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Anaerobic digestion and recycling of kitchen waste: a review

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Abstract
About 1.6 billion tons of food are wasted worldwide annually, calling for advanced methods to recycle food waste into energy and materials. Anaerobic digestion of kitchen waste allows the efficient recovery of energy, and induces low-carbon emissions. Nonetheless, digestion stability and biogas production are variables, due to dietary habits and seasonal diet variations that modify the components of kitchen waste. Another challenge is the recycling of the digestate, which could be partly solved by more efficient reactors of anaerobic digestion. Here, we review the bottlenecks of anaerobic digestion treatment of kitchen waste, with focus on components inhibition, and energy recovery from biogas slurry and residue. We provide rules for the optimal treatment of the organic fraction of kitchen waste, and guidelines to upgrade the anaerobic digestion processes. We propose a strategy using an anaerobic dynamic membrane bioreactor to improve anaerobic digestion of kitchen waste, and a model for the complete transformation and recycling of kitchen waste, based on component properties.

Keywords Kitchen waste · Anaerobic digestion · Component characteristics · Full quantitative utilization · Regulatory strategies

Introduction

According to the Food and Agriculture Organization (FAO) of the United Nations, currently the global volume of food wastage amounts to about 1.6 billion tonnes per year, with carbon footprint estimated to be 3.3 billion tonnes of CO_2 equivalents. Kitchen waste, a major component of municipal solid waste, includes food waste and peels (Ajay et al. 2021). These organic wastes are discharged from various sources including households, schools, restaurants, and leftovers from food industries. Kitchen waste consists of raw food and deli food residues consisting of rice, meat, fruits, vegetables, bones, oil, and inert substances (Hafid et al. 2017).

The growth rate of kitchen waste is gradually increasing with the development progress of economic and population (O'Connor et al. 2021). According to the China Statistical Yearbook (2020), municipal solid waste production in China has been continuously increasing at a steady growth rate of 5–6%, with a total amount of 254.79 million tons in 2020, while kitchen waste production in 2020 is about 72.44–127.40 million tons in China, accounting for 30–50% of municipal solid waste (Wang et al. 2019). With the change in culinary habits and food consumption, the proportion of kitchen waste in municipal solid waste is increasing (Bolzonella et al. 2018). Statistics from the Shanghai Greening and Amenities Administration indicated that the average amount of wet waste, mainly kitchen waste, was 9453 tons per day in 2020, representing a 23.2% increase from the end of 2019 (Xiao et al. 2020). Since large amounts of kitchen waste could cause environmental problems and bring about the waste of resources, recycling and utilization of kitchen waste are necessary.

Kitchen waste treatment and disposal include landfilling, incineration, and resource recovery (Chiu and

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Lo 2016). Disposal of municipal solid waste in China is mainly using sanitary landfill and incineration, with an environmentally sound treatment rate of over 90% (Jin et al. 2021). Although sanitary landfill is generally cheap, the high moisture content of kitchen waste can easily cause secondary pollution during transportation and disposal stages (Zhang et al. 2019b). The high cost of incineration with low-resource utilization rate is not a sustainable option for the management of kitchen waste (Li et al. 2015). Therefore, low-energy biological treatments are preferred in recent years for kitchen waste disposal (Wang et al. 2021b).

Three main processes are used to treat and dispose kitchen waste, i.e., anaerobic digestion, composting, and feedification (Ajay et al. 2021). Although composting is proposed to reduce greenhouse gas emissions and is adapted to decentralized kitchen waste treatments, the composting process produces malodorous gases such as ammonia (NH_3) and hydrogen sulfide (H_2S) (Yuan et al. 2015). Feeding kitchen waste to animals is not desirable neither, due to the protein homogeneous pollution, which is a potential risk for disease transmission from animals that consume animal-derived feed produced from the meat, bone, blood, and other animal tissues (Jin et al. 2021). Kitchen waste is a suitable substrate for anaerobic digestion since it is enriched in biomass, carbon, moisture and is generally biodegradable (Ajay et al. 2021). Anaerobic digestion also has a lower global warming footprint than composting and landfilling (Edwards et al. 2018). Moreover, anaerobic digestion is optimal to treat organic waste since it has a low life cycle cost in aspects of economic sustainability (Lee et al. 2020). Therefore, anaerobic digestion treatment of kitchen waste is promising in the context of fossil fuel exhaustion and the goal of reducing greenhouse gas emissions.

Kitchen waste characteristics are changing with seasons and dietary habits, calling for suitable treatment and disposal adaptations. Due to differences in the components of kitchen waste, the application of simple conventional treatment processes is difficult to achieve the efficient utilization of organic components. Kitchen waste management has been reviewed before (Li et al. 2019), but there are few focus perspectives on the impact of kitchen waste components on anaerobic digestion performances and further use of the digestate. Therefore, this review focuses on inhibition effects of kitchen waste components on performances of the anaerobic digestion process and the challenges of digestate utilization after anaerobic digestion treatment. Then, a quantitative model aiming at the complete transformation and recycling of kitchen waste is proposed based on literature reviewing.

Constraints of anaerobic digestion performances in kitchen waste disposal

Due to regional differences in dietary habits, the nature of kitchen waste components varies greatly. Table 1 shows the composition of kitchen waste in China by physical and chemical properties. Generally, kitchen waste contains organic matter, oil and grease, and salt. The anaerobic digestion of kitchen waste is vulnerable to ammonia inhibition and acidification. The presence of inert materials can also inhibit the performance of anaerobic digestion.

Ammonia inhibition

Ammonia inhibition is a major factor influencing anaerobic digestion treatment of kitchen waste because a high concentration of total ammonia nitrogen (TAN) is generated during the digestion process (Li et al. 2018a). Free ammonia nitrogen (NH_3-N, FAN) and ionized ammonia (NH_4^+-N) are the two forms of reduced inorganic nitrogen that exist in equilibrium depending upon the pH and temperature of the aqueous phase (Mutegoa et al. 2020). Free ammonia nitrogen is considered to be the main contributor to ammonia inhibition (Tian et al. 2018). Excess ammonium causes an increase in pH and a higher proportion of free ammonia nitrogen, which could penetrate bacterial cell membranes, changing intracellular pH and affecting proton balance and ion concentration (Chen et al. 2008). In addition, high FAN/TAN ratios inhibit methanogenesis and thus decrease methane production (Capson-Tojo et al. 2020). The temperature could also change the concentration of free ammonia nitrogen. The thermophilic digestion operates typically at 50–55 °C, which is more likely to be inhibited than the mesophilic treatment below 35 °C (Jiang et al. 2019; Yenigün and Demirel 2013). To overcome ammonia inhibition, recent researches focus on the domestication of ammonia-tolerant methanogenic consortia (Tian et al. 2017). For example, domestication increased methanogen relative abundance and in turn enhanced ammonia tolerance and gas production up to 58 L/d during anaerobic digestion treatment of kitchen waste (Gao et al. 2015). In practical engineering, the complexity of the feedstock and the diversity of the process make the anaerobic digestion process particularly complicated. Exploring microbial community distribution and metabolic pathways can be one of the options to alleviate the impact of ammonia inhibition.

