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# Latest research progress on food waste management: a comprehensive review

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**Abstract.** Since a large amount of food supplying is provided as a basic line measuring increasing residents' life standard, food waste has become progressively numeral considerable. Much attention has been drawn to this problem. This work gave an overview on latest researches about anaerobic digestion, composting, generalized management and other developments on management of food waste. Different technologies were introduced and evaluated. Further views on future research in such a field were proposed.

## 1. Introduction

Food waste (FW) is composed of household food waste, food-processing waste, canteen and restaurant waste, which is one of the components of municipal solid waste [1]. The accumulation of FW cannot be neglected because of tremendous environmental and sanitary problems with it. FW amount is estimated to quickly increase from 2.78 billion tons to 4.16 billion tons in Asian countries by 2025[1]. About 1.3billion tons of food, fully one-third of all food produced is lost along the food supply chain every year [7]. While economy is still accelerated, FW grows larger at the same time. However, it is significant to see that FW management also takes an important role in the renewable energy and sustainable development for values like Biomethane potential(BMP) of FW. With rising attention being moved on this field, technologies developments for this have been made continually.

Anaerobic digestion (AD) has always been the hot research trend for its relatively cost-effectiveness, renewable energy production and waste treatment of high-moisture and energy-rich material [2]. During AD process, biomass and organic fraction of municipal solid waste (OFMSW) can be converted into combustible biogas (mainly methane, and other gases like hydrogen and hydrogen sulfide) [2]. Parameters such as methane yield and volatile solids reduction or so were used to assess experiment performance. In order to enhance methane generation performance, various aspects of AD were researched. Additive supplementation, operational alternations, parameters optimization and microbial actions have been discussed by researchers. In addition to AD, composting, co-pyrolysis and other FW managements pathways also have been conducted to research results. At the same time, investigations and sorting systems were made for governments to implement better decisions on FW management.

This paper aims to critically give an overview on latest research progress and novel developments of FW management in 2018. Further views on future research needs in such a field were proposed simultaneously.



Table 1. Abbreviation

AC	Activated Carbon	OLR	Organic loading rate
AD	Anaerobic digestion	PA	Partial alkalinity
ADS	Anaerobic digestion sludge	RFW	Restaurant food waste
BC	Biomass concentration	SCOD	Soluble COD
BMP	Biomethane potential	SC	Substrate concentration
COD	Chemical oxygen demand	TCOD	Total COD
EE	Ether Extract	TPAD	Temperature-phased anaerobic digestion
IA	Intermediate alkalinity	TS	Total solids
IoT	Internet of Things	VS	Volatile solids
OFMSW	Organic fraction of municipal solid waste	VFA	Volatile fatty acids

Table 2. Characteristic comparison of different anaerobic digestion experiments.

Reference	Country	Source	CH <sub>4</sub> yield/ (m <sup>3</sup> /kg VS)	OLR/(gVS·L <sup>-1</sup> ·d <sup>-1</sup> )	TS	VS	VS/TS	C/N	pH	Explanation
Zhang et al., 2018	Singapore	FW: a university canteen	0.659	1.6	28.6%	27.42%	0.96	17.33	7.25	Add AC
Park et al., 2018	Korea	FW:a university cafeteria	0.32	2.5	170230g/L	158270g/L	0.93	-	7.4	Continuous diluted FW feeding
Ghanimeh et al., 2018	Lebanon	-	0.405	0.5	33.1%	31.2%	0.94	-	5.1	Various mixing intensities
Xiao et al., 2018	China	-	-	-	10.69%	10.06%	0.94	-	4.18	TPAD
Micolucci et al., 2018	Denmark	-	0.88	-	29.82%	26.76%	0.90	-	8.0	Single/double-stage thermophilic AD
Parra-Orobio et al., 2018	Colombia	FW:a University restaurant	0.14	-	110730mg/L	93410mg/L	0.8	33.6	5.6	Trace elements optimization
Li et al., 2018	China	FW:a school canteen	0.90	-	3.65%	2.42%	0.66	7.01	7.34	EE/VS and F/I ratios
Hobbs et al., 2018	USA	FW:University	0.639	-	34.1g/L	24.8g/L	0.73	-	6.8	ratio

## 2. Anaerobic digestion

Anaerobic digestion (AD) is a multiple process that involved actions of bacteria and methanogenic archaea. The decomposition of organic matter could be divided into four stages of hydrolysis, acidogenesis, acetogenesis and methanogenesis. During this process, macromolecular organic matter is broken into easily dissolved monomers and then smaller molecules of short-chain fatty acid, amino acid, pyruvic acid, acetic acid and so on. They finally are digested into hydrogen and acetic acids which are transformed into methane by methanogenic archaea [1], while FW is regarded ideal for AD biomethane potential estimated at between 200 and 670ml CH<sub>4</sub>/g added VS [7].

