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Advancing the bioconversion process of food waste into methane: A systematic review

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Abstract

With the continuous rise of food waste (FW) throughout the world, a research effort to reveal its potential for bioenergy production is surging. There is a lack of harmonized information and publications available that evaluate the state-of-advance for FW-derived methane production process, particularly from an engineering and sustainability point of view. Anaerobic digestion (AD) has shown remarkable efficiency in the bioconversion of FW to methane. This paper reviews the current research progress, gaps, and prospects in pre-AD, AD, and post-AD processes of FW-derived methane production. Briefly, the review highlights innovative FW collection and optimization routes such as AI that enable efficient FW valorization processes. As weather changes and the FW sources may affect the AD efficiency, it is important to assess the spatio-seasonal variations and microphysical properties of the FW to be valorized. In that case, developing weather-resistant bioreactors and cost-effective mechanisms to modify the raw substrate morphology is necessary. An AI-guided reactor could have high performance when the internal environment of the centralized operation is monitored in real-time and not susceptible to changes in FW variety. Monitoring solvent degradation and fugitive gases during biogas purification is a challenging task, especially for large-scale plants. Furthermore, this review links scientific evidence in the field with full-scale case studies from different countries. It also highlights the potential contribution of ADFW to carbon neutrality efforts. Regarding future research needs, in addition to the smart collection scheme, attention should be paid to the management and utilization of FW impurities, to ensure sustainable AD operations.

Keywords: Anaerobic Digestion, Biogas, Exergy, Food waste, Methane, Pretreatment

Nomenclature

AcoD	Anaerobic co-digestion	GHG	Greenhouse gases
AD	Anaerobic digestion	IoT	Internet of things
ADFW	Anaerobic Digestion of Food Waste	OLR	Organic loading rate
AI	Artificial intelligence	THP	Heat hydrolysis
C/N	Carbon to nitrogen	TOC	Total organic carbon
CHP	Combined heat and power	TS	Total solids
COD	Chemical oxygen demand	VS	Volatile solids

1. Introduction

With rapid urbanization and population increases, the surge in municipal solid waste is a worldwide concern. Food waste (FW), a biodegradable waste produced mainly by households, food services and retails, constitutes 50–60% of municipal solid waste (Ren et al., 2018). It is estimated that more than 1.3 billion tons of FW are generated along the whole food supply chain, from the agricultural to final consumption stages (Amicarelli et al., 2021). This number can be exchanged for 30% of total global greenhouse gas emissions (1 kg of FW could emit 2.5 kg of CO_2), 30% of end-user available energy, 20% of all cultivated land, 25% of the world's freshwater supply used to grow food that is never eaten and generally results in 14% of world population food insecurity and wasting the equivalent of $1 trillion annually (Fao, 2013; Hall et al., 2009; UNEP, n.d.). Globally, 2.5 billion tonnes of FW are expected to be produced by 2025; that must be recycled to create a green economy (Karthikeyan et al., 2018). Since this problem impacts the whole biosphere and is not location-specific, it needs to be treated as an urgent area for action (FAO, 2015).

Current FW management techniques include landfill, composting, incineration, and anaerobic digestion (AD). However, some of them have long been blamed for their aftermath environmental effects, high operational costs, and a large carbon footprint. For example, landfills are environmentally disadvantageous due to their high GHG emissions and leachate content (Cheng et al., 2020). Similarly, incineration is costly and energy-intensive beyond its suitability to the nature of FW and the emission of air pollutants such as NOx, particulate matter, etc. (Kumar et al., 2021).

Therefore, the main concerns with the selection of FW management techniques are sustainability, environmental protection, social equity, and economic benefits. Due to its excellent energy recovery performance (Isah & Ozbay, 2020) and its integration into the perspective of a circular economy, the anaerobic digestion of food waste (ADFW) is perhaps a viable choice that has shown remarkable efficiency compared to landfills and incineration (Czekała et al., 2020; Yazdanpanah et al., 2018). This bio-approach option is widely used in industrial and household applications worldwide. It consists of a series of biochemical processes carried out by specific bacterial species that convert organic materials into methane (CH_4), carbon dioxide (CO_2), and bacterial biomass (Blumenstein et al., 2016). Briefly, AD occurs through four successive stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The biochemical processes in each stage vary depending on the FW type, as there are several FW varieties along with widely varied compositions (Table S1).

Although ADFW is an ideal choice, its overall sustainability is inherently associated with advanced management of pre-digestion, anaerobic digestion and post-digestion processes. Pre-digestion management may include source identification and collection, sorting, transportation, storage, and conditioning of raw FW. Once the raw FW is pre-managed, it goes to the four-stage AD process, for pretreatment and biogas production. Following the AD process, the produced biogas and by-products will be subjected to post-treatment and potential value assessment.

Some recent literature has reported *in-situ* ADFW performance enhancement through various biochemical processes using additives, pretreatment and controlling the operational and microbial environment of AD (Isah & Ozbay, 2020; Komilis et al., 2017; Ren et al., 2018; Zhao et al., 2021). Furthermore, life cycle assessment studies on the bioconversion of FW to biogas and its national or regional importance have been reviewed (Chew et al., 2021; M. Kumar et al., 2021; Negri et al., 2020; Ren et al., 2018; P. Wang et al., 2018). However, these studies have limitations. First, the pre-digestion management of FW, including collection, sorting, and transport optimization, has been overlooked. Second, most of these reviews focus on the biochemical treatment and processing of AD, while discussions available on physical and/or mechanical processes are rare. Third, the evaluation of the energy quality (exergy) of CH_4 has not yet been reviewed. Fourth, for the most part, existing research has focused on the positive contribution to carbon reduction while AD itself can contribute to carbon emission. This paper reviews the present state of advanced FW-derived CH_4 production processes by discussing pre-digestion FW management techniques, the *in situ* AD process with a special focus on engineering aspects, and post-production analysis. This paper also considers 'synergy and trade-off' to represent both -ve and +ve effects on carbon neutrality. Furthermore, this review exclusively analyzes the scientific and practical knowledge gap based on case studies from different countries and encourages future research.