Hydrolytic acidification

Since kitchen waste is biomass-rich, the hydrolytic acidification of soluble organic matter produces an excess of volatile

Table 1 Composition of Chinese kitchen waste

Protein (%TS)	Carbohydrate (%TS)	Lipid (%TS)	Na^+ (g/L)	Total Solids (%w)	Volatile Solids (%w)	C (%TS)	H (%TS)	O (%TS)	N (%TS)	S (%TS)	C/N (%TS)	References
13.20	73.60	3.40	NR	10.57	10.36	44.5	2.64	NR	2.6	NR	17.12	Li et al. (2017)
3.07	82.10	NR	NR	82.30	81.20	47.80	4.72	27.3	5.71	0.87	8.37	Tian et al. (2015)
15.26	89.14	25.39	1.84	22.74	20.27	50.30	7.10	29.1	2.70	NR	18.63	Zhang et al. (2015)
NR	NR	NR	NR	25.10	22.64	46.70	6.60	44.2	2.20	0.30	21.23	Wang et al. (2020)
16.88	21.60	33.82	NR	22.17	NR	54.05	6.59	35.72	2.87	0.27	13.98	Wang et al. (2014)
14.97	46.43	30.27	NR	18.81	17.24	51.83	7.50	NR	2.75	0.50	18.85	Tian et al. (2018)
14.90	52.30	28.10	NR	13.10	12.50	NR	NR	NR	NR	NR	27.30	Chen et al. (2019)
21.41	42.62	23.15	NR	29.26	26.78	51.16	8.52	29.27	2.08	NR	24.60	Wang et al. (2017a)

Protein, carbohydrate, lipid and VS were present in %TS based on TS; moisture and TS contents were present in %w based on wet weight; NR: not reported

fatty acids (VFAs) (Nikitina et al. 2020), which cannot be metabolized fast enough by methanogenic archaea. This leads to the accumulation of volatile fatty acids such as propionic acid, butyric acid, and valeric acid, and in turn causes microbial inhibition, pH decrease, and decline of biogas production (Wang et al. 2021a; Yun et al. 2018). To solve this issue, Wang et al. (2021c) proposed the addition of iron/carbon in the acidification and methanogenesis phases to change the distribution of volatile fatty acids and enhance the methanogenic performance, with a methane yield of 475.47 ± 4.68 mL/g volatile solids (VS), with the biodegradation rate up to 87.6%. Similarly, Wang et al. (2017b) used Na_2CO_3 as the initial buffer and 10 mol/L NaOH as the regulator to control pH in the acidification stage, thus improving the removal of total solids (TS) up to 44.8% and volative solids (VS) up to 58.7%. One of the difficulties in the practical application of anaerobic digestion for kitchen waste disposal is to consume the accumulated volatile fatty acids rapidly and attain a speedy recovery of methane production. Monitoring the changes in concentration of volatile fatty acids closely and using exogenous additives when necessary are of significant importance to maintain the stability of the anaerobic digestion system.

Accumulation of greasy long-chain fatty acids

The accumulation of greasy long-chain fatty acids (LCFAs) inhibits the biodegradation of kitchen waste (Bong et al. 2018). The accumulation of long-chain fatty acids can form a blocking layer on the cell surface, limit the access of microorganisms to nutrients, and thus lead to an imbalance in intracellular homeostasis (Elsamadony et al. 2021). In addition, the hydrophobic lipids can trap biogas and trigger biogas bubbling, which results in abundant foaming (Lienen et al. 2014). Due to differences in dietary habits, the oil content of kitchen waste varies in different regions, and the biogas production performance varies with concentrations of initial substrates. For example, Li et al. (2018d) found that the highest methane production from kitchen waste digestion was achieved at an extract/volatile solid ratio of 43% and an inoculum ratio of 0.7. Carbon-rich hydrated compounds tend to cause acidic inhibition, which will increase the amount of volatile fatty acids and limit the β-oxidation of long-chain fatty acids, thus induce their accumulation (Srivastava et al. 2021). Synergistic inhibition by different components is likely due to complicated compositions of kitchen waste. Therefore, changes of intermediate product concentrations should be monitored to achieve stable operation of biogas plants. It is possible to detect problems of the anaerobic digestion process in advance based on effective monitoring of the intermediate products and then improve the stability of process operation by adjusting process parameters such as feed load, temperature, pH, and hydraulic retention time

(HRT). On the other hand, the oil and grease compositions in kitchen waste could be converted into bio-diesel by bio-refining, which increases the commercial value of anaerobic digestion (Li et al. 2018c).

Inhibition by high salt content

An appropriate salt concentration (Na^+) facilitates the growth of methanogens and methane production from kitchen waste with anaerobic digestion disposal, yet the performance of anaerobic digestion could be inhibited when salt concentration in kitchen waste is high (Li et al. 2021). *Methanogens* are more sensitive to rise salt concentrations compared to other bacteria, resulting in inhibition of microbial growth and cell death by dehydration (Zhang et al. 2020). In addition, salt accumulation inhibits fermentation when the biogas slurry is recirculated, which is detrimental to the reuse of derived by-products after anaerobic digestion disposal. Therefore, efficient desalination techniques have been sought to avoid inhibition of high salt contents to the performance of anaerobic digestion. For example, Liu et al. (2019) added 2.5 g/L of glycine betaine into an anaerobe's reactor containing kitchen waste with a sodium content of 10 g/L and increased the methane production by 63.5%. The presence of high salt and oil may have a complex inhibitory effect on the anaerobic digestion system. However, it has also reported that adding 6 g/L of salt to the system can trigger positive effects when the concentration of oil is below 15 g/L (Liu and Jiang 2020). Liu et al. (2017) found that the coexistence of salt content at 6 g/L and oil content at 5 g/L in kitchen waste resulted in a steady increase in VFA content, which is beneficial to subsequent anaerobic digestion process. Overall, osmoprotectant dosage, diluting of salt concentration, and balancing the concentrations of salts and oils are essential measures to improve anaerobic digestion performances for kitchen waste disposal.

Presence of inert materials

The mixing of inert materials such as plastic tableware and disposable chopsticks in kitchen waste is a real challenge to its anaerobic digestion disposal (Yates et al. 2021). Worldwide kitchen waste is still mixed with other domestic wastes in many cities, which results in large amounts of plastic materials and disposable chopsticks collected with food waste. Studies show contrasting results regarding the effect of plastics on anaerobic digestion. Zhang et al. (2021) found that mixing of high-density polyethylene and polystyrene with kitchen waste enhanced the rate of acidic fermentation and thus facilitated the generation of volatile fatty acids. In addition, the incorporation of plastic materials increased the relative abundance of dominant bacterial populations, which favored the increase of plastics biodegradation. However, the presence of plastics inhibits methanogenic processes with rising inhibition effects increasing with surface area (Lim et al. 2018). Wei et al. (2019) found that toxic substances such as bisphenol-A polyvinyl chloride were released from the surface layer of microplastics, and that 90.6% of methanogens were inhibited at a microplastic concentration of 20 particles per g or total solids. Although solid materials can be biodegraded during anaerobic digestion, it is not recommended to use anaerobic digestion as a disposal route for inert materials in kitchen waste (Selke et al. 2015). Ideally, inert materials should be separated before fermentation and digestion, then treated by pyrolysis to generate energy that could be used to heat the anaerobic digestion system, achieving full utilization of the whole compositions of kitchen waste.

