007). *Bacillus* sp. are known to produces surfactins and cyclic lipopeptides (Jajor et al., 2016). The strains such as *Corynebacterium, Mycobacterium* and *Nocardia* sp., have ability to synthesis Trehalolipids (Franzetti et al., 2010). Whereas the microorganism such as *Acinetobacter* and Archaea produces high molecular weight polymers which can be used as emulsifiers. The renewable substrates from food industries used for biosurfactant production is depicted in Table 1.

A marine bacterium *Bacillus megaterium* was cultivated by supplementing food waste (noodle processing water along with chemical fertilizers consisting of approx. 35 g/L carbohydrates) to produce lipopeptides. The process parameters like temperature, pH, agitation, and aeration were optimized using artificial neural network algorithms, and with the optimum parameters resulted in 6.58 g/L lipopeptide with an increment of 46 % in comparison to the unoptimized process (Dhanarajan et al., 2014). Similarly process optimization was carried out for *P. aeruginosa* PG1 strain using bakery waste as the sole carbon source along with mineral salt media resulting in rhamnolipids productivity of 11.6 g/L/day (Patowary et al., 2019).

Cashew apple juice (CAJ) which is a by-product of cashew nut industry is an inexpensive substrate available at 1 USD/kg. (Rocha et al., 2007) used CAJ supplemented with peptone to produce biosurfactant from *P. aeruginosa*. The same group has used *Acinetobacter calcoaceticus* RAG-1 for the production high molecular weight emulsans using CAJ (Rocha et al., 2006). Banana peel is one more prominent by-product by banana processing industries and encompasses noteworthy amount of carbohydrates, proteins, minerals. (Chooklin et al., 2014) screened 71 strains and found *Halobacteriaceae archaeon* AS65 as the superior producer of biosurfactant using banana peel and monosodium glutamate as carbon and nitrogen source respectively. *Bacillus licheniformis* and *P. aeruginosa* was used to produce lipopeptide and rhamnolipids, respectively using orange peel as substrate (Kumar et al., 2016). Paraszkiewicz et al., (2018) reported the production of 0.428 g/L of iturin by *B. subtilis* using carrot peel as substrate.

Li et al. (2016a) isolated a *Bacillus pseudomycoides* BS6 from soil contaminated with edible oil. The isolated bacterium can produce biosurfactant using soya bean waste oil, showing good interfacial reducing property. In another study, solid state fermentation was employed to produce sophorolipids by *Starmerella bombicola* using winterization oil cake (WOC, a residual oil cake from the oil refining industry after subsequent cooling and removal of waxes from sunflower oil) as substrate (Jiménez-Peñalver et al., 2016). *Pseudomonas aeruginosa* PAO1 produced 0.43 g/L of rhamnolipids when grown on palm fatty acid distillate (PFAD). The rhamnolipid showed emulsion index of 30 % and have the critical micellar concentration (CMC) of 420 mg/L (Radzuan et al., 2017). The rhamnolipid was produced by *P. aeruginosa* using waste cooking oil. The process has been optimized in batch cultivation condition. The produced rhamnolipid was used for the treatment of oil sludge and kitchen waste oil contaminated cotton cloth. Kourmentza and associates (Kourmentza et al., 2018) reported simultaneous production of rhamnolipid and polyhydroxy butyrate (PHB) was performed using waste cooking oil derived from sunflower using *B. thailandensis*. The strain accumulated 60 % PHB on dry cell weight basis and 2.2 g/L of rhamnolipid. *Streptomyces* sp. DPUA1559 isolated from amazon region was grown on fried soybean oil as a sole carbon source. The organism displayed a biosurfactant titer of 1.74 g/L and reduced the surface tension of the medium from 60 mN/m to 27.14 mN/m (Santos et al., 2018). *Starmerella bombicola* was able to produce 51.1 g/L of sophorolipids using sunflower acid oil as feedstock. The strain displayed outstanding emulsification and wettable properties and the foaming was also diminished (Jadhav et al., 2019). Optimization study has been carried out for the production of mannosylerythritol lipids (MELs) by *Pseudozyma aphidis* ZJUDM34 using waste cooking oil as the main carbon source (Niu et al., 2019). *Bacillus cereus* UCP1615 was grown on medium supplemented with waste soybean oil the strain displayed higher potential of biosurfactant which has superior emulsion property, antioxidant, and toxicity property (Durval et al., 2021).

