A Comprehensive Review on Anaerobic Digestion of Organic Fraction of Municipal Solid Waste

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Abstract

This article aims to comprehensively review the anaerobic digestion (AD) process utilising the organic fraction of municipal solid waste (OFMSW) substrate. The AD of OFMSW has received considerable attention due to its significant energy and nutrient recovery as well as its greenhouse gas (GHG) mitigation potential. AD is a biological process involving treating and stabilising organic matter in the absence of oxygen accomplished by a consortium of microorganisms and occurs under hydrolysis, acidogenesis, acetogenesis, and methanogenesis phases. The hydrolysis phase is recognised as the primary rate-limiting step. Thus, exploring the ways to speed up the hydrolysis process will maximise biogas production. The key factors affecting the digestion efficiency include feedstock quality, pre-treatment process, design and selection of digestion process and process conditions including pH, temperature, carbon to nitrogen (C: N) ratio, organic loading rate and hydraulic retention time. The review reveals that solid-state anaerobic digestion (SSAD) is best suited for OFMSW due to its high solid concentration (>15%) and better process performance. The continuous digestion with thermophilic temperatures was found to be the best condition for high solid AD process. The plug flow and continuous stir tank reactors were the best performing options to control the biological conditions for the digestate post-treatment. Proper selection of the parameters for the whole process is crucial in ensuring process feasibility and economic sustainability of AD of OFMSW. The study revealed that the AD of OFMSW could play a significant role to mitigate waste and waste-related problems.

Keywords: Organic fraction of municipal solid waste; Anaerobic digestion process; Biogas reactor; Bioenergy; Substrate pre-treatment; Bio-recovery post-treatment

Table of Abbreviations

AD	Anaerobic digestion
APFR	Anaerobic plug flow reactor
COD	Chemical oxygen demand

CSTR	Continuous stir tank reactor
EBA	European Biogas Association
EBPR	Enhanced biological phosphate removal
FOG	Fat, oil and grease
GHG	Greenhouse gas
HRT	Hydraulic retention time
LCFA	Long-chain fatty acids
LSAD	Liquid state anaerobic digestion
MSW	Municipal solid waste
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
PSA	Pressure swing adsorption
SSAD	Solid-state anaerobic digestion
TP	Total phosphorus
TS	Total solid
TVS	Total volatile solids
US	United States
VFA	Volatile fatty acids
VOC	Volatile organic compounds

1. Introduction

The limited reserve, ever-increasing price of fossil fuel with the adverse implication towards climate change, have motivated the policymakers to look for alternative sources of energy [1-5]. Using renewable energy sources can help reduce negative environmental impact, especially related to global warming created by GHG emission [6, 7]. Non-edible resources such as the non-edible oils, waste oils, lignocellulosic biomass, organic fraction of municipal solid waste (OFMSW) that are available abundantly can be used as a bioenergy resource [8-10]. OFMSW is a mixture of materials that are disposed of by residential and commercial establishments [11, 12]. The OFMSW is mainly comprised of recyclable and non-recyclable materials that are categorised into organic and inorganic wastes that include food waste, paper, glass and other types of wastes. The exponential population growth, economic development, and rapid urbanisation are the key contributors to MSW generation [13]. Besides, the high consumption rate and consumer-based lifestyle have been the driving factors towards an increase in MSW generation [14, 15]. This increased rate of MSW generation is one of the global issues that contribute to socio-economic and environmental problems [16]. These waste accumulations have caused severe ecological problems involving air and water pollutions. Besides, uncontrolled increase in waste could trigger a shortage of waste disposal areas [17]. In 2018, an estimated average of 2 billion metric tons/year of waste was generated worldwide, which is predicted to rise to 3.40 billion tonnes by 2050 [18]. According to the global waste index data, the highest per capita waste is produced in the United States (809 kg) followed by Denmark, New Zealand and Canada, as shown in **Figure 1**. The global major fractions for MSW are comprised of organic (46%), paper (17%), plastics (10%), glass (5%), metals (4%), and other types of waste (18%) [19]. Organic waste is considered as the highest contributor to MSW throughout the world, which represents almost 50% of the generated waste [20]. This massive amount of putrescible waste has a tremendous global warming potential that contributes to rapid climatic change through the unutilised methane gas release [21]. To solve this, the unutilised OFMSW is mainly passed through a waste treatment process that converts organic matters into valuable bioenergy products.

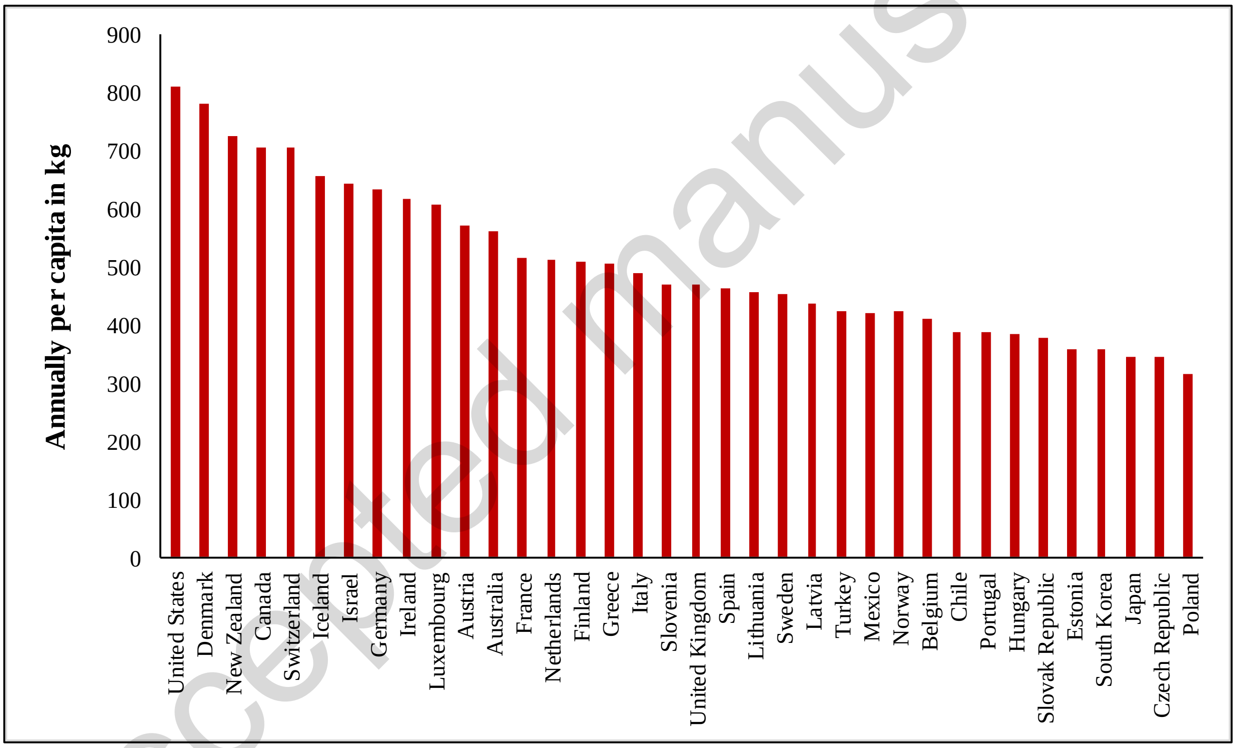

Figure 1: Global per capita waste generation [22]

The environmental problem of waste, waste-related challenges and sustainable energy supply is being minimised through a range of approaches: AD, gasification, fermentation, pyrolysis, and liquefaction [23-26]. AD has been established as a sustainable approach to the recovery of renewable energy from various kinds of organic streams [27]. AD is considered as a reliable process owing to the economic and technical viability compared to other available approaches such as pyrolysis, torrefaction, incineration, gasification and composting method [14, 28, 29]. Besides, AD has less impact on air quality than combustion dependent processes and helps to minimise carbon emissions by generating energy to replace fossil fuel [7, 30, 31]. Reducing GHG emissions using AD technologies would have a major effect on the fulfilment of the 2016 Paris agreement, aimed at limiting the global average temperature rise to less than 2 °C. In the AD process, microbes digest the waste and produce methane gas, which is also known as biogas. The waste may be processed and distributed to fields directly, or biogas itself may be used as a fuel [32]. Almost any organic waste can be used in the process. However, factors such as pH and temperature affect gas production. **Figure 2** shows the potential route of AD for energy recovery from OFMSW [20]. Biogas plants play a significant role in reducing the global warming effect because of methane gas collection potential utilizing waste [33]. Besides, the AD process can address waste, energy and nutrient recycling challenges efficiently and circularly. For example, the production of biogas utilises organic, natural materials that can be reused. The by-product of a biogas plant can be used as a useful complement or alternative to chemical fertilisers that are harmful and hazardous [34]. Organic digestion can then speed up plant growth and disease resistance. As a result, the whole process becomes a sustainable approach. Finally, due to lower construction costs and the availability of wastes, biogas can be especially useful in remote and undeveloped areas.

The process of AD is conducted using various substrates which are classified into three primary sources viz. agricultural, industrial and community wastes. Among the sources, agricultural waste is regarded as the most extensive substrates for AD applications [35]. However, the application of the feedstocks relies upon the resource availability in the specific country. For example, most AD plants in Europe are mainly operated using waste manure, harvest residues, and energy crops as feedstock [36]. The recent European Biogas Association (EBA) report stated that the number of new AD plants has dramatically increased from 6227 in 2009 to 17439 in 2016 [37]. The highest number of AD plants were reported to be running on agricultural resources at 12496 plants, followed by 2838 plants on wastewater sludge, 1604 plants on landfills and 688 plants on various other types of wastes [38]. In the United States, on the other hand, the number of AD plants is relatively low with 2000 plants which consist of three types of plants, e.g. anaerobic digester, landfill and covered lagoon [39]. However, a recent report from the American Biogas Council stated that 14000 potentially new biogas plants are going to be installed over the next few years [40]. AD plants of China mainly operate using livestock manure, human excreta, and agriculture residues [41]. Again, the rural household AD plant is the largest producer (about 40 million household digester) of biogas in China [42]. In this regard, the agricultural substrates are predominantly used for most of the AD plants. Nevertheless, compared to the agriculture substrates, the organic fraction of community biodegradable substrates can become a promising solution to environmental and energy sustainability by reducing the use of land area and water as well as eliminating the waste management issues.