AD is drawing increasing attention because of its high valorisation value for waste and it offers opportunities for energy renewable and nutrient reclamation. Compared to landfilling, AD requires less requirement for space and input energy to operate and is still potential for efficiency enhancing [3]. In order to improve the methane yield and give advice on this, latest researches on additive

supplementation, operational alternation, parameters analysis and microbial action and communities were conducted. Characteristic comparison is made in the Table 2.

### 2.1. Additive supplementation (activated carbon)

Additive supplementation is a strategy for enhancing AD performance which has advantages of easy application, economical cost and no change of digesters. As a effective additive, activated carbon (AC) is thought to be an promising carbonaceous material applying in AD process. AC as an amorphous carbonaceous material with high surface area has high absorption ability, which can be a good immobilization matrix for bacteria growth and can easily prepare via steam activation from char [4].

Zhang et al. [4] conducted experiments in various sizes of digesters - 1 L, 8 L and a pilot-scale 1000 L to investigate effects of adding AC into AD process. They made the determination of optimal dosage of AC at least  $12 \text{ g/L}_{\text{working volume}}$  in the 1L lab-scale experiments and this optimal dosage of 15 g AC per L was applied in the larger digester experiments. Results of 8L showed that AD process with AC supplementation resisted higher OLR impact and had better stability under the same OLR condition compared to the control. Abundance of predominant phyla Firmicutes, Elusimicrobia and Proteobacteria were enhanced by 1.7-fold, 2.9-fold and 2.1-fold, respectively in 8L experiment. Pilot-scale results exhibited that average methane yield was improved by 41% from  $0.466 \text{ L} \cdot (\text{gVS})^{-1} \cdot \text{d}^{-1}$  to  $0.659 \text{ L} \cdot (\text{gVS})^{-1} \cdot \text{d}^{-1}$  at optimal OLR of  $1.6 \text{ g VS}_{\text{FW}} \cdot \text{L}^{-1} \cdot \text{d}^{-1}$ . Great color removal from the liquid phase of the digestate was also to be found [4]. Activated carbon supplementation method is useful for improving the performance of industrial AD plants for biogas production.

Search for different additive supplementation that can influence and adjust AD conditions like pH, consortium of bacterial, average particle size is important. Researches of additive applying could keep drawing attention on different fine peculiarities of materials and make full use of them in AD digester structure and internal environment.

### 2.2. Operational alternation

For AD process is taken place in designed digesters (fermentation reactors) and experiment is operated by certain procedure, many researches has drawn on reactor structure, whole AD system and operation steps to obtain an ideal methane yield. Different operational strategies were adopted and investigated in latest researches.

Effect of feeding mode and dilution on the AD performance was studied by Park et al. [5] and the result showed that the highest methane productivity of  $325 \text{ L CH}_4/\text{gCOD}$  was achieved at  $8.6 \text{ kg COD/m}^3/\text{d}$  under continuous feeding mode of diluted FW. Stepwise feeding mode without dilution had a lower performance and instability because of insufficient contact between substrate and microorganisms and decrease of effective volume. Ghanimeh et al. [6] put the research on varied mixing intensity strategy in thermophilic FW anaerobic digestion. They found that high mixing velocities (120 and 160 rpm) were harmful to the digestion process with 18-30% reduction in methane yield and 1.8 to 3.8 times increase in VFA concentrations which has inhibitive effect on AD process when VFA content is overmuch. The best methane generation ( $573 \text{ ml/gVS}$ ) was brought by the mild 50 rpm mixing speed and a stable operation was existed in this moderate intensity (50-80 rpm), retaining an IA/PA ratio below 0.4, VFA concentrations below  $2 \text{ g/L}$  and TCOD and SCOD removal rates of 83-85% and 75-83%, respectively.