Copious number of microorganisms have been utilized to produce biosurfactants using FW as a substrate. The combination of hydrophilic and hydrophobic substrates can induce higher surfactant production. Making use of FW and industrial wastes as co-substrates for the biosurfactant production can reduce the overall production cost considerably making the process sustainable, economical, and feasible in nature and paving a way for a new avenue in development biosurfactant industries.

5. Biopolymer production using food waste

Microbial-produced biopolymers knowingly polyhydroxyalkanoates (PHA) are produced using FW or other organic waste-derived sugars as carbon sources. PHAs are completely biodegradable plastics and they could be replaced with synthetic plastics (Kumar et al., 2021a; 2021b). There are 150 diverse PHA monomers have been identified. Based on the carbon monomers present in the 3-hydroxyalkanoate units PHAs are categorized as short-chain-length (C_3-C_5) and medium-chain-length PHAs (C_6-C_{14}). The global market for biopolymers and bioplastics was observed to be $10.7 billion in 2021 and expected to grow at a CGPR of 22.7 % to $29.7 billion by 2026. For instance, PHB: poly-3-hydroxybutyrate, PHV: poly-3-hydroxy valerate along with their copolymer PHBV:poly-3-hydroxybutyrate-*co*-3-hydroxy valerate are listed as short-chain PHAs. Conversely, (PHHx) poly-3-hydroxyhexanoate, PHHe: 3-hydroxyheptanoate, PHD: poly- 3-hydroxydecanoate are listed as medium-chain PHAs (Li et al., 2016b). PHAs have multiple applications in food packaging, utility item creation, biomedical, etc. Recently, PHAs are extensively used in therapeutic applications, vascular tissue engineering, heart valve tissue engineering, bone tissue engineering, drug delivery carrier matrix, etc (Zhang et al., 2018).

Biopolymers are polymeric biomolecules composed of a lengthy chain of monomeric units that are covalently connected. In contrast to synthetic polymers, biopolymers possess a molecular assembly that results in a well-defined three-dimensional structure. FW can be used to make a variety of interesting value-added products, including biopolymers, which are biodegradable and biocompatible. To obtain fermentable sugars from the FW, it should be processed that might include drying, acid, or enzymatic saccharification. The bacteria responsible for biopolymer production will then metabolize the available carbon to produce PHAs. There have been reports of successful testing of biopolymers as bioplastics including Polyhydroxyalkanoate (PHAs), polylactides, polysaccharides, and aliphatic polyesters, because their chemical and physical properties are identical to those of traditional synthetic polymers (Pagliano et al., 2017). Prospects for PHA production primarily focus on encouraging less expensive substrates, enhanced microbe growing strategies, and simpler downstream processing processes, all of which are necessary to reduce production costs (Pagliano et al., 2017). PHA and PHB are made from various feedstocks like dairy, potato processing, sugarcane industry, fish, poultry, fat-containing (wastewater from olive mills, waste cooking oil, and palm oil wastes), fruit and vegetable, spent coffee grounds, rice mill, grist mill, and malt house wastes. These wastes are produced in large quantities and can be obtained at very low costs (Talan et al., 2021). Few examples with yields were listed in Table 1.

PHA's are the most well-known biopolymers among biodegradable plastics, not only for their biodegradability but also for their thermoplastic properties that rival those of petroleum-based plastics. The PHA's are accumulated by numerous microorganisms, including *Cupriavidus necator*, *Haloferax* sp., *Rhodobacter* sp., Sphaerotilus sp., *Azotobacter* sp., *Azospirilum* sp., *Burkholderia* sp., *Pseudomonas* sp., *recombinant E. coli, Bacillus* sp., *Haloferax* sp., *Acenetobacter* sp., *Aeromonas sp.* (Ranganathan et al., 2020). It has been reported that acidogenic fermentation of FW can be integrated with PHA production, resulting in a PHA concentration of 23.7 % (w/w) (Amulya et al., 2015). When hydrolyzed jambul (*Syzygium cumini*) seeds were used, they were the only source of carbon in the production medium, where 41.7 and 42.2 % PHA accumulation was obtained using *Ralstonia eutropha* and SPY-1 (unidentified) strains, respectively (Preethi et al., 2012). To produce PHB, *C. necator* DSM 428 has been cultivated only on used cooking oil where biomass concentration limit was 11.6 ± 1.7 g/L with 63.01 ± 0.7 % (w/w) polymer content and 3.6 ± 0.5 g/L/day volumetric productivity. A purity of over 90 % was found in the collected PHB granules, although the product yield was only 0.77 ± 0.04 g/g on the substrate (Cruz et al., 2015). Using *Bacillus* sp. NII2 strain, 1.41 mg/L of PHB granules were produced using glucose-rich acid hydrolysate obtained from the pretreatment of damaged wheat grains (Sirohi, 2021). Whereas another organism of *Bacillus* sp., *B. megaterium* was fed with medium consisting of VFAs obtained after the fermentation of FW for 72 h, the VFAs was completely utilized resulting in 9 – 10 % PHA accumulation on cell dry weight basis (Vu et al., 2021).

