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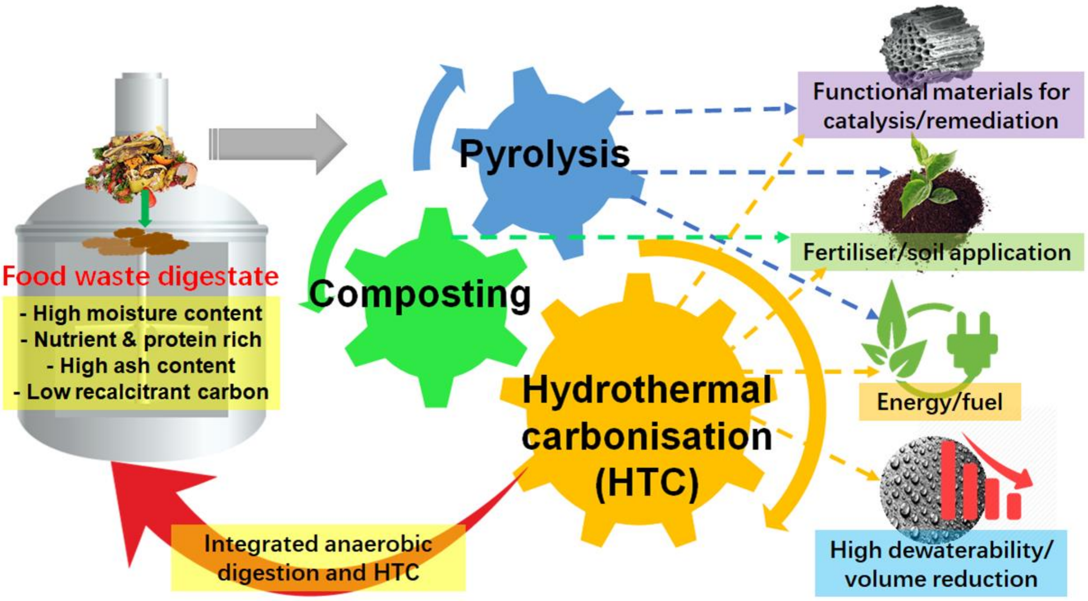
Sustainable management and recycling of food waste anaerobic digestate: A review

Shanta Dutta[a], Mingjing He[a], Xinni Xiong[a], Daniel C.W. Tsang[a,*]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

* Corresponding author: dan.tsang@polyu.edu.hk

Graphical Abstract:



Abstract

Anaerobic digestion (AD) is a widely used technology to valorise food waste for biogas production yet a considerable amount of digestate remains under-utilised. Sustainable management and recycling of the nutrient-rich food waste anaerobic digestate (FWD) is highly desirable for closing resource loop and actualising circular economy. This work reviews the distinct properties of FWD and the existing treatment technologies.FWD shows great prospects as a nutrient source for microalgal cultivation and biofuel production. Emerging technologies such as thermal conversion (*e.g.,* pyrolysis and hydrothermal treatment) of FWD into value-added products such as functionalised biochar/hydrochar with diverse applications would be attractive and warrant further research investigation. Integrated AD with subsequent valorisation facilities is highly encouraged to achieve complete utilisation of resources and reduce carbon emissions.

Keywords: Hydrochar production; engineered biochar; pyrolysis; hydrothermal carbonisation; bioenergy recovery; sustainable waste management.

1. Introduction

In the past few decades, growing demand for energy and resources has aroused public attention to recover materials and energy from waste biomass and provide sustainable alternatives to petroleum-based resources. Food waste with an estimated annual generation of 931 million tons (at the consumer level) is turning into a significant environmental concern (Forbes et al., 2021). In this regard, considerable research interests are devoted to exploring innovative and effective ways to recycle food waste into useful materials and energy (Xiong et al., 2019). Compared with conventional food waste disposal approaches such as incineration, and landfilling, anaerobic digestion (AD) is preferred as a sustainable energy recovery approach for producing biogas (methane; CH_4), which is especially beneficial for high-moisture waste biomass such as food waste and sewage sludge. AD of food waste usually undergoes three stages, including hydrolysis, acidogenesis (followed by acetogenesis), and methanogenesis (Kumar et al., 2021; Xiong et al., 2019). The organic biomass is decomposed into biogas (50–75% CH_4, 25–50% CO_2, and 1–2% H_2S, H_2, and NH_3) by a microbial consortium, generating a considerable amount of nutrient-rich and partially degraded organic residues following the digestion process which is referred as solid digestate (Atelge et al., 2020; Kaur et al., 2020). It was estimated that an AD plant with a 500 kW power generation has a yearly generation of solid digestate at over 10,000 tons (Kaur et al., 2020). The management of growing amount of solid digestate with high moisture content has become an increasing challenge.

Owing to the rich amounts of salts and proteins in food waste, the food waste anaerobic digesate (FWD) generated from AD process contained a high concentration of phosphate (PO_4^{3-}), ammonium (NH_4^+), Na^+, K^+, and Cl^- ions (Cheong et al., 2020). Thus, recycling the FWD into renewable and value-added products such as biofertiliser, solid biofuel, and carbon-based materials shows a great potential for diverse environmental applications. Composting is considered as an effective strategy for valorising FWD into biofertiliser (Du et al., 2018). The concept of Back to Earth Alternative (BEA) can be adopted for digestate management with a well-designed strategy to meet specific requirements (Peng and Pivato, 2019). For instance, the food waste-to-energy facility in Hong Kong (O•Park 1) utilised AD to recycle source-separated food waste with a design daily capacity of 200 tons per day into CH_4-rich biogas for electricity generation, and the generated FWD of ~20 tons per day was dewatered and composted for landscaping and agriculture applications (HK EPD, 2020). Furthermore, pyrolysis is an emerging option for digestate conversion into biochar, bio-oil, and pyrolytic gas in an oxygen-limited environment. Hydrothermal carbonisation is another increasingly popular alternative to stabilise the waste biomass with high moisture content using relatively low energy input. In addition, FWD can be applied as a nutrient media for microalgae cultivation (Chuka-ogwude et al., 2020). Possible means of recycling and valorisation of FWD are illustrated in **Figure 1**.