Performance optimization of anaerobic digestion of kitchen waste

Pre-treatments

Hydrolysis is considered to be the rate-limiting step of anaerobic digestion (Zou et al. 2020). The rate of hydrolysis depends on the nature and concentrations of organic fractions of kitchen waste. In general, hydrolysis is slowed down by high lignin content, high grease levels, coarse fibers, and large particle-size matter. Table 2 shows pre-treatment methods in common practice, including physical pre-treatments (such as ultrasonic, pyrolysis, hydrolysis, microwave, hyperbaric, freezing and mechanical grinding), chemical pre-treatments (such as acidation, alkalization, and oxidation), biological pre-treatments (such as enzymes and micro-oxygen), and combined pre-treatments (such as microwave-alkali, thermal-alkali/acid, and acid-enzymes). Yue et al. (2021) indicated that ultrasound and microwave pre-treatments slowed the accumulation of fatty acids in the system and thus enhanced substrate utilization by microorganisms. They also observed that the energy conversion using ultrasound pre-treatment was 18% higher than the microwave pre-treatment. Sun et al. (2020) used microwave-$Ca(OH)_2$ to pretreat kitchen waste seeking better pre-treatment effects and achieved enhanced protease activity with methane production capacity of 430.4 N mL CH_4/g VS.

Pre-treatment steps are necessary to accelerate the decomposition of resistant organic matter, reduce particle size, and disaggregate flocs, colloids, and cells and thus improve the efficient use of organic fraction of kitchen waste and enhance its solubility and methane production rate. Besides beneficial effects, pre-treatments have also drawbacks such as the consumption of more energy (Zhao et al. 2016). Therefore, appropriate biogas engineering

Table 2 Pre-treatments of kitchen waste prior to anaerobic digestion and disposal

Digestion substrates	Pre-treatments	Details/Parameters	Performances	References
Kitchen waste (KW)	Separation screen	10-mm screen	Up to 98% biogas recovery	Alessi et al. (2020)
Kitchen waste + sugarcane rind slurry (SR)	Microwave-$Ca(OH)_2$	4% $Ca(OH)_2$ coupled with microwave heating	Enhancing process stability, methane production of 430.4 mL/g VS	Sun et al. (2020)
Kitchen waste	Lactic acid	*Lactobacillus casei*	Promoting bacteriostatic and hydrolytic acidification effects	Zhao et al. (2016)
Kitchen waste	Ultrasound	28 kHz, 1600 W for 30 min	Enhancing the caproic acid production (207.80 mg COD/g) and reducing volatile fatty acids	Ma et al. (2021)
Kitchen waste	Micro-oxygen	Micro-oxygen at 20 mL	Cumulative methane yield 399.25 mL/g VS	Zhen et al. (2020)
Kitchen waste	Potassium ferrate	0.4 g/g total suspended solids	Maximal hydrogen yield 173.5 mL/g	Kuang et al. (2020)
Kitchen waste	Microwave	145 °C, 2.7 °C/min	SCOD/TCOD ratios increase from 0.38–0.44 to 0.42–0.51	Shahriari et al. (2013)
Kitchen waste	Hydrothermal	225℃, 4.5 h	Increasing methane yield up to 19%	Zhou et al. (2020)
Organic fraction of municipal solid waste (OFMSW)	Enzymatic pre-hydrolysis	*Aspergillus niger* fermentation at 50 °C and pH of 4.5	Methane potential increased by 220%	Mlaik et al. (2019)
Kitchen waste	Acid-enzymatic hydrolysis	Hydrochloric acid 1.5% (v/v), 85 U/mL glucoamylase	Fermentable sugar production increase 2.04-fold with conversion efficiency of 86.8%	Hafid et al. (2017)
Kitchen waste	Thermal	90–120 °C for 15–30 min	Organic nitrogen in total nitrogen content decreases by 3.0–47.9%	Li et al. (2016b)
		55–160 °C for 15–120 min	Improve the subsequent anaerobic digestion efficiency and longer treatment durations	Li et al. (2016a)
Kitchen waste	Thermo-alkali and enzymatic hydrolysis	1% KOH, 0 °C, 20 min 1.1% α-amylase, 0.4 amyl glucosidase	The glucose concentration increased by 300%, total soluble sugars yield increases by 75.6%	Vavouraki et al. (2014)
Kitchen waste	Thermo-acid and enzymatic hydrolysis	2% HCl, 80 °C, 80 min 0.1% α-amylase, amyl glucosidase		
Kitchen waste + distillers' grain	Ethanol pre-fermentation	0.5‰ of the alcohol active dry yeast at 35 ± 2 °C for 24 h	Remain system stable; methane yield increased by 26.8%	Yu et al. (2018)

KW: kitchen waste. VS: volatile solids. VFA: volatile fatty acids. SR: sugarcane rind slurry, OFMSW: organic fraction of municipal solid waste, DG: distillers' grain; SCOD: dissolved chemical oxygen demand; TCOD: total chemical oxygen demand

should consider trade-off of the technical and economic benefits and drawbacks of pre-treatment methods. Typically, high energy consumption pre-treatments are not logically reasonable when energy consumption is higher than energy produced. Physical pre-treatments such as mechanical grinding, pyrolysis, and hydrolysis are widely used in engineering applications.

Co-digestion of kitchen waste with other substrates

Kitchen waste is typically enriched in carbohydrates and the COD/NH_4-N ratio of 200/0.14–0.36 is much higher than the recommended value of 200/5 according to anaerobic digestion guidelines (COD: chemical oxygen demand) (Hassan et al. 2017; Odejobi et al. 2021). Consequently, too rapid degradation of organics in kitchen waste causes the

accumulation of volatile fatty acids, which may decrease the performance of anaerobic digestion. To solve this issue, co-digestion of kitchen waste with nitrogen-rich substrates such as municipal sludge, toilet water, animal manure, microalgae, and agricultural waste could balance the COD/NH_4-N ratio, promote nutrient balance, dilute toxic agents, and enhance the operational stability. Therefore, co-digestion is an attractive strategy to improve anaerobic digestion performance and increase multi-resource utilization efficiency. Table 3 presents examples of co-digestion processes for kitchen waste disposal. Zhao and Ruan (2013) increased the C/N ratio of kitchen waste to 15/1 by adding algae, and the biogas yield raised to 388.6 mL/g TS, which was 1.18-fold higher than without algae dosage. Li et al. (2020a) found that co-digestion of kitchen waste and fruit–vegetable waste effectively prevents the accumulation of volatile fatty acids and maintains the system's stability, leading to a maximum methane production rate of 354.51 mL/g VS with a kitchen waste/fruit–vegetable waste ratio of 2/3.