2. Methodology

To provide a complete understanding of ADFW methane production, this review examines a wide range of recent scientific literature searched using different keywords and phrases related to the topic in the Web of Science™ and Scopus® databases. The search was on a "topic" basis and "or" and "and" were used as Boolean operators. The keywords and/or phrases used were therefore lemmatized to "food waste" or "food waste" and "management" or "food waste" and "anaerobic digestion" or "food waste" and "methane production". Through this search strategy, a total of 11,805 documents were obtained. Five research items were from the Web of Science™; articles, books, features, proceedings, and brief communications; and two more items were found in Scopus®, including technical notes and case reports. The retrieved documents were also analyzed for specific bibliometric indicators such as year-wise publication trends and active field departments (Figure 1). The first refining step was excluding the resources published before

2016, which led to 4671 documents. Language restrictions were not imposed. The documents were then refined and examined based on the objectives, relevancy, and cogency (for company reports), which resulted in 224 documents for in-depth analysis. Further cross-checking of the refined results for missing data or duplicates led to exclusion of 54 and the inclusion of 175 documents. A search of corporate, intergovernmental, and non-governmental resources was also conducted and 14 AD pilot case studies were found, three of which were considered due to their relevancy and cogency. These case studies are separately organized in Appendix.

Figure 1. The general analysis and results of literature resources used for this review; (a) annual publication trend, (b) search strategies, and (c) the subject or research theme.

3. Advances in methane production from food waste by anaerobic digestion

3.1. Pre-digestion management

3.1.1. Physico-chemical components of food waste

FW pre-digestion management includes source identification to deliver FW onsite to the AD plant and the conditioning step. However, it is noteworthy to analyze the FW constituents and how they respond to the AD process, particularly regarding the CH_4 yield.

FW is composed of dissimilar or diverse constituents, which may result in varying and unpredictable bioconversion efficiencies. Even with FW of a similar type, significant heterogeneity can be introduced by preparation methods, cooking techniques, consumption habits, customer age, socio-economic status and cultural practices, and the local climate (Kuczman et al., 2018). In general, a typical FW usually consists of moisture, lipids, proteins, and carbohydrates, and volatile fatty acids, total solids, volatile solids, Nitrogen (N), and Carbon (C).

Of these components, high moisture and organic matter content are predominant. Details about each physico-chemical property of FW and its associated effect on methane production has been provided in the supplementary information.

3.1.2. Adopting a smart food waste collection and transportation scheme

The feasibility and efficiency of AD could be influenced by context-awareness ('smartness') and optimization of the FW collection and transport network devices and components (Panaretou et al., 2021). Smart generally refers to connected context-aware devices with some degree of interactive and autonomous capabilities (Silverio-Fernández et al., 2018). According to Abdallah et al. (2019), a smart waste collection system reduced operating costs (19%), CO_2 emissions (5−22%), and trip times (≤42%). Robotic technology, the Internet of Things (IoT), optical systems, geographic information systems (GIS), smart sensors, and intelligent machines have brought about a fundamental change in the pre-digestion management of organic waste, including FW (Abdallah et al., 2019; C. Wang et al., 2021; Woon et al., 2021). In particular, artificial intelligence (AI)-assisted collection systems are recent technological developments that involve optimizing complicated routes, identifying waste types, and anticipating waste composition and generation (Figure 2) (Cinar et al., 2021; Joshi et al., 2021). This includes recognizing the physical and nutritional characteristics and possible methods of managing the food items thrown in the AI-guided bin.

The technology components utilized in AI-enabled waste management go back decades (Nordsense, 2020), although smart waste bin technology was first introduced in 2010 and is now used extensively (Pardini et al., 2020). AI-enabled technology utilizes smart peripherals like cameras, GPS trackers, and weight sensors to track location and movement; algorithms for component recognition; and dedicated software for flow analysis and optimization. Systems such as Winnow Vision® can be 'trained' to differentiate food waste from contaminants and others, like the Greyparrot Automated Garbage Monitoring System® monitor and analyze live image feeds of waste flows in real-time (Balacky, 2022).

These systems can automatedly recognize most organic wastes, with personnel simply indicating kitchen-specific menu items throughout the training and automation phase. Over time, the algorithm learns to detect discarded goods in the bin with more precision than the human eye. Additionally, AI can instantaneously detect the quantity of FW in real-time and the relevant sectors can be informed accordingly. Forecasting can also be done based on the collected history of thrown items analyzed on an hourly or daily basis.

An AI-supported waste monitoring system enables evaluating and determining the correct value of collected waste; giving corresponding rewards to residents is also of great significance for motivating people to actively participate in environmental protection activities (Wang et al., 2021). Some researchers have used neural networks, deep learning, artificial neural network, decision tree, and decision tree-random forest to advance these systems (Joshi et al., 2021). Wang et al. developed a proof of concept for smart municipal waste classification through deep learning convolution neural networks and cloud computing techniques to realize high accuracy (91.9% to 94.6%) of waste classification at the beginning of garbage collection. To achieve this accuracy, the smart garbage bins are equipped with a set of gas sensors and ultrasonic wave sensors for real-time abnormally released gas monitoring, and then, all collected data are sent to an opensource IoT platform for analysis and decision-making (Wang et al., 2021).

3.1.2.1. Optimization of collection network and transport routes

As FW originates from various sites, including domestic, commercial sites, institutions, and factories (Labatut & Pronto, 2018), setting a single or random set of collection bins, collection centers, and transport channels alone results in poor and costly management and inconsistent substrate supply both in volume and frequency for AD. An optimized FW collection network of bins/dumpsters, more collection centers and some transfer stations may be necessary (Figure 2). Herein, optimization is not only aimed at reducing waste collection and transportation costs; it also minimizes time, energy consumption, and pollution emissions (Das & Bhattacharyya, 2015; Shah et al., 2018). However, various decision variables such as waste collection rate and efficiency, waste coverage, personnel capacity, budget allocation, political interest, and social learning should be considered for more accurate optimization (Lavigne et al., 2021). For example, optimizing transportation routes depends mainly on two factors, the amount of FW to be transported and the distance from/to the treatment plant, transfer station, collection center and collection bin (Shahid & Hittinger, 2021).

The collection of FW and distribution of nutrient-rich AD by-products such as digestate contributed to a larger global warming potential (before applying it as a fertilizer) (Chiew et al., 2015). Therefore, the transportation distances for the waste collection and digestate applications must be optimized (Slorach et al., 2019). Researchers have proposed optimization models for various waste collections. Das & Bhattacharyya, (2015) proposed a heuristic model for optimal waste collection and transportation problems. The proposed scheme computes the optimal waste collection and transportation path at each stage and can reduce ≥30% of the total waste collection path length. Lavigne et al. (2021) developed a mixed-integer linear programming model that calculates the overall transportation costs for a particular given network design and the amount of waste to be collected at various demand sites to minimize the costs of route and vehicle investment. They observed that combining FW collection with three composting facilities leads to the greatest cost savings (≤31%). Policymakers can use the model to simulate waste collection scenarios and evaluate the impact of policy decisions on costs and the required waste collection fleet. Shah et al. (2018) developed a stochastic optimization model based on chance-constrained programming to optimize waste collection operations; reducing overall transportation costs while maximizing value recovery from waste bins. Due to the unpredictable condition and quality of FW, the collected waste value is represented as an uncertain parameter to reflect the uncertain value that can be recovered from each trash bin. A heuristic approach appears most suited for larger cases or situations where a more detailed district level is required owing to a significant rise in the authorized number of pick-ups each trip. Slow convergence, complex theory, poor search capacity, and tiresome parameter tuning are limitations of contemporary optimization methods (Hannan et al., 2020). Herein, the AI-supported optimization system could also be an interesting avenue for future research to advance the FW collection optimality.