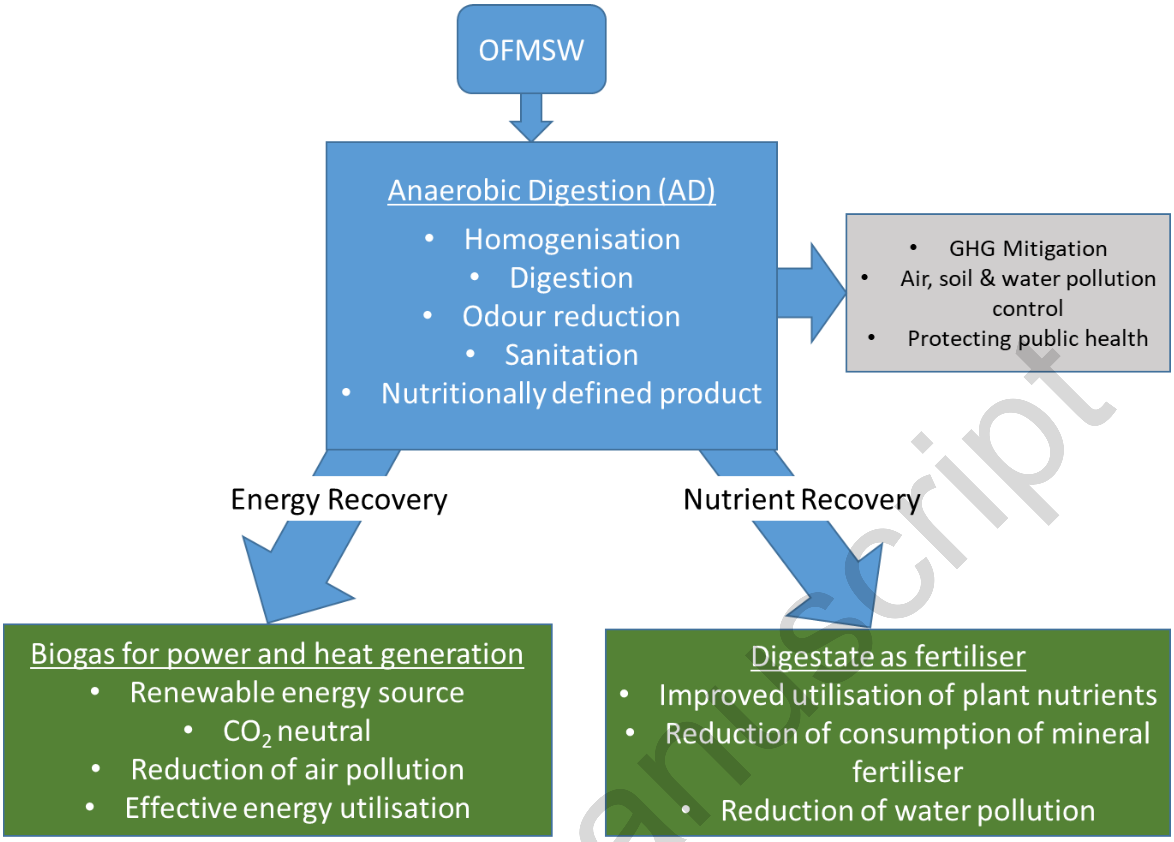

Figure 2: Potential of AD process in energy recovery and GHG emission reduction; reproduced with permission from reference [20]

Recently many articles have been published on the AD process of OFMSW, but a few researchers have analysed and reviewed them extensively. According to 'title search' results in Scopus using the keywords "anaerobic digestion" and "organic fraction of municipal solid waste", only 16 review papers have been published on OFMSW from 2015-2020. Most of the review has been focused on a particular area of AD process such as co-digestion [20, 43, 44], energy recovery [45], dry AD [46], AD process in the regional area [36, 47], carbonaceous and lignocellulose feedstock [48, 49]. Therefore, this paper attempts to comprehensively review the AD of OFMSW, focusing on the efficiencies and feasibilities for energy and biofertiliser production. Analysis of current progress in realising the optimum quality of renewable products as well as the main aspects of OFMSW characterisation for AD implementation is listed to identify the primary key factors of process performance and sustainability. Besides, energy and economic feasibility are also included in selecting the best approach for the substrates. Finally, the evaluation of the current state, challenges, and potential of OFMSW digestion are summarised for future planning considerations.

2. OFMSW collection and characterisation

2.1. OFMSW segregation methods selection

OFMSW is a biodegradable waste that comprises of heterogeneous waste originating from gardens, parks, households, restaurants, catering, retail premises and food industry and are collected by the municipal bodies [50]. Typically, they contain a mixture of food, garden waste, mixed papers, newspapers, wood, and cardboard. However, the categorisation and characteristics of OFMSW for each country vary widely and depend on different factors. Based on the previous research reports, there were 16 fractions of OFMSW consisting of various food preparation residuals which are different fractional components such as fruit and vegetables and their peelings, bread, meat and fish, snacks and sweets, dairy, tea bags and coffee granules, cereals and other leftover foods [51]. The simultaneous presence of non-biodegradable and biodegradable waste (eggshell, bio bags and bones) that have a deleterious effect on the AD and non-biodegradable wastes are considered as physical impurities.

The characteristics and composition of OFMSW mainly rely on the adopted waste management system. In Europe, the collection system of OFMSW primarily uses the mechanical separation method (MS-OFMSW), separate and collect method (SC-OFMSW) and sorting at source method (SS-OFMSW) [52]. The separation of OFMSW using MS-OFMSW method is suitable for non-segregated waste that combined with the large grain sized collected waste**.** The waste separation is carried out mainly to reduce the amount of waste, separate the inorganic waste from high calorific value organic fraction waste and homogenise those for subsequent energy recovery [53]. Dehkordi *et al.* [54] reported that MC-OFMSW could significantly improve the surface area and enhance the contact between the substrate and the inoculum. However, the MS-OFMSW collection system is less preferred due to the lower nutrient recovery in terms of biomethane as well as the production of significant quantities of inert material. Besides, this method does not entirely separate the inorganic fractions due to high dry solid content [55]. Usually a high total volatile solids (VS) values signify a high collection of organic fractions from the systems, where the SS-OFMSW and SC-OFMSW are reported as the most suitable approaches [56]. The SC-OFMSW are conducted through pre-sorting of inert waste from mixed waste sources which reduce the content of the inert materials in the hydrolysate as well as increase the content of organic matter available for the conversion process. The SC-OFMSW were reported to be able to yield the highest concentration of sugars and the lowest concentration of lactic acid after hydrolysis, which highlights the importance of this collection system in the digestion process [57]. Therefore, the SC-OFMSW resulted in a better performance compared to MS-OFMSW. On the other hand, SS-OFMSW method enhances the waste collection system by sorting the waste from the sources. This method provides an improved startup of the AD process, where the characteristics of the organic fraction are better controlled through the pre-sorting process and has enhanced biodegradability of the substrate. This control over biodegradability speeds up the digestion stabilisation contributing to a high methane yield [58].

2.2. *OFMSW characteristics*

OFMSW primarily consists of carbohydrates, proteins and lipid substances that contribute to its bioenergy potential [59]. Proteins and lipids in OFMSW have more significant biomethane content than starch, cellulose or hemicellulose [60]. Meanwhile, carbohydrate is reported to have the potential for high hydrogen recovery [61]. Nevertheless, due to numerous factors, the generated OFMSW has various fractions of chemical composition that influence the variability of bioenergy potential. Therefore, OFMSW characteristics could not be generalised or fixed at a specific condition. Besides, none of the current investigations provides a complete list of each OFMSW attribute. There is a wide range of characteristics that could affect the behaviour of OFMSW in the AD process. The overall characterisations of OFMSW that considerably contribute to AD efficiencies are shown in **Figure 3**.

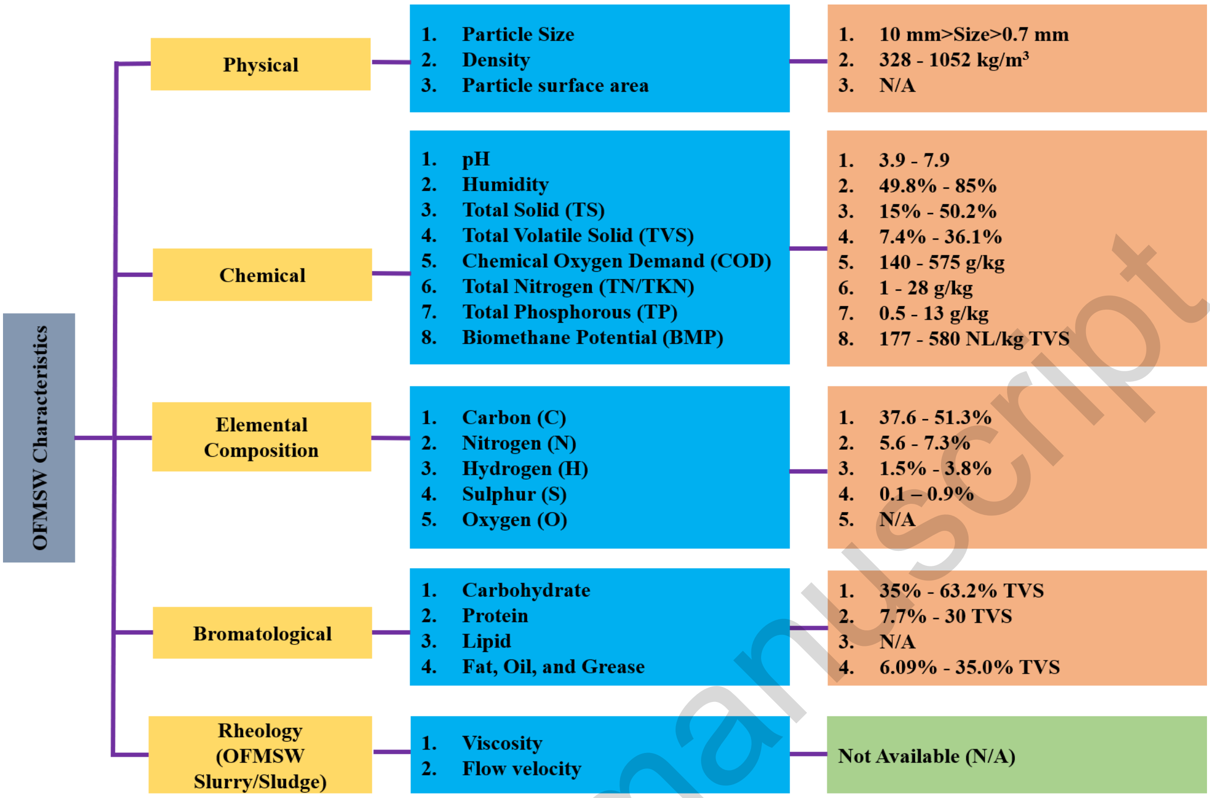

Figure 3: Overall characterisation of OFMSW for the AD process [51, 59]

