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A review on strategies to optimize metabolic stages of anaerobic digestion of municipal solid wastes towards enhanced resources recovery

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Abstract

Recently, there are increased efforts by municipals and researchers to investigate the potential of utilizing municipal solid wastes (MSW) for resources recovery. In many parts of developing countries, MSW is mostly collected for disposal with little emphasis on resources recovery. However, the MSW has high organic and moisture contents, and are suitable substrates for anaerobic digestion (AD) process to recover biogas for energy and digestate which can be used as fertilizers or for soil amendments. Resources recovery from the AD process consists of four metabolic stages; hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These metabolic stages can be affected by several factors such as the nature of substrates, accumulation of volatile fatty acids, and ammonia inhibition. In this review, different optimization strategies towards resources recoveries such as pre-treatment, co-digestion, trace elements supplementation, optimization of key parameters and the use of granular activated carbon are discussed. The review reveals that the currently employed optimization strategies fall short in several ways and proposes the need for improvements.

Keywords: Municipal solid wastes, Resource recovery, Anaerobic digestion

Introduction

By the year 2012, about 1300 Mt of municipal solid wastes (MSW) were being generated annually, worldwide [1]. The MSW generation rate is projected to increase and could reach over 2000 Mt by 2025, of which more than 40% will be organic [1, 2]. Among the factors associated with this increase include; population increase, increased urbanization rates, industrialization, economic growth, and changing food habits and consumption patterns [3, 4]. Currently, MSW causes a management burden for municipals, some of which fail to collect all the wastes produced. In most developing countries, MSW management entails the collection, transportation, and disposal with little or no emphasis on resources recovery. The efficient and effective MSW management requires among other things, routine bin collections, proper route-planning, waste separation as well as appropriate waste collection schedules [5].

In developing countries, the transfer and transportation of MSW are affected by many factors including inaccessible roads, poor financial management, outdated machinery and equipment and lack of information about the waste collection schedules [6, 7]. Furthermore, the very low budgetary allocations by local government authorities can manage only a small percentage of MSW. Consequently, waste generators resort to crude dumping of wastes in unauthorized sites [8–10]. Hoornweg and Bhada-Tata [11] found that low-income countries have a low wastes collection ratio of about 41% as compared to 98% in high-income countries. This poor MSW management in developing countries is further exacerbated by rapid urbanization especially in slums and other unplanned areas, where there is inadequate infrastructure to facilitate waste-collection services. In countries like

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Ghana and Nigeria, less than 20% of solid wastes are properly managed and approximately 80% is disposed of through crude dumping [12].

In Dar es Salaam, Tanzania's largest city, about more than 5000 t of daily solid wastes are generated but only 40% of these wastes are collected by municipal councils in partnership with private sectors for disposal [13]. Such inadequate MSW disposal can affect human health through direct exposure or consumption of contaminated foods [14, 15]. For instance, some diseases such as diarrhoea, dengue fever, and malaria have been linked to poor solid wastes management practices [16]. Collection of wastes for recovery of resources such as biogas and soil conditioners by anaerobic digestion (AD) processes can be a viable option in such circumstances. Furthermore, the recovered products can be a supplementary source of energy and fertilizers and can be sold to offset the costs required for managing MSW.

The purpose of this review is to update our knowledge of the AD process for MSW and strategies to optimize it. The review further evaluates resources recovery options from AD processes and provides some future perspectives concerning these strategies for effective MSW management. The emphasis to deal with MSW in cities is quickly gaining traction. This review shows that AD systems can be used for alternative MSW management and high-value products can be derived from the process.

MSW generation and compositions

Although the definition of MSW varies among scholars, in general, it covers all solid wastes generated in community places such as residential, commercial, and institutions, excluding the hazardous wastes [17]. Whereas waste generation data are available in most developed countries, in developing countries, and particularly in sub-Saharan Africa, such data are scarce [11]. Comparison of available waste generation data between developed and developing countries shows that the generation rates are higher in developed than in developing countries [3, 18]. The generation also varies among cities and towns in both developed and developing countries.

In developing countries, the generated wastes are rich in organics and have high moisture content (MC). Reports show that the MC composition of wastes in developing and developed countries range between 50 and 70% and 20–30% respectively [19, 20]. The high organic and MC of wastes in developing countries make composting or AD suitable treatment options for resource recovery processes [21]. The global waste streams (Table 1) comprises of six waste categories of which 46% are organic waste fractions [11]. The higher percentage of organics in the global waste stream further suggests that MSW has a high potential for resources recovery. The MSW in developed countries also has high calorific values as compared to the wastes in developing countries (Table 2). These differences can be attributed to the differences in waste sorting programs. Whereas sorting programs are widely applied in developed countries, less sorting is done in developing countries which leave a lot of inert materials in MSW [22, 23].

Table 2 indicates the various calorific values of MSW which demonstrate that MSW has a high potential for energy recovery [18, 22–28]. The lack of waste-separation programs in most cities of developing countries limits the utilization of AD technology for MSW management. Therefore, preferences are given to either incineration or landfills with limited resources recovery from the wastes. Considering the nature of wastes and the multiple benefits AD can offer, there is a need to identify strategies of improving waste-sorting programs in these countries. In countries where segregation programs exist, resources such as biogas and composts are recovered from MSW to reduce the wastes that could otherwise end in landfills and incineration [6]. AD thus offers the recovery of resources such as biogas for energy and effluent slurry for soil conditioners with less environmental repercussions.