In an integrated biorefinery approach Valentino and associates designed a mixed culture sequential batch process in a pilot scale (100 L) supplementing with volatile fatty acids (VFAs) rich fermentation liquid from anaerobic wastewater treatment and waste activated sludge. In the initial step, the bioreactor was operated at 2.0–4.4 kg COD/m^{3}d under dynamic feeding regime for selection of PHA production strains and in the next step PHA was accumulated with 1.02–1.82 g/L/d productivity and 36–48 % yield (Valentino et al., 2020).

Biopolymers and the precursors for bioplastics like lactic acid can be produced using FW as the sole carbon source, but the limitations include the type of FW, composition, physical, chemical or enzymatic pretreatments methods for saccharification, strain with resistance to crude carbon sources. With the advancement in the molecular and microbial technologies, various native and non-native strains have been developed to produce these value compounds. However, the major hurdles still lie in the yields, scalability, separation, and purification of these biopolymers for the end-application.

6. Biosynthesis of diols using food waste

Diols are chemical compounds with two hydroxyl groups knowingly 1,3 and 1,2 propanediol (1,3 and 1, 2-PDO), 1,4-butanediol (1,4-BDO), and 2,3-butanediol (2,3-BDO). Diols are important platform green chemicals and have wider applications as monomers for polymer synthesis, solvents, pharmaceutical, and cosmetics ingredients, feed additives, etc (Liu et al., 2022). Diols are building block hydrocarbons with two hydroxyl groups with wide applications ranging from precursor of bio-fuel and rubber to pharmaceutics (Narisetty et al., 2022b). The literature indicates feasibility of microbial conversion of FW derived carbohydrate to 4-diols primarily i.e., 1,3-Propanediol (1,3-PDO); 2,3-butanediol (2,3-BDO); 1,4-butanediol (1,4-BDO), and 1,2-propanediol (1,2-PDO).

1,2-PDO is a major commodity chemical with diverse applications as resin, biofuel, detergents, and anti-freeze components that is currently derived from non-renewable propylene. The current market evaluation of 1,2-PDO stands at $0.37 billion in 2020 with expected projection of $0.39 billion by 2026 with a CAGR of 1.6 %. The R and S stereoisomers exists for 1,2-PDO, and the carbon sources can lead to different isomers. For example, fucose and rhamnose can generate S-form while glucose and xylose result in R-isomer. Several native and non-native microorganisms are known to ferment glucose to 1,2-PDO, for example *Clostridium thermosaccharolyticum,* and *Saccharomyces cerevisiae* (Tao et al., 2021). Other examples include metabolically engineered *Escherichia coli* and *Corynebacterium glutamicum* where 0.7 and 1.83 g/L of 1,2-PDO was obtained (Niimi et al., 2011; Altaras and Cameron 2000). Therefore, diverting the FW towards 1,2-PDO can be a sustainable route for circular bioeconomy reusing the carbohydrate rich FW and further process optimizing using this rich feedstock could improve the titers and yield of 1,2-PDO.