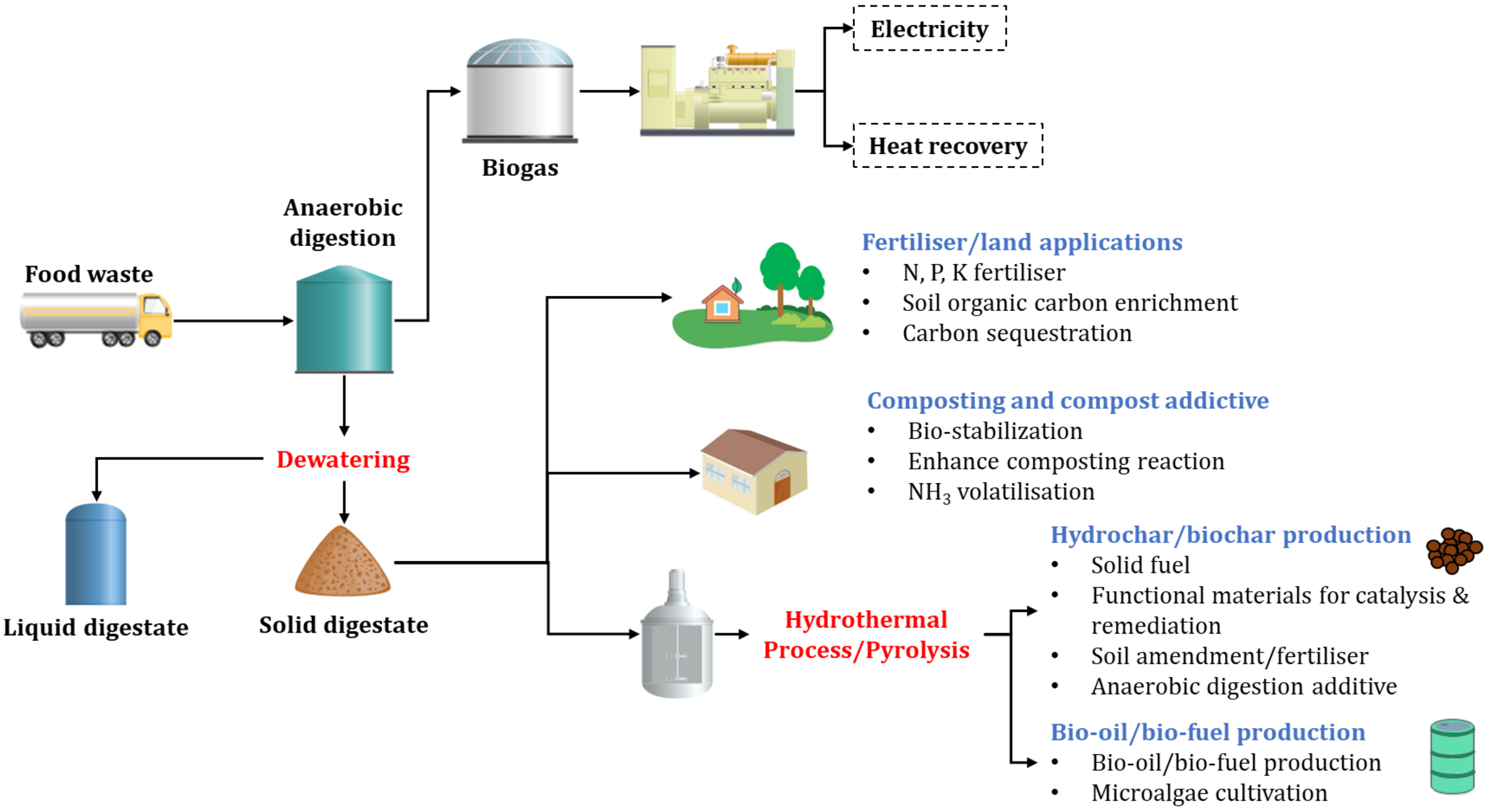


Figure 1. Characteristics and recycling approaches for valorisation of food waste digestate

Recent reviews focused on the rheological properties of digestate from high solid AD (Peng et al., 2020), management options of digestate from organic solid waste (Cesaro, 2021), potential and feasibility of solid/liquid digestate valorisation from various biomass feedstock (Wang and Lee, 2020), or available processing technologies and technical issues related to different markets of digestate products (Guilayn et al., 2020). However, these reviews scarcely distinguish the variety of feedstock sources for AD (*e.g.*, sewage sludge, agricultural residue, manure, food waste), which is a crucial factor in determining the properties of the resultant digestate and affecting the selection of further valorization processing for diverse applications.

As AD has increasingly become a preferable treatment option for sustainable food waste management, this work aims to specifically review the distinct properties of FWD and state-of-the-art knowledge on FWD valorisation into biofertiliser, value-added materials, and renewable energy. The potential FWD treatment and valorisation processes are critically compared to provide a comprehensive outlook on the future development of FWD valorisation for realising a circular bio-economy.