2.2.1. Physical characteristics

Physical characteristics of the OFMSW substrate are commonly quantified by particle size and density. Typically, the bulky OFMSW substrate requires size reduction to promote early solubilisation of the digestion process [62]. The reduction of the solid particle size will result in the surface enlargement of the substrate, enhancing the effectiveness of microorganisms during the digestion process. Besides, the size reduction could also avoid clogging during digestion. According to Raposo *et al.* [63], the size of solid organic particle substrates is suggested to be reduced below 10 mm. However, the extensive reduction of substrate particle size could reflect in a decrease in pH, in turn, the efficiency of the AD process. As reported by Jain *et al.* [64], a small particle size below 0.7 mm may result in volatile fatty acids (VFA) accumulation which promotes excessive acidic intermediates. Thus, the substrate surface area is a significant parameter for the degradation rate. However, the effect of the OFMSW surface area on the digestion rate has not been investigated thoroughly. In addition, the density denotes the composition of OFMSW collected. As reported by Campozano *et al.* [51], the highest density meant the low amount of unwanted substances and materials in the OFMSW substrates. This observation was taken from the study conducted from 43 cities in 22 countries which recorded OFMSW density ranges varying from 328 to 1052 kg/m^3.

2.2.2. Chemical characteristics

Chemical characteristics of OFMSW substrates are evaluated based on the main properties that include: 1) pH, 2) humidity, 3) total solid (TS), 4) total volatile solids (TVS), 5) chemical oxygen demand

(COD), 6) total nitrogen (TN), 7) total phosphorus (TP) and 8) biomethane potential (BMP). These characteristics directly influence the microbial behaviour of the AD process. pH range is the most important property in indicating the microorganism population. In the digestion process, the microorganisms are very active and efficient between 6.5 and 7.5 pH range [64]. Thus, the pH of OFMSW should be balanced with the addition of any material to ensure the continued existence of the active bacterial population, usually between 3.9 - 7.9. The humidity content of the substrates also affects the biogas generation rate. At oxygen-free conditions, bacteria require high humidity to propagate the AD. A report by Schirmer *et al.* [65] showed that high humidity content (90%) had resulted in a high biogas generation rate. As such, to achieve a high yield of biogas, the increase in humidity of OFMSW substrates is required. Besides, the moisture content is also important for the determination of BMP. TS and TVS are the primary indicators of volatile organic matter losses for biogas conversion. At a high TS value, the level of microbial activity is reduced due to low water content. According to Motte *et al.* [66], the decrease in water content leads to high apparent metabolite concentration which highly inhibits the methanogenic activity. Consequently, the high TVS value for OFMSW substrates is preferred for the AD process.

TN and TP content represents the accumulation of nitrogen and phosphorus traces in the tested compounds, which are essential for the growth and synthesis of the new microbial cell. According to Boonsawang *et al.* [67], the high supplies of nitrogen and phosphorus reflect a higher long carbon chain production in the acidogenic stage. The low nitrogen content of OFMSW could be altered through the nitrification process. However, excess nitrogen supplement could produce the inhibition of methanogenic bacteria [68]. Thus, methane production relies on suitable nitrogen to phosphorus ratio. The degradation of the OFMSW substrate could be observed from the reduction of COD value which represents the solubility of the organic matter in forming conversions to biogas yield [64]. OFMSW substrates with high COD solubility have a high potential for methane production rate. Methane production of a specific substrate could be initially investigated through the BMP test. The methane potential can be calculated using the Buswell Equation [69]. As shown in **Figure 3**, methane potential for OFMSW was recorded from 177 NL/kg TVS to 580 NL/kg TVS range. The data attributes high biodegradability of OFMSW substrates to biogas conversion. Nevertheless, the biogas conversion rate is dependent on the element in substrates composition.

2.2.3. Elemental characteristics

The OFMSW substrates comprise of carbon (C), hydrogen (H), nitrogen (N), oxygen (O) and sulphur (S) elements. Typically, the elemental composition could be used to determine the empirical amounts of biogas produced using Boyle's formula [70]. However, these elemental compositions were commonly being used to describe the non-aqueous components of the substrates and the C: N ratio balancing of the digestion process. Overall, C is the primary element in the composition of the OFMSW substrate (> 50% TS) followed by N, H and S [71]. The composition of oxygen has rarely been reported but can be measured by calculating the contents from the TS, i.e. through the sum of C, H, N, S and ash [72]. In general, C and N are dominant in the OFMSW elemental composition. These elements are the primary sources of energy and cell building for anaerobic bacteria [73].

2.2.4. Bromatological characteristics

The organic components for OFMSW substrates are comprised of the mixture of carbohydrates, proteins, lipids and fat sources. **Table 1** shows the description of the bromatological characteristics of OFMSW in AD.

MSW substrates contain high moisture and VS. The VS consists of carbohydrates, protein, lipids, cellulose, hemicellulose, starch, lignin etc. According to Lopez *et al.* [60], the organic component balance (ratio of organic components and VS) range from 0.85 to 1.06 which indicates that majority of the organic components are present in the MSW. Carbohydrates is generally categorised to soluble and non-soluble components [74]. These components are mainly derived from the waste stream of food, fruits and garden sources. In comparison, starch, glucose, fructose, and sucrose are the soluble carbohydrates that are highly biodegradable in AD [60, 75]. Meanwhile, cellulose, hemicellulose, and lignin are considered to be non-soluble components since they exhibit a robust refractory structure for biodegradation [76]. Starch is composed of a similar glucose monomer to that of cellulose. However, the chemical structure for the glucose monomer are differentiated based on α- 1,4 (starch) and β- 1,4 (cellulose) linkages [77]. In contrast, hemicellulose was formed through different monosaccharides such as xylose, pentoses, and hexoses [78]. Besides, the random, amorphous and branched structure of hemicellulose creates little resistance to hydrolysation compared to that of cellulose [79]. Also, lignin is the third primary heterogeneous polymer constructed from complex molecules of aromatic alcohols which are linked in a three-dimensional structure [80]. The strong structural support and binder behaviour have made lignin a high resistance component to microbial attack and enzymatic degradation [81, 82]. Thus, lignin is known to be the most challenging component for hydrolysation under anaerobic conditions.

Other than that, protein is a linear bond linked by peptide bonds between α-amino and α-carbocyclic monomers [83]. This configuration has made protein as the only organic component that contains nitrogen and sulphur [84]. The OFMSW substrates with high protein fraction were characterised as having high methane production potential due to the favourable behaviour to AD [59]. However, excessive decomposition of protein could lead to the formation of free ammonia and toxic biogas constituents [85]. A similar condition was observed in the lipid fraction, which is calculated to have twice the methane potential than those of starch, cellulose, and hemicellulose [86]. The high loading of lipid fraction would result in inhibitory effect on the digestion process [87]. For example, it has been reported that the palmitic acid loading at a level of > 1.1 g/L hinders AD process in mesophilic conditions by around 50% [88]. As reported by Lopez *et al.* [60], waste with the lowest lipid content is proportional to the highest maximum biomethane production rate and longest lag time, and vice versa. This long-chain fatty acid is an essential intermediate for biogas conversion.

Table 1. OFMSW bromatological characteristics

Components	Chemical Formula	Characteristics	Waste Sources
Carbohydrates: **1) Soluble** **a) Starch (a mixture of soluble monomer etc. glucose, fructose, sucrose)** **2)Non-soluble** **a) Cellulose** **b) Hemicellulose** **c) Lignin**	Cellulose and Starch ($C_6H_{10}O_5$), Hemicellulose ($C_5H_8O_4$),	i. Starch, glucose, fructose, and sucrose are the soluble carbohydrates that are highly biodegradable in AD. ii. Cellulose, hemicellulose, and lignin are considered as the non-soluble components that exhibit strong refractory structure for biodegradation. iii. The chemical structure for the glucose monomer was different based on α- 1,4 (starch) and β-1,4 (cellulose) linkages. iv. Hemicellulose was formed through different monosaccharides like xylose, pentoses, and hexoses. v. The random, amorphous and branched structure of hemicellulose has created little resistance to hydrolysation vi. Lignin is constructed from complex molecules of aromatic alcohols that having high resistance to microbial attack and enzymatic degradation. It is the most challenging component to be hydrolysed under anaerobic condition due to the strong structural support and binder behaviour	Kitchen, Garden, and Landscape Waste
Proteins	(C_5H_7NO)	i. The excessive decomposition of protein could form toxics constituents (hydrogen sulphide) and ammonia biogas. ii. Proteins comprised of the combination between the amino acid and carbocyclic monomer. iii. The only organic component is consisting of nitrogen and sulphur.	Kitchen Waste, Market Waste
Lipid	$C_{57}H_{104}O_6$	i. Lipids are calculated to have high methane potential, which is twice the potential of starch, cellulose, and hemicellulose. ii. The lipid content is inversely proportional with the biomethane production, i.e. low lipid content would result in high biomethane production.	Food Waste
Fat Oil and Grease	$CH_3(CH_2)_nCOOH$	i. The mixture of fatty acid and glycerol that are generated from high lipid compound ii. Insoluble in water. iii. Long-chain fatty acid (LCFA) is the primary component of fat, oil and grease (FOG), are degraded anaerobically to form biomethane.	Food Sources; Animal Dairy Plant and Cooking Oil

Other than the lipid, fat fraction also has long-chain fatty acid sources. This fat fraction mainly comes from dairies and vegetal wastes that are easily converted to hydrogen and methane biogas in AD [89]. However, the fat fraction is inclusive of the FOG component of glycerol [90]. These accumulated FOG able to trap the biomass via floatation properties that easily attracted to substrates particles during the hydrolysis stage [20]. Nevertheless, this risk could be mitigated through the co-digestion process with suitable substrate selection.