The AD process

The AD process comprises of a series of metabolic stages namely; hydrolysis, acidogenesis, acetogenesis, and methanogenesis which are further described in this section.

Table 1 Typical global waste composition and sources [11]

Composition	%	Sources
Organic	46	Food scraps, yard (leaves, grass, brush) waste, wood, process residues
Paper	17	Paper scraps, cardboard, newspapers, magazines, bags, boxes, wrapping paper, telephone books, shredded paper, paper beverage cups
Plastic	10	Bottles, packaging, containers, bags, lids, cups
Glass	5	Bottles, broken glassware, light bulbs, coloured glass
Metal	4	Cans, foil, tins, non-hazardous aerosol cans, appliances (white goods), railings, bicycles
Others	18	Textiles, leather, rubber, multi-laminated, e-waste, appliances, ash, other inert materials

Table 2 Compositions of municipal solid wastes in different cities around the world

City	Organic (%)	Paper (%)	Glass (%)	Plastic (%)	Metal (%)	Others (%)	Calorific value (MJ kg^{-1})	Ref.
Berlin (German)	15	20	7	23	2	33	–	[18]
Dhanbad (India)	75	0.6	0.5	20.7	0.3	2.9	10.7–13.0	[22]
Australia (Greater Brisbane)	53.3	13	4.2	14.7	2.7	12.1	7.8–10.7	[23]
Arusha (Tanzania)	67	11	4	7	1	10	12.42	[24]
Nairobi (Kenya)	58.5	11.3	–	13.8	–	16.4	12.48	[25]
Algeria (country)	62	9	1	12	2	14	5.86–6.69	[26]
Kathmandu (Nepal)	71	7.5	1.3	12	0.5	7.7	–	[27]
Mende, Lozère, (France)	29.6	23.3	4.2	14.8	5.4	22.9	–	[28]

Hydrolysis

Hydrolysis is the first stage of the AD process where complex molecular compounds such as carbohydrates, proteins, and fatty acids are transformed into simpler and soluble molecular compounds such as sugars, amino acids and fatty acids [29]. Equation (1) represents the overall reaction in this stage.

$$(C_6H_{12}O_6)_x + H_2O \rightarrow \times (C_6H_{12}O_6) \tag{1}$$

Microorganisms which are responsible for hydrolysis release extracellular enzymes which cause the transformation to occur [30]. The hydrolysis of complex organic compounds such as lignocelluloses materials is very slow and is the rate-limiting step during the AD process [31–33]. Therefore, investigations towards improving the hydrolysis step are among the strategies to optimize the AD process. Different techniques are used to improve the hydrolysis process to enhance resources recovery from organic fraction municipal solid wastes (OFMSW) [34–39] as discussed in section 3 and summarized in Table 3.

Acidogenesis and acetogenesis

In the second stage of the AD process which is acidogenesis, a large group of facultative and obligate anaerobic bacteria converts the products of hydrolysis into other forms to be used in subsequent phases. For instance, sugars, amino acids, and fatty acids are converted into organic acids or volatile fatty acids (VFAs), alcohols, and some inorganic compounds such as CO_2, H_2, H_2S and NH_3 [33]. Equations (2), (3) and (4) represent the reactions in this stage.

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \tag{2}$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \tag{3}$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \tag{4}$$

Acetogenesis is the third stage of the anaerobic metabolic stage where acetogenic bacteria convert the products of acidogenesis into acetate, hydrogen and carbon dioxide [29, 40].The overall reactions in this stage are represented by Eqs. (5), (6) and (7).

Table 3 Summary of organic fraction municipal solid wastes optimizing pretreatment conditions

Strategy	Substrates	AD conditions	Results	Ref.
Mechanical (Bead milling at 1000 rpm)	OFMSW (Food Wastes)	Batch, 37 °C	Particle size reduction from 0.8 to 0.7 mm improved hydrolysis step and increased methane yields by 28% at 1000 rpm	[34]
Thermal pre-treatment (at 65 °C)	OFMSW, sewage, and leachates	Batch, 37 °C	Thermal pre-treatment at 65 °C accelerated hydrolysis stage and increased biogas yields by 7%	[35]
Thermal pre-treatment (Steam explosion)	OFMSW and citrus wastes	Batch, 55 °C	The steam pretreated citrus wastes co-digested with MSW had a higher methane yield of 0.53 m^3 kg^{-1} VS^{-1} which was 426% higher than the corresponding untreated substrates	[36]
Chemical (5 N NaOH and 5 N KOH at pH 13 and temp 80 °C)	OFMSW (kitchen wastes)	Batch, 35 °C, 90 rpm	The pretreatment of OFMSW with 5 N NaOH and 5 N KOH at a retention time of 10 d increased the solubility of OFMSW and enhanced the biogas increase by 18 and 30% respectively as compared with the untreated OFMSW	[37]
Microbial (wood-rotting fungi)	chestnut and hay leaves	Batch, 37–38 °C	The biogas production was enhanced by 15% as compared to the untreated substrates	[38]
Microbial (white-rot fungi at 60 °C) moisture content)	Yard trimmings	Batch, 37 °C	Pre-treatment of yard-trimmings with *Ceriporiopsis subvermispora*, white-rot fungi at 60% moisture content enhanced methane production by 106%	[39]

$$CH_3CH_2COOH + 2H_2O \rightarrow CH_3COOH + CO_2 + 3H_2 \quad (5)$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (6)$$

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + H^+ + 4H_2 \quad (7)$$

Different kinds of VFAs such as acetic, propionic, butyric, valeric, formic, and caproic acids are the intermediate products of the second and third stages; acidogenesis and acetogenesis of AD [41, 42]. These VFAs are important while assessing the performance and monitoring of the stability of AD processes [42, 43]. VFA accumulation is usually an outcome of the imbalance between acid producers in acidogenesis phases and acid consumers in subsequent methanogenic phase [44]. High VFA concentrations can also lead to a drop of pH in the reactors which is unfavorable for the methanogens. Although the AD process can proceed at a wide range of pH values at different stages, the optimal range for methanogens is 6.5–7.5 and should be maintained to enhance the activities of these bacteria [45–47]. Therefore sufficient alkalinity is required during the AD process to counteract instability and system failure in the process [45].