An single-stage thermophilic anaerobic digestion (TPAD) process was researched by Xiao et al. [7]. TPAD is composed of a short thermophilic pretreatment stage followed by a second mesophilic stage over a longer retention time. Xiao et al. got the result that the biogas and methane yields of  $0.759 \text{ L/g added VS}$  and  $0.454 \text{ L/g added VS}$  in the TPAD were lower than those in the single-stage AD processes during the steady period, and the improper sludge retention time may be the reason for this lower methane production. On the basis of traditional single-phase AD research, two-phase anaerobic digestion system was considered as more efficient way to increase methane generation than a single-phase one by a lot of researches [1]. In a two-stage AD system, hydrolysis and acidogenesis happen in one reactor and acids utilization takes place in another one. Micolucci et al. [8] set a pilot scale system

composed of single and double-stage thermophilic AD parts and made comparison between them. The results indicated that the two-stage system had a specific gas production 17% higher than the single-stage and its specific methane production reached 0.55 L/kgVS while the single-stage was of 0.45 L/kgVS.

Optimization in AD reactors and experimental strategies is a necessary procedure to find novel ways in enhancing biogas and methane yield. Condition disturbance in experiments are worthy of attention to seriously monitor and thoroughly analyze in order to discover improvement points of parameters and operations. Two-stage AD system is still an important direction of research.

### 2.3. Parameters optimization

Various parameters of AD process such as substrate concentration (SC), biomass concentration (BC), substrate/inoculum ratio (S/I) or feed/inoculum ratio (F/I), trace elements concentration characterize properties and affect stability of each certain AD process and different useful optimization researches about them were implemented.

Li et al. introduced various kinetic models to evaluate digestion kinetics and gave correlation of kinetic parameters with operational conditions and process performance [9]. In first-order kinetic and modified Gompertz models,  $k$  is the hydrolysis rate constant ( $\text{d}^{-1}$ ) and  $R_m$  is the maximum methane production rate ( $\text{mL}\cdot\text{gVS}^{-1}\cdot\text{d}^{-1}$ ). A novel indication of the results is that the  $k/R_m$  was negatively correlated with process efficiency while the methane recovery rate exceeded 90% at  $1.55 < k/R_m < 3.13$  but was reduced by 50% at  $k/R_m > 4.64$  ( $p = 0.05$ ). The  $k/R_m$  was influenced by substrate load (SC and S/I) positively via its effects on VFA and pH but negatively by BC for BC increased the alkalinity of the system [9]. Parra-Orobio et al. found that the content of trace elements indeed altered the requirements and methane generation of the AD process [10]. Potentially inhibitory concentrations of Zn and Al negatively affected methane production ( $<70 \text{ mL CH}_4\cdot\text{gVS}^{-1}$ ), the hydrolysis constant ( $<0.19 \text{ d}^{-1}$ ), and the lag-phase ( $>7$  days). Moreover, high concentrations of trace elements of Ni (35.2 mg/kg) and Mo (15.4 mg/kg) in the inoculum improved methane yield ( $140.7 \text{ mL CH}_4\cdot\text{gVS}^{-1}$ ) and hydrolysis constant ( $>0.18 \text{ d}^{-1}$ ) and presented short lag-phase ( $<1$  day) in the AD [10].

Feed/inoculum (F/I) ratio as the predominant factor affecting AD was set tests by Li et al. [11] And Hobbs et al. [12]. Li et al. performed batch tests to estimate the effects of waste cooking oil content (33-53%) and feed/inoculum (F/I) ratios (0.5-1.2) on biogas/methane yield. They concluded that the F/I ratio lower than 0.70 could maintain a high biogas conversion ratio (82-94%) with high organics reduction and a short lag time (267-430h) because high EE/VS ratios brought possible inhibition. The optimum EE/VS and F/I ratios for the AD of FW are 43% and 0.70. Hobbs et al. [12] used Anaerobic digester sludge (ADS) as the inoculum and obtained the highest  $\text{CH}_4$ -COD recovery at the 1.42 ratio: 90% of the initial TCOD from FW followed by ratios 0.42 and 3.0 at 69% and 57%, giving the best balance of high methane yield with a short lag time [12].