Anaerobic co-digestion with several substrates is an effective approach for optimal resource utilization of kitchen waste, which increases biogas production and reduces CO_2 emissions (Guo and Dai 2017). Wu et al. (2020) even recovered phosphorus in the form of blue vivianite crystals with a purity of 83.1% during the co-digestion of waste activated sludge and kitchen waste. Co-digestion substrates for kitchen waste include municipal sludges, agricultural waste, livestock manure, brown water, and microalgae. In engineering applications, suitable nitrogen-rich materials can be selected for co-digestion according to the characteristics of local kitchen waste components to improve the maximum recycling of materials for the full utilization of regional waste. Further research should focus on deciphering synergistic mechanisms and improving the recovery of biogas and

Table 3 Co-digestion of kitchen waste with other substrates

Digestion substrates	Ratios	Digestion conditions	Performances of co-digestion	References
Kitchen waste + fruit/vegetable waste	2:3(VS)	$T = 37 \pm 0.5$ ℃, $V = 500$ mL	Methane yield 354.51 mL/g VS	Li et al. (2020a)
Kitchen waste + black water	2:1(VS)	$T = 35$ ℃, 120 rpm, $V = 500$ mL	Hydrolysis efficiency 87 ± 8%, methane yield 449 ± 32 ml /g VS	Zhang et al. (2019a)
Kitchen waste + corn stalk	4:1(VS)	$T = 37$℃, $V = 10$L	Bio-methane production increased by 41.55%	Zhou et al. (2015)
Kitchen waste + algae	1:15(C/N)	$T = 55 \pm 1$ ℃, 70 rpm	Biogas yield 388.6 mL/g TS	Zhao and Ruan (2013)
Kitchen waste + sewage sludge	50:50(VS)	$T = 37 \pm 1$ ℃, stirring for 1 min after every 30 min at 50 rpm	Highest biodegradability up to 91%	Varsha et al. (2020)
Kitchen waste + poultry manure	2:1(gm)	Constant loading rate 300 mg/L with 50 gm cow manure at 30 ℃	Cumulative biogas yield 920 ± 11 mL, methane content 48%	Rahman et al. (2021)
Kitchen waste + black water	1:1(TS)	$T = 38 \pm 1$ ℃, $V = 500$ mL	Cumulative methane yield 313.2 mL/g	Wang et al. (2020)
Kitchen waste + wastewater sludge	1:1(TS)	$T = 35 \pm 1$ ℃, total volume of the tank 300 m^3	Methane content 43.6%	Antony and Murugavelh (2016)
Kitchen waste + rice straw	0.4:1(VS)	Water bath at 37 ± 1 ℃, $V = 2.5$ L	Methane content 45.9–70.0%	Ye et al. (2013)
Kitchen waste + fruit/vegetable waste	8:5(VS)	$T = 35 \pm 1$ ℃, 120 r/min, $V = 1.5$L	Methane yield 725 mL CH_4/g VS	Wang et al. (2014)
Kitchen waste + excess sludge	4:1(TS)	$T = 35$ ℃, $V = 1000$ mL	COD, TS and VS degradation reach 49.7%, 37.8% and 30.0%	Han et al. (2016)
Kitchen waste + cow manure	2.5:1(VS)	$T = 39$ ℃, 120 rpm, $V = 120$ mL, OLR 1.07 ± 0.01 g COD/L/d	Methane production 441 mL CH_4/g VS	Xing et al. (2020a)
Kitchen waste + cow manure	3.4:1(VS)	$T = 39$ ℃, $V = 0.7$ L, domesticated sludge 550 d	Increasing the contents of enzyme and lignocellulose	Xing et al. (2020b)
Kitchen waste + floatable oil (FO)	25:1(Mass)	$T = 35$℃, FO concentration 5–40 g/L	TS and VS reductions 70.7% ~ 86.1% and 87.5% ~ 91.4%, methane yield 846.9 mL/g VS	Meng et al. (2015)

VS volatile solids, *TS* total solids, *COD* chemical oxygen demand

nutrients. In addition, decentralized treatment models based on life cycle assessment are needed for rural areas.

Additives

Additives play an important role in maintaining efficient methane production of biogas plants and long-term operational stability of the anaerobic digestion system. In recent years, studies have increasingly focused on investigating the gas production efficiency and process stability by adding additives to anaerobic digestion reactors (Cai et al. 2017). Table 4 shows the commonly used additives, including trace elements such as iron (Fe), cobalt (Co), nickel (Ni), molybdenum (Mo) and tungsten (W), solid additives such as biochar, mineral, graphite, bentonite and clinoptilolite, and biological additives such as bactericide, gene bacteria, rumen bacteria and enzyme. Wu et al. (2015) found that the dosage of potassium (K), magnesium (Mg), and manganese (Mn) accelerated the digestion of kitchen waste, with optimal micro-metal additions of 720.2 mg of K, 47.3 mg of Mg, and 11.6 mg of Mn per g of COD. Jiang et al. (2020b) found that when citrus biochar at 1.5 g/g VS was used as solid additive, the methanogenic lag time was reduced to 3.5 days and the specific methane production rate was increased by 33.0%. Jiang et al. (2020a) used bioaugmentation to increase the population of *archaea*, and the volumetric biogas production (VBP) increased 12-fold compared to the control group in optimal conditions of 0.25 g/(L-d) per three-day dosing. In addition, synergistic effect of multiple additive materials is also one of the main research directions at present. Capson-Tojo et al. (2019) further obtained a higher methane yield of 1.75 L/day when a combined biochar-$FeCl_3$ additive was dosed.

It is necessary to understand the potential environmental risk of the dosage of additives clearly, with a focus on exploring the nutrient elements content in digestate products and reducing the accumulation of heavy metals (Yuan. et al. 2021). The optimal dosage should be optimized to ensure the stability of anaerobic digestion based on different fermentation substrates and process technologies, while reducing its negative impact on the environment. Carbon-based materials and enzymes are often used as additives to promote methane production due to its high efficiency and low environmental risk (Yuan et al. 2021). Reusing biogas residues as biochar additives promotes methane production and can be used as one of the disposal methods for full quantitative utilization. In particular, it is essential to introduce high-performance organisms and improve the number of specific microbial populations according to the digestive characteristics of different substrates, while strengthening the economic feasibility analysis to meet profit maximization.