Different VFA inhibition levels have been reported by various authors. For instance, VFA concentrations of between 5800 and 6900 mg L^{-1} are reported to inhibit the methanogenic activities in the AD of kitchen wastes [48]. Zhang and Jahng [49] also reported inhibition of methanogenic activities at VFA concentrations of 18,000 mg L^{-1} in a semi-continuous AD of food wastes (FW). In another study by Wei et al. [50], it was indicated that in the AD of FW, methanogenic activities were strongly inhibited at VFA concentrations of 30,000 mg L^{-1}. Similar results were also obtained by Zhang et al. [51] who indicated the same inhibition levels at an organic loading rate of 4.0 g volatile solids (VS) L^{-1} d^{-1} in AD treatment of FW. According to these findings, VFA inhibition levels depend on many factors including; the type of a substrate, type of reactors and other operating parameters. The use of the pH adjustment to prevent VFA inhibition though helpful in delaying process failures is a temporary solution and cannot be used to reverse the process imbalances [52]. Therefore, different strategies including addition of trace elements (TE) and use of granular activated carbon (GAC) to improve acidogenesis and acetogenesis phases of AD process are used [49, 50, 53–58] (Table 4).

Methanogenesis

Methanogenesis is the final metabolic stage of the AD process where degradation of organic materials and the formation of biogas can be accomplished mainly by acetotrophic methanogens and hydrogenotrophic methanogens. Usually, hydrogen is in limited supply in AD systems, and therefore the majority of methane approximately 70% is derived from acetate and less than 30% is produced by hydrogenotrophic methanogens [29]. Whereas acetotrophic methanogens degrade acetate to methane and carbon dioxide, hydrogenotrophic methanogens use carbon dioxide and hydrogen to produce methane (Eqs. (8) and (9)). Methane can also be formed from ethanol by substrate oxidation (Eq. (10)), [29, 51].

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (8)$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad (9)$$

Table 4 Summary of results from trace elements and granular activated carbon supplementation in the anaerobic digestion process

Strategy	Type of feedstock	Influence of the strategy	Ref.
TE supplementation	Food wastes supplemented with Fe, Co, Mo and Ni	Addition of TEs stopped VFA inhibition	[49]
TE supplementation	Food wastes supplemented with Fe, Co, and Ni	Addition of TEs gradually decreased VFA inhibition and maintained process stability, and allowed higher organic loading operations	[50]
TE supplementation	Food wastes supplemented with Se and Co	Se and Co supplementation in food wastes digestion prevented VFA accumulations, increased methane yields and resulted in stable operations	[53]
Co-digestion	co-digestion of FW (83%) and PW (17)	The highest concentrations of TE in piggery wastewater almost doubled the methane production and prevented VFA accumulations	[54]
Co-digestion	Food waste (66.7%) mixed with cattle manure (33.3%)	TE available in cattle manure; Mg (4.99%), Ca (2.27%), Mn (950 ppm) and Zn (250 ppm) increased total methane yield by 42%	[55]
GAC supplementation	Synthetic wastewater supplemented with coal-based GAC	GAC supplementation enhanced methane productions, biomass growth, and acclimatization of microorganisms	[56]
GAC supplementation	VFAs (acetate, propionate, and butyrate) supplemented with GAC	GAC addition enhanced VFA degradation and increased methane yields	[57]
GAC supplementation	OFMSW supplemented with GAC	GAC supplementation increased syntrophic associations between bacteria and methanogens	[58]

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \tag{10}$$

Strategies to optimize the anaerobic digestion process of municipal solid wastes

Different strategies can be used to optimize metabolic stages of AD process for resource recovery from OFMSW as summarized in Fig. 1.

Optimizing the hydrolysis phase

Different pre-treatment methods including mechanical, thermal, chemical, and biological treatment are used to improve the hydrolysis stage of AD of OFMSW. A summary of the pros and cons of each of the pretreatment options is provided in Table 5. Mechanical pre-treatment which mainly focuses on the reduction of particle size and crystallinity nature of lignocellulosic materials has widely been used compared to the other pre-treatment options. Izumi et al. [34] showed that particle size reduction of FW by bead-milling improved the hydrolysis step and enhanced biogas production. However, excessive particle size reduction resulted in VFA accumulation and decreased biogas production. Mechanical pre-treatment has the disadvantage of high power requirement, especially when treating lignocellulosic-based OFMSW [59]. Among the mechanical pretreatments methods for OFMSW, the simplest are maceration, sonication, and high-pressure homogenizer [60].