2.2.5. Rheological characteristics

The characterisation of rheological properties is essential to represent substrates behaviour in the liquid fraction. In this regard, viscosity and flow velocity behaviour are the significant characteristics to represent the handling condition of the OFMSW liquid mixture in the AD system. Practically, there are OFMSW substrates that are introduced to AD in a mixture of slurry and sludge conditions [91]. However, the influence of rheological properties of OFMSW substrate has not been investigated extensively [92]. In addition, the effects of rheological properties for the inoculum substrates with OFMSW co-digestion have not been reported extensively.

3. OFMSW AD process difficulties

AD is a biological process involving treating and stabilising organic matter in the absence of oxygen accomplished by a consortium of microorganisms and occurs under hydrolysis, acidogenesis, acetogenesis, and methanogenesis phases [93]. The lack of O_2 in OFMSW allows the microorganism to degrade the organic matter to produce stabilised sludge (anaerobic digester effluent, also known as digestate) and biogas. During the first stage, the high molecular weight complex insoluble organic matter is degraded into simple soluble molecules by the extracellular enzymes [94]. In this phase, the organic components of carbohydrate, protein, and lipid polymers are hydrolysed into simple sugar, amino acid, and long-chain fatty acid, respectively [95]. Meanwhile, the insoluble compounds of cellulose and hemicellulose are hydrolysed by enzymatic hydrolysis microorganisms (*Streptococcus* and *Enterobacterium*) to produce monosaccharides [76, 96]. However, the strong intermolecular hydrogen bond of lignin is resistant to the penetration of microorganisms for enzymatic hydrolysis process. At this stage, the rigid lignin structures require pre-treatment such as delignification, to undergo biodegradation [97]. According to Ali Shah *et al.* [96], other than the size of particles and pH, hydrolysis rate depends on enzymatic parameters such as the enzymes production, diffusion, and adsorption on the digestion matter particles. Therefore, at this digestion stage, only 50% of organic matter is degraded, and the remaining portion stays at the primary state due to lack of degradation participation [98].

In the acidogenesis phase, the acid phase bacteria (*Clostridium, Peptococcus Anaerobus, Lactobacillus, and Actinomyces*) utilises both dissolved and bounded oxygens in the solution and carbon, respectively [99, 100]. The water-soluble and hydrolysis products (simple sugar, amino acid, and long-chain fatty acid) were further degraded to short-chain organic acids (formic, acetic, propionic, butyric, and pentanoic), alcohols (methanol, ethanol), aldehydes, carbon dioxide, and hydrogen [96]. The acidogenic bacteria are the most abundant bacteria and highly active fermenters in AD [94]. These active bacteria species come to the following genera: *Aminobacterium, Psychrobacter, Anaerococcus, Bacteroides, Acetivibrio, Butyrivibrio, Halocella, Spirochaeta, Caldicellulosiruptor, and Cellulomonas*

[101]. Alcohol and VFA that are produced by these acidogenesis bacteria are further processed in the acetogenesis phase.

The acetogenesis phase produces essential intermediate products for methane generations. In this phase, the syntrophic acetogenic bacteria viz. *Syntrophomonas, Syntrophobacter* and *Smithella* etc. syntrophically metabolises the VFA, alcohols, some amino acids and aromatic compounds into methanogenesis substrates viz. acetate, hydrogen, and carbon dioxide [102]. The presence of hydrogenotrophic bacteria favours this conversion [103]. These hydrogenotrohphs produce acetate from the reduction of carbon dioxide with hydrogen via the acetyl Co-A pathway [101]. However, the accumulation of VFA could result in a decrease in pH, thereby increasing acidification and eliminating the acidogenic bacteria. Therefore, the VFA consumption via acetoclastic (pH, 6 – 8) or via hydrogenoclastic (pH, 9 – 10) archaebacterial should be monitored [95]. The route of the methane production is mainly derived from the acetotrophic, hydrogenotrophic and methylotrophic pathways.

In the methanogenesis phase, acetic acid and hydrogen that formed in acetogenesis phase are transformed to biomethane via methanogenic microorganisms. During the process, the pH of the conversion process will rise to neutral values within the range of 6.8 to 8 [104]. The bacteria responsible for this methane fermentation phase belong to *archaebacteria* genera: *Crenarchaeota, Euryarchaeota*, etc. The morphology of methanogenic bacteria is very heterogeneous compared to those of acidogenesis and acetogenesis bacteria [99]. Moreover, there are diverse methanogenic bacteria that have different properties which are sensitive to temperature and pH distraction [105]. Therefore, the methanogenesis phase effectiveness is very reliant on the balanced relationship between microorganisms' bio-kinetics with its growth environment (food supply and accessibility) [106].

4. Key factors affecting OFMSW digestions efficiency

4.1. Feedstock quality and pre-treatment process

Feedstock quality is an essential factor for AD bio-kinetics optimisation [107]. Ideally, the OFMSW feedstock quality is assessed based on organic matter separation, solubilisation and biodegradability condition [56]. Usually, the OFMSW feedstock is commonly pretreated and activated to enhance and optimise the digestion activity. **Table 2** shows the pre-treatment methods of OFMSW substrates before the AD process.

Table 2. The OFMSW pre-treatment method before the AD process

Pre-treatment Methods	Technology	Application	Advantages	Disadvantages	Ref
Physical	Mechanical (Beads Mill)	Lab-Scale	Can reduce particle size into fine particles which enhances biomethane generation and performs better than household disposal pre-treatment.	The extreme particles size reduction would reduce biomethane generation as a result of increased VFA growth.	[62]
	Mechanical Rotary Drum (RDR)	Full Scale	Produced organic materials have low moisture. The process operates at low capital and energy with a minimum retention time.	The retention time in the drum varies between 2 and 5 days. For short retention time operation require more feeding batch and additional workforce.	[108]
	Mechanical (Screw press)	Full Scale	The large selective effect via water routing yielded small particle size substrates that possess less inert materials and high enzymatic and degraded organic compounds.	Resulted in a loss of dry organic compound as the treatment method are preferable for the soluble waste compound.	[109]
	Mechanical (Screen Shredder)	Full Scale	Results in higher biomass content with denser and larger compounds.	Large inert material was also collected due to the large screener size.	[109]
	Thermal (Heating Shell Reactor)	Full Scale	Reducing digestion time by accelerating the hydrolysis step of AD. Solubilised the high refractory compound such as hemicellulose & lignin.	The higher temperature (>150 °C) or longer heating period might result in an inert and complex material structured, which are challenging to degrade.	[110, 111]
	Thermal (Microwave)	Lab-Scale	Can produce high higher substrates solubilisation. Increases the soluble COD and have higher heating energy efficiency than standard thermal method.	Methane yields were not enough to compensate for the required energy.	[112]
	Wave (Ultrasound)	Lab-Scale	Shows good performance in treating a various type of fat-based substrates. Provides volatile acid desorption and direct particle disruption from substrate particle surfaces. Increases microbial growth by eliminating soluble inhabitants.	High cost due to energy consumption and requires frequent maintenance for operation.	[56, 113]
Chemical	Ozone (Oxidation)	Lab-Scale	Improves the anaerobic biodegradability of contaminated organic solid waste by eliminating the toxical (inhibitory) effects.	High operational cost and dependency on its biological stability. Requires partially biodegraded organic materials.	[114]
	Acid Hydrolysis HCl, H_2SO_4, HNO_3,	Full Scale	Facilitates large-scale production of desirable chemical intermediates. Increases the efficiency of substrate utilisation and improve the hydrolysis process.	Deterrent to large-scale implementation due to the cost recovery.	[115]
	Alkaline Analysis $Ca(OH)_2$,	Full Scale	Substantially enhances the microbes accessibility via effective surface area increment of organic structure.	Not suitable for substrates with low lignin content.	[116, 117]

	NaOH, $Mg(OH)_2$ KOH				
	Additive Cobalt, Iron, Nickel	Full Scale	Improves the biomethane generation and elongates the digestion constancy through stable process control with inhibitory compounds mitigation.	The excessive additive load lead to instability of the digester due to the occurrence of excessive ions.	[118]
Biological	Microorganism Fungi, Enzymatic (peptidase, carbohydrolase and lipase)	Full Scale	Improves biodegradation by the reducing number of steps for the treatment process as well as avoids processing of inhibitory products	Expensive for the full-scale plant. A longer period of degradation due to slow reaction and growth rate of the microorganisms or enzymes used.	[119] [120]
	Microaeration (Oxygen)	Full Scale	Enhances the hydrolysis of carbohydrates and proteins. Reduces the lipids toxic and inhibitions that promote unstable degradation.	Increase the organisms growth competition due to the excess of oxygen supply.	[121]
	Two-Stage AD Anaerobic Hydrolytic Leach Bed (AHLB),	Full Scale	Enhances the methanogens activity for higher methane yield. Increases volatile solid reduction and highly potent for removing pathogens.	Increase in cost due to technical complexity. Create inhibition of acid-forming bacteria due to hydrogen build-up. Can eliminate possible interdependent nutrient requirements for the methane forming bacteria.	[122] [123]
	Temperature AD Thermophilic and Mesophilic	Full Scale	Thermophilic configuration increases the rate of the process stability. Improves the biomethane generation and reduces digestate amount. Meanwhile, the mesophilic configuration eliminates the risk of inhibits and improved the time of operation.	Requires higher energy input. Extreme temperature resulting in accumulation of isovalerate compound that degrades slowly.	[124, 125]
Combined Treatment	Thermal Microwave and autoclave pre-treatments	Lab-Scale	Improves the removal of pollutant contaminants and increases the degradability of high refractory compound in the earlier stage of digestion.	Have low energy gain compared to the process consumption.	[126]
	Physicochemical Optical sorter, Wet Crusher and Hydro-cyclone Decanter	Full Scale	The methane yield higher than previously reported plants. Produce high energy efficiency index at 2.2 kWh produced/kWh consumed through energy consumption and recovery of 3650 MWh and 8150 MWh respectively. Increase the digester feedstock quality and biogas production.	Have a challenge in eliminating the pollutant contamination of H_2S and propionic acid in the biogas digester.	[127]

	Chemical – Biological	Full Scale	Produces high quality of solid and liquid digestate with a high yield of biomethane generation.	Complex in monitoring and controlling the process mass balance for nutrients and inhabitants stability.	[128]

Typically, the effectiveness of the pre-treatment method relies on the biodegradability properties of the OFMSW mixtures. The OFMSW mixture with high lignocellulosic content requires a stronger treatment in various types of method like alkali, thermal, and thermochemical methods to enhance the degradation of refractory substances [129]. Meanwhile, the less lignocellulosic mixtures are commonly pre-treated with physical and conventional chemical methods to remove the undesired impurities materials from the destined stream of the biological process [130, 131]. However, the consideration of performance based on the process effectiveness, viability of economic, and impacts towards environmental are needed in selecting the anticipated pre-treatment approach. Besides, the optimal pre-treatment methods for high biogas recovery are hard to determine due to the diverse conditions associated with each AD plant process.