Another important chemical is 1,3-PDO, which is one of the most industrially relevant diols owing to its use in solvents, adhesives, resins, detergents and cosmetics. Other important application includes its use as monomer for synthesis of polyester with applications in fibres, textiles, carpets, coatings and so on. Polytrimethylene terephthalate (PTT) was previously produced based on chemically synthesized 1,3-PDO. Nakamura and Whited, 2003 demonstrated production of 1,3-PDO from glucose as sole carbon source. DuPont and Genencor took lead for the industrial production of 1,3-PDO from glucose (Nakamura and Whited, 2003). While glucose supports 1,3-PDO production, the natural carbon source for its production is glycerol. Over years, a large number of strains are discovered which had an inherent pathway to ferment glycerol to 1,3-PDO (Durgapal et al., 2014; Pflügl et al., 2014; Vivek et al., 2016). The production yield of 1,3-PDO is reported as 0.63 mol$_{1,3\text{-PDO}}$/mol$_{\text{glycerol}}$ in *C. butyricum* CNCM 1211 (Himmi et al., 1999), whereas the yield from glucose by engineered *Escherichia coli* strain is 0.43 mol/mol. In natural 1,3-PDO producers like lactic acid bacteria, the cultivation requires a co-substrate unlike other strains like *Klebsiella, Clostridium, and Citrobacter*. Alphy and associates supplemented sweet sorghum juice as co-substrate along with crude glycerol to *L. brevis* N1E9.3.3 isolate resulting in 38.4 g/L 1,3-PDO with 0.64 g/g yield. Alternatively, the glucose-rich FW hydrolysates can be potential co-substrates and it is known that lactic acid bacteria have glucoamylase activity that further saccharifies residual starch present in the hydrolysates increasing the process yields.

Like other diols, 2,3-butanediol (2,3-BDO) has diverse applications with huge commercial importance. Several Gram-negative and Gram-positive bacteria are known for the production of 2,3-BDO in titers > 100 g/L. FW generated in a campus food preparation centre was hydrolysed using α-amylase (Liquozyme SC) and glucoamylase (Spirizyme Fuel). The obtained glucose-rich hydrolysate was supplemented for 2,3-BDO fermentation using *B. licheniformis* YNP5-TSU resulting in 36.7 g/L with 0.47 g/g yield (Yu et al., 2022). Liakou and associates utilised fruit and vegetables waste derived reducing sugars as the feedstocks for 2,3-BDO using Enterobacter ludwigii FMCC 204 resulting in 50 and 17.6 g/L, 0.40 and 0.32 g/g, and 0.41 and 0.39 g/L.h, concentration, yield, and productivity, respectively (Liakou et al., 2018). From the same group using *B. amyloliquefaciens* as the chassis strain using bakery waste as the feedstock, led to higher concentrations up to 103.9 g/L including acetoin, *meso* and D-BDO corresponding to 0.39 g/g yield and 0.87 g/L.h productivity (Maina et al., 2021). In a recent report Vivek and associates has reported highest ever titers of 2,3-BDO produced using a waste feedstock. A mutant strain of *E. ludwigii* was supplemented using acid and enzymatic hydrolysates of bread waste resulting in concentrations of 135.4 and 138.8 g/L, corresponding to 0.42 and 0.48 g/g yield (Narisetty et al., 2022b). Overall, integrated process of coupling of FW pre-treatment to liberate fermentable sugars and biobased diol production provides an efficient and economical means of diol production in a commercial scale and environmentally friendly reutilization of FW.

7. Anaerobic digestion and biomethane potential of food waste

Anaerobic digestion (AD) is a complex multistage microbial process that breaks down organic matter sequentially in the absence of oxygen. The primary product of AD is biogas which is predominantly a mixture of CH_4 and CO_2. The methane to carbon dioxide ratio in biogas depends on the type of feedstock used for digestion. AD typically involves four stages, namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis is the first stage where hydrolytic bacteria break down polymers to their respective soluble monomers. In the next stage, these soluble monomers are utilised by acidogenic bacteria to produce volatile fatty acids (VFA) such as acetic acid, butyric acid, propionic acid, etc. The acetogenic stage involves the production of acetic acid from higher VFAs. Acetic acid is the predominant precursor for biogas production. H_2 and CO_2 are produced as by-products in the acidogenic and acetogenic stages of AD. The final stage in AD is methanogenesis, where methanogenic archaea utilise acetic acid to produce biogas (acetoclastic methanogenesis). The H_2 and CO_2 produced in various stages can also be utilised as substrate by hydrogenotrophic methanogens to produce methane. Apart from biogas, a range of other products such as lactate and alcohols can also be generated in the digester depending upon the type of feedstock and the composition of the microbial inoculum (Hegde and Trabold, 2019; Kaur et al., 2019b). Methane in biogas has an energy content of $\sim$ 39 MJ/m^3 that is similar to natural gas and hence can be used as a renewable alternative to support the circular economy framework. It is therefore imperative to maximise feedstock conversion to enhance yields of biogas.