3.1.3. Management and utilization of impurities from the raw FW

FW impurities can be separated mechanically by screening (sedimentation or suspension) or mechanical means if they are heavy and/or large enough to be settled or filtered in suspension (Dalke et al., 2021). The process starts with passing the pretreated FW through a 10 mm mesh, which traps larger particles. Other standard processes in mechanical separation include presses and metal separators, which are used to separate the remaining impurities based on size and composition (Alessi et al., 2020). As the mechanical separation of inorganic impurities is extensively studied and reviewed, the focus of this review is on improving the substrate quality by extracting waste oil or growing salt-tolerant fermentation microorganisms. Even if the FW has been collected effectively with source-separated methods, diverse impurities, including high oil, grease, and saline content, can still be found, which even causes AD shutdown (Cesaro & Belgiorno, 2021). These impurities can be converted to value-added resources via gasification and transesterification processes. Gasification, a thermochemical process, can be operated integrally with the main AD system, where impurities are converted to hydrogen-rich synthesis gas (syngas) and pure FW is converted to CH_4-rich biogas simultaneously (J. Zhang et al., 2020).

Since syngas contains a high content of H_2, it can be considered a potential energy source. The fat and oils (triglycerides) separated from FW can be converted into usable form usually for biodiesel by recycling polyesters into individual monomers through a chemical process called transesterification (Topi, 2020). The transesterification conversion of FW-derived oil could be enhanced by the addition of external chemical catalysts. Degfie et al., (2019) studied the effect of the CaO nanocatalyst on the conversion of cooking oil waste to biodiesel. They discovered a high biodiesel yield (96%) under optimum reaction conditions (50 °C, 1:8 methanol to oil, and 1 wt.% CaO loading rate). In addition, 97.74% biodiesel was produced from frying oil (60 °C, 11:6 methanol to oil) and a powdered limestone catalyst (travertine 1.36 wt.%) (Talavari et al., 2021). Recently, the catalytic co-transesterification of waste frying oil shows a promising result (F. Li et al., 2021). Heat-moisture treatment and flash evaporation are also actively being investigated to improve the recycling rate of oil contained in FW.

Figure 2. AI-supported FW logistic system and impurity management during the pre-digestion stage

3.1.4. Pretreatment options to enhance the biodegradability of FW

Despite the cost incurred and the large footprint, FW pretreatment enhances AD output (M. Kumar et al., 2021). In the absence of pretreatment, methanogenesis might become the rate-limiting step due to the carbohydrate content of the FW (Srisowmeya et al., 2020). Although many pretreatment technologies have been developed to improve the AD process, physical pretreatment methods such as size reductions and shredding primarily work for FW to increase surface area and bio-accessibility by altering the morphology (Abraham et al., 2020) and reducing the degree of polymerization of the polymeric fraction (M. Kumar et al., 2021).

The methanogenesis process, and more specifically the functions of the methanogens, are found to be significantly influenced by particle size. When the FW particle size drop from 8 mm to 2.5 mm, the methane yields 22–26% higher under semi-solid digestion conditions due to releasing the intracellular organic matter and accelerated kinetics (Karthikeyan et al., 2018).

Even if the heat process could be helpful to minimize the lactic acid bacteria, which might accelerate acidification during ADFW and change the routes for producing acids, the temperature's intensity and duration need to be optimized. With reference to the previous studies, the optimal thermal intensity and exposure time are 60−150 °C and 20–60 min, respectively (Parra-Orobio et al., 2021). The maximum soluble carbohydrate concentration and increased methane output were produced by FW varieties, especially with a high carbohydrate content when the temperature was lower. While higher temperatures cause FW to produce melanoidin chemicals and solubilize proteins (Yeshanew et al., 2016).

Biological pretreatments with inoculated microorganisms and enzymes have become another popular research topic in the field of AD. This method promotes the hydrolysis of the FW and increases the digestion rate. Because no external energy is needed, compared to mechanical or thermos-mechanical pretreatment, this option is considered greener, more environmentally friendly, and appropriate to promote the performance of ADFW (Paritosh et al., 2018). However, existing full-scale FW treatment plants mainly use thermo-mechanical pretreatment as the main way to improve the effect of AD. Currently, there are technical and economic barriers to biological and hybrid thermo-mechanical pretreatments, but these applications may have future viability. Some other pretreatment options such as microwave, hydrothermal and chemical pretreatments are not necessarily applicable as FW by itself is highly biodegradable and generates high volatile fatty acids during AD.

3.2. Onsite anaerobic digestion processes of food waste (ADFW)

AD is a well-known technology for dual missions in FW management, preventing pollution emanating from the FW and converting it into a valuable product. The main product of AD is methane, (CH_4), produced through a series of biochemical processes in the AD reactor: i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Battista et al., 2019). During this process, the CH_4 rises to the top of the digester, at which time the bacteria devour the FW while leaving a nutrient-rich slurry by-product known as digestate (Figure 3). The product (CH_4) and byproduct (digestate) have the potential as fuel and organic fertilizer, respectively. These potential values can be enhanced by controlling some basic operational parameters, such as organic loading rate (OLR), retention time, pH, C/N ratio, particle size, and temperature, as well as some key parameters including the type of substrate, type of pretreatment applied and the operation mode (Table S2). Controlling these parameters will ensure optimal microbial activity. The key parameters are directly related to AD performance (Kumar & Samadder, 2020).

Figure 3. A typical industrial-scale AD process with FW as a substrate

3.2.1. Anaerobic Co-digestion (AcoD) of food waste with other substrates

The methane yield and digestate quality can also be improved by adding trace elements to the FW (Shamurad et al., 2020) and by combining FW with other organic waste co-substrates such as sewage sludge, animal manure, biomass, etc. which achieves a symbiotic relationship in the reactor (Azarmanesh et al., 2020; Barua et al., 2018). However, AcoD of FW which is often generated in urban areas where there is no manure or agro-residues is not a good option since it is not economical to haul them far from the city. In this case, sewage sludge is perhaps the best option. Jin et al. (2021) noted that AcoD helps manage a FW substrate with a C/N of ≤20, and a poor concentration of microelements would be unfavorable to the digestion process. However, in the absence of an optimal substrate mixing ratio, especially without considering the carbohydrate content, which is the largest resource for CH_4 production, AcoD of FW can negatively affect the biogas production rate (Li et al., 2020).