Process optimization

The improvement of anaerobic digestion performance can be achieved by multi-stage digestion, reactor optimization and process combination. Table 5 presents recent studies on optimizing the anaerobic digestion performance

Table 4 Strategies of additive dosage to improve methane production

Additive types	Digestion substrate	Dosages	Performances	References
Carbon nutrition	Kitchen waste	Biochar (10 – 100 g/L)—$FeCl_3$ (0.1—0.2 g/L)	Maximum methane production rates from 897 up to 1494 mL/day	Capson-Tojo et al. (2019)
Trace metals	Kitchen waste	Ni 1 mg/L, Co 1 mg/L, Mo 0.2 mg/L, W 0.2 mg/kg, Se 0.2 mg/L,	Methane yield increased by 50%	Molaey et al. (2018)
Micro-materials	Kitchen waste	Zero-valent iron 5 g/L	Enhancing the hydrogenotrophic methanogenesis pathway	Yuan et al. (2021)
Graphite	Kitchen waste	Graphite 1 g/L	Biogas yield 1128.46 mL/g VS (increased by 19.57%)	Muratcobanoglu et al. (2020)
Carbon-based materials	Kitchen waste	Citrus peel biochar 1.5 g/g VS	Promoting DIET, methane yield 250.8 mL/g VS	Jiang et al. (2020b)
Biological additives	Kitchen waste	Bioaugmentation seed 0.25 g/(L·d)	The abundance of metanephric increased by 81%–86%, VBP increased 12 times	Jiang et al. (2020a)
Rumen bacteria	Cattle manure	Rumen fluid volume fraction 20%	Enhancing lignocellulose degradation and increasing methane production	Nagler et al. (2019)
Enzyme	Chicken manure	1% enzyme-treated	Improving hydrolysis, methane yield 460.8 mL/g VS	Bhatnagar et al. (2020)

VS volatile solids, *DIET* direct interspecies electron transfer, *VBP* volumetric biogas production

Table 5 Process optimization to improve anaerobic digestion of kitchen waste

Optimization subjects	Digestion substrates	Configuration of reactors	Performances	References
Start-up	Kitchen waste	Continuous stirred tank reactor	Methane yield 217.28–325.92 mL/L	Feng et al. (2015)
Two-stage	Kitchen waste	Psychrophilic	Higher substrate utilization, methane yield 0.80 m3 kg/VS	Rusin et al. (2021)
Two-stage	Kitchen waste	High-solid system	Improving methane production (113.4 mL/g VS) and removal efficiency (increased by 57.30%)	Li et al. (2018b)
Modeling approach	Kitchen waste	Multi-criteria decision modeling	Multi-performance optimization, methane yield 544 ± 65 mL/gVS	Kesharwani and Bajpai (2020)
Combined process	Effluent from kitchen waste	Combined process	High NH + 4-N and NO- 2-N removal efficiency (88% and 96%)	Gao et al. (2020)
Mixer	Cow manure + municipal solid waste + kitchen waste	Pneu-mechanical mixers	Increasing methane production (by 123%) and enrich microbial community (by 3000%)	Mahmoodi-Eshkaftaki and Ebrahimi (2019)
Reactor	Kitchen waste	Inclined plug flow reactor	Hydrogen production 72 mL/g VS	Jayalakshmi et al. (2009)

VS volatile solids

of kitchen waste disposal. For example, a two-stage anaerobic system provides optimal process stability, increased energy efficiency and better control over crucial parameters governing performance and energy recovery (Srisowmeya et al. 2020). The separate operation of the hydrolytic acidification and the methanogenesis phases in two reactors enhances the buffering capacity of the system and optimizes the microbial population structure. Li et al. (2018b) compared the performance of single-stage and two-stage anaerobic digestion of kitchen waste and showed that the two-stage digestion had higher process stability, leading to an increase in removal efficiency of 57.3%. The energy recovery rate from the two-stage digestion of kitchen waste is 20% higher than the one-stage digestion (De Gioannis et al. 2017). Rusin et al. (2021) optimized the process parameters for the two-stage operation and found that the utilization of the kitchen waste substrate was higher under psychrophilic conditions, with a 6.5% increase in biogas production compared to medium temperature. Mahmoodi-Eshkaftaki and Ebrahimi (2019) developed a new mechanical mixer, which increased methane production rate by 123% and enriched microbial community richness by 30 times. Nonetheless, due to the higher economic cost, two-stage processes are not cost-effectively applied in large scales. It is important to optimize the process parameters and develop economically viable processes.

Recycling of the treated residue

Constraints on digestive recovery

The treated residue from anaerobic digestion is enriched in nutrients, e.g., nitrogen/phosphorus/potassium (N/P/K) and trace elements such as Fe, Mn, Mg, and Zn (Liang et al. 2021). The treated residue after anaerobic digestion treatment is generally used in agriculture to enhance soil fertility. Yu et al. (2010) indicated that the application of concentrated digestion improved the quality of tomatoes, including increases in organic matter, and fruit contents of amino acids, protein and soluble sugar. Nonetheless, the treatment and discharge of increased total nitrogen (TN) and total phosphorus (TP) of the treated residue is still a major issue (Tan et al. 2021). The remains of digested manure (the treated residue) are nutrient-rich with excessive nitrogen and phosphorus potentially causing eutrophication of groundwater (Nkoa 2013). In addition, soil enzyme activity may be negatively affected by the properties of organic matter and the presence of organic pollutants in the treated residue, which could reduce the quality of agricultural soils (Kocyigit et al. 2017; Zheng et al. 2021). Pathogenic microorganisms and plant toxins in the treated residue can also pollute soils and contaminate humans and other animals via the food chain

(Arthurson 2009). There is a tendency to accumulate and enrich tetracyclines and antibiotic resistance genes in soil with the application period of treated residue (Lu et al. 2021). Zinc (Zn), copper (Cu), cadmium (Cd), arsenic (As), and other heavy metals are commonly found in treated residue, which may cause heavy metal pollution and affect the cultivation of edible crops (Lichtfouse et al. 2005). Duan et al. (2012) found that the long-term application of anaerobic digestion-treated pig manure residue in rice fields induced the As, Cd, Cu, and Zn accumulation in the tillage layer.

Utilization pathway of kitchen waste

Graded utilization of digestion products is one of the effective disposal methods for kitchen waste. The treated residue can be divided into biogas slurry and biogas residue after solid–liquid separation. The biogas slurry is considered as a kind of potential organic fertilizer due to its high decomposition and facile absorption by crops. Algae can effectively absorb NH_4-N and phosphate in the biogas slurry as a source of nitrogen and phosphorus (Zhu et al. 2016). Li et al. (2020b) found that *Chlorella* could efficiently uptake nutrients from chicken manure and digestated biogas slurry, respectively, with the highest removal rates of 90.6% and 89.8% for TN. In addition, specific microbial populations are enriched in the biogas slurry, which not only dilutes the feed salt ion concentration, but also promotes anaerobic digestion performance after returning to the system. The biogas residue could be used as plant fertilizer, soil conditioner and biochar after treatment. Pyrolysis is an effective method for the sustainable treatment of biogas residues. The produced biochar is cheap, is stable, and can be applied to in situ soil remediation, in complement to the commercial activated carbon (Pan et al. 2020). Biochar with conductive surface alkaline can maintain pH balance of the system as well as contain a variety of organic functional groups that can effectively improve direct interspecies electron transfer (DIET) (Zhao et al., 2021). Alghashm et al. (2018) used biogas residue from the anaerobic digestion of kitchen waste to prepare biochar with pyrolysis at 900 °C. They found that the biochar had better P adsorption than other biochars and could be used as a soil conditioner for cabbage growth. Similarly, Kizito et al. (2019) prepared digestion-rich biochar that improved soil organic matter by 232%–514% and nutrients by 110%–230%. Biochar production from biogas residue is an effective method for subsequent anaerobic digestion treatment. Reusing it to the anaerobic digestion system not only promotes methane production, but also enables the full quantitative utilization of kitchen waste.