The application of thermal pre-treatment can be employed to enable the conversion of lignocellulosic OFMSW before AD process to enable the conversion of lignocellulosic OFMSW before AD process. The high temperatures enable the melting of lignin and are freed from shielding the cellulose and hemicelluloses framework from chemical or bacteria digestion. This option can be very expensive due to the high heat requirement. However, in the industrial application, the costs can be offset if the generated biogas is used as a source of heat for treatment. The effect of thermal pretreatment on anaerobic co-digestion of OFMSW, leachates, and sludge was investigated using batch experiments [35]. The results indicated an improvement in the hydrolysis step and a 7% increase of biogas generation. Forgacs et al. [36] assessed the effects of steam pretreatment of citrus waste and MSW. The pretreatment achieved a 426% increase in methane yield compared to unpretreated substrates.

Chemicals such as alkalis, acids, and ozone have also been used to pre-treat lignocellulosic-based OFMSW. The findings from Liew et al. [31] indicated a 20% increase of methane yields after pre-treatment of fallen leaves with 3.5% NaOH compared to unpretreated ones. Alqaralleh et al. [37] also investigated the pretreatment of OFMSW with NaOH and KOH at a retention time of 10 d. The NaOH and KOH pre-treatments enhanced the biogas production by 18 and 30% respectively as

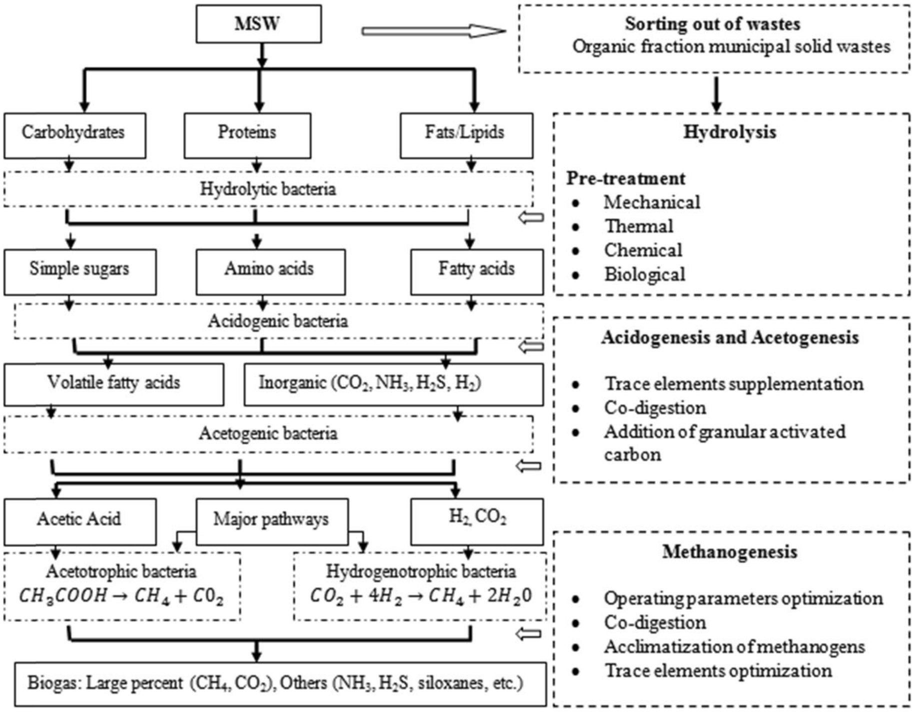

Fig. 1 Strategies to improve metabolic stages of the anaerobic digestion process of organic fraction municipal solid wastes

Table 5 Summary of pro and cons of pretreatment strategies to optimize the hydrolysis stage

Strategy	Pro	Cons
Mechanical	• Particle size reduction increases the surface area available for microorganisms resulting in improved anaerobic degradability • Promotes rapid digestion of lignocellulosic-based OFMSW	• Excessive particle size reductions may result in pH decrease resulting in decreased methane yields • High energy requirements and the possibility of impurity contaminations during particle size reductions process
Thermal	• Accelerate lignin solubilization of lignocellulosic-based OFMSW and shortening hydraulic retention time • Removal of pathogens in substrates with subsequent enhancement of digestate handling	• High running costs due to high heating energy requirements for running the process • High temperatures may result in the creation of chemical bonds and agglomeration of particles
Chemical	• Alkali and acid pretreatment enhances removal of lignin which enhances better contact of substrates and microorganisms • Alkali pre-treatment with NaOH and KOH enhance COD solubilization of OFMSW which accelerates methane production • When used at a small scale, chemical pre-treatment has low capital costs	• Use of chemical pre-treatment may lead to the formation of inhibitory products such as phenolic compounds, furans, and carboxylic acids which may inhibit the growth of the methanogens • Acid pre-treatment may lead to the corrosion of equipment which may be very expensive to repair. • A high-cost requirement of chemicals in large scale biogas productions • Digestate produced may require careful handling due to by-products formed
Microbial	• Facilitates removal of lignin and hemicelluloses degradation of lignocellulosic-based OFMS which enhances better contact of substrates and microorganisms • Due to low or no use of chemicals, there is little corrosiveness and by-product formation • Can be applied in milder conditions • May lead to the production of the safe digestate with minimum disposal costs • Considered to be an environmental friend with low capital costs and energy requirements	• A slow process and hence degradation of lignocellulosic-based OFMSW may take several weeks to months • Due to the heterogeneous nature of OFMSW, different specific enzymes may be required. • Require sterile environments

compared to untreated OFMSW. Some of the drawbacks of chemical pre-treatments include the formation of inhibitory products such as phenolic compounds, furans, and carboxylic acids that can inhibit the growth of the methanogenic bacteria [61]. Furthermore, higher amounts of chemicals may be required in large scale biogas production which may increase operating costs. Due to this, the use of chemicals, especially alkalis, is preferred for temporary pH adjustments during the AD process to counteract VFA accumulations and maintain process stability [45, 59].