3.2.2. Methane production from the anaerobic digestion of food waste

3.2.2.1. Emerging Reactor's design deployed for CH_4 production

Reactor design and routine parameters are important factors for effective AD operation and CH_4 production (Paritosh et al., 2017). Conventional reactors mainly contain single-phase or two-phase anaerobic digestion systems. In the case of phased digestion systems, a higher CH_4 yield is usually expected from a two-phase anaerobic digester than from a single-phase digester due to the high content of CO_2 that could already be released by hydrolysis and acidogenesis of FW in the first phase, followed by the utilization of those acids by methanogenesis that occurs in the second phase of the two-phase anaerobic digester (Ding et al., 2021). In other words, multi-phase systems are capable of preventing the pH inhibition issues of single-stage systems. Some studies have also been done that develop a compact three-stage anaerobic digester for ADFW (J. Zhang et al., 2017). Three independent chambers for hydrolysis, acidification, and methanogenic activity were combined into one independent chamber, and a high CH_4 yield of 24−54% was achieved compared to a single-phase or two-phase anaerobic digestion system. In principle, AD reactors should be designed solely in a technically simple way, large enough, require a low land and energy footprint, are unsusceptible to both internal and external environments, and minimize the aftermath effects. All these principles will generally be judged by the process stability, CH_4 production rate, and LCA results.

The third-generation anaerobic digestion reactors, such as continuous stirred tank reactor, expanded granular sludge bed reactor, internal circulation reactor, anaerobic membrane bioreactor and anaerobic anaerobic bioelectrochemical digestion reactor, are the main directions from an engineering perspective. Because of its ability to handle high solid content, a continuous stirred tank reactor is comparatively more beneficial for ADFW. Furthermore, a continuous stirred tank reactor with high solid treatment technology allows for managing large amounts of FW per unit of digester volume, avoiding water dilution and minimizing the requirement for substrate pretreatment and digestate dewatering (Westerholm et al., 2020). Regarding the chemical oxygen demand (COD) reduction and process stability, the anaerobic membrane bioreactor also performs as a continuous stirred tank reactor, while the former provides more process stability by prolonging the solid retention time (Lutze & Engelhart, 2020). The anaerobic membrane bioreactor system is a pneumatically submerged membrane reactor built with a continuous stirred tank reactor and a separate membrane unit (Cheng et al., 2020). This reactor shows the highest sensitivity to FW conversion, with significant effects on energy production and environmental protection (Becker et al., 2017). Recently, some advances have been conducted for this reactor. For example, a high solid thermophilic anaerobic membrane bioreactor with the help of membrane filtration demonstrates excellent efficiency in the removal of total solids, COD, and H_2S for both mono-digestion and AcoD of FW and sludge (Li et al., 2020).

The internal circulation and expanded granular sludge bed reactor reactors also demonstrated high OLR and buffering capacity. However, they are blamed for their requirement for higher upflow velocities and lower solid content (Srisowmeya et al., 2020). It is suggested that the particle size of FW should be reduced to handle the problem related to total solid content. The internal circulation reactor, a rangy and high-rate system with a low land footprint, shows powerful stress resistance and operational stability. A high COD removal rate (88%) was achieved from enzymatically pretreated FW digestion using an expanded granular sludge bed reactor (S. Zhang et al., 2020). Although the expanded granular sludge bed reactor enables microbes to adapt to sudden changes during operation, it has also been blamed for some operational problems associated with odor nuisance and scum deposition in the settler compartment and the gas-liquid-solid separator (Mainardis et al., 2020). Meanwhile, both internal circulation and expanded granular sludge bed reactor contain 3-phase separation modules that can simultaneously separate the gas, the liquid, and the biomass; therefore, devices for precipitation separation, auxiliary degassing, and reflux are not required. Furthermore, investments and operational cost savings can be realized.

The anaerobic bioelectrochemical digestion reactor is another widely utilized reactor for energy recovery and wastewater treatment and can be equipped with anode and cathode electrodes to be inserted in an existing conventional anaerobic digester and operated by maintaining electrode potentials (Song et al., 2016). An, Z et al. (2020) reported a 53.5% increase in CH_4 yield using an anaerobic bioelectrochemical digestion reactor equipped with a carbon-modified copper foam electrode. This was ascribed to the electroactive bacteria promoted by the carbon-modified copper foam electrode, further stimulating direct interspecies electron transfer pathways for CH_4 generation.

Nevertheless, bearing in mind that FW is miscellany in nature, innovative solutions should be rethought since there still needs to consider changing the operational parameters of the digester as per the variety of FW. Unfortunately, the contemporary anaerobic digesters lack flexibility during operation across the variety and components of FW. This means that when the type of FW to be fed changes, the operational parameters of the digester need reconfiguration according to each variety's behavior. However, this issue can be solved through a novel AI-supported digester which is built with a sensor and real-time computerized system. In this case, the digester can automatically maintain its operational parameters using the sensor along with the pre-settled algorithm regardless of whichever FW type is fed. The algorithm can be set either by connecting the digester with the collection AI-bin (i.e., if only the AI-Bin is capable of identifying and quantifying the FW varieties) or by an *in-situ* sample sensor installed on the digester itself. Although further research needs for its design, materials and practicability, such AI-based techniques could also be helpful beyond maintaining the internal environment, especially in auto-controlling the response to a change in the external environment like atmospheric temperature. Moreover, anaerobic digesters should be built as much as compactly in structure to reduce footprint and vertical position to take advantage of the gravity to mix and move the digested matter instead of using mechanical devices (Degueurce et al., 2022).

3.2.3. Prediction of AD performance for CH_4 production using numerical models

Sufficient operational monitoring alone cannot help for improved forecasting of biogas plants. Because microorganisms cannot be classified as stable systems, standardizing the requirements for process optimization are impossible in dynamic systems, which is why conventional monitoring methods cannot be used to track them. Instead, modern models can monitor and measure this dynamic behavior and interpret it accurately. Therefore, detailed modeling of the AD process is required. A predictive model could not only eliminate the need for extensive pilot testing and reduce the overall cost and time required to implement and operate AD (Tan et al., 2018), but it could also maintain energy production flexibility and stabilize the process (Cinar et al., 2021). In terms of CH_4 yield, digestate quality, and energy turnover, predictions of AD performance based on kinetic and mathematical modeling coincided with experimental data (Carlos-Pinedo et al., 2020). However, to benefit from predictive analytics, a substantial amount of input data must be obtained, such as volatile solids per total solids (VS/TS), C/N, soluble COD, total volatile fatty acids, digestion time, and so on must be obtained (Montecchio et al., 2019). This is because the substrate properties and bacterial community in the reactor, which impact parameters in the model, fluctuate over time, necessitating substantial datasets and a thorough understanding of each sub-process for calibration (Seo et al., 2021). Kinetic models may anticipate CH_4 production more accurately, preventing overestimation or underestimation. Kinetic models were used to estimate the ADFW performance of a up-flow anaerobic sludge reactor, and the logistic function offered the optimum settings to forecast CH_4 production and the lag phase ($R^2 > 0.9$) (Parra-Orobio et al., 2017).