In the AD process research, proper analytic model like the Gompertz model etc. are significant to present assessment of experiment results. Parameters of the model taken and specific experimental measuring are highly meaningful to be investigated so as to illustrate more detailed mechanism of AD and reach optimization for best energy conversion and system stability.

### 2.4. Microbial action

Anaerobic digestion is a complex and multistep microbial process that involves cooperation between microorganisms which can be divided into bacteria and archaea [1]. Microbial communities differ in each specific experiment for different inoculum or sludge sources and compositions. Sequencing technologies like pyrosequence allow researches detect microbial constituents and changes in AD process.

Distribution's change and characteristics of microorganisms is observed as a part of AD experiment. Park et al. found increase of *Proteiniphilum* spp. and concurrent propionic acid accumulation in deterioration period of AD. The distribution of bacteria and archaea presented little change according to OLR when the mode of diluted FW and continuous feeding was adopted [5].



Ghanimeh et al. set digesters under various mixing velocities and they were all dominated by one bacterial genus (*Petrotoga*; phylum *Thermotogae*) but at 0 rpm by another bacterial genus (*Anaerobaculum*; phylum *Synergistetes*) [6]. Zhang et al. got the AC supplemented results that the abundances of predominant phyla *Firmicutes*, *Elusimicrobia* and *Proteobacteria* were selectively enhanced by 1.7-fold, 2.9-fold and 2.1-fold, respectively [4].

Realizing more about microbial actions and mechanism of AD is beneficial for further optimization and kinetic adjustment during the process. It is also useful for further research to isolate archaea and bacterial strains and exploit their potentials from specific single strain and combined strains.

### 3. Composting

FW composting is the developed technology that organic matter of FW could be decomposed and recycled as a fertilizer and soil amendment. In composting process, FW known as green waste contributes of making a heap of wet organic matter. Real-time parameters of composting process were monitored and novel operations were put to illuminate mechanism of FW composting, improve degradation efficiency and make better use of composting technologies in FW managements in various conditions.

Margaritis et al. set a study on the process of composting in a prototype home-scale system specially focusing on process improvement by using different additives (i.e. woodchips, perlite, vermiculite and zeolite). In terms of efficient temperature evolution ( $>55^{\circ}\text{C}$  for 4 consecutive days), the case of zeolite and perlite provided the best results decreasing C/N ratios by 40% from the initial values among additives while they all enhanced composting process [13]. Wang et al. investigated the odour emission during composting under the influence of lime addition, and struvite formation. They found that trapping ammonia through struvite formation greatly reduced the maximum odour unit of ammonia from  $3.0 \times 10^4$  to  $1.8 \times 10^4$  and the variation of total bacterial was improved in treatment of phosphate salts addition with struvite formation [14]. Giwa et al. connected composting with pyrolysis in their research. They found that the composting residues (mixture of lignin, bone, and plastic at a ratio of 69:18:12) could be a suitable feedstock for pyrolysis from the energy aspect with activation energy ranging from 25.68 to 41.89 kJ/mol and the lower heat value of around 15.72 MJ/kg [15].

Methods taking composting residues as value-added byproducts are of promising prospect to improve the use ration of FW in its life circle and efforts on seeking procedures designing of further organic matter reduction should be paid.

### 4. Generalized management

General FW management is constructed on the basis of political decisions and nation's collection and arrangement systems. Residents individual life preference and society collective factors all have impacts on the efficiency of recycling along the whole food life cycle.

The waste hierarchy, introduced by the Waste Framework Directive, has been the rule followed to prioritize food waste prevention and management measures. Cristóbal et al. in Europe addressed the situation where a decision maker has to design a food waste prevention programme considering the limited economic resources and the results highlighted that to set the targets at the level of environmental impact is of importance instead of setting the targets at the level of avoided food waste generation (in mass) when FW prevention strategy requires planning [16]. While in China, Wen et al. studied a case on evaluation of a sensor-based Internet of Things (IoT) network technology for restaurant food waste management. Advantages of the IoT system were concluded of better management of RFW generation (a 20.5% increase), better process optimization across the RFW value chain and better law enforcement due to its monitoring capabilities in response to RFW malpractice [17]. Fadi Abdelradi made a survey on the behavioral model of 1000 respondents in Egypt and concluded that the individuals perception about food waste was related with food quantities wasted at the household level [18]. Pålledal et al. carried comparison experiments on FW collection methods and found that more biomethane from OFMSW was collected in plastic bags during the warm season, since they have a more preservative effect on OFMSW than paper bags [19].