2. Characteristics, dewatering, and subsequent treatment of FWD

Digestate is the major byproduct of the AD process, which is a semi-stabilised solid mixture consisting of partially degraded organic matter, minerals, microbial biomass, carbohydrate, lipids, and protein, etc. (Cesaro, 2021). FWD is characterised by the high contents of moisture, organic matter, nutrients, and protein (Wang et al., 2021; Grigatti et al., 2020; Opatokun et al., 2017)). Typical properties of FWD reported in the recent studies are summarised in **Table 1**. FWD is slightly alkaline in nature with pH ranging from ~7.5 to 9, moisture content ranging from ~70% to 96%, organic matter ranging from ~38% to 91%, and total nitrogen ranging from ~1.1% to 9.6% (Peng and Pivato, 2019; Manu et al., 2021). FWD usually contains a higher amount of ammonia nitrogen (NH_4^+-N) ranging from 800-6000 mg/kg, and higher nitrogen-to-phosphorus ratio compared to other digestate such as sludge or dairy waste anaerobic digestate (Song et al., 2021; Chuka-ogwude et al., 2020). Lignocellulosic compositional analysis of FWD revealed a similar content of cellulose and hemicellulose (~32-33%) and ~13.4% lignin as reported by previous studies (Opatokun et al., 2016). Lignin content in FWD was reported to be higher compared to food waste, due to the low biodegradability of the complex organic polymers in the AD process (Wang et al., 2021).

Digestate is commonly separated into solid and liquid fractions by solid–liquid separation units such as decanter centrifuges and screw press separators for dewatering. According to an evaluation for the mass balance of food waste AD process, liquid digestate constituted ~90% of the total digestate, with 10% of the solid digestate; and the overall mass of generated digestate accounted for 87% of the intial food waste input (Tampio et al., 2016). Solid-liquid separation of digestate could reduce the transportation requirement for further handling and treatment off-site (Lu and Xu, 2021). This process could also effectively minimise the environmental impacts on

Table 1. Food waste digestate properties

pH	**COD**	**Volatile matter**	**Fixed carbon**	**Ash**	**total solids**	**Total carbon**	**H**	**N**	**Ammonia-N**	**O**	**S**	**K**	**P**	**References**
-	-	0.62%	0.13%	0.26%	-	0.42%	0.05%	0.06%		0.20%	0.0091%	-	-	Opatokun et al.., 2015
8.1	-	-	-	-	5.1 kg/t	-	-	0.8 kg/t	0.58 kg/t	-	-	-	-	Nicholson et al., 2017
8.4	-	-	-	-	6.1 kg/t	-	-	0.54 kg/t	0.39 kg/t	-	-	-	-	
8.8	-	-	-	-	5.4 kg/t	-	-	0.78 kg/t	0.63 kg/t	-	-	-	-	
7.81	8960 mg/L	-	-	-	-	-	-	-	0.00%	-	-	-	0.17%	Cheong et al., 2020
7.72	11800 mg/L	-	-	-	2300 mg/L	-	-	-	-	-	-	-	-	Lee et al., 2021
7.9	2257 mg/L	-	-	-	0.1101	-	-	-	310 mg/L	-	-	-	-	Li et al., 2020
-	-	0.66%	0.24%	0.10%	-	0.44%	0.05%	0.02%	-	0.39%	0.0011%	-	-	Liu et al., 2020
8.6	23541 mg/L	9100 mg/L	-	-	19400 mg/L	-	-	4778.1 mg/L	2546.7 mg/L	-	-	-	527.9 mg/L	Wang et al., 2020

-	-	-		0.22%	-	0.49%	0.07%	0.06477	-	0.16%	0.0149%	-	-	Huang et al., 2020
-	-	-	-	0.53%	-	-	-	-	-	-	-	-	-	Zhang et al., 2021
-	-	0.77%	0.17%	0.06%	-	0.47%	0.06%	0.01%	-	0.41%	0.0008%	-	-	Cao et al., 2020
8.02	-	-	-	25.60%	89.70%	42.10%	-	5.81%	0.15%	-	-	0.62%	1.97%	Opatokun et al., 2017
8	-	45.6 g/kg	-	-	67.4 g/kg	386.1 g/kg	-	-	4.07 g/kg	-	-	10.31 g/kg	6.5 g/kg	Tampio_2015
-	-	-	-	-	-	-	-	5164 mg/L	3192 mg/L	-	13 (µg L−	150 mg/L	136 mg/L	Mayers et al., 2017
-	5923 mg/L	-	-	-	-	-	-	2370 mg/L	-	-	-	-	47.8 mg/L	Shin et al., 2015
-	-	0.70%	-	0.08%	-	0.46%	0.06%	0.03%	-	0.37%	0.0032%	-	-	akarsu et al., 2019

potential land application by reducing ammonia volatilisation to air and phosphate leaching to soil (Tiwary et al., 2015). To sterilise the digestate and concentrate its nutrients in the liquid fraction for subsequent biological treatment, various technologies could be deployed for the inactivation/removal of pathogens and adjustment of nitrogen/phosphorous content. For instance, membrane technology including microfiltration and ultrafiltration were employed to separate the liquid phase from the digestate for microalgae cultivation and polyhydroxyalkanoate (PHA) bioplastic production (Kaur et al., 2020). Chemical agents such as polyacrylamide, ferric coagulants, and lime could be applied to impove the agglomeration characteristics of the digestate.