Although numerical (mathematic or kinetic-based) prediction models are useful, the absence of biochemical reaction equations and non-linear correlations between performance and operational parameters make them difficult to apply in forecasting AD performance (Kumar & Ramanathan, 2019). Models based on neural networks, such as recurrent neural networks and artificial neural network, show better results with lower deviations and higher prediction precision (Park et al., 2021). The biogas production rate of dry ADFW was effectively predicted using a recurrent neural network, the so-called "black-box" model, based on retention time, soluble COD, total volatile fatty acids, total NH_3, and free NH_3. This model may be used as a novel framework for system control (e.g., early detection of system failure) and optimization of complex and nonlinear systems, including the AD process (Seo et al., 2021). The adaptive neural-fuzzy inference system is another hybrid meta-heuristic model, which is also a “black box” model with high learning ability. This model is not only accepting multiple inputs but also adapts and learns from historical data. In addition, it can improve the convergence speed and prediction accuracy (Tan et al., 2018), though comprehensive research is still needed on an industrial scale.

3.3. Post-digestion management

3.3.1. Methane purification and utilization

Although the quality of raw biogas depends on the type of reactor, the operating environment and the microelement composition of the substrate, the biogas derived from the typical AD of FW usually contains 55–60% of CH_4, 40–45% CO_2, and 0.1–3.0% H_2S (Selvam et al., 2021).

Additionally, it includes other undesirable and dangerous elements like Si, VOCs, CO, NH_3, siloxanes, etc. Such biogas portions are dangerous and highly corrosive despite their low concentration, harming combined heat and power units and metal components (Uddin et al., 2021). There are some specific factors associated with the formation of such gases in biogas from ADFW. First, since each FW varieties have its major macronutrient (i.e., proteins, lipids, carbohydrates, and cellulose) the change in varieties such as fruit, vegetable, or bakeries, etc results in a variable concentration of gases. For FW which mainly contains vegetables, the chance of H_2S formation would be low owing to the low amount of sulfur present in vegetables (Marín et al., 2022). Second, the operational parameters could also be contributing to variable biogas composition with, for example, high OLR leads to high H_2S and CO_2 concentration because lower reaction ratio of methanogenesis (Cheng et al., 2018). Thirdly, the addition of external chemicals like biochar, activated carbon, iron nanoparticles and injection of H_2 and O_2 gas during AD operation could enhance the quality of methane produced from FW. As an illustration, the chance for the formation of H_2S can be initially reduced during AD operation through a chemoautotrophic biological CO_2 conversion process. This process can be conducted by supplying hydrogen gas (H_2), which influences a temporal microbial shift in substrate utilization from dissolved organic nutrients to H_2 and CO_2. As a result, the release of hydrogen as degradation goes advanced, further boosting hydrogenotrophic methanogenesis. With a 12.1% rise in biomethane and a 38.9% decrease in CO_2, the biogas upgrading was improved as a consequence (Okoro-Shekwaga et al., 2019).

While hydrogen sulfide generation is significantly decreased when a small amount of oxygen is added, the rate of methane production does not change and may even rise. FW-derived biogas with an injection of a small content of O_2 gas also had low siloxane and halocarbon concentrations made up mostly of D4 (decamethyltetrasiloxane) and D5 (dodecamethylpentasiloxane) species (Y. Li et al., 2019). However, barely detectable Siloxanes (20 ppbv) are might be expected in a FW originating from industrial areas. In the case of the Co-digestion of FW, some amount of terpenes could be formed (Calbry-Muzyka et al., 2022). Nevertheless, the proper dosage of these additives for ADFW has yet to be assessed unless it would be a detrimental effect on the digester environment and its output (Linville et al., 2017).

Even with the presence of the above-mentioned non-methane gas reduction strategies, the biogas still needs to be purified or upgraded to be equivalent to natural gas (i.e., CH_4>95%). However, the main question is the selection of suitable purification techniques that consider cost, material and energy demand, unique biogas needs, local site conditions, and other case-sensitive factors. There are several methods for cleaning gases, including adsorption, scrubbing, membrane separation (Žák et al., 2018), cryogenic liquefaction (Byun & Han, 2021; Yousef et al., 2018), desulfurization (Abdeen et al., 2016), biofiltration, or biomethanation (Deschamps et al., 2021), though physical absorption and chemical adsorption are the most effective and simple (Lora Grando et al., 2017). Water scrubbing is a physical absorption method that is more suitable for moderate and colder climates (Budzianowski et al., 2017). This method shows high exergy efficiency (Vilardi et al., 2020), low operation and maintenance costs, along with low energy consumption, while the lowest capital cost refers to membrane separation plants (Baena-Moreno et al., 2019). On the other hand, the biomethanation process imposed a significant environmental and economic impact due to the use of high energy for H_2 generation, implying that H_2associated issues should be resolved in the future (Tian et al., 2021). Technically, chemical adsorption gives high-purity CH_4, and cryogenic separation is much better in reducing CH_4 loss during the purification process. However, the environmental impact of each purification method primarily depends on where the absorbed/adsorbed or filtered CO_2 goes (i.e., released or used for other purposes). Therefore, further research is needed on the use of biogas impurities, especially for large-scale operations.

3.3.1.1. Exergy analysis

After the purification step, the CH_4 is ready to be supplied to consumers by direct injection into the gas pipeline network to heat or convert it to electrical power. Methane is usually converted to electrical power through CHP and combined cycle system technologies in the full-scale AD plant. The general electrical efficiency of these CH_4 power generation technologies can range from 15 to 45% (Tian et al., 2021). Their feasibility is mainly associated with heat demand and investment costs. Meanwhile, the overall feasibility of CH_4 production through the AD process can be judged by the exergy efficiency. Exergy, unlike energy, is a qualitative analysis of the CH_4 working potential produced in a thermodynamic equilibrium system boundary. The total exergy efficiency in the production of CH_4 from FW can be determined by Eq. (1), which is the ratio between the exergy of CH_4 and the total exergy input. The methane exergy can be determined by Eq. (1).

$$Ex = (H - H_0) - T_0(S - S_0) \tag{1}$$

Where H and S are the enthalpy and entropy of the material, respectively, H_0 and S_0 are the enthalpy and entropy of the material at the temperature of T (25 °C) and the pressure of p (1 atm), respectively (Xiao et al., 2019).