As shown in **Table 2**, the physical pre-treatment methods are conducted by the mechanical, thermal and wave-based approaches. The mechanical pre-treatments are mainly done to reduce the feedstock particles and separate the inert materials from propagating solubilisation for high biogas production. Grinding, shredding and rotary drum are the major processes used in the full scale of the OFMSW AD process [108]. Meanwhile, the thermal treatment is used to accelerate the feedstock solubilisation process by adopting the energy from the reactor heating shell and internal microwave heating. As reported, the thermal pre-treatment able to remove the pathogens, enhance dewatering efficiency and reduce the digested viscosity [132]. However, the disadvantage of thermal pre-treatment is high energy consumption and the agglomeration of the heated compound, which makes it hard to degrade [122]. Besides, the energy drawback is similar to the ultrasound pre-treatment. Although the treatment provided an efficient direct particle disruption from substrate particle surfaces, the maintenance, and energy requirement have discouraged the full-scale implementation of the treatment for OFMSW feedstock [56, 113].

Chemical pre-treatments are generally administered using ozone oxidation, alkali reagents together with thermal processes, alcohols, organic acids, and organic solvents to enhance the biodegradability of the organic fractions. The oxidation process is associated with an oxidising agent, typically ozone, to promote compound delignification (lowering the molecular weight) as well as to improve the anaerobic biodegradability of the contaminated organic fraction by eliminating the inhibitory effects of oxidation mechanism [114, 133]. Cesaro *et al.* [114] studied the ozone effect on the biodegradability of the substrate. They reported that the ozone effect is mainly influenced by the oxidation process, which can be either through direct and indirect mechanisms. Direct oxidation is facilitated by molecular ozone and generally happens at very low pH. On the other hand, indirect oxidation occurs typically at high pH facilitated through hydroxyl radicals that generate from ozone decomposition in aqueous solution. They showed that doses up to 0.16 gO_3/g TS enhance the overall biodegradability of the samples, which in turn increases the biogas production. Hydrolysis through the use of strong acid and alkali is also used to improve the biodegradability and stabilise the microbe accessibility in the digestion process [134]. Rajan and Carrier [135] determined the optimal conditions for the pre-treating wheat straw to be 30 min reaction time, 140 °C reaction temperature and 1% (v/v) H_2SO_4 which resulted in 89% of theoretical maximum glucose yield. The acid hydrolysis pre-treatment could generate a large-scale production of desirable chemical intermediates by the destruction of rigid compounds [115]. In addition, alkali substantially enhanced microbes accessibility via the substrate surface area [128]. However, as stressed by You *et al.* [136], these methods are not suitable for the organic fraction mixtures with low lignin content. Besides, Wang *et al.* [137] figured out that chemical pre-treatment is not suitable for feedstock which contains a high amount of easily degradable carbohydrate, due to the subsequent accumulation of VFA which might inhibit the methanogenesis stage. In this regard, the additive (Co, Fe, and Ni) approach could improve and prolong process stability through constant process control with inhibitory compounds mitigation [118]. Nevertheless, the excessive load of the additive could also inhabit the process due to the excessive loading of ions.

Biological methods are predominately utilised in the full scale of OFMSW pre-treatment methods. These pre-treatment methods are comprised of temperature phase AD (TPAD), two-stage AD (TSAD), micro aeration and microorganisms (fungi, microbial enzyme, etc.). As reported by Cesaro *et al.* [56], biological pre-treatments are often preferred owing to better performance than the chemical, thermal method in improving the biological degradation rate. Besides, it has been proved by Fernandez *et al.* [110] that the effectiveness of TPAD processes resulted in better and significant removal of organic matter (16%, 10% and 30% for DOC, COD soluble and VS, respectively) and increased the biomethane generation (26 – 60%) than single-stage systems. Indeed, the double stages concentration permits a better process of OFMSW substrates degradation to be completed in a shorter time [110]. Meanwhile, TSAD pre-treatment methods are a combination of two anaerobic reactor digesters in different stages. The proposed system works through the separation and stabilization (pH and VFA condition), of hydrolysis, acidogenesis and methanogenesis in the first and second reactor, respectively [138]. However, the different stages could create an inhibition of acid-forming bacteria due to hydrogen build-up that eliminates the methanogenesis microbes for the biomethane formation [122]. Similarly, the TPAD pre-treatments would result in better accumulation of an isovalerate compound that slowly degraded [139]. The microorganisms (microbial enzymes and various types of fungi) are usually used in the pre-treatment of lignocellulosic biomass rather than OFMSW mixtures [129]. As reported previously, the process improved the biodegradation by reducing the number of steps for the treatment process as well as avoiding inhibitory products [119]. Nevertheless, the process could create a longer period of degradation due to the slow rate of microorganism growth and reaction [120].

Overall, the application of the pre-treatment methods relies on the condition of the degrading mechanisms of the feedstock. Although the use of single pre-treatment could dissolve the organic matter during the digestion process, a combination of different processes is the most effective way for the OFMSW feedstock biodegradation. Recent full-scale pre-treatment investigations provided successful combinations of pre-treatment processes. For example, Pecorini *et al.* [140] showed that autoclaving and microwaving resulted in improved hydrolysis of a significant fraction of the non-biodegradable organic substances that are recalcitrant to the AD process. Besides, the combination of mechanical pre-treatment stages has produced high energy efficiency index at 2.2 kWh produced/kWh through energy consumption and recovery of 3650 MWh and 8150 MWh, respectively [127]. Moreover, a combination of aerobic – anaerobic OFMSW pre-treatments ensured the better recovery of both energy and digestate nutrients [130]. Nevertheless, the combination requires an accurate system of monitoring in propagating the appropriate performance of OFMSW digestions. This effort requires a full balancing of the pre-treatment processes in measuring and mitigating the quality of the feedstock utilisation.

4.2. Digestion process designs and selection

AD is commonly performed in either wet (liquid state) or dry (solid-state) anaerobic digestion. The average solid level of dry AD is between 20 – 40% while for wet AD is less than 15% [35, 141]. Dry and wet AD systems reported HRT, OLR and VSR levels of 14 – 60 days, 12 – 15 kg per day VS/m^3 /day, 40 – 70% and 25 – 60 days and less than 5 kg per day VS/m^3/day [35]. The biogas output rate of the wet AD is less than that of the dry AD system. Analysis into dry and wet systems reveals that the dry system improves the CH_4 performance by 0.48 L/g VS and lowers the VSR rate by 85.6% than the wet process [125]. The AD process of OFMSW is primarily operated using the SSAD system due to its high solid concentration (>15%) and better process performance [142]. In comparison with LSAD, SSAD provides a less critical process and offer efficient processes at low energy and water consumption [35]. Practically, there are various types of SSAD systems that have been developed by European based industries such as Dranco, Kompogas and Valorga SSAD systems [143]. In the SSAD system, the digesters are operated at variable design conditions that includes: digester flow (batch, semicontinuous and continuous reactor), digester stage (single-stage and multiple stages), digester design (plug-flow and complete-mix), temperature condition (psychrophilic, mesophilic and thermophilic) range of TS content in the reactor (20 - 40%) [144] and other process conditions. **Table 3** and **Table 4** show the comparisons and the variables of OFMSW digester selection.

Table 3. The SSAD system description for OFMSW feedstock

System	Operation Condition	Advantages	Disadvantages	References
Valorga	TS- 25% to 30% DF- Continuous DS- Single-Stage DD- continuous stir tank reactor (CSTR), Vertical Plug Flow Reactor	i. The inoculum was not required for feeding the new fresh substrate ii. Low cost of maintenance requirement as few numbers of replacing part and components due to the simple system design of vessel, pipe and reactor. iii. Perform better mixing interaction through a combination of fresh and matured substrate in a proper mixing system.	The nozzle stands in the mixing system for sparging biogas having clogging risk during operation.	[35, 144, 145]
Dranco	TS- 30% to 40% DF- Continuous DS- Single-Stage DD-Vertical Plug Flow Reactor	i. Provide better performance at high TS amount ii. Low cost of operation maintenance due to the adequate number of part and component in simple and efficient system design.	Require high energy for mixing the high slurry substrates in recycling with the incoming feeding.	[35, 144, 145]
Kompo-gas	TS- 23% to 28% DF- Continuous DS- Single-Stage DD- Horizontal Plug Flow Reactor	The low horizontal digester design provides lower pumping energy in feeding the substrate to the system.	The mixing system design using impeller for horizontal digester requires high cost due to the high energy requirement.	[35, 144, 145]
Bio percolate	TS- 2% to 15% DF- Continuous DS- Two-Stage DD- UASB Horizontal Plug Flow Reactor	Low amount of TS reduced the operation time that improves the quality and stability of production and revenue, respectively.	Consume high energy due to the continuous operation of the double stages digester.	[35, 145]
Becon	TS- 30% to 40% DF- Batch DS- Single-Stage DD- Garage Type Digester	The high amount of process substrate due to large bay system design	Less efficient process due to lack of biological control and monitoring system.	[144]