Carbon neutrality in anaerobic digestion disposal of kitchen waste

Energy supply chains for anaerobic digestion disposal of kitchen waste

The optimization of kitchen waste digestion for energy production is rapidly developing. Besides optimizing process parameters, front-end waste sorting and end-product recycling are also important measurements to reach carbon peaks and carbon neutrality. Life cycle and carbon footprint investigations show that unsatisfactory front-end sorting of kitchen waste causes waste of food resources and unnecessary greenhouse gases emissions during transportation and storage (Lee et al. 2020). Although the coupling of bio-refinery technology and biogas engineering has enabled the development of bio-diesel, there is still a lack of systematic industrial planning for the digested product, including the promotion of agricultural recycling of digested products, which hindered the rapid development of the industry (Sakarika et al. 2020).

Figure 1 demonstrates layout optimization of the energy supply chains for anaerobic digestion treatment of kitchen waste. It is crucial to well manage the sorting of kitchen waste at the front-end strictly because the source separation of wet and dry wastes is a prerequisite to achieve efficient utilization of kitchen waste. Incineration of the dry waste is an important manifestation to low-carbon economy. The mid-end treatment of kitchen waste contributes to carbon neutrality. The waste oil extracted by the grease extraction system can be converted to biodiesel by transesterification. After oil–water separation, kitchen waste is converted into biogas for combined heat and power generation. Residual products after anaerobic digestion treatment of kitchen waste are converted into soil conditioners or organic liquid fertilizers reused in the eco-farmland. The energy chains enable the assessment of carbon emissions from land-use change and provide a reference achieving circular economy and low-carbon emission development.

Reduction of carbon emissions by anaerobic digestion of kitchen waste

On the one hand, anaerobic digestion of kitchen waste reduces carbon emissions through the production of biogas and bio-diesel that could replace fossil fuels and is considered as a renewable, carbon–neutral source (Sarkar et al. 2021). Carbon emissions in anaerobic digestion treatment include consumption of external energy and materials during the collection and treatment process, and indirect

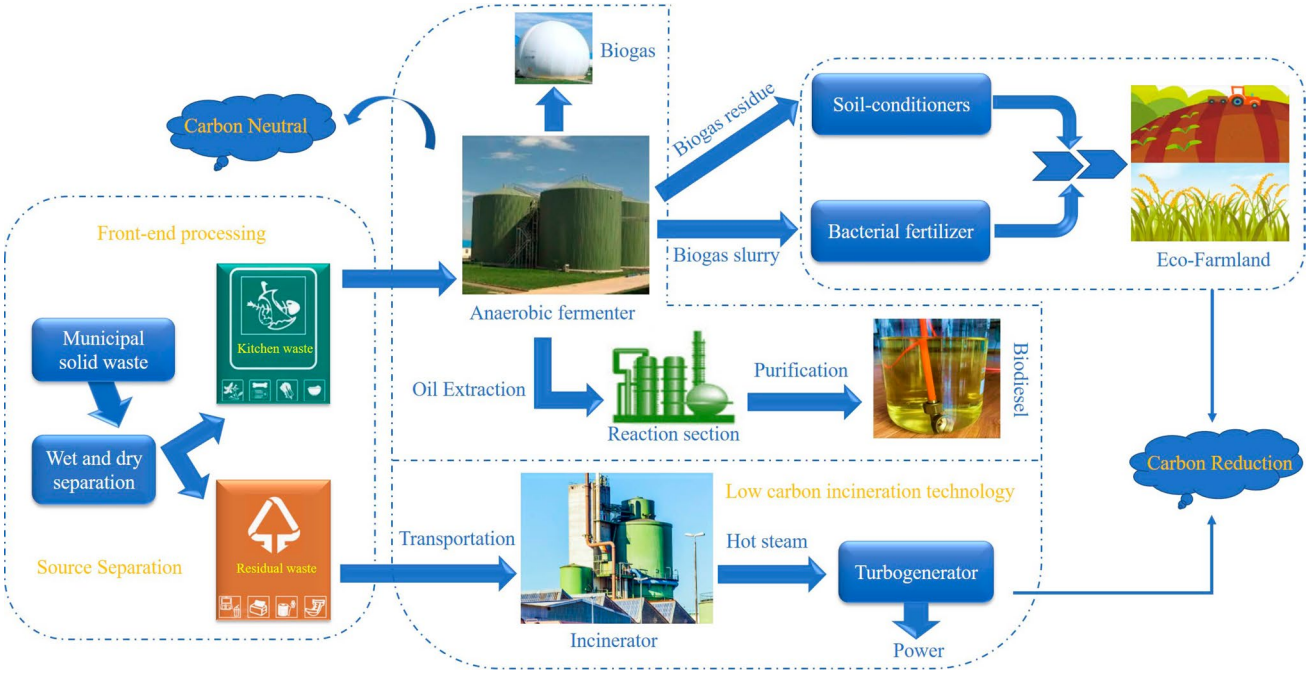

Fig. 1 Optimization of the energy supply chain layout for anaerobic digestion of kitchen waste based on source separation and carbon reduction

carbon emissions such as methane leakage from the system. Here we evaluated carbon emissions in carbon dioxide equivalent with the net carbon emission, the system carbon emission, and the carbon reduction calculated by Eqs. (1), (2), and (3), respectively.

$$\Delta E_{CO_2} = \Delta M_{emission} - \Delta N_{reduction} \quad (1)$$

$$\Delta M_{emission} = C_{extra} + C_{indirect} \quad (2)$$

$$\Delta N_{reduction} = W_{biogas} \cdot \rho + \alpha \bullet Q_{crude} \bullet \eta \quad (3)$$

where ΔE_{CO_2}: the net carbon emission (kg CO_2 equivalent·t^{-1}); $\Delta M_{emission}$: the system carbon emission (kg CO_2 equivalent·t^{-1}); $\Delta N_{reduction}$: the carbon reduction (kg CO_2 equivalent·t^{-1}); C_{extra}: the additional carbon emissions (kg CO_2 equivalent·t^{-1}); $C_{indirect}$: the indirect carbon emissions (kg CO_2 equivalent·t^{-1}); W_{biogas}: the biogas outgoing power (kg CO_2 equivalent·t^{-1}); ρ: the carbon emission factor of external power transmission; Q_{crude}: the amount of crude oil (kg CO_2 equivalent·t^{-1}); α: the efficiency of bio-diesel conversion; η: the carbon emission factor of diesel fuel.

According to the literature (Amon et al. 2021; Di et al. 2007; Uusitalo et al. 2014; Yu et al. 2020), the additional carbon emissions from anaerobic digestion ranged from 34.3 to 82.8 (kg CO_2 equivalent·t^{-1}) with 70 (kg CO_2 equivalent·t^{-1}) as a reference value in this study. The organic matter degradation rate of kitchen waste is 60%–80%, and the rate of biogas production per unit of organic matter from degradation is 1m^3·kg^{-1} with 60–70% methane content. In this study, the organic matter degradation rate was 70% and the methane content was 65%. The methane leakage rate was 5% according to International Panel on Climate Change (IPCC), which resulted in 3.75 m^3·t (2.36 kg·t^{-1}) of methane leakage, corresponding to 66.08 (kg CO_2 equivalent·t^{-1}) of carbon emission. The calorific value of biogas was 6.02 kWh·m^{-3}, and the heat efficiency of biogas utilization was 33.5%. Therefore, the external power of biogas was 232.93 kWh·t^{-1}. The carbon reduction factor for outgoing electricity was 0.88 kg·$(kWh)^{-1}$. The crude oil yield was 25 (kg CO_2 equivalent·t^{-1}), and the bio-diesel conversion efficiency was 80%, with a diesel carbon emission factor of 3.1 kg·kg^{-1}. The final calculation results were $\Delta M_{emission}$= 136.08 (kg CO_2 equivalent·t^{-1}), $\Delta N_{reduction}$ = 220.98 (kg CO_2 equivalent·t^{-1}), ΔE_{CO_2} = -84.90 (kg CO_2 equivalent·t^{-1}). Therefore, it has a high potential for carbon reduction and conforms to the sustainable development route.