4. Lessons learned from the case studies

Several case studies on an industrial-scale ADFW process from different countries are discussed in the supplementary information. The collection and diversion of FW from sources worldwide is a concern that must be resolved quickly in the future. FW treatment plants in different countries have followed different operating and application scenarios. The performance of each plant also varied because of their differences in the overall design, input content, and climate. Large-scale central AD plants in China are mostly built for wastes originating from restaurants and kitchens serving major cities. Being large in scale or centralized in design makes them advantageous in densely populated areas associated with high waste output and disadvantageous because of high energy consumption and infrastructure cost. Although those plants are adopted in-situ and post-AD processes including digestate treatment, there is still some practical gap in the source-to-site management of FW. On the other hand, there is a potential to create bio-fertilizer to close the loop on resource recovery since most Chinese AD plants (e.g., Hangzhou Tianziling FW treatment plant) are equipped with digestate treatment facilities. The number of AD plants in Europe is significant, but the size of one project is tiny and usually serves communities or villages. Some FW treatment plants have not yet fully utilized their potential due to a shortage of suitable substrates or technical limitations such as poor reactor performance. In this case, there is a need to facilitate the FW supply chain even with neighboring states/countries that are good at it and to strengthen human power, such as well-trained operators and engineers in the field. In terms of the treatment process, though, there is a green light for introducing AI-oriented waste management at the source and integrating it with the main AD operation. When the technology reaches its maturity stage, it could lead to a more resilient FW bioconversion process in particular and municipal solid waste management in general. Some AD plants in Europe, for example, the UK's Poplars FW to energy plant, are also equipped with an advanced odor-controlling system, which is crucial especially if the plant is installed in nearby villages. It is noted that the ADFW plants be located near existing water treatment facilities because the ADFW plants have a small land footprint and the proximity to existing features can reduce costs. Additionally, the decentralized system with a central control system provides a better operation trend, occupies a smaller area, has lower GHG emissions than centralized AD systems, and is most suitable for densely populated cities.

Setting new rules and organizing financial aid for the AD project, increasing taxes for landfill and incineration to encourage AD as a last resort and implementing obligatory FW measurement and reporting for all significant farm-to-fork food enterprises are recommended strategies for successful FW resource recovery.

5. Food waste anaerobic digestion contribution to the carbon neutrality efforts

In particular, FW has become a global concern due to its quantitative increase and potentially adverse effect on the environment. More than 1.3 billion tons of FW are estimated to be generated along the entire food supply chain and emit ~6% of the total anthropogenic GHG (Amicarelli et al., 2021). Therefore, any attempt to stop the potentially dangerous effect of organic waste while taking advantage of the chemical composition of these wastes to produce renewable energy is a pillar for building a safe environment, a green economy, and a healthy society (Negri et al., 2020). In this context, AD plays an important role in reducing FW environmental burdens in soil, water, biodiversity, and air (GHG, CH_4, and CO_2) (Ambaye et al., 2021). If all household FW in the UK, for example, were treated via AD, biogas could cover approximately 0.37% of the national electricity demand in the UK and save 190,000 t CO_2 equivalent/year compared to the grid electricity (Slorach et al., 2019). According to Jin et al. (2021), the reduction in carbon from biogas generation is 46.68 kg CO_2/t Chinese FW, and the global warming of the use of electrical power produced from the AD of this waste is 43% lower than that of the conventional grid. However, the carbon footprint of the smart FW collection network over the conventional one needs to be assessed for compressive figurative judgments.

On the other side, FW-derived CH_4 and biofertilizers through AD could reduce CO_2 emissions by replacing fossil fuels and mineral fertilizers. The global warming potential of the energy system and the substitutions of AD biosystem (mineral fertilizer) substitutions are -341 and -312 kg of CO_2/tons, respectively, followed by a huge gap with the substitution of composting biosystems

(360 kg CO_2-eq/ton), the energy system of landfill energy systems (1476 CO_2-eq/ton) and the incineration of FW (405 CO_2-eq/ton) (Bernstad Saraiva Schott et al., 2016; Thyberg & Tonjes, 2017; Xu et al., 2015). Herein, ADFW and other manure-based substrates are particularly favored for carbon neutralization rather than for the use of energy crops (Scott & Blanchard, 2021). However, in the absence of a robust AD system and consistent emission measurements, AD itself could be a potential source of pollution by emitting 0.02 to 8.1% of the total produced CH_4 (Bakkaloglu et al., 2021). Furthermore, some fugitive CO_2 is released into the environment mainly during the post-AD stage; biogas upgrading and combustion. Although several studies have argued that biogas-derived CO_2 is considered biogenic on a mass basis and is calculated to be neutral in terms of the climate effect (Paolini et al., 2018), its potential to cause global warming while it remains in the atmosphere should not be ignored (Anil, 2014; Berndes et al., 2016; Cusenza et al., 2021). Thus, researching a possible biogenic CO_2 valorization method is maybe arguable. To illustrate, the biological bioconversion of CO_2 to CH_4 by methanogenic archaea without adding H_2 and thermochemical valorization pathways are a contemporary area of interest. In the former case, the reduction of CO_2 by homoacetogenesis followed by acetoclastic methanogenesis was proposed as a CO_2 utilization mechanism, which requires validation by radio-labelling or carbon isotope analysis (Bajón Fernández et al., 2019). The thermochemical pathway, however, is blamed for changes in alkalinity levels, increases in H_2 levels, and dissolved CO_2 levels since increased CO_2 gas solubility in aqueous environment results in the formation of carbonic acid (H_2CO_3), which then dissociates into protons (H^+) and bicarbonates (HCO_3^{2-}) (Bajón Fernández et al., 2017), Therefore, more studies are needed to determine the optimum CO_2 injection parameters for efficient carbon management during the AD process.