Table 4. Comparison of digester condition selection for SSAD-OFMSW

Features	**Description**	**Advantages**	**Disadvantages**	**References**
DF (Batch)	i. Having different types of batch systems 2) Solid content 25- 40% 3) Volatile solid destruction 40-70%	i. Have a low cost of operation with the simple system that provides minimal process equipment and low cost of maintenance ii. Less energy consumption	i. Require large land footprint ii. The channelling and clogging system reduced the biomethane collection and having the risk of explosion	[35, 143]
DF (Semicontinuous)	i. The substrates feeding digestate removal were operated in regular process interval	i. Semicontinuous system having an improved biomethane production due to the higher rate of kinetic reaction with low digestate amount compared to batch and continuous system	i. Low biogas production compared to the batch system ii. Organic material is not entirely digested	[116, 117]
DF (Continuous)	i. Types of continuous reactor: Plug flow, CSTR ii. Require regular feeding interval iii. Operate with 25-35 % solid content. iv. Volatile solid destruction 40-75%	i. Simplicity in design and operation ii. Constant biogas production iii. Low capital costs	i. Rapid acidification ii. Large VFA formation	[35, 143]
DS (Single-Stage)	i. The process contains a single digester ii. Operate with 20 - 40 % solid content iii. Moderate VS destruction	i. Constant rate of organic loading and digestate that been recirculated provide adequate and efficient biodegradation ii. Simple system flow with a robust operation	i. Higher retention time ii. Foam and scum formation	[35, 143]
DS (multiple stages)	i. Operate with 2 -15 % solid content ii. High VS destruction	i. Provide optimum biological process condition for substrate degradation ii. Low retention time	The second stage requires additional pre-treatment of particle removals	[35, 143]
DD -ASBR	i. Utilised a single digester reactor for multiple processes	i. Flexible and straightforward system ii. Provide multiple utilisation at a lower cost of operation and having the efficient performance of biomethane generation	Require additional and regular maintenance due to the multiple and flexible utilisation of reactor	[142]
DD -CSTR	i. Digestate is continuously stirred and completely mixed	i. Highly reliable for high solid content digestion	i. Insufficient microbe population due to the continuous digestate effluent removal	[142]

	ii. The feed is introduced in the reactor at a rate proportional to the rate of effluent removed	ii. An adequate mixture of the substrate with less process resistance	ii. The continuous pre-treatment process easily promote the occurrence of inhabitants due to the VFA accumulation	
DD -anaerobic plug flow reactor (APFR)	i.An incomplete mixture of semisolid digestion ii. Digester operated at 20% of solid content iii. The reactor was designed for highly viscous systems	i. Suitable digester for semisolid feedstock with dry and high viscous properties. ii. Operated at maximum capability with high efficiency	i. Require complete and perfect substrate condition for digestion efficiency ii. Require robust facilities for viscous digestate post-treatment	[142]
DD-UASB	i. Provide methanogenesis process condition for the feedstock by separating the gas, digestion working volume and digestate at extreme operation condition	i. The separated digestion process provide adequate nutrient for the microbes ii. Operated at the optimum process condition and system design iii. Not require microbe circulation in the reactor	i. The unstable sludge granule characteristics for each changing of feedstocks ii. performance of digester based on the feedstock condition	[142]

The SSAD for OFMSW is commonly operated either in batch or in a continuous digester system [146]. Although there is also an option for the semicontinuous digester, this system is mainly implemented in lab-scale operation [116]. Typically, a batch digester is loaded with fresh feedstock at a time, with TS content range from 25% to 40% [143]. Besides, the batch digester is applicable for a large volume of feedstock digestion with 40% to 70% of VS destruction [35]. In a batch operation, simple style of batch digestion is included with several options of the up flow anaerobic sludge blanket (UASB) reactor, sequential batch system and single-stage batch system. This multiple batch operation is implemented mainly to optimise the less efficient process of the batch system. As reported by Li *et al.* [144], the stagnant digesting condition (none mixing process) has shifted the bacteria population to the VFAs accumulation which developed unstable pH conditions and inhibited the methanogenesis microbes activity. Nevertheless, this technically simple batch system provides the advantages of the minimum capital cost of operation with low energy loss and requirements of maintenance [145].

In contrast, a continuous digester system operates by adding the feedstock into the digester at a consistent time interval, and volume of processed products with TS content ranges from 25% to 35% [147]. Besides, the continuous system provides higher ranges of VS destruction (40-75%) compared to the batch digestion system (40-70%). In industrial operation, the CSTR and APFR are the most utilised digester aimed at OFMSW feedstock. Comparatively, APFR performs at a better efficiency than CSTR in the overall bioconversion process [142]. The APFR is generally used for SSAD with high solids input that ranges from 25% to 35% of TS [144]. Moreover, it provides a stable reactor performance with low VFA accumulation and high retention time of digestate [142]. Besides, this continuous system requires low initial investment and maintenance at a relatively simple operation [35]. However, at a lower solids content of feedstocks (<20%), sediment can quickly accumulate in the reactor, which requires highly expensive and robust instruments for handling and transporting the slurry [137].

In the full-scale OFMFSW digestion plant, a continuous digestion system is carried out mostly in a single-stage operation system. The Valorga, Kompogas, and Dranco are among the most prevalent single-stage SSAD system for OFMSW digestion with TS content ranging from 20% to 40% at both thermophilic or mesophilic conditions [123]. Predominately, these single-stage processes provide all digestion steps in a single digester. However, the dry materials of high viscosity substrate do not flow freely in the digester [148]. Thus, these systems operated at an equal interval time of feedstock loading and removal to ensure continuous digestion. In Valorga system (operating at 25 to 35% of TS content), the sparging system (mixing biogas system) is used in the tank to create adequate local interaction between fresh products and mature digestate. Consequently, the inoculation for new feedstock does not need the utilisation of finished products outside of the tank before feeding [145]. However, the nozzles for the sparging process could promote the risk of clogging during operation [143]. Meanwhile, the Dranco digester (30% to 40% of TS) was designed for operation in a vertical digester with bottom discharge system [123]. In this system, the pre-mixing process was separated from the digester, and the feeding process included with the recycled digestate at 6:1 ratio [149]. Practically, this approached denotes low costs for the digester system maintenances by operating using minimal moving parts in the digester. However, the energy requirements for mixing may be increased due to the high slurry recycle ratio that should be homogenised for each incoming feed [35]. As reported by Kothari *et al.* [35] and Li *et al.* [144], the Kampogas system (23% to 28% of TS) offers a relatively minimal energy utilisation for the material feeding through an agitator that helps the material carrying process completely. Therefore, in enhancing the digestion process, multistage digestion approach could lead to a better and efficient solid degradation of the continuous single-stage process. As reported by Khanal *et al.* [150], the Biopercolate multistage approach has reduced the hydraulic retention time (7 days), which translates to an increase in production as well as revenue. In this system, the hydrolysis and acidification digester (plug flow) are separated from the methanogenic digester (UASB). This double stage digester design accelerates the stability attenuation (7 days HRT) than in single-stage reactors (15 to 20 days HRT). The utilisation of the multistage digester in the full scale plant is still limited compared to the single-stage design.

4.3. *Digestion process conditions and their optimisation*

Working conditions generally influence the formation of biogas and biofertiliser digestate of OFMSW. In AD, the degradation process is affected by the factors that include pH, temperature, carbon: nitrogen (C: N) ratio, organic loading rate (OLR), HRT and stirring. The optimum condition for each digestion parameter for AD of OFMSW is discussed in this section.

4.3.1. pH

The pH value is an essential factor that categorises alkalinity or acidity of the substrate [151, 152]. The stability of the activity of acidogenic and methanogenic bacteria is directly affected by the changes in pH [126]. Ideally, the optimum pH for acidogenesis and methanogenic stages ranges from pH 5.5 to 6.5 and from 6.5 to 8.2, respectively [142, 153]. In the acidogenic process, the acidogenic bacteria transform the soluble organic matter of the hydrolysis process into VFA. Wang et al. [154] showed that acidogenesis could be inhibited when the pH was less than 4.0 due to the suppressed activity of the microorganisms. In addition, the methanogens are susceptible to VFA formation. The accumulation of the VFA at high acidic pH inhibits the methanogenic bacteria through the dissociation of acids leading to a decoupling of the membranous proton motive force [155, 156]. Hence, a low pH in the digester inhibits the activity of both acidogens and methanogens.

Ideally, the optimum pH for acidogenesis and methanogenic stages ranges from pH 5.5 to 6.5 and from 6.5 to 8.2, respectively [142, 153]. There are many reported findings of optimum pH conditions for high methane yield recovery in AD. For example, Paudel et al. [157] reported this to be pH 6 to 7. Liu *et al.* [158] reported that for the optimum biogas yield of OFMSW in AD, optimal pH range should be 6.5 - 7.5. However, the results vary depending on the OFMSW properties and acid conditions. In maintaining the pH stability for the continuous process, alkali-based chemicals such as sodium bicarbonate ($NaHCO_3$) and sodium hydroxide (NaOH) could be used at the initial process startup [131]. In cases of a very high or low pH of anaerobic digestion feedstock, neutralisation is necessary before the plant is fed. The pH is chemically improved by adding the base, such as lime, to the reactor if negligible acidification happens during the AD process [159, 160].

4.3.2. Temperature

Temperature is having a significant impact on AD biomethane generation through the stability of the enzymes and co-enzymes activity [161, 162]. Efficient AD process is dependent on the optimum temperature [162, 163]. The anaerobic microorganisms temperature for digestion process could be operated in psychrophilic (10 – 30 °C), mesophilic (30 – 40 °C) or thermophilic (50 – 60 °C) conditions [164-166]. The mesophilic temperature condition is commonly applied for AD due to the stability and diversity of microbial activity in the digestion process [167, 168]. The psychrophilic condition is less preferred due to lower biomethane generation at a high degree of retention [169]. Typically, OFMSW

AD is mostly applied in thermophilic and mesophilic conditions. Indeed, the thermophilic condition is found to be a more reliable option compared to mesophilic operation [170]. The mesophilic methanogenic process is reported to hold better process stability. As reviewed by Hartmann *et al.* [171], the effective hygienisation of the thermophilic process eliminated the occurrence of pathogens at a minimum time of operation. Besides, Lu *et al.* [172] showed that thermophilic conditions show better startup performance and double biogas production compared to the mesophilic conditions for OFMSW.

4.3.3. Carbon to nitrogen ratio (C: N ratio)

The ratio of carbon to nitrogen signifies the relationship between the amount of carbon and nitrogen present in organic materials and an optimum C: N ratio is generally required for an effective AD process [173, 174]. Carbon and nitrogen are the essential sources for energy and development of new cell structure [64]. Besides both elements used to indicate the substrate nutrient level in the AD process [142]. A high C: N ratio indicated the low nitrogen sources that are needed to sustain the material supply for the digestion. Meanwhile, the low C: N ratio signified the potential of NH_4^+ inhibition in the digestion process. Ideally, the optimum C: N ratio for the AD process is within the range of 20 to 35 [175, 176]. In practice, due to the different organic fractions, the desired C: N ratio could be developed through the different ratio fractions configuration. The C: N ratio for OFMSW with a high content of carbon could be stabilised by nutrient supplementation from livestock manure, and food waste [177]. Moreover, the high ammonia concentration of OFMSW could be reduced by balancing the C: N ratio in the mixture through the combination with the co-substrates. Besides, the co-digestion of OFMSW substrates significantly improve the biogas yield and solid and liquid digestate condition. Nevertheless, the balancing process is dependent on the properties of the co-substrates.