Anaerobic dynamic membrane bioreactor for better waste disposal

Anaerobic digestion has the advantages of efficient energy recovery and low-carbon emissions, which makes it the mainstream technology for the treatment of kitchen waste with lower global warming potential than aerobic composting and sanitary landfills (Edwards et al. 2018). However, the conventional anaerobic digestion process such as continuous stirred tank reactor (CSTR) still hold specific drawbacks,

such as a long start-up time in order to maintain high biomass retention in the reactor and a deteriorating performance with operational instability that limits the performance of the anaerobic digestion process significantly (Lin et al. 2013; Song et al. 2018). The CSTR process has the disadvantage of high energy supplementation and low nutrient recovery rate. The digested products are rich in nitrogen and phosphorus, which requires subsequent treatments (Maaz et al. 2019). One of the main challenges that the CSTR process is currently facing is recovering the high concentration of dissolved methane in the effluent. Dissolved methane can be released into the environment, causing the accumulation of greenhouse gases (Velasco et al. 2021). Therefore, to remedy the deficiencies of conventional anaerobic digestion, it is increasingly important to select high-performance processes and optimize the reactor configuration constantly.

In recent years, there has been increasing interests in applying anaerobic membrane bioreactors (AnMBR) for kitchen waste treatment. The shortcomings of conventional anaerobic digestion are avoided by combining bioreactors with microfiltration or ultrafiltration membranes. Due to the high mass transfer area of the membrane, it has a high potential to recover dissolved methane (Dereli et al. 2012). AnMBR separates the hydraulic retention time from the solids retention time (SRT) and retains the total biomass retention, which results in efficient removal of organic matter and high-quality effluent (Aslam et al. 2018). Membrane separation processes can achieve selective separation or direct recovery of nutrients (Ma et al. 2018). Compared to conventional processes, AnMBR has the advantages of a small carbon footprint, low sludge production rate, strong resistance to inhibitory or toxic substrates, and the ability to produce methane-rich biogas. In addition, AnMBR can reduce net energy demand by almost 37.3% (Hu et al. 2016). Therefore, the use of AnMBR brings about energy neutrality and positive effects for anaerobic digestion treatment of kitchen waste. Cheng et al. (2020) indicated that AnMBR had a high methane yield of 570 mL/g VS for the long-term anaerobic digestion operation of kitchen waste. Jeong et al. (2017) used AnMBR to treat kitchen waste recycling wastewater with a high COD removal rate of $98.3 \pm 1.0\%$ and an average methane production of 0.21 ± 0.1 L CH_4/g $COD_{removed}$.

However, the issue of membrane fouling and expensive membrane cost are two major constraints to the engineering application of AnMBR. In recent years, dynamic membrane (DM) technology has been proposed as an effective alternative to microfiltration or ultrafiltration membranes because of its high membrane flux, low membrane cost, and convenient membrane cleaning properties (Hu et al. 2018). Figure 2 shows the competitive advantages of anaerobic dynamic membrane bioreactors (AnDMBR). AnDMBR uses a more extensive pore size support material (non-woven fabric, screen, industrial filter cloth, etc.) as the filtration substrate. The support layer retains the suspended particles and forms a biomass filtration layer on its surface, which acts as a secondary membrane filtration layer (Hu et al. 2020). In addition, it is easy to use back-washing to control membrane fouling because the cake layer consists mainly of the sludge cake and microorganisms, and the dynamic

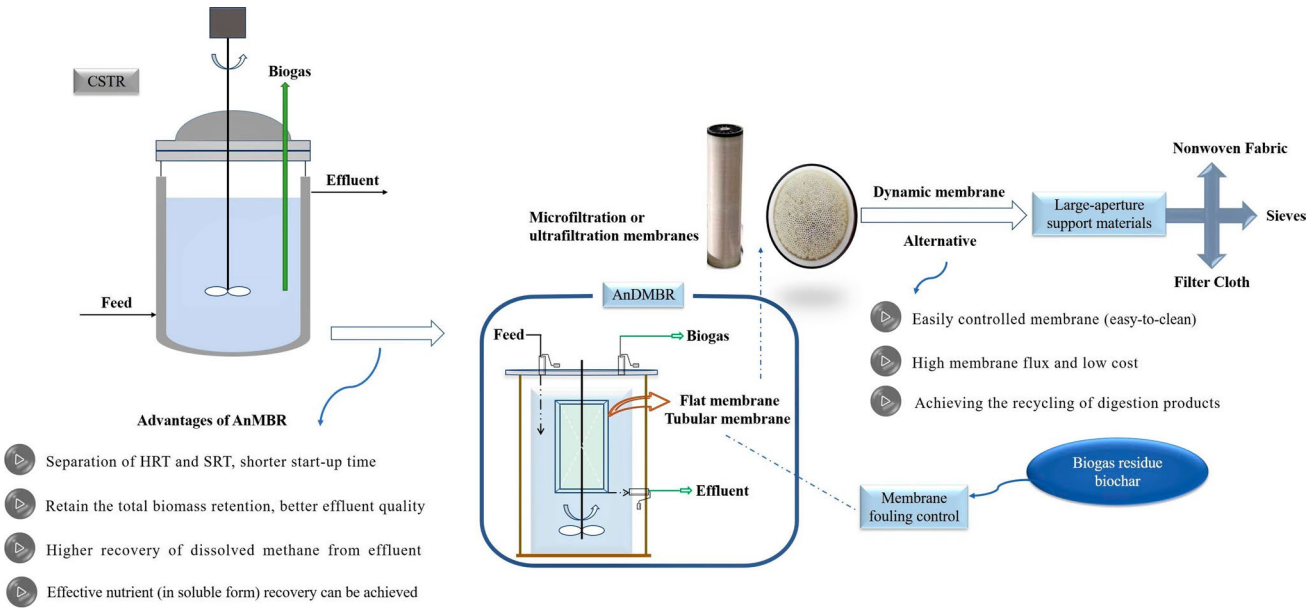

Fig. 2 Competitive advantages of the anaerobic dynamic membrane bioreactor (AnDMBR) for kitchen waste disposal compared to conventional anaerobic bioreactors (CSTR)

membrane formation cycle is as short as 8 h (Ersahin et al. 2016). Although the combination of dynamic membrane technology with the anaerobic reactor is still in the early research stage, it has excellent treatment and economic benefits for kitchen waste disposal and can realize the recycling of resources. Therefore, AnDMBR can be used as one of the major options for the full quantitative utilization of kitchen waste in the future.