The microbial pre-treatments have also been used to treat lignocellulosic OFMSW. Mackulak et al. [38] investigated the effects of pre-treatment of sweet chestnut leaves and hay with Auricularia auricular-judae, white-rot fungi. The results showed that biogas production was enhanced by 15% compared to non-pretreated substrates. In another study by Zhao et al. [39], the effect of pre-treatment of yard-trimmings with Ceriporiopsis subvermispora, white-rot fungi indicated a 106% increase in methane yields at 60% MC in pre-treated samples as compared to non-pretreated ones. Some of the advantages of microbial pre-treatments include less corrosiveness and formation of less harmful products due to the absence of chemicals [62]. However, microbial pre-treatment processes are very slow and require several specific enzymes because of the heterogeneous composition of OFMSW [30, 59].

Whereas thermal and mechanical pre-treatments have widely been applied at industrial scales, microbial and chemical pre-treatments are rarely applied. The use of chemical pre-treatment at industrial levels has high costs implications. However, as the demand for more energy and adequate urban wastes management increase around the globe, all these options can be applied for OFMSW pre-treatment at the industrial scale. Different pre-treatment technologies can also be combined upon evaluation on their economic, technical and environmental feasibilities. Furthermore, there is still a need to investigate new pre-treatment options that can be used to improve the hydrolysis process for biogas production. Improvement of the hydrolysis step will facilitate biogas recovery, reduce greenhouse gases emissions, and facilitate low-cost environmental management.

Optimizing the acidogenesis and acetogenesis phases

Addition of TE and co-digestion

Generally, the absence of TE is regarded as one of the contributing factors for process instabilities and process failure in the AD process. It is believed that the addition of TE in the AD process can improve activities of enzymes, growth of methanogens and process stability of the AD system [53, 63]. In the AD of OFMSW, TE can be added through co-digestion of OFMSW with substrates that are rich in TE or through direct addition of external TE [51]. Several studies on TE supplementations have confirmed that it improves the performance of the AD systems (Table 5). Co-digestion of wastes has advantages of dilution of inhibitory substances, balancing of carbon-to-nitrogen (C/N) ratio, and improving synergetic effects of microorganisms [64, 65]. Zhang et al. [54] investigated the effects of the co-digestion of FW and piggery wastes (PW) and the results indicated an increase of methane yields to 388 mL CH_4 g^{-1} VS^{-1} which was twice as much as yields generated from mono digestion of FW. The higher concentrations of TE in PW were the key factors for the improved performance in the co-digestion and prevention of VFA inhibitions. Similarly, Zhang et al. [55] studied the effects of co-digestion of FW and cattle manure (CM). The results indicated that the total volume of methane produced was higher in co-digested mixtures as compared to digestion of single FW or CM. The co-digestion of FW and CM at the ratio of 2:1 had the highest total methane yield, mainly due to the high concentration of TE (Mg, Ca, Mn, and Zn) in the mixtures.

Direct supplementation of TE has been studied by several researchers. Banks et al. [53] studied the effects of direct supplementation of selenium (Se) and Cobalt (Co) in the AD process of FW at elevated ammonia concentration and high propionic acid accumulation. The results indicated that Se and Co supplementation improved the process stability and prevented process failures. Wei et al. [50] also found that addition of Iron (Fe), Co, and Nickel (Ni) in the AD of FW in decreasing VFA inhibition and increasing methane production and process stability of the digesters. Similarly, Zhang and Jahng [49] also indicated that TE supplementation to long term AD of FW resulted in stable operations and prevented VFA accumulations. These findings suggest that the shortage of TE in most of the substrates is one of the contributing factors for VFA accumulations and inhibitions. Future studies on TE should focus on understanding the relationship between microbial activities in response to TE supplementations on OFMSW. This will help to further improve the AD process and to maximize resources recovery.

Addition of GAC

Addition of GAC has been used to improve the acidogenesis and acetogenesis phases of the AD process (Table 5). Due to the pores on their surfaces, GAC can serve purposes such as immobilization of syntrophic microorganisms, adsorption of inhibitors, and promotion of direct interspecies electron transfer in AD process [66–69]. In a study by Capson-Tojo et al. [40], the addition of GAC on the AD of FW resulted in in enhanced VFA consumption, increased methane production, promoted growth of methanogens and reduced the lag phase. In another study, Lee et al. [56] investigated the influence of GAC on AD of synthetic wastewater (SWW). The results indicated that GAC supplementation to SWW enhanced methane production 1.8-fold higher than the reactor with no GAC supplementation. Xu et al. [57] also studied the effects of GAC on methanogenic degradation of VFAs and the results showed that GAC addition accelerated the degradation of propionate and butyrate under high organic load which subsequently increased methane production. It is believed that high VFA degradation upon GAC supplementation was due to enhanced syntrophic associations between the bacteria. Similarly, Dang et al. [58] indicated that addition of GAC to the AD of OFMSW promoted the growth of bacteria and methanogens, improved VFA degradation, and increased methane production rates. Due to energy shortages and waste management problems, OFMSW holds a sustainable future for biogas production due to their abundance.

Although the use of GAC has been shown to enhance biogas production of OFMSW and other wastes in lab-scale experiments and at industrial levels in the developed countries, operating biogas plants with GAC requires very strict techniques [70]. Therefore, studies on how to operate biogas plants with GAC in developing countries are still needed. Furthermore, future investigations on new materials with adsorptive or conductive properties that can be used to manufacture GAC are still needed in order to improve the AD process.