Dewaterability is an important indicator to reflect the performance of solid-liquid separation. Unlike waste activated sludge, FWD can be hardly dewatered due to the extracellular polymeric substance (EPS) from microbial metabolites as well as the large amount of undigested organic matter that primarily exists as colloids with tightly bound water molecule. Dewaterability was revealed to be more correlated to the content of protein in the FWD than that of polysaccharides and humic substances (Wang et al., 2020). It was found that hydrothermal treatment could effectively enhance the FWD dewaterability by increasing temperature from 110 to 200 ^{o}C, yet prolonging the residence time from 30 to 90 min had negligible effect (Li et al., 2020). Other treatments such as settling and conditioning could improve the rheological behaviour of digestate (*e.g.*, stability, density, and shear viscosity) (Peng et al., 2020). Recently, a conditioning method using thermally-activated persulfate was found effective to improve the digestate dewaterability by reducing the pH and decomposing organic substances in the digestate by persulfate-relevant radicals (Wang et al., 2020).

The resultant dewatered digestate requires further treatment before environmental applications. Digestate treatments include a broad spectrum of physical (*e.g.,* screw press, belt dryer, drum dryer, solar dryer, ultrasound), chemical (*e.g.*, coagulation/flocculation), and biological (*e.g.,* composting, algae) technologies (Herbes et al., 2020).

The liquid stream of digestate approximately accounts for 80-90% of the total mass of digestate, and retains 70-80% of dissolved nutrients which enhance turf growth and food crop growing (Fuldauer et al., 2018). However, it cannot be directly used for agricultural purposes, thus requiring further processing *via* biological or physicochemical treatments. Many wastewater treatment and nutrient recovery techniques were developed to treat or utilise liquid digestate including membrane purification, scraped surface heat exchanger, struvite precipitation, ammonia stripping, algal cultivation, constructed wetland, biological oxidation, ANAMMOX, ethanol fermentation, as well as production of hydroponics, algae, and microbial fuel cells for electricity generation (Sheets et al., 2015; Chuka-ogwude et al., 2020; Peng and Pivato, 2019). It should be noted that the bacterial contents of digestate are mainly determined by the sources of feedstock, pH and temperature of AD process, and inherent chemical pollutants in the feedstock (Aigle et al., 2021).

Several technologies are developed for liquid digestate treatment to concentrate nutrients (*e.g.,* P and N) into liquid fertiliser products, such as ammonia stripping, reverse osmosis (RO), evaporation, and combinations of abovementioned technologies (Tampio et al., 2016). It was reported that such technologies could concentrate up to 67% of the feedstock nitrogen into transportable fertiliser products and consume less than 10% of the produced energy. Liquid digestate treatment *via* the combination of evaporation and RO could result in the most concentrated nutrient product from 60 kt/y original food waste into 16 kt/y (Tampio et al., 2016). The concentrated fraction that is rich in nutrients can serve as a liquid biofertiliser for soil amendment. The purified water from RO process, as reclaimed water, can be further reused in wastewater treatment plant. Nevertheless, the processing cost of the liquid digestate, varying from 18 €/m^3 to 35 €/m^3, could be nearly ten times higher than digestate land application according to a sustainability assessment (Di Marian and Sisani, 2019).

3. FWD valorisation as biofertiliser

3.1 Land application

FWD represents a potential biofertiliser considering its high nutrient concentration, high water retention capacity, and low contents of metals/metalloids and pathogenic microorganisms (O’Connor et al., 2021; Lu and Xu, 2021; Cheong et al., 2020). The NPK (nitrogen-potassium-phosphorus) ratio of FWD can be comparable to chemical fertiliser, which makes FWD suitable for agricultural application (Tampio et al., 2015). A recent study that investigated the nutrient properties of co-digestate of food waste and dairy manure revealed that the existing forms of N and P in the digestate are highly plant-available and can function as a slow-release fertiliser over a long period of time. Moreover, the solid digestate might contain beneficial microorganisms which can inhibit harmful fungal pathogens, suggesting the potential of digestate in improving soil fertility and nurturing beneficial microbial community (O'Brien et al., 2020).

Another recent study investigated the direct application of FWD (diluted to various concentration) as an alternative to commercial fertiliser for leafy green vegetable (*Brassica rapa)* cultivation. Compared to commercial NPK fertiliser, FWD provided even better fertiliser performance through improving crop yield and chlorophyll content in plants. FWD enriched dissolved organic matter in soil, provided a sustained release of nutrients, and enhanced the microbial diversity. Sanitization of FWD before land application was not required, which otherwise was recommended for digestate derived from animal products (Cheong et al., 2020). Similarly, compared to mineral fertiliser, higher yield of tomatoes was reported when applying liquid FWD as a biofertilser by drip fertigation system. Both quantity and quality of tomatoes could be improved, while further research was needed regarding the processing/storage and long-term effects of biofertiliser application with respect to soil quality and environmental risks (Barzee et al., 2019).

FWD contains a higher amount of partially degraded organic matter and NH_4^+-N content compared to digestate derived from other feeds such as agricultural residue and animal manure (Tambone et al., 2015; Teglia et al., 2011). The high organic matter content in FWD might improve soil physical properties, and the slightly alkaline nature of FWD could be beneficial for contaminant immobilization in degraded farmland, thus representing added values of FWD for soil amendment and remediation, in addition to its use as a biofertiliser. However, the application of FWD might increase NH_3 emission, pose phytotoxic risks to plants, or induce environmental problems such as acidification and eutrophication (Manu et al., 2021; Rincón et al., 2019; Tiwary et al., 2015), which should be prudently considered and evaluated beforehand.