6. Techno-economic challenges and prospects

Above all, raising a positive attitude toward FW prevention in the community is more sustainable than any other advanced FW management. Beyond that, the FW physicochemical properties can easily be changed, as it easily susceptible to natural elements and fluctuations in weather conditions (Awosusi et al., 2021). This could be exacerbated by poor storage and source-separated collection facilities. Most importantly, the change in the textural or morphological properties of FW affects its biogas production potential. However, these properties along with their modification mechanism remain unclear, since studies so far have mainly focused on chemical and macro-physical properties. From an economic point of view, the longer distance between the AD plant and the origin of the FW refers to the increased operating cost of the plant. Thus, further research must focus on AI-supported raw FW safety preservation and strengthening the source-to-site transport optimization, thereby reducing the onsite pollution and overall operational cost. In addition, it is important to assess the spatio-seasonal behavior of FW to be anaerobically digested to investigate the potential effect of FW sources (point and non-point) and seasonal change on AD efficiency. Moreover, there is limited research output on the utilization of FW impurities, particularly through the integrated or in situ impurities management system. In AD operation, low CH_4 yield and unstable processes are governed by substrate pretreatment, reactor design, and key control parameters. These are by far the major steps for the overall success of bio-energy production plans from organic waste such as FW. However, since each pretreatment method has faced technical, economic, or environmental issues, the combined application of such methods, for instance, a hybrid thermomechanical process, can be an interesting option. In addition, the development of a reactor with compressed size and high resistance to change in ambient temperature is necessary, especially for cooler or hot regions. Most importantly, at the initial stage of designing AD systems, the actual quality and quantity of

FW in the region or country must be considered based on where the system is to be deployed, rather than just importing from abroad without preliminary assessment. In the post-digestion of FW, solvent degradation and energy loss during biogas purification are a big challenge, especially for large-scale plants. Although more research is yet to come, the deployment of sound and feasible CH_4 in the natural gas pipeline network technology and purification method to use it as a vehicle fuel and bio-SNG are encouraged to increase the biogas (Linyi et al., 2020). Current work shows that there is still substantial room for the recovery and utilization of in situ biogas impurities to ensure the sustainability of the system.

Miscellaneously, FW can be managed by engineered equipment and public awareness development. Thus, publicizing the concern for food waste and strengthening the policy toward obligatory FW recycling management among FW producing agents and the market-oriented AD operation through the promotion of private investment in the field are urgent actions. Furthermore, there are fugitive CH_4 losses from faulty engineered equipment, weakly constructed and ad-hoc materials, and poorly controlled operations. As also noted from the case studies, there is a great technological and management gap in pilot-scale and industrial-scale AD projects. Addressing such challenges in the ADFW process can help advance the CH_4 production chain, thus ensuring plant sustainability.

7. Conclusions

This paper reviews the present state of research progresses, challenges and prospects for advanced FW-derived CH_4 production processes. A FW composed of high content of moisture and organic matter is beneficial. On the contrary, FW with unproportioned microelements and macro-elements, C/N ratio and high protein content is unsuitable for CH_4 production. Adopting optimized transportation and an AI-supported FW collection system is crucial to reducing the cost and carbon associated with the digestion process. For FW with minor impurities, conditioning alone through mechanical means can be fed directly into the AD reactor without further pretreatment. Beyond that, the thermomechanical method can be applied as a feasible and feasible techno-economic pretreatment option. However, it should be noted that the adoption of an integrated impurity management system is necessary to increase both the economic and environmental sustainability of ADFW. The Co-FW substrate, principally with sewage sludge, shows a stable AD process and better CH_4 yield compared to FW alone. Decentralized AD with an AI-supported and/or computerized reactor configuration demonstrates effective CH_4 yield. High-purity CH_4 can be obtained from the chemical adsorption purification method. The exergy analysis allows quantifying the overall thermodynamic potential of FW-derived CH_4. The ADFW plants be located near existing water treatment facilities because the ADFW plants have a small land footprint and the proximity to existing features can reduce costs. Integrating a digestate treatment facility, reducing investment costs, increasing the power export rate, and adopting a self-energy reliance system can assure the overall sustainability of the ADFW plant. Source-to-site logistic optimization, smart collection networks, impurity management, management systems (for in situ impurities, substrate, and biogas), development of a weather-change resistant reactor, and market-oriented policy support are the main areas of interest in the literature.