Optimizing the methanogenesis phases

Ammonia inhibition is a major factor in the methanogenesis stage. During the AD process for biogas production, ammonia is produced from various sources like the breakdown of proteins and amino acids [71]. Under aerobic conditions, ammonia is microbially oxidized to nitrite and nitrate. Consequently, ammonia may accumulate under anaerobic conditions due to the absence of oxygen oxidant. At optimal concentrations, ammonia is important for microbial growth and forms $NH_4(HCO_3)$ when combined with CO_2 and H_2O which increases the buffering capacity and maintain the stability of the AD process [72, 73]. At high concentrations, ammonia is toxic to microorganisms and is widely reported to inhibit methanogenic activities [65, 71].

In aqueous anaerobic processes, ammonia exists in two principal forms; unionized ammonia (NH_3) and ionized ammonia (NH_4^+) which together form total ammonia nitrogen (TAN) [74]. NH_3 and NH_4^+exist in equilibrium and are reversible depending on temperature and pH (Eqs. (11) and (12)). The toxic level of ammonia is caused by unionized ammonia due to its capability to penetrate microbial cell membrane leading to disruption of potassium and proton balances.

$$[NH_3] + [H^+] \leftrightarrow [NH_4^+] \tag{11}$$

$$[\mathrm{TAN}] = [\mathrm{NH_4}^+] + [\mathrm{NH_3}] \tag{12}$$

where, [TAN] = Total ammonia concentration in mg L^{-1}, $[NH_4^+]$ = NH_4^+ concentration in mg L^{-1}, and $[NH_3]$ = NH_3 concentration in mg L^{-1}

Unionized ammonia and ionized ammonia and ammonium equilibrium constant are related by Eq. (13).

$$\mathrm{Ka} = [\mathrm{NH_3}]\ [\mathrm{H}^+]/[\mathrm{NH_4}^+] \tag{13}$$

$$\text{Where, } [\mathrm{H}^+] = \frac{1}{10^{\mathrm{pH}}} \tag{14}$$

Therefore, from Eqs. (11), (12), (13) and (14) the concentration of proportion of NH_3, NH_4^+ to TAN can be given by Eqs. (15) and (16).

$$\frac{[\mathrm{NH_3}]}{[\mathrm{TAN}]} = \frac{1}{1+\frac{[\mathrm{H}^+]}{\mathrm{Ka}}} \tag{15}$$

$$\frac{[\mathrm{NH_4}^+]}{[\mathrm{TAN}]} = \frac{1}{1+\frac{\mathrm{Ka}}{[\mathrm{H}^+]}} \tag{16}$$

where Ka is equilibrium constant and is a function of the temperature (T). Ji [74] reported the Ka to be given by Eq. (17).

$$\mathrm{Log_{10}\ Ka} = 0.2976–0.001225.T–(2835.76/(T + 273.15)) \tag{17}$$

Figure 2 depicts the variations of NH_4^+ and NH_3 concentrations with pH and temperatures of water as calculated from Eqs. (15), (16) and (17). From Fig. 2, at pH 6.5 and temperatures of between 25 and 37 °C, unionized ammonia is almost 0% and at the temperature of 55 °C, unionized ammonia is almost 5% indicating less toxicity in AD system. Similarly, at pH 8.5 and temperatures of between 25 and 37 °C, free ammonia is approximately 15 and 30%. At the same pH of 8.5 but higher temperatures of 55 °C, the concentration of the free ammonia is almost 60% indicating high toxicity in the AD systems. It can be concluded that as the pH and temperature increase, the concentration of the un-ionized ammonia also increases. However, ammonia inhibitory level depends on many factors such as feedstock, microbial community and thus inhibitory investigation studies on different substrates and conditions are required.

While several investigations have tried to improve the methanogenesis step through optimization of single parameters such as temperature or pH [75, 76], it is clear that operation parameters relate to each other and thus optimization study should not only focus single parameters. The methodologies which can be used to optimize and understand the relationship between temperatures, pH and ammonia concentration in the AD process are thus required.

Other strategies to counteract ammonia inhibition include the blending of feedstock to achieve a favorable C/N ratio, acclimatization, and TE optimization [55, 71, 77]. A C/N ratio of 20–35:1 is often recommended for the AD process [64]. However, C/N ratios vary among various feedstock and so the optimum ratio to improve AD process stability can be achieved

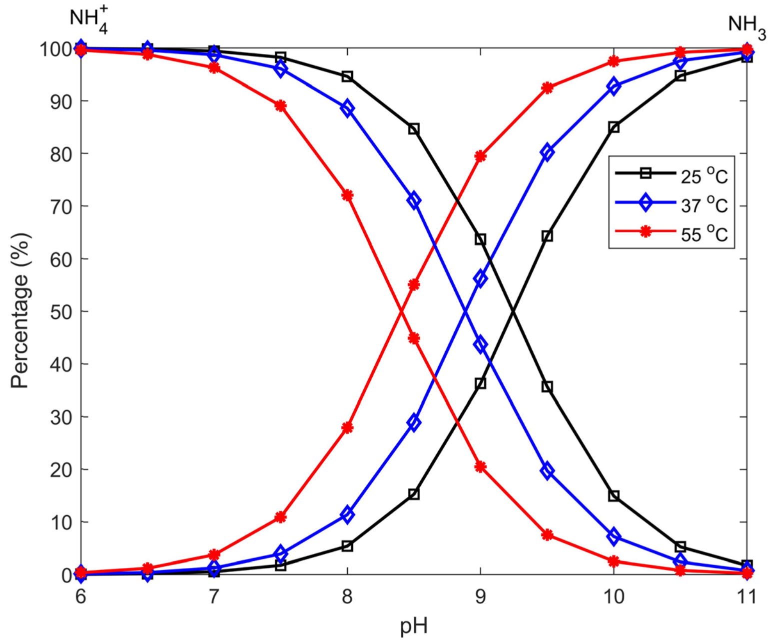

Fig. 2 Variations of un-ionized ammonia and ionized ammonia concentration with pH and temperature

through the mixing of substrates with low and high C/N ratio [78].