FW include vegetable and fruit peels, slaughterhouse waste, cooked FW, oils and fats. Bones and scales, food packaging often found as part of the FW are fractions that may not be digested anaerobically. Due to the presence of large fractions of biodegradable components in FW and high moisture content (>70 % moisture), legislation and regulations are in place to divert FW from land filling and incineration (Kumar and Longhurst, 2018). For instance, the UK's 25-year environmental plan aims to avoid FW entering landfills by 2030. This is mainly because, the organic matter in FW can cause environmental concerns such as leaching, eutrophication and fugitive emissions and the high moisture content can decrease the incineration efficiency. Therefore, a suitable alternative is needed, and AD has the potential to bridge this gap. AD of FW is not uncommon and has been practiced globally to stabilise the waste and recover energy in the form of biogas. For instance, in UK there are currently > 640 CE plants and $\sim$ 10 % of these plants operate solely on FW as the feedstock. Another 10 % of the plants operate with FW as a co-digestion feedstock. In addition to generating energy, odour minimisation and reduction of pathogens are also possible during AD, making it an attractive alternative to current FW management practices (Jiang et al., 2020; Sheets et al., 2015; Orzi et al., 2015).

Amongst the available feedstocks that are currently used to generate biogas, FW has the highest biochemical methane potential (BMP). The key components in FWs can be categorised as carbohydrates [$(C_6H_{10}O_5)_n$], lipids [$C_{57}H_{104}O_6$] and proteins [$C_5H_7NO_2$]. Using the Buswell-Mueller equation (Buswell and Mueller, 1952), the theoretical BMP of these components can be determined to be 415, 1014 and 496 ml CH_4/g volatile solids (VS) respectively (Angelidaki and Sanders, 2004). Depending upon the proportion of each of these components in FW, up to a maximum of 1014 ml CH_4/g vS can be generated. While this is the theoretical limit, the actual maxima will be much lower due to the utilisation of nutrients by the microflora for its growth and metabolism. For example, in a recent study the bread waste (BW) hydrolysates obtained after acid hydrolysis and enzymatic saccharification were used as sole carbon sources to produce ethanol (Narisetty et al., 2022a) and lactic acid (Cox et al., 2022). Further the solids obtained from the two steps (i) BW hydrolysis, and (ii) fermentation (Microbial cells and other suspended solids) were subjected to AD, that resulted in BMP values between 345 and 553 ml CH_4/g vS (Narisetty et al., 2022a; Cox et al., 2022). Another fraction of the FW, while being potentially biodegradable might not be readily bioavailable and hence can also influence in reducing the BMP. For instance, fats, oils, and grease, commonly known as FOGs contain long chain fatty acids (LCFA) that may not be readily biodegradable in digesters and in fact can cause an inhibitory effect (Long et al., 2012; Usman et al., 2020). Improving the bioavailability will hence lead to maximising the conversion of FW via AD, increasing the biogas yield and thereby the overall revenue potential. To achieve an enhanced biogas potential from FW, process intensification is required. The intensification strategies range from optimising of process parameters, supplementing the feedstock with additives, enabling co-digestion and pre-treatment. Optimising process parameters include identifying the ideal temperature, pH, organic loading rates (OLR) and hydraulic residence times (HRT). Additives discussed here spans across carbon to nitrogen ratio, metal supplements as well as addition of biochar. Finally, the feedstock dependent complexities requiring pre-treatment and need for co-digestion are also discussed here.