3.2 Composting of FWD

Due to high NH_4^+-N content in FWD, ~60-70% of total N loss could be expected in case of direct land application. A high amount of unstable organic matter in FWD might sharply enhance the soil microbial activities and result in the temporary unavailability of nitrogen. Therefore, further bio-stabilisation of FWD through aerobic processes such as composting has been suggested before land application (Manu et al., 2021; Song et al., 2021). However, some adjustments or modifications would be necessary for ensuring a good performance of composting of FWD. The C/N ratio of FWD was typically low (~11) due to the high N content which failed to comply with the required C/N ratio for efficient composting. Besides, the low C/N ratio was found to be responsible for excessive NH_3 release during the composting process (Wang et al., 2021); and adjusting the C/N ratio was highly recommended before FWD composting (Rodriguez et al., 2019; Cerda et al., 2019). Co-composting of FWD with selected bulking agents has been considered as an useful strategy that could provide several benefits, such as regulating the moisture content, adjusting the C/N ratio, serving as the sink for NH_4^+/NH_3 to mitigate NH_3/N_2O emission, and accelerating biodegradation rate during the composting process (Song et al., 2021; Arab and McCartney, 2017; Zeng et al., 2016). For example, 90% fixation of the initial NH_4^+/NH_3 was reported for digestate composting at an optimal volumetric dry wood chips:digestate mixing ratio of 4:1 (Zeng et al., 2016). A recent study investigated co-composting of FWD with sawdust and/or mature compost and reported significant enhancement of reaction rate and obtained quality compost in a week while reducing the NH_3 volatilisation effectiuvely up to ~83% (Song et al., 2021).

4. FWD valorization for value-added materials and energy

FWD is commonly used as a biofertiliser for improving soil fertility to close the nutrient loop. However, the growing amount of digestate due to increasing AD plants, high transportation costs, overabundance of nutrients, varying seasonal needs in the agricultural sector, and relatively low user acceptance have been identified as major hurdles obstructing the large-scale applications of digestate as a biofertiliser (Peng and Pivato, 2019). Therefore, it is crucial to find alternative approaches for FWD management and utilisation options beyond agricultural applications, such as energy recovery and carbon-based material production, which might provide better economic incentives encouraging sustainable recycling of FWD (Kaur et al., 2020; Parmar and Ross, 2019).

4.1 Nutrient source for microalgae cultivation

AD can be integrated with microalgae cultivation by converting the liquid fraction of FWD into culture media for large-scale algal biomass production. Microalgae can sequester CO_2 into biomass through photosynthesis and produce valuable lipids, carbohydrates, proteins, pigments, and vitamins, which can be further transformed into feed, biofuel, and other bio-compounds. Cultivation of a wide spectrum of microalgae species have been investigated using FWD effluent, including *Chlorella pyrenoidosa*, *Chlorella PY-ZU1*, *C. pyrenoidosa*, *C. vulgaris*, *N. oleoabundans*, and *S. obliquus* (Chuka-ogwude et al., 2020). Algal consortia and algal-bacteria consortia are preferred for large-scale cultivation on digestate effluent than unicellular culture, which might provide symbiotic benefits (Stiles et al., 2018). However, attention should be paid to the critical success factors for optimum agal growth such as turbidity, light requirement, ammonium toxicity, etc. (Chuka-ogwude et al., 2020).

Maintaining an optimal nutrient concentration is critical for microalgae cultivation, and often dilution of digestate effluent is necessary before its application as a nutrient source (Kaur et al., 2020). For example, FWD after suitable dilution was found to provide 100% nitrogen demands and 16% phosphorus demands for the growth of the marine microalga *Nannochloropsis sp.*, which saved over 90% of the cost and mitigated the environmental impact of nitrogen and phosphorus compared with the use of artificial fertilisers (Mayers et al., 2017). In this way, residual nutrients (N and P) in FWD could be recovered for algal cultivation. Moreover, this process can be accompanied with municipal wastewater treatment. A study showed that production of biodiesel was accomplished by growing *Scenedesmus bijuga* in FWD with primary effluent of municipal wastewater, while simultaneously achieving the removal of soluble COD, total nitrogen, and total phosphorus in the mixed wastewater (Shin et al., 2015). The NH_4^+-N in the digestate should be the most favourable nitrogen source for algal growth. It was found that 1/20 diluted FWD showed the highest algal biomass production (1.49 g/L) with the highest lipid content (35.1%) and lipid productivity (15.6 mg/L/d) (Shin et al., 2015). Another study diluted the digestate feedstock by 30 times and supplemented with acetate (35 g/L) as inorganic carbon source to enhance the heterotrophic growth rates for an optimized performance of algal growth; and NH_4 was recommended to be reduced to 15 g/L through membrane filtration technology to reach a favourable C:N:P ratio (Stiles et al., 2018).

4.2 Pyrolysis of FWD

Biochar production through pyrolysis could be an attractive option for FWD management, where the solid digestate is dried and heated in an oxygen-limited environment at 300–900 °C. In recent years, biochar as a carbon-negative material has attracted extensive public interest and scientific attention. However, only a few studies evaluated the potential use of FWD as a biochar precursor (**Table 2**). The abundant nature and characteristics of FWD as revealed in the previous sections may render it as a promising feedstock for biochar production and application, especially for soil amendment, synthesis of functionalised materials, and renewable energy sources. Biochar characteristics are critically influenced by the types of selected feedstock (Kumar et al., 2021), and FWD is rich in organic carbon which is conducive for extensive pore formation with large specific surface area under adequate pyrolysis conditions, affording good adsorption performance and/or abundant catalytically active sites (Huang et al., 2020).