Resources recovery from the AD of MSW

Globally, industrial applications of the AD process of OFMSW as the main substrate for energy recovery is still not well developed. In most existing large plants, OFMSW has been used as co-substrates to supplement other substrates such as sludge. When AD plants are only for the treatment of wastewater, products such as biogas and digestate are of less value to biogas plant operators and therefore not well utilized. The biogas produced is therefore often self-utilized in the plants and the excess is flared. Similarly, the digestate in most developing countries is of no importance to the operators of the anaerobic digesters who normally discharge it into the sewer lines [45].

Currently, the demand for energy, food security, and urban waste management in most cities around the world is evident. This means that AD-derived products which were previously less valued by operators now need to be recovered to improve energy, environment and agricultural sectors. The global population is expected to reach approximately 10 billion by 2050 and most of this growth which will take place in Africa accompanied by increased energy demands and urban wastes generation [79]. Production and promotion of useful products from OFMSW has the possibility of improving energy production and wastes management. The best way to promote valuable products from the AD process is through the optimization of the metabolic process so as to maximize the recovery of the derived products.

Utilization of biogas as an energy source

Biogas can be produced when MSW is digested by microorganisms under anaerobic conditions. Biogas composition is dependent on the waste compositions and is typically comprised of large per cent methane (50–75%), and carbon dioxide (25–75%). Biogas also contains a small percentage of hydrogen, hydrogen sulfide, oxygen, ammonia, siloxanes, and aromatic and halogenated compounds [1, 80, 81]. In small scales, biogas can be used to meet energy requirements such as cooking, heating, and lightning [82].

In most urban areas of sub-Saharan Africa, people predominately use wood-fuel for the majority of their cooking needs. Wood is logged in forests far away, transported and sold at a high cost for consumers. Therefore, biogas production from MSW can be used to replace or supplement the traditional cooking wood-fuel. Due to the shortage of energy and the current problems of MSW, the use of a large-scale biogas technology can be a viable solution. Under large scale applications, biogas-producing plants can utilize several types of organic wastes from the livestock waste, food-processing industry, sewage sludge, and MSW to generate electricity [83]. Some of the challenges of using MSW in AD systems for electricity generation include inert impurities in wastes which require particular attention during the processing of wastes [84].

The development of large-scale technology for processing MSW is still in its infancy in most cities of developing countries. However, several studies indicate that MSW of developing countries has an energy potential which can be enhanced to generate electricity. For instance, Al-Hamamre et al. [85] reported that about 387 kt of MSW per year are produced in Jordan of which 42% are available for energy generation and biogas production. Similarly, in SouthAfrica, a report by Laks [86] indicates that there are about 38 commercial biogas projects in operation, producing about 50–70 MW from different kinds of wastes including MSW.

Upon purification to remove CO_2, H_2S, water vapour, and other impurities, biogas can be used for many applications. For instance, it can be used as transport fuel injected in natural gas pipelines, combined heat, and power and as a vehicle fuel [83, 87]. As a result, research on the development of biogas upgrading technologies has gained traction among various scholars all over the globe [88, 89].

Utilization of digestate as fertilizer or soil amendment

The constant application of chemical fertilizers is implicated in problems of soil degradation and environmental pollution [90, 91]. In addition, most developing countries import these fertilizers making their usage expensive [92]. Digestate (or effluent slurry), the product derived from the AD process can be used to supplement or replace the use of chemical fertilizers. Therefore, large quantities of MSW produced in cities can be processed to valuable products such as digestate that can be used to replenish nutrients in the soil.

Digestate from the AD of MSW is rich in nutrients such as nitrogen, phosphorus, potassium, and TE which are suitable for land applications to improve soil structures [93, 94]. In the AD of OFMSW, the digestate may contain up to 50% organic nitrogen and 50% ammonia. While ammonia is readily available for plant uptake, organic nitrogen, on the other hand, requires ammonification/mineralization before uptake by plants [95, 96]. The quality of the digestate depends on several factors such as the nature of the materials to be digested, digestion process, operation temperatures, and retention time [96]. The digestate may contain pathogens, hence, pretreatments may be necessary before discharge or re-use to obtain the quality and safe digestate [97, 98]. The mono-digestion of OFMSW can produce a digestate which is safe to re-use as a fertilizer or for soil amendments. However, large scale biogas production can utilize several kinds of wastes including sewage and therefore digestate may not be suitable for direct reuse or discharge.