Temperature is an important parameter that influences the microbial enzymatic activity. The most investigated temperature ranges for FW AD are mesophilic (30-45^{O}C) and thermophilic (45-60^{O}C) ranges (Kim et al., 2017; Xiao et al., 2018; Zamanzadeh et al., 2016). Mesophilic digestion of FW has been reported to be beneficial compared to thermophilic AD for maximising biogas yields. Particularly, it was determined that acetoclastic methanogenesis dominated in the generation of biogas under mesophilic conditions, whereas synergistic acetate oxidation and hydrogenotrophic methanogenesis dominated under thermophilic conditions ranges (Kim et al., 2017; Zamanzadeh et al., 2016). Mesophilic temperatures also offer a stable digester operation compared to its thermophilic counterpart. The ability of mesophilic digesters to recover quickly from process failure and the capability to handle feed fluctuations also make it attractive. Thermophilic AD offers higher hydrolysis and digestion rates, however, the resulting rapid accumulation of volatile fatty acids (VFAs) and ammonia coupled with the risk of denaturing enzymes make it unfavourable for large scale operation. Psychrophilic ranges (less than20^{O}C) have also been however investigated as an option (Muñoz, 2019; Rusín et al., 2021; Tiwari et al., 2021). It has been hypothesised that mesophilic microbes adapt to psychrophilic conditions to perform digestion (Kashyap et al., 2003). As a result, changes to cellular permeability leading to cell lysis may occur (Gounot, 1986). Therefore, the presented results under psychrophilic digestion are inconclusive at this stage and requires more investigation. Besides temperature, pH is a critical indicator of digester stability as well as an important parameter that determines microbial activity within the digester. Various classes of microbes in the anaerobic consortium have different pH optima. For example, hydrolytic and acidogenic bacteria have an optimal pH in the range of 5.5–6.5, whereas methanogens have an optimum pH in the narrow range of 6.5–7.2 (Ward et al., 2008; Zhang et al., 2014), while being active until pH 8.2 (Mao et al., 2015). Therefore, to maintain a proper balance between the production and utilisation of VFAs (key intermediates in AD), stable digesters always operate around pH 7. Fluctuations in pH can be used as indicators to predict digester failures. Furthermore, inhibition due to ammonia coupled with a higher pH and temperature can adversely affect the digestion process and methane yields. Therefore, maintaining an appropriate pH is important for the stable operation of the digester.

OLR is another process parameter that needs to be optimised for maximising the vS conversion to biogas (Ferguson et al., 2016). For instance, at a higher organic loading rate (OLR), hydrolysis proceeds faster than methanogenesis leading to an imbalance in VFA uptake. In such cases, the predominance of VFAs leading to an acidic environment completely inhibits methanogenesis. Recovery in these cases involves, triggering acetate oxidation to synergistically improve the abundance of hydrogenotrophic methanogens or reduce/stop feeding the digester intermittently to revive acetoclastic methanogenesis. Another case could also occur with FW AD, where nitrogen rich substrates are broken down to form ammonia. In these instances, for an initial threshold phase, the microbes will utilise ammonia as a source of nitrogen from protein/enzyme synthesis. When the concentration of ammonia however is in excess, methanogenesis is greatly affected. Free ammonia is more toxic to cells compared to its ionised form (Ren et al., 2018) and the concentration of free ammonia increases with increase in both pH and temperature. This was demonstrated in Browne and Murphy's work where they showed that increasing the OLR beyond 20 kg VS/m^3/day resulted in inhibition of methanogenesis (Browne and Murphy, 2014).

Hydraulic residence time (HRT) which is dependent on the digester working volume and feed inflow rate is a parameter that is often investigated in combination with OLR to optimise food wate AD performance. For the same OLR, decreasing the HRT eventually will lead to VFA accumulation and an eventual microbial washout (Nagarajan et al., 2021; Nagarajan and Ranade, 2021) leading to a lower methane yield. Therefore, a proper balance between OLR and HRT has to be achieved for optimal vS destruction and biogas production. For instance, Bi et al., investigated the effect of HRT on the co-digestion of cattle manure and FW (Bi et al., 2020). Maximum methane yields were reported under mesophilic conditions for an HRT $\geq$ 15 days. Decreasing the HRT below 10 days resulted in lower biogas yields with a complete inhibition in gas production and process failure at an HRT of 4 days due to VFA accumulation and washout of microbes.