Optimal pyrolysis temperature of 500 °C for biochar production from FWD was recommended in a pilot-scale test (Li et al., 2020). The resultant FWD-derived biochar could not only serve as a solid fuel to replace petroleum-based fuel but also as a biofertiliser or soil conditioner. Another study found that FWD pyrolyzed at 300−700 °C could produce biochar with 34.0−45.4% of total carbon, 1.9%−5.4% of total nitrogen, and 35.7−60.2% of ash content (Opatokun et al., 2017). Pyrolysis resulted in the enrichment of P, K, and other micronutrients in the biochar, and the enhancement of germination index of plants was positively correlated with pyrolysis temperature. During the pyrolysis of FWD, dehydration occurred and abundant organic content was transformed into gaseous products (CO_2, NO_x, NH_3, and SO_2), resulting in a porous

Table 2 Biochar production from food waste digestate

AD feedstock	Thermal treatment	Temperature (^{o}C)	Time (h)	Yield	Biochar type	Biochar application	References
herbaceous biomass and agro-industrial residues	slow pyrolysis	500	1	33.10%	pyrochar	soil improvers/amendments in agriculture	Miliotti et al., 2020
	hydrothermal carbonization	200-250	0.5-3	51.0% to 72.6%	hydrochar		
rice straw	pyrolysis	500	2		biochar-Cu NP composite	adsorption and degradation of tetracycline	Fu et al., 2017
maize silage	hydrothermal carbonization	180, 200, and 220	0.5	60.7-70%	hydrochar	combustibility; energy recovery	Cao et al., 2020
food waste	pyrolysis	400 to 800	0.5	60.99-77.86%	biochar	application in acidic soils to improve soil properties	Li et al., 2020
food waste	pyrolysis	800	1.67	54.20%	biochar	simulated textile wastewater treatment	Huang et al., 2020
food waste	pyrolysis	400, 500, 600, 700, and 800,	2	36.13-44.26%	biochar	product properties investigation	Liu et al., 2020
paper mill sludge	pyrolysis	700		35%	biochar	mixed with forest soils.	Mohammadi et al., 2019

herbaceous biomass and agro-industrial residues.	hydrothermal carbonization	200–250	0.5-3	max 72.6%w/w	hydrochar	soil improvers/amendments in agriculture	Miliotti et al., 2020
	pyrolysis	500	1	33.1%w/w	biochar		

structure with mesopores and macropores (Liu et al., 2020). It was found that the ash content and fixed carbon increased with temperature, and the surface area of biochar varied from 4.7 m^2/g to 462.8 m^2/g with increasing pyrolysis temperature from 400 to 800 ºC (Liu et al., 2020).

The FWD-derived biochar can be further tailored with specific functionalities and serve as an effective material in a broad spectrum of applications, such as catalysis, wastewater treatment, and soil remediation (Xiong et al., 2017; Kumar et al., 2020). Biochar derived from FWD possessed lower metal contents compared with other types of feedstock (*e.g.*, sludge). However, FWD-derived biochar might have a higher proportion of mineral ash (up to 40–60%) when produced at a higher temperature (Guilayn et al., 2020). In addition, elements such as sulphur and nitrogen could contribute to the formation of functional groups and embedded heteroatoms during pyrolysis, rendering its application as active catalysts in environmental application (Huang et al., 2020). For example, N-doped biochar without additional modification could be obtained by pyrolysis of municipal biowaste at 540 °C (Nisticò et al., 2019). A temperature of 800 ºC was suggested to be an optimal condition to produce biochar with a large specific surface area (>100 m^2/g) from swine manure (Hung et al., 2017), whether this condition is applicable for FWD should be further investigated.

The AD digestate has a good potential in synthesis of biochar with specific functionalities. For instance, a study synthesized a biochar-Cu composite from the solid digestate from AD of rice straw, achieving up to 97.8% tetracycline removal in the presence of hydrogen peroxide (Fu et al., 2017). A recent study investigated FWD-derived biochar for activating peroxymonosulfate for textile wastewater treatment, achieving > 99% removal of a representative azo dye pollutant within 10 min (Huang et al., 2020). It was reported that the enriched nitrogen components (*e.g.,* graphitic nitrogen and pyridinic nitrogen) of digestate-derived biochar contributed to the catalytic reactivity. Research studies on digestate-derived biochar produced from other biomass sources might provide references for the potential use of FWD-derived biochar, such as antibiotics removal, pollutants adsorption, microbial immobilization, and CO_2 capture, etc. (Luo et al., 2020; Wang and Lee, 2021).

The FWD could also be potentially valorised for the production of solid biofuel. The biofuel properties can be indicated by higher heating value (HHV), combustion reactivity, and fuel ratio (fixed carbon to volatile matter) (Akarsu et al., 2019). It was reported that HHV of the FWD was 17.2 MJ/kg, which could yield 5.3 wt% syngas, 42.5 wt% biochar (13.0 MJ/kg), and 52.2 wt% bio-oil (13.5 MJ/kg) after pyrolysis at 500 ºC, representing an increase of 77.3% in energy efficiency (Opatokun et al., 2015). The bio-oil contained phenols, esters, and derivatives of hydrocarbons (Opatokun et al., 2016). It was found that HHV of the digestate-derived biochar showed a negative correlation with increasing pyrolysis temperature, as the high temperature led to the increase of aromatic carbon clusters while retaining the mineral constiuents (Hung et al., 2017). The high water-soluble concentrations of the FWD and the relatively high HHV of the FWD-derived biochar demonstrated its application for energy recovery.