4.3.4. Organic loading rate (OLR)

Typically, a decrease in biogas yield indicates an excessive degradation capacity of the reactor due to high OLR [178]. The increment of OLR will increase the inhabitant concentration (VFA concentration and soluble COD) that contributed to excessive degradation [179]. In organic digestion, the OLR range from 1.2 to 12 kg of VS/m^3/day or 2.2 to 33.7 kg of COD/m^3/day [180, 181]. Nevertheless, the OLR behaviour relies on the characteristics of the substrates, temperature condition and HRT of the AD operation. The optimum OLR could be specified based on the investigation of the variability of OFMSW mixtures condition. As reported by Hartmann *et al.* [177], the high biogas for OFMSW digestion could be achieved at 0.3 to 0.5 m^3/kg VS by optimising the OLR higher or around 6 kg VS/m^3/day. Too little OLRs may cause malnutrition of microorganisms and adversely affects the AD [182]. Most high OLRs may cause insufficient resources to support the development of microbial organisms. In contrast, high loads result in VFA build-up in the fermentation process that prevents bacterial activity, provides lower effectiveness and leading to the collapse of the process [183].

4.3.5. Hydraulic retention time (HRT)

HRT is defined as the retention period of the substrates inside the digester for biogas generation. The period depends on the types of feedstock and digestor temperature [64]. Higher OLR in AD means lower HRT [184]. Lower HRT increases the possibility of VFAs accumulation [185]. High HRT will contribute to a high reduction of total VS mass that results in high biogas yields [186]. In addition, the buffering capacity at high HRT provides the process protection against the shock loadings effects, toxic compounds, and biological acclimation to toxic compounds, respectively [187]. Therefore, the complex mixture of OFMSW substrates commonly requires higher HRT in providing a sufficient digestion process of the organic matter involved. In general, OFMSW that contains a high mixture of carbohydrate, cellulose, protein, lipid and fat compounds, require a high HRT period. In a plant operation, the optimum HRT for OFMSW digestion is in the range of 15 to 20 days which depends on the temperature (thermophilic 50 - 55 ℃) and digester condition (single or multistage) [145]. The impact of HRTs on AD shows that the rise in HRTs decreases the VSR [188]. Longer HRTs can generate more biogas. Shi et al. [189] investigated the impact of HRT (20-60-days) on AD of the corn-starch. They reported that 60 days of HRT produce 42.3 mL/g TS and 9.2 mL/g TS more biogas than 20 days and 40 days HRT, respectively. They also reported that higher HRTs offer higher methane content than the lower HRTs. Rivard et al. [190] suggested that 60-90 days should be required for the entire digestion of polymer substrates while Banks [191] suggested a 20 days HRT for digesting the maize substrate. The lower HRT is beneficial since it explicitly relates to the cost of production and the enhancement of process efficiency [192].

5. Post-treatment and product recovery

Ideally, the products of the AD process are generated for the promising green renewable energy and biofertiliser utilisation. The biogas produced from the OFMSW AD process was primarily comprised of methane and carbon dioxide gases with a concentration range of 50-70% and 30–50% respectively [193]. In addition, the produced also consists of traces gases of N_2, H_2S, H_2O vapor, VOC, siloxanes, CO and ammonia in tiny fractions [194]. Similarly, the broad organic nutrients of digestate produced from the AD process also contaminatted with heavy metal and other impurities due to mineralisation and transformation during the operations [195]. In this regard, the post-treatment process for both generated products of biogas and digestate nutrient is prerequisite before gas storage and waste disposal. **Figure 4** shows the flow diagram of post-treatment and recovery of OFMSW AD products.

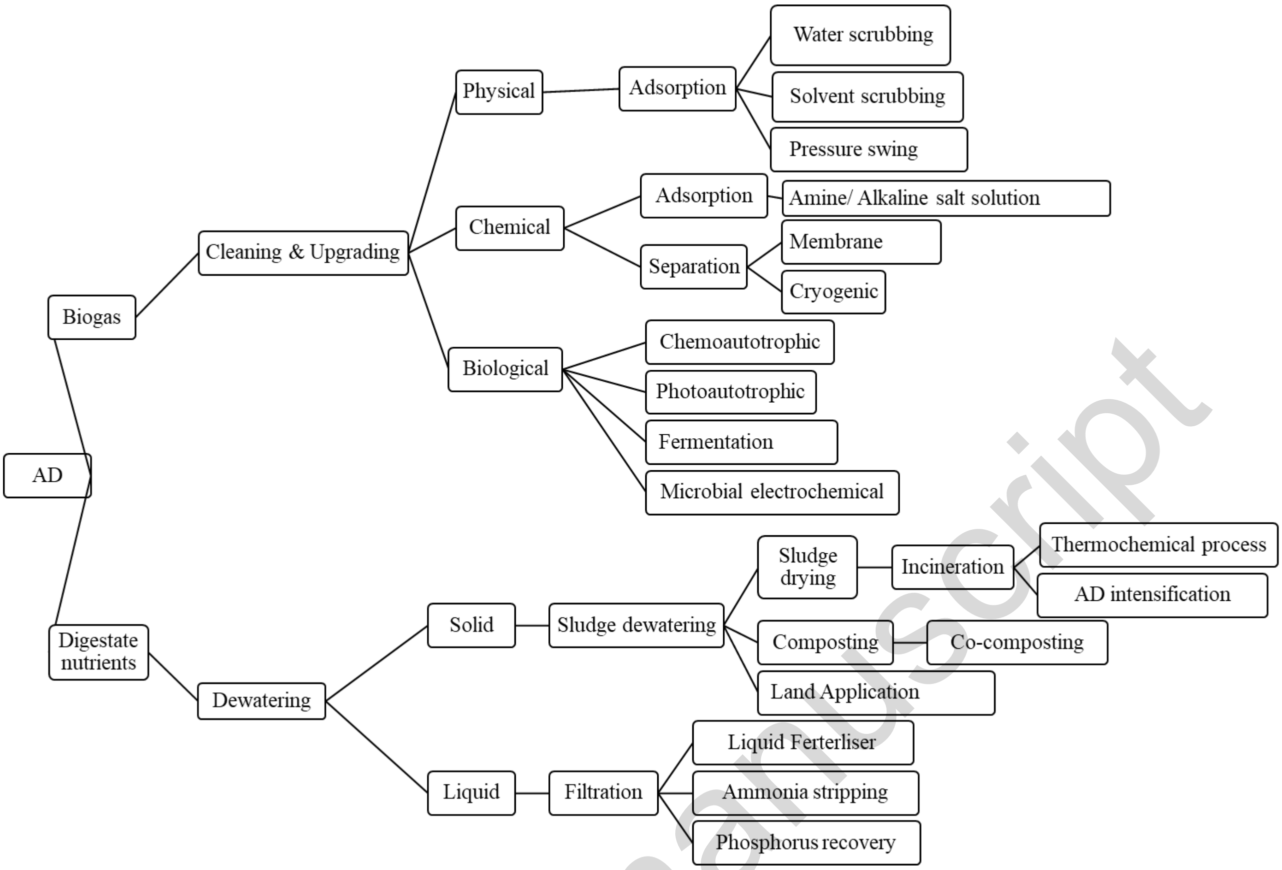

Figure 4: The post-treatment and upgrading of AD product recovery [196]

5.1. Biogas cleaning and upgrading process

As summarised by Agelidaki *et al.* [197], the treatment process for biogas is a combination of the cleaning process of harmful toxic compounds and the upgrading process for the low calorific value of biogas to a higher one i.e. biomethane (through carbon dioxide (CO_2) treatment and methanation process). Indeed, the cleaning and upgrading of the biogas process involve various types of methods that include physical, chemical and biological processes.

The toxic and harmful gases (mainly H_2S and CO_2) are removed using the adsorption method, through water and organic solvent scrubbing [198]. In this upgrading process, CH_4 (98 to 99% purity) is freely discharged, whereas water and organic solvent are circulated back into the column [199]. In another option, the cleaning and upgrading process could also be done using the pressure swing adsorption (PSA) method. As reported by Augelleti *et al.* [200], the separation of the toxic gases (H_2S, CO_2, N_2, and H_2O) from CH_4 by PSA method is dependent on the physical and chemical characteristic of the adsorbent material, their affinity and molecular behaviour. This method provides advantages including compactness of the equipment, low capital investment cost, low energy requirements, and safety and simplicity of operation. However, in the PSA operation, the upgraded CH_4 (96-98% purity) could be lost up to 4% within the off-gas stream [201].

In the chemical treatment processes, the cleaning and upgrading process is commonly conducted through the application of adsorption (amine/alkaline solution) and separation (membrane and cryogenic) method. In the adsorption method, CO_2 and H_2S are bound and completely adsorbed in a amine scrubber (mono-, di- or tri-ethanolamine) [197]. Practically, in the amine scrubbing system, the CO_2 which is bounded by the solvent exothermic chemical reaction is cooled in the condenser to allow the recirculation of the condensate to the stripper and releasing the entrapped CO_2. However, the adsorption capacity of amine solution is lower compared to that of other alkaline salts (sodium, potassium and calcium hydroxide) [202]. Besides, the process of amine adsorption requires significant energy and capital cost with the potential of amine losses during the evaporation compared to alkaline salts [203]. Nevertheless, the upgraded CH_4 obtained is of 99% purity as the chemical reaction is strongly selective, with only 0.1% of CH_4 loss [197].

The membrane separation method can be conducted in dry (gas/gas separation) and wet (gas/liquid) membrane separation [204]. Initially, the cleaning process is required to separate the biogas (H_2S and H_2O) before being compressed and injected into the membrane unit to avoid corrosion potential [198]. Practically, polymeric membrane (cellulose acetate and polyamide) is used to separate the CO_2 and CH_4 [205]. As reported by Agellidaki *et al.* [197], the mechanism of the gas separation has relied on the hydrophobic adsorption capability of the diffused gas molecule through the microporous membrane where the biomethane was remained and collected.

the cryogenic method mainly separates CH_4 (97% purity) from the impurities (H_2O, H_2S, siloxanes, halogens) through the liquefaction process at low temperatures (-110 °C) and high pressure (80 bars) [201]. However, the commercialisation of cryogenic process facilities is still very few owing to its high operational cost [206].