The elemental composition of FW is useful to determine the C/N ratio. Higher ratio indicates a lower N content which might be a limiting factor for microbial multiplication and protein production. In the case of a smaller ratio, the excess N content will lead to the accumulation of ammonia over a longer time frame leading to process inhibition and possibly failure when left unnoticed. C/N in the range of 20–30 is typically reported to be the optimal for methanogenesis (Drosg et al., 2013; Nagarajan and Ranade, 2021). Optimal digestion has however also been reported beyond this range (Marañón et al., 2012). Apart from C and N, elements such as P, S, K and metals such as Mg, Na and Ca are commonly required by the anaerobic microflora for purposes such as nucleic acid production, protein and amino acid synthesis as well as stabilising cell walls (Angelidaki and Sanders, 2004). Apart from these typical elements and macronutrients, a range of micronutrients are specifically required for FW AD. Except Se (0.2 mg/L) and Co (0.35 mg/L), the micronutrients such as Ni (1 mg/L), Mo (0.2 mg/L), Fe (10 mg/L) and W (0.2 mg/L) are generally present in sufficient quantities in FW. The addition of these micronutrients must only be carried out if necessary. For instance, Se can be added to the digester to boost the abundance of syntrophic acetate oxidising bacteria and hydrogenotrophic methanogens. Such a supplementation will help adapt to the rising ammonia concentrations because of higher OLR.

While the process parameters and additives play an important role in intensifying AD of FW, the type of FW itself determines what kind of intensification is required. For instance, if the FW is generated in domestic households and catering outlets, the proportion of processed FW is higher and therefore does not require any treatment prior AD. A high destruction of vS content (~85 %) in this case is possible. In other cases, such as FOGs and slaughterhouse waste, the presence of LCFAs and undigested fibres (in paunch) respectively needs pre-treatment to make the substrate more bioavailable for digestion. LCFAs generally has the tendency to inhibit methanogenesis beyond an optimum concentration and have been reported to be toxic to the acetoclastic methanogens (Rinzema et al., 1994). Whiles fatty acids in theory have a high methane potential, the concentration of the LCFAs, type and mixture of LCFAs present in the feedstock affect the AD process by limiting mass transfer and reducing nutrient transport to cells (Palatsi et al., 2009; Rasit et al., 2015). For instance, Usman et al, reported that an enhanced biomethane yield compared to the control was possible until an LCFA loading of 1 % (Usman et al., 2020). When the FOG concentration was however > 1.5 %, VFA accumulation and inhibition of methanogenesis was observed. While LCFAs form a small fraction of the overall FW generated, there are exclusive FOG wastes such as dairy industry wastes that require attention when subjected to AD. Pre-treatment is therefore a possible option to evade the negative effects of FOGs by hydrolysing the LCFAs to short chain fatty acids to promote the rate of methanogenesis. Several pre-treatment categories have been reported for AD such as physical, chemical, biological and physico-chemical; however, in the context of FW AD, biological and physico-chemical means are more promising methods. Li et al reported that a thermo-chemical treatment at an alkaline pH and a temperature of 55 ^{0}C was beneficial in improving the soluble COD concentration upon pre-treatment that lead to ~ 10 % increase in methane yields (Li et al., 2013). At similar conditions, using a two-staged thermophilic digester they improved the biogas gas productivity by ~ 35 % (Li et al., 2015). Similar lipase treatment have also been reported to improve the biogas potential of FOG rich FW (Malayil and Chanakya, 2020). Paunch is another kind of FW that originates in slaughterhouses. It is the undigested fibre fraction fed to the cattle present in the gut along with digestive enzymes, tissue, and fats. Therefore, in addition to dealing with LCFAs, lignin recalcitrance and long fibre lengths with structural integrity must be broken down effectively to be used for biogas generation. Conventional thermo-chemical pre-treatment have been reported to enhance the biogas production from paunch. Nkemka and associates pre-treated paunch at 70 °C for 24 h with 6 % NaOH/g vS and reported a higher rate of methanogenesis compared to the control (Nkemka et al., 2015). With slaughterhouse waste such as paunch, proper characterisation of the feedstock is important as the N content will be significantly higher (similar to or at times higher than traditional FW). Therefore, there is a risk of ammonia inhibition at higher pH and temperatures. To combat this issue, FW with higher N content is often co-digested with other low N containing feedstock such as Agri and forest residues.

Overall, AD is a promising option to valorise FW. However, the limitations around higher N content, inhibition due to a fraction of the feedstock (LCFA) or by products (ammonia) must be addressed effectively and appropriately to maximise conversion to biogas. Furthermore, to enhance the valorisation potential of FW, alternative strategies such as utilising the effluent of FW fermentation streams as reported by (Cox et al., 2022; Narisetty et al., 2022a) can be exploited.