A quantitative model for recycling kitchen waste

The bio-refinery-based kitchen waste conversion model can meet resource treatment requirements (Ren et al. 2018). However, the model does not involve the effect of non-organic matter fractions on performance of anaerobic digestion, nor does it address the resource utilization of the treated residue. Therefore, we propose a fully quantitative utilization model as shown in Fig. 3 after literature reviewing. Kitchen waste is firstly separated and pre-treated to separate oil from water efficiently, leaving solid organic phase and inert materials. Waste oils and grease are purified and transformed into bio-diesel, while water and organic components are recycled stepwise. Kitchen waste contains some non-organic component substances, such as plastics, lunch boxes, chopsticks, and other inert substances, whose presence can affect the stability of the anaerobic digestion process. Pyrolysis is an excellent treatment method that effectively treats solid inert materials and generates thermal energy to power the anaerobic digestion system. This review suggests a novel anaerobic dynamic membrane bioreactor (AnDMBR) as an entire quantification reactor for organic slurries based on literature reviewing. Biogas is used as an energy source, and the membrane effluent is reused. The specific bacteria cultured with biogas slurry are introduced to the anaerobic digestion system to enhance the abundance and diversity of archaeal microorganisms. Biogas residue biochar can alleviate dynamic membrane pollution and enhance methanogenic performance and improve reactor performances. The full quantitative utilization model realizes the efficient resource utilization of the whole industrial chain from the front to the end of kitchen waste disposal, enhances the utilization efficiency of derived by-products of anaerobic digestion, and strives for carbon neutrality of kitchen waste disposal.

Researches on measurements to improve anaerobic digestion performance of kitchen waste (pre-treatments, co-digestion, dosing additives, process optimization) are relatively extensive. However, the digestion of kitchen waste in the future still needs to be strengthened from the following aspects: (i) it is necessary to establish a characterization system for kitchen

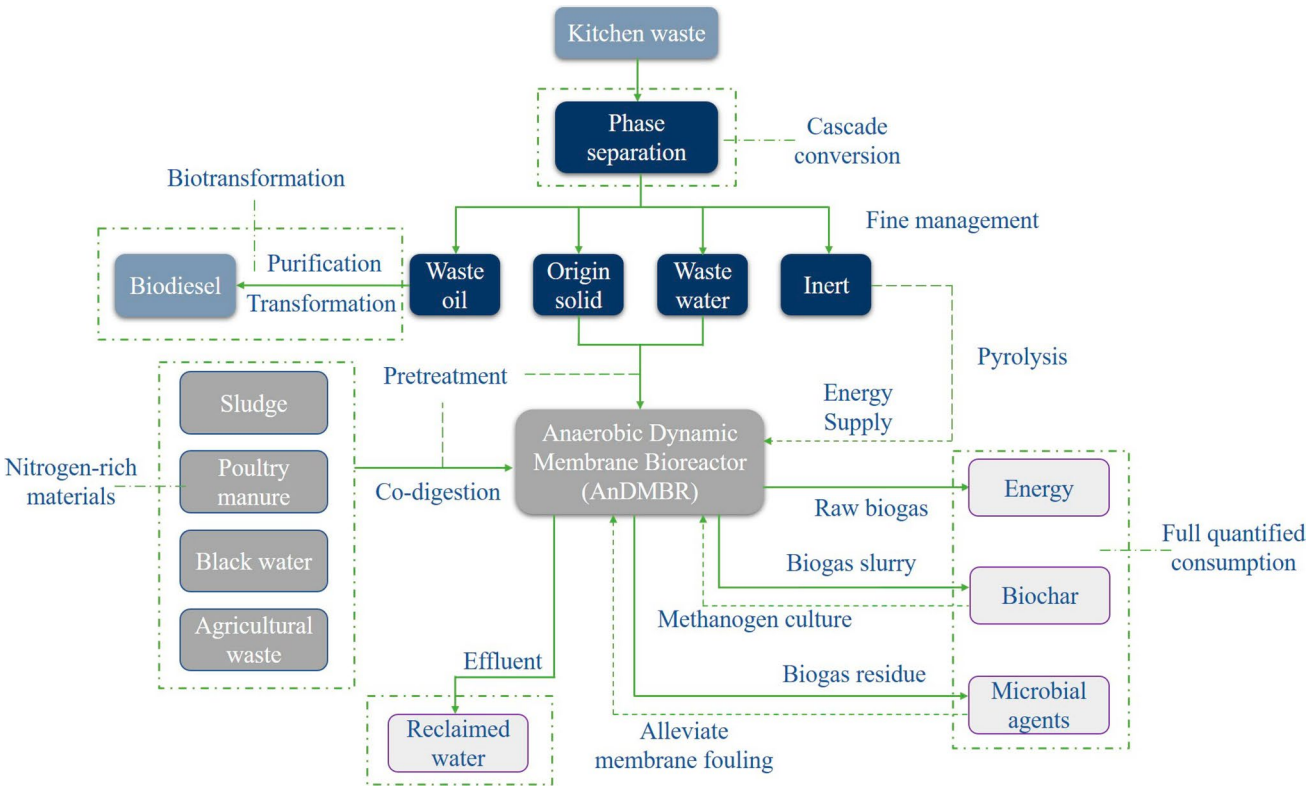

Fig. 3 Proposed full quantitative model for recycling kitchen waste

waste in the context of disposal adaptability; (ii) in order to realize the step transformation and utilization of kitchen waste components with low-carbon footprint, the mass flow of kitchen waste could be further introduced to the whole life cycle of kitchen waste from collection, transportation, and disposal to achieve the goal of "zero-carbon emission and zero pollution"; (iii) it is essential to fulfill the efficient conversion and full quantification of organic components in kitchen waste, as well as to promote the recovery of nutrients (N, P) from the digestion products of kitchen waste disposal; and (iv) studies on the synergistic inhibition effect of multiple components on the anaerobic digestion performance of kitchen waste disposal should be strengthened in future researches.

Conclusion

Anaerobic digestion is an efficient method for kitchen waste treatment and disposal. Pre-treatments, co-digestion, dosing of additives, and process optimization are effective measures to alleviate the inhibition of hazardous kitchen waste components on the performance of the anaerobic digestion process. Resource utilization efficiency of the kitchen waste could be enhanced by selecting suitable process configurations and optimizing parameters according to the regional characteristics of the components of kitchen waste. The reuse of treated residue can increase the additional value of derived products from anaerobic digestion significantly and improve the commercial value of kitchen waste to biogas projects. Compared with the conventional anaerobic digestion technology, anaerobic dynamic membrane bioreactor can break the bottleneck of anaerobic digestion on kitchen waste disposal and is considered as an appealing alternative to kitchen waste treatment. In addition, this paper proposes a full quantitative utilization model based on literature reviewing, which forms a closed-loop resourcelization chain from the front to the end to achieve the fine management and full quantitative consumption of kitchen waste.

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Declarations

Competing interest The authors declare that there has been no competing financial interest or personal relationship conflict in this article.

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