The biological approaches are composed of chemoautotrophic, photoautotrophic, fermentation and microbial electrochemical methods through the utilisation of clean CO_2 recovery [197]. The chemoautotrophic method is operated through utilising H_2 and CO_2 gases for CH_4 conversion by adopting the hydrogenotrophic methanogens (in-situ, ex-situ, hybrid) process and the exergonic process of homoacetogenic bacteria [207]. Meanwhile, the photoautotrophic approach produces high CH_4 recovery (97%) by using catalytic phototrophic organism (e.g. algae) in closed or open photobioreactors under 54% of CO_2 utilisation [197]. In addition, the upgrading process of CO_2 gases to CH_4 conversion could be achieved by multiple stages of the fermentation process. The conversion process is applied by the assimilation (Wood-Ljungdahl pathway) of CO_2 gases using acetogen microorganisms [208]. Besides, the integration of CO_2 with *actinobacillus succinogenes* bacteria could produce bio-succinic acid that is valuable for other chemicals product synthesis [209]. The fermentation process can increase CH_4 content by up to 95% [210].

5.2. Digestate post-treatment and recovery

The decomposition of OFMSW in the AD also produces large quantities of nutrients digestates, both in solid and liquid form [211]. In practice, the formation of the digestate is due to the degradation of the organic components, which mineralises and solubilises during the digestion process [212]. However, the excess solubilised mineral accumulation can develop stable compound precipitation. Besides, the complexation of high-affinity heavy metal ions with the availability of anions leads to the precipitation of heavy metal enrichment in the solid digestate [195]. As reported by Akhiar *et al.* [213], the high nutrient concentration of the released liquid digestate has a limited application due to the issue of land and aquatic life pollution. Therefore, the release of this large nutrient requires proper management to avoid waste biomass and nutrient depletion. In this regard, the integrated system of post-treatment and recovery of digestate nutrient is essential. As mentioned by Scaglione *et al.* [214], the digestate produced from AD-OFMSW was followed by a complete wastewater treatment system prior to the standard of discharge limit. As shown in **Figure 4**, the AD-OFMSW digestate is separated into the various post-treatment method and recovery potential.

As reported by Ma *et al.* [215], the digestate that is primarily recovered through dewatering treatment is separated into the sludge dewatering and filtration process. Specifically, each of the treatments is comprised of different target treatment properties that relied on nutrient recovery and utilisation. Before the sludge dewatering treatment, the process includes sludge incineration, composting and land application. Meanwhile, the filtrated liquid is separated for liquid fertiliser, ammonia stripping, and phosphorus recovery. Practically, the sludge incineration method is primarily conducted through the combustion of organic matter before ash utilisation and disposal [216]. In this process, the digestate with high calorific value is preferable for combustion enhancement. The ash bottom produce from the process has a high level of phosphorus, potassium and heavy metal content [216]. The incineration of ash residual is commonly been carried out through thermochemical treatment that produces a high quality of organic compound [217].

Meanwhile, composting is a typical aerobic treatment for OFMSW digestate improvement and nutrient recovery [218]. This composting process could be upgraded by introducing the co-composting process to the digestate. As evaluated by Arab *et al.* [218], the co-composting method was able to increase the reaction rate of composting process by up to 40% of the digestate. However, the high concentrations of the co-composting process could propagate the inhibition of composting rates. In contrast, sludge digestate is usable for land application by directly returning that to prolong the soil stability. Nevertheless, due to the constraints of land usage from waste-based nutrients, risks involved with contamination and regulatory measures have restricted the implementation [219].

Typically, the separated liquid digestate from the dewatering process is further treated before utilisation and discharge regulations. The treated liquid digestate, which contains high concentrated nitrogen and potassium compounds, is potentially being used as a soil conditioner and green fertiliser [220]. Besides, the mixture of raw digestate and concentrated treated digestate is able to provide a sustainable substitution for mineral fertilisers [221]. The membrane filtration is the primary approach that is utilised for nutrient recovery for the liquid digestate due to the simple and low-cost operation [222]. However, the membrane recovery efficiency rely on the permeability and fouling limitation of the membrane treatment selectivity (e.g. microfiltration, ultrafiltration, nanofiltration, etc.) [222].

Meanwhile, the striping treatment (air and steam) is the most applicable method for the ammonia removal in liquid digestate due to simple operation and less sludge accumulation [215]. This adsorption process operates through the desorption column which releases the ammonia into a sulphuric acid solution to forming ammonium sulphate fertiliser [220]. The effluent from the stripping process requires further treatment process prior to wastewater discharge [215]. Ammonium sulphate produced from the process is highly applicable as plant fertiliser. On the other hand, the phosphate recovery from the liquid digestate is effectively done through the chemical precipitation and enhanced biological phosphate removal (EBPR) process [223]. The chemical precipitation and EBPR process provide an advantage in operational cost as well as process efficiency through the biological combination of phosphorus removal [215]. Moreover, as confirmed by Muhmood *et al.* [224], the fertilisers produced are suitable for farm usage and can be used as a secondary resource. However, the efficiency of the fertiliser strongly depends on the recovery process conditions (phosphorus precipitation, pH, temperature and duration) [223].

6. Techno-economic feasibility of AD

A techno-economic analysis and life cycle evaluation is critical for sustainable processes and can be evaluated using three criteria, such as economic viability, technological viability and sustainability. Most companies and investors are looking at generating biogas using AD to produce electricity. It is often regarded as a high-risk investment by processes like raw material distribution, waste sorting, types of feedstock, and profit issues [225]. Based on the above evidence, several governments support and allow companies to provide funds for this sector. Techno-economic analysis and life cycle evaluation offer insight into the viability of the AD system, which is very important [226]. The techno-economic analysis by Dereli *et al.* [227] indicates that the AD of sewage sludge and OFMSW mixture could produce 3.33 times more power compared to the primary sludge digestion. The AD process for sewage sludge and OFMSW can yield approximately 56,000 kWh/d of energy which corresponds to the total profits of about € 1.5 million in methane used by the internal combustion engine and power generation system. According to Bolzonella *et al.* [228], the AD of OFMSW with the sewage sludge increased biogas production by 240 percent. At an average concentration of 50 tonnes/week, the average treatment cost was € 50/tonne OFMSW. A life cycle analysis shows that the AD of OFMSW and sewage sludge offers an environmentally friendly waste management alternative for small-scale systems [229]. Based on the life cycle analysis, Edward *et al.* [230] claimed that AD has fewer effects on the atmosphere, lower global warming potential, less impact on acidification, and minimal fossil fuel depletion potential compared to the current waste management service.

However, robust design and organisation of facility and good operating practices are crucial for commercial success. Low returns can be caused by the absence or reduction in waste disposal fees. It has been reported that the AD process is commercially feasible, and it can play a significant role in gaining revenue. For example, Moraes *et al.* [231] reported that AD of vinasse from sugarcane biorefinery could potentially lead to profits from energy, environmental, and economic perspectives, thus optimising the plants in terms of sustainability. Andlay [232] reported that AD of algal biomass could be a source of revenue to the order of almost $ 10.6 million every year.

7. Future challenges and potential

The complex characteristics of OFMSW substrate highly influence the AD process efficiency. Indeed, the standardisation of the substrate quality requires a complete analysis of system considering the collection, sorting and pre-treatments before AD process. In this regard, a proper model of the analysis system for standardising the OFMSW substrate quality could be one of the steps to resolve the variability of the substrate mixture.

The behavior of microbial communities is very sensitive towards the productivity and quality of biogas and biofertiliser. Besides, the emergence of uninvited toxicity and valuable intermediate products are also gaining serious attention in maintaining the digester process stability. These issues are primarily affected by the process condition of OFMSW digestion involving feedstock pre-treatments and process parameter optimisation. As a solution, a complete inhibitory analysis of the pre-treatments should be provided to identify the early prevention measures on the specific characteristic of the substrates. Besides, the high solid hydrolysis stage for OFMSW digestion is required for a multistage process to allow diverse microbial communities growth. The study of more than two stages digester for OFMSW substrates can enhance the microbial buffering ability in stabilising the AD process. Moreover, the use of recent genetic engineering technologies (gene sequencing technologies, metagenome technology, and synthetic biology) could enhance the specific microbial activity for digestion process.

Meanwhile, comprehensive post-treatment and the quality of OFMSW digestate biofertiliser enhancement are rarely been reported by the researchers. Besides, the characteristics of OFMSW biofertiliser usage suitability are not being fully addressed. One of the most important challenges for OFMSW AD is to provide the process recovery value, which governs the environment, process, and economic feasibility. In this regard, the combination of technology from multiple enhancement techniques could provide a synergistic effect on the OFMSW digestion process. This process mainly involves a selection of suitable methods covering pre-treatments, the digestion process designs as well as the product recovery and enrichment. The multiple models of integrated conceptual design could be proposed in identifying the best approaches. The comparison of the performance could provide the optimum selection for the best process recovery value.

8. Conclusions

The characteristics of OFMSW such the stability of the nutrients, moisture balance as well as the buffering capacity etc. significantly affect the AD process efficiency. In this regard, the selection of suitable pre-treatment process, their operating parameters, as well as the appropriate digester system selection, are important factors that need to be taken into account. In addition, the energy consumption, operational practicality as well as flexibility are the critical process configuration that needs to be considered for the digester design. There are several specific operational conditions for the AD of OFMSW that provide a high-efficiency performance of the process. The continuous digestion with thermophilic temperatures is the best option for the OFMSW SSAD process. The plug flow and CSTR reactors are the most reliable options to control the biological conditions owing to the variability of OFMSW characteristics. Besides, the process also provides a stable product recovery. Meanwhile, the optimum process condition for AD of OFMSW requires specific parametric conditions viz. pH of 6.5 - 7.5, the temperature of 50 - 55 °C, particle size between 0.7 mm and 10 mm, C: N ratio of 20 - 30, OLR of equal or more than 6 kg VS/m^3/day and HRT of 15 - 20 days. The unstable biological products of solid and liquid digestate are effectively treated using the physicochemical treatment approach. Although there are other effective biological treatments available, those are only limited to the lab-scale design. In this regard, a reliable treatment method for full scale should be selected to ensure process feasibilities and sustainability.

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Highlights

- Studies on organic fraction of municipality solid waste are reviewed
- Pretreatment is required to achieve optimum results in anaerobic digestion
- The digestion operating conditions significantly controls the biogas output
- The products of digestate require post-treatment for maximised output