8. Food waste management: Limitations, challenges, and future perspectives

To kerb the FW various governing bodies are looking at alternative strategies like recycling the edible portions through food donors or global food bank network, feed applications, and the non-edible portions are mostly diverted to anaerobic digestion for biogas generation. Although these processes help in reduction of wastes, transportation costs, and GHG emissions, these are economically low hanging fruits, as the FW is a rich source of carbohydrates, proteins, lipids, etc. high value, and high-potential chemicals can be produced. This non-conventional process of kerbing the FW could address the waste recycling, contribute to nations economy, and increase the employment rate, as biorefineries dealing with these wastes require skilled and unskilled personnel at maximum. FW is generated at every level of the supply chain from the farm to the fork, and at each stage the type of waste generated, and its composition varies, hence developing a universal process for valorization is tedious. Rather than global, local refineries, regulations, and legislations that provide adequate technical knowledge for segregation, collection, and management of FW must be made priority. Therefore, research confined to that location could provide knowledge on the strategies of dealing FW either towards production of value-added chemicals or AD for biogas generation. Thi and associates have provided in detail on the various policies that can be placed by governing bodies of well-developed, developing, and under-developed countries to prevent the FW (Thi et al., 2015).

Decades of research has been dedicated to understanding renewable and sustainable feedstocks for the bio-based processes. Microbes are promising biocatalysts to turn FW into wealth, although most of them cannot utilize the complex polymer matrices found in natural renewable feedstocks and requires pretreatment for the production of monosaccharide formation that can be easily assimilated by microbes for value-addition. Chemical methods using alkali/acids hydrolyze the bonds but also produces undesirable microbial growth inhibitory compounds like furfurals, phenols, and organic acids. On the other hand, enzymatic methods will be milder in nature and maximize the release of fermentable sugars (Narisetty et al., 2021b) but the process will be cost intensive and uneconomical. Whereas FW is a complex and suitable source for bio-based processes and establishing a biorefinery based on FW could include climate, ecosystem, and resource security. However, constraints like high costs of transportation, demand, and requirement, would reduce the expression of interest and demonstration of commercial feasibility. The implementation of FW-based biorefinery depends on following factors like quality of the FW, volume, sources of FW, effective segregation, collection, and transportation pattern. Further if the biorefinery is designed for multiple feedstocks and products, based on the demand the product can be generated maintaining the revenue. Most importantly valorization of FW will result in reduced biowaste and carbon neutral society.

Overall, in future following strategies can be idealized; (i) developing an effective saccharification enzyme cocktails that could improve the release of fermentable sugars from the FW, (ii) construction of chassis strains with higher resistance towards fermentation inhibitors and that can accumulate higher concentrations of product of interest, (iii) demonstration of cost-effective and highly feasible downstream processes, that can separate and purify the product of interest, (iv) finally and significant step, the life cycle and techno-economic feasibility analysis identifying the hotspots of the nation where FW is highly generated, which could assist in building of local refineries can be one of the essential topics to be concentrated.

9. Conclusion

The synergy of FW with the bio-based refineries could improve its recyclability, environmental security, and economic feasibility to the refinery by providing adequate desired products. Current studies available on FW may not showcase the commercial value but developing an integrated bioprocesses where every component of FW can be used to produce respective value-added products could improve the effectiveness. However, based on few reports production of organic acids, alcohols, biopolymers or biomethane should be viable if supply and demand ratio has been addressed. Further technological advancements towards net-zero carbon could showcase the value of FW in circular economy.

CRediT authorship contribution statement

Vivek Narisetty: Conceptualizing, Writing – original draft, Writing and Editing. **Nidhi Adlakha:** Writing and Editing. **Navodit Kumar Singh:** Writing – original draft. **Sudipt Kumar Dalei:** Writing – original draft. **Ashish A Prabhu:** Writing and Editing. **Sanjay Nagarajan:** Writing and Editing. **A. Naresh Kumar:** Reviewing and Editing. **Joseph Amruthraj Nagoth:** Reviewing and Editing. **Gopalakrishnan Kumar:** Reviewing and Editing. **Vijai Singh:** Reviewing and Editing. **Vinod Kumar:** Supervision, Conceptualization, and Editing.

Declaration of Competing Interest

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

Data availability

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

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