Declaration of competing interest

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

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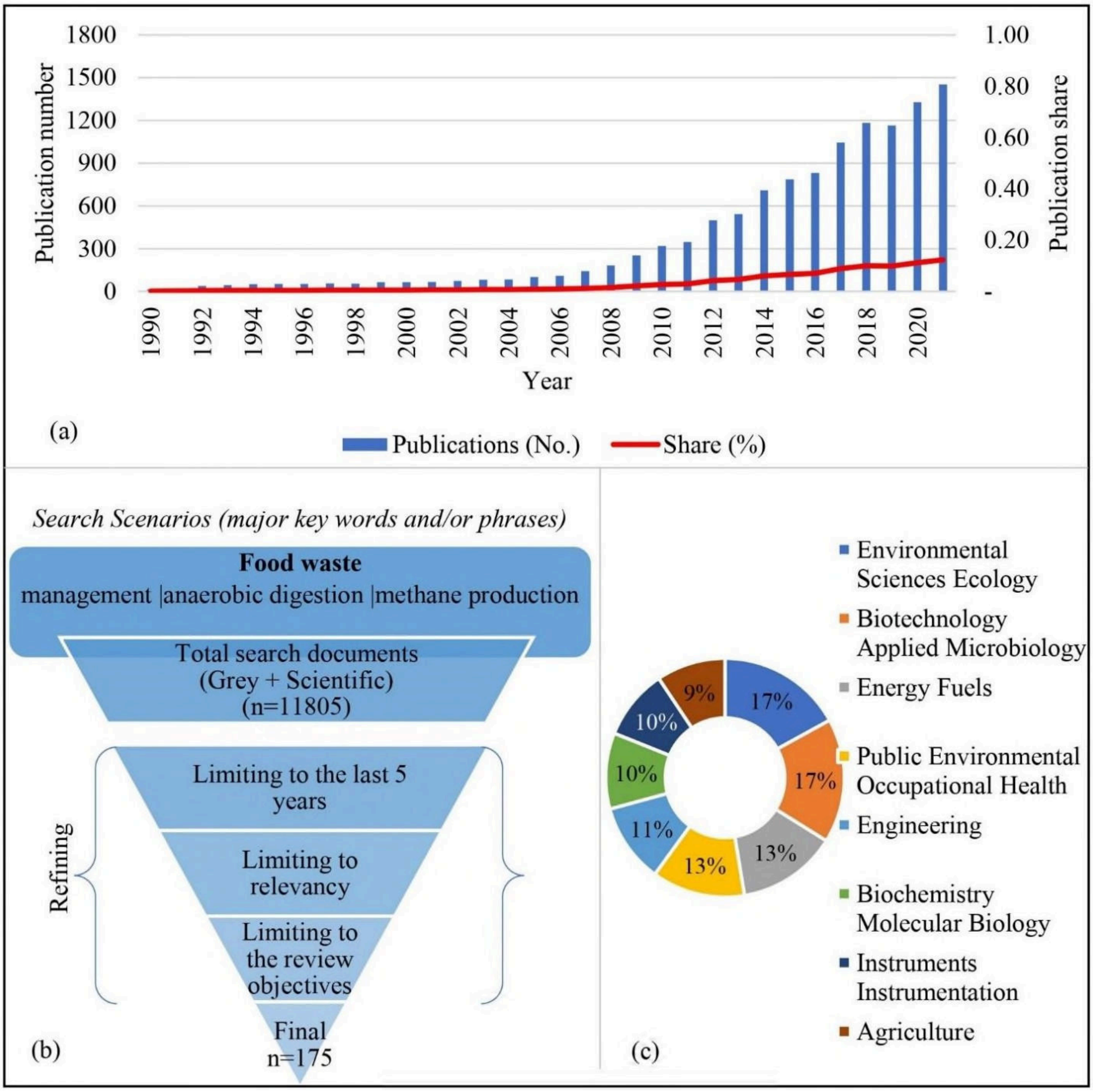
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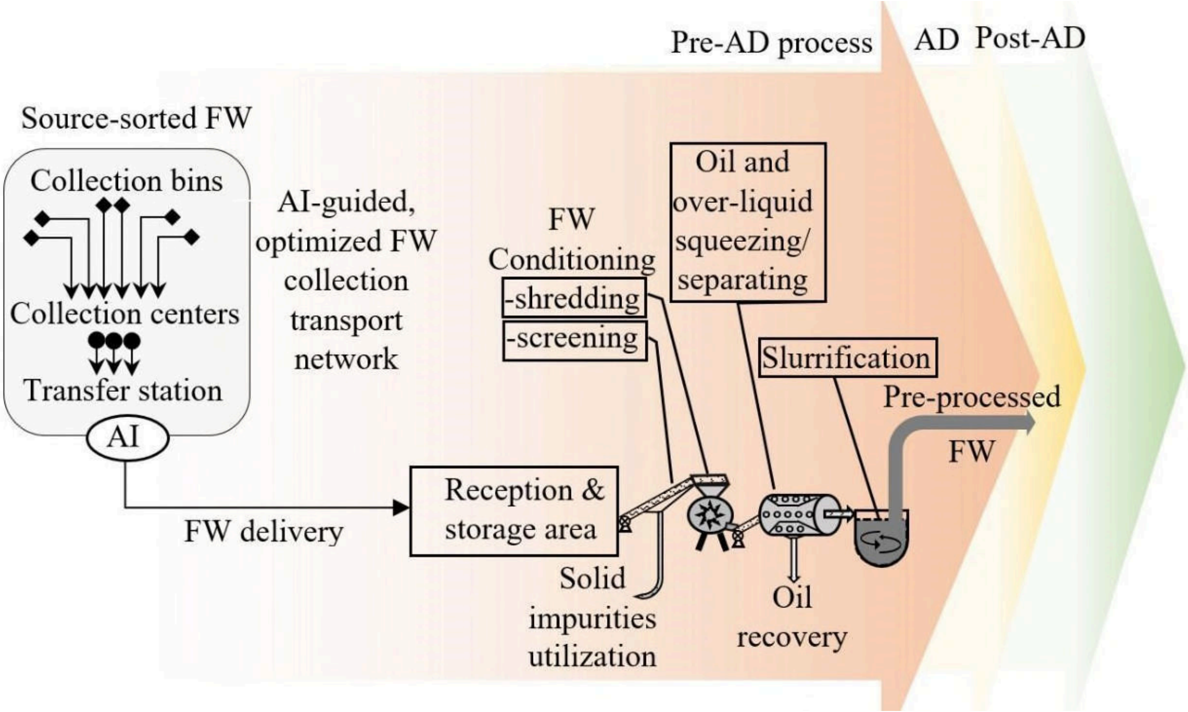
Figure 1



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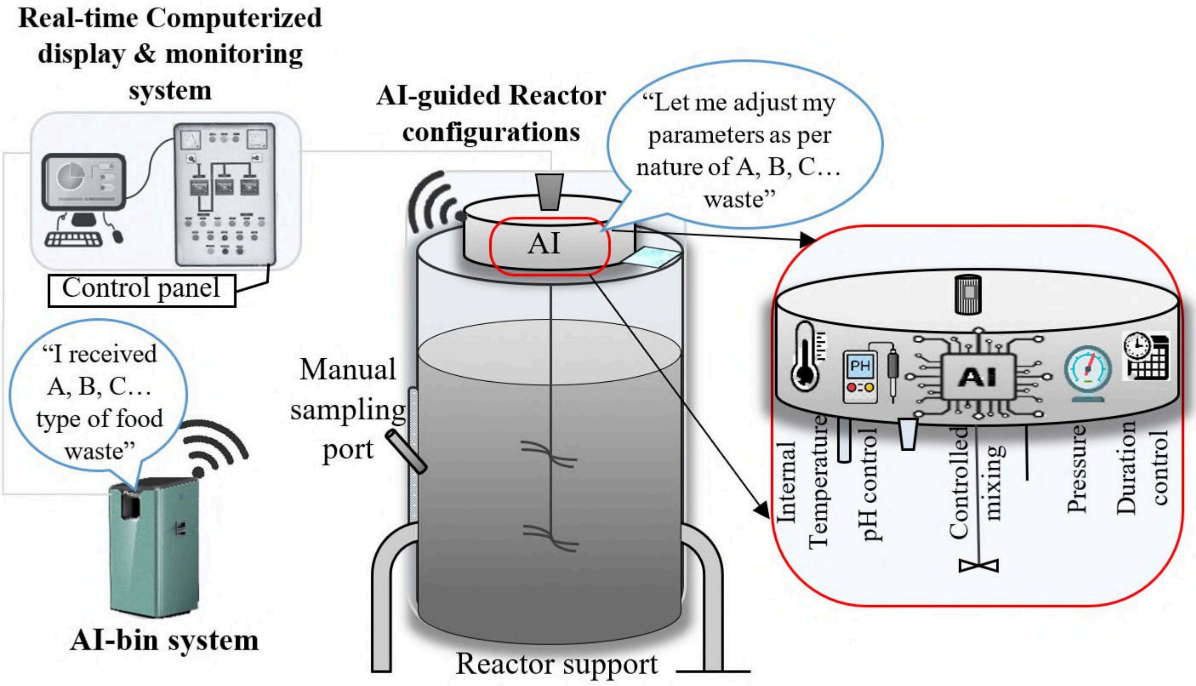

Figure 3