4.3 Hydrothermal carbonisation of FWD

Hydrothermal carbonisation (HTC) is defined as a thermal treatment conducted in aqueous medium at a relatively moderate temperature (180–250 °C) and auto-generated pressure (Akarsu et al., 2019; Nicolae et al., 2020). The most desirable benefit of HTC is that the thermochemical reaction can be conducted in water, thus eliminating the energy-intensive feedstock drying step which is a pre-requisite for pyrolysis and gasification (Cao et al., 2019; Wang et al., 2019). HTC could offer advantages in energy efficiency and emission control compared with pyrolysis and gasification. The high moisture content of FWD renders it an ideal substrate for HTC conversion with high carbon sequestration and production of functional materials with diverse applications (**Figure 2**). The HTC process can be a highly effective recycling approach for FWD allowing for high dewaterability while producing valuable hydrochar and nutrient-rich process water. Recent studies highlighted the efficiency of HTC for significantly improving the dewaterability of high-moisture substrates (Li et al., 2020; Kim et al., 2020). A study investigated the HTC of FWD at 120-200°C and reported up to 37% and 69% reduction in solid residue mass and digestate cake volume, respectively, while the hydrophobicity was also improved. It should be noted that temperature below 140°C showed little influence on the dewaterability of FWD. The resulting hydrochar was considered as a stable and environmentally safe product that could be applied for various purposes (Zhang et al., 2021).

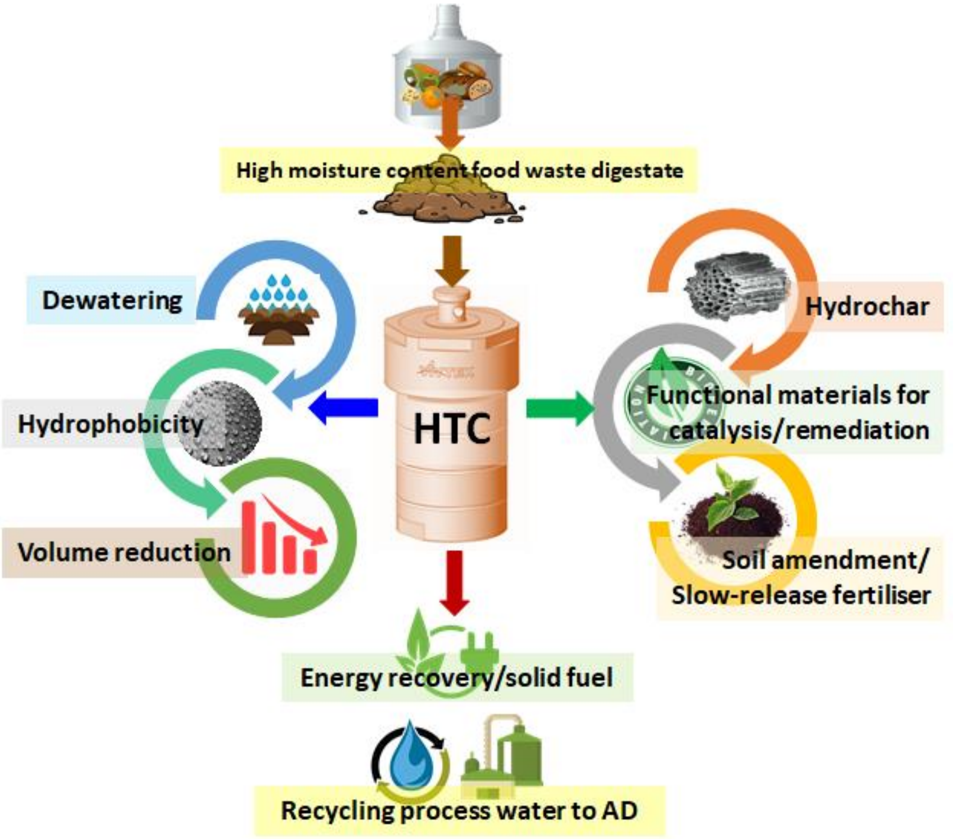


Figure 2. Potential benefits of hydrothermal carbonisation of food waste digestate

Potential uses of hydrochar include soil amendment, functional materials for catalysis and remediation, and use as a solid fuel. The HTC process involves reactions such as hydrolysis, dehydration, decarboxylation, condensation, polymerisation, and aromatization, resulting in hydrochar enriched with diverse functional groups (Akarsu et al., 2019; Liu et al., 2021; Nicolae et al., 2020). Previous studies reported that hydrochar application in agriculture showed a positive influence on soil properties, promoted carbon sequestration, improved plant growth, and enhanced soil microbial communities (Baronti et al., 2017; Sun et al., 2020). The latest studies further engineered the hydrochar with desirable functionalities for adsorption and catalytic degradation of contaminants in the wastewater treatment, such as metals/metalloids, pharamceuticals, dyes, etc. (Fernández-Sanromán et al., 2021; Liu et al., 2021). Further research needs to be conducted to fully explore the potential of FWD-derived hydrochar.