Researches and investigations of residents individual waste behavior and better municipal trash regulator control are still needed for optimal decision making by governments and relevant corporations.

## 5. Other latest researches

Studies of FW management are distributed in many aspects from proper FW dispose, application in energy conversion and substrates for reactions etc.. Maragkaki et al. fed dosages of thermal dried mixtures of food waste, cheese whey and olive mill wastewater at 3%, 5% and 7% concentrations in anaerobic co-digestion of sewage sludge. Reactor generated 287 ml CH<sub>4</sub> /L<sub>reactor</sub>/d before the addition and then 815 ml CH<sub>4</sub> /L<sub>reactor</sub> /d (5% v/v in the feed) [23]. Pahla et al. took torrefaction of landfill food waste and the calorific value was upgraded from 19.76 MJ/kg for dried raw food waste to 26.15 MJ/kg for torrefied food waste at the appropriate conditions which were 275 °C, 40 min and 10 °C/min [24]. Co-pyrolysis characteristics of organic food waste and plastic were analyzed by Tang et al. They measured that the reaction activation energy needed were 2-13% lower for the mixture degradation compared with linear calculation while the maximum reaction rates were 12-16% higher than calculation [25].

Researches on specific archaea and bacterial strains were conducted and impressive results were showed. Awasthi et al. isolated four potential thermophilic amylolytic and cellulolytic bacteria producing amylase and cellulase enzymes at a wide range of temperature (40-80 °C) and pH (4.0-10.0) which belong to the amylolytic strains, *Brevibacillus borstelensis* and *Bacillus licheniformis*; cellulolytic strains, *Bacillus thuringiensis* and *Bacillus licheniformis*, respectively. Furthermore, 1:1 ratio of pre and post-consumed FWs were adequately degraded by the inoculation of bacterial consortium [20]. Johnravindar et al. employed food waste leachate as a substrate for evaluating lipid accumulation potential of different oleaginous yeasts and found that better VFAs removal could be achieved by using *Yarrowia lipolytica* that accumulated a maximum of 48% lipid in total biomass while acetic acid up to ~31 g/ L would be toxic for *Y. lipolytica* [21]. Awasthi et al. isolated a novel thermophilic bacterial strain and then developed a bacterial consortium for bio-degradation of oily FW and concluded that the bacterial consortium could reduce oil more efficiently compared to single bacterial strain [22].

## 6. Further views

Food waste management involves a lot of aspects from source characteristics of FW to combined applications with other substrates. Further researches could focus on these several directions: (1) Understanding more thoroughly about microbial actions and mechanism of AD process to give precise control and ensure the stability of the process. (2) Isolating archaea and bacterial strains and to exploit their potentials of specific strain and combined strains are useful for increasing methane yield in AD. (3) Search for efficient additive during AD process is worthy of attention. (4) More separate experimental parameters and their relationship in AD could be monitored and analyzed. (5) Two-stage AD system is worth of more study to make best advantages of it compared to single-stage system. (6) Applications taking composting residues as value-added byproducts are of promising prospect to improve the use ration of FW in its life circle and seeking procedures designing of further step organic matter degradation should be taken. (7) Residents individual waste behavior could be investigated to make better civil FW prevention and provide suggestions for governments and relevant corporations. (8) Appropriate FW sorting and collecting system designing is significant work with calculation technologies' high-level development. (9) Developing more reformative methods of bio-hydrogen production and lipid accumulation converted from FW.

## 7. Conclusions

Food waste is thought to be considerable and of great importance to manage and dispose appropriately. It is a renewable energy source for sustainable development in the future owing to its organic rich feature. Anaerobic digestion, composting, generalized management and other developments on

management of food waste were investigated in latest researches from different countries. Many optimized experiment performances were presented and new investigation and technologies were introduced. AD is still a hot field of research and many other novel applications in FW management are also valuable. Further views on future research were given on basis of these multiple works.

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