Anaerobic digestate can either be used as fertilizers or organic amendments depending on the nutrients contained in them. Generally, the higher the percentage of the mineral nitrogen in the digestate relative to organic fraction, the more the waste is suitable for use as fertilizers [99]. Conversely, the lower the per cent of mineral nitrogen fraction relative to the organic the more the digestate is suitable for use as an organic amendment. Apart from the use of a digestate as fertilizer or soil organic amendment, it can also be used as a solid biomass fuel. Kratzeisen et al. [100] investigated the net calorific value of a digestate from a silage maize co-digestion with field crops and animal residue. The results showed that the calorific values were between 15 to 15.8 MJ kg^{-1}, which is higher, compared to wood-fuel. This demonstrated that digestate can be used as alternative wood-fuel energy. In summary, digestate can be used in several ways and thus further investigation on the proper way that can bring maximum benefits from the utilization of a digestate is needed.

Environmental and economic evaluations of MSW treatment options

In order to make decisions on technological selections to treat MSW, several factors must be considered including technical, economic, environmental, socio-cultural, political, institutional, organizations and legal aspects of the local environment [101]. However analysis of all factors is often complex in developing countries due to the lack of data, and a few factors like the economic cost (EcC) and environmental cost (EnC) are often used as the basis of these analyses [13, 102, 103]. Table 6 depicts the average EcC and EnC costs (in USD) for treating 1 ton of MSW in developing countries for five treatment options as computed by various authors. Whereas the computation of EcC considers operating costs for the treatment options, EnC is analyzed based on CO_2 emissions from various treatment options. From the comparison table, the negative values indicate an advantage after the adoption of the treatment option. For instance, the recycling and incineration of paper wastes in comparison to the plastic wastes represents an advantage in environment costs due to greater avoided impacts in CO_2 emission.

With an average unit of EcC and EnC costs per ton of MSW, the total cost for the total MSW generated in different cities can be estimated and through the use of multi-criteria analysis approach (ELECTRE Method), the best scenarios with optimal EcC and EnC costs can be selected.

Kazuva and Zhang [13] investigated the MSW treatment scenarios with lowest EcC and EnC in rapid urban cities of developing countries using Dar es Salaam city in Tanzania as the case study. Using the ELECTRE Method, the best scenarios were found to be; composting for organic wastes, recycling for plastic, paper, glass and other waste to be landfilled. Similar results were obtained by De Medina-Salas et al. [102] who analyzed the lowest EcC and EnC MSW treatment scenarios and landfilling in a medium-sized city using the ELECTRE Method. In another study by Qazi et al. [104], waste to energy options for MSW treatment with the lowest EcC and EnC in Sultanate of Oman were also investigated using the same method and the results indicated that AD is the best scenario for organic fractions of MSW with low EcC and EnC costs. Due to variations in waste quantities and compositions, different cities can have different best scenarios reflecting the conditions of the concerned locality. Optimization of the AD process and other treatment options is very crucial and can significantly contribute to the reduction of the EcC and EnC of the selected treatment scenarios.

Table 6 Average economic and environmental cost of municipal solid waste treatment options (USD t^{-1})

Treatment option	Cost	Organic waste	Plastic	Paper	Glass	Others	Refs
Anaerobic digestion	EcC	115.25	–	–	–	–	
	EnC	−0.56	–	–	–	–	
Land filling	EcC	58.25	71.10	67.25	70.32	68.33	[13]
	EnC	0.47	0.04	0.44	0.44	0.48	
Incineration	EcC	–	20.00	20.00	–	55.05	[13, 102]
	EnC	–	1.38	−0.49	–	–	
Recycling	EcC	–	93.89	−67.00	20.12	–	[102, 103]
	EnC	–	−1.30	−3.89	−0.31	–	
Composting	EcC	47.00	–	–	–	–	[102, 103]
	EnC	0.09	–	–	–	–	

Conclusions and future perspectives

This review paper discusses different strategies for optimization of metabolic stages of the AD process, with particular attention to the organic fraction MSW. The four metabolic stages of anaerobic digestion systems and previous studies used to optimize the process have been analyzed. The challenges with the current optimization strategies were pointed out and likely areas for further improvement have also been evaluated.

The available literature reveals that mechanical pre-treatment has widely been used to enhance the hydrolysis process. Maceration, sonication, and high-pressure homogenizer are simple mechanical pre-treatment methods that can enhance the solubilization of OFMSW. Although mechanical pre-treatment promotes rapid digestion of lignocellulosic-based OFMSW, it has high power requirements and there is the possibility of contaminations from impurities during the process. Future studies on mechanical pre-treatments should focus on optimizing power consumption and possibilities of abating contaminations during the process. Chemical and microbial pre-treatments are rarely used at industrial applications; however, they can be suitable with other pre-treatment technologies. Future studies should similarly focus on evaluations of feasibilities of combining the pre-treatment technologies and investigating of the new pre-treatment technologies.

To optimize the acidogenesis and acetogenesis phases of AD, the addition of TE and GAC have proven to be successful. The uses of TE and GAC have the advantages of counteracting VFA inhibition to improve process stability, enhancing activities of enzymes and promoting the growth of methanogens. Future studies on TE should focus on investigating the relationship between microbial activities in the digesters in response to TE supplementation on OFMSW. Such studies will help to improve the AD systems to maximize resources recovery. Operating biogas plants with GAC is complicated and requires high-level techniques. Therefore, future studies on GAC should both focus on the identification of new GAC materials and development of simple techniques to operate GAC in developing countries.

With regards to the methanogenesis stages optimization, several techniques including optimization of operating parameters, blending of feedstock to achieve a favorable C/N ratios, and acclimatization have widely being applied. This review demonstrates that optimization of a single parameter for controlling ammonia inhibition may be inadequate as parameters relate to each other. Thus, further studies should focus on controlling ammonia inhibitions and understanding how operating parameters are related.

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