Moreover, recent studies conducted comprehensive investigation on the combustion characteristics and calorific value of hydrochar to evaluate its applicability as a solid fuel (Akarsu et al., 2019; Cao et al., 2021; Parmar and Ross 2019). For example, the yield of FWD-derived hydrochar ranged between 43% and 58%, and it demonstrated higher combustion reactivity than lignite (Akarsu et al., 2019). However, the low carbon content and high ash content of FWD could be an issue that adversely influence the slagging and fouling behaviour during combustion, thereby limiting the applicability of FWD-derived hydrochar as a renewable solid fuel (Cao et al., 2021; Parmar and Ross, 2019). In another study, the hydrochar derived from mixed food waste (vegetables and fruits) and garden waste digestate was characterised by ~27-32% carbon content, ~53-59% ash content, and provided a HHV of ~15 MJ/kg (dry basis), which was comparable to the hydrochar derived from MSW digestate but lower than that of agricultural residue digestate (Parmar and Ross., 2019). As high-temperature treatment might not necessarily improve the HHV of high-ash feedstock, a moderate-temperature HTC treatment (*e.g.*, 210°C) was recommended for FWD considering the advantages for the environment and process economy (Cao et al., 2021; Smith et al., 2016). In addition, the process water generated from HTC contained substantial amounts of soluble organics and value-added intermediates such as furan derivatives and carboxylic acids due to the partial degradation of FWD (Cao et al., 2021), which should be further recycled in the HTC process or valorised into other products in the future studies.

4.4 Valorisation for other bio-based products

Recent studies showed that the upgraded digestate products (*e.g.,* pellets, compost, and growing media) had an expanding market for farmers, horticulturists, and domestic consumers. The properties of digestate products such as higher nutrient and lower water contents are preferred, whereas better education should be delivered to consumers in terms of safety and benefits of digestate products to explore the unexploited market (Dahlin et al., 2015). The adoption of innovative solutions to inevitably change the conventional agricultural practices and this may often be a bottleneck to large-scale commercialisation (Barampouti et al., 2020).

Considering the FWD as a renewable feedstock, sustainable production of diverse range of products can be achieved *via* thermochemical or biological means, which can refer to a recent review on green biorefinery from food supply chain waste (Xiong et al., 2019). The FWD can undergo similar conversion processes to actualise an integrated biorefinery. For example, the production of hydrolytic enzymes, biosurfactants, and biopesticides can be realised through solid-state fermentation of biowaste digestate at a pilot scale (Rodriguez et al., 2019; Cerda et al., 2019), whereas using FWD as the substrate requires further investigation. It is necessary to characterise, evaluate, and validate the products from FWD valorisation in terms of physicochemical and biological properties to alleviate health risks and devise market entry strategy (Barampouti et al., 2020).

5. Integrated AD with digestate valorisation system

Integration of AD with other infrastructures is a feasible way to fully utilise resources in the food waste stream and minimise secondary pollution as well as environmental impact. For instance, it was suggested to adopt an energy harvesting system using one-stage mesophilic AD followed by pyrolysis, optimising the heat of combustion in the digestate products (*e.g.,* biogas, bio-oil, and biochar) (Opatokun et al., 2015). An integrated system recently combined AD, digestate pyrolysis, and syngas biomethanation (Yang et al., 2020). In addition to 54-69% of energy converted to biochar and bio-oil during digestate pyrolysis at 700 ºC, syngas with 65.5% of flammable components was produced and further utilised for biomethanation. This integrated process could improve biofuel recovery and promote a circular economy.

Furthermore, biochar can serve as an additive in the AD process of food waste and sludge, which has been demonstrated economically feasible in a recent review (Kumar et al., 2021). Biochar-augmented co-digestion approach exhibits a positive synergy in the reduction of reactor volume and production of bioenergy. Biochar could be used for the recovery of nutrients in the FWD and utilised as a biofertiliser, offering comparable performance as a commercial fertiliser in terms of aerial fresh weight growth of kale, lettuce, and rocket salad (Lee et al., 2021). This suggests a feasible option for digestate valorisation combined with biochar utilisation. Similarly, an integration of AD with HTC can potentially present a broad range of economic and environmental benefits, which are yet to be explored and validated in the future studies. Therefore, it is highly desirable to boost the integration of AD with digestate pyrolysis/HTC for full resource utilisation and closing the carbon loop.

6. Prospects and Challenges

Valorisation of FWD is an environmentally benign and sustainable approach to fully recycle food waste as a renewable resource. Land application of FWD promotes the closed loop of nutrient and carbon utilisation, yet it may pose the risks of nitrogen loss in the environment. Other approaches for FWD valorisation such as energy recovery and conversion into value-added products require further research into both fundamental knowledge and process optimisation of the operating parameters. Moreover, life cycle assessment as well as material and energy flow analysis are encouraged to improve the overall process. The transportation cost and the energy input in upstream processing of FWD should be considered in the cost-benefit analysis. Product marketability and marketing concept are a crucial factor for commercial viability and field-scale application. In addition, the legislation support and regulatory framework are necessary for establishing specific standards and promoting green procurement of FWD-derived products. Carbon trading market (emissions-trading scheme) is also essential for incentivising and fostering sustainable waste management in the future.

7. Conclusions

This review highlights potential valorisation strategies for food waste digestate, such as biofertiliser application, production of value-added materials, and energy recovery. Among various recycling processes, hydrothermal carbonisation can be considered as an emerging and energy-efficient valorisation technology for high-moisture digestate, providing benefits of improved dewaterability, functional carbon materials, and solid fuel production. Integrating anaerobic digestion of food waste with subsequent valorisation technology can close the resource loop and actualise a circular economy.

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