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Review

Recovery of Household Waste by Generation of Biogas as Energy and Compost as Bio-Fertilizer—A Review

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Abstract: Nowadays, organic waste and especially household waste represents a significant global issue due to population growth. The anaerobic digestion (AD) process is an essential operation contributing powerfully to the valorization of organic waste including food waste in terms of renewable energy generation (biogas) and the rich-nutrient residue that can be utilized as bio-fertilizer. Thus, this process (AD) allows for good recovery of household waste by generating biogas and compost. However, the AD operation has been affected by several key factors. In this paper, we aim to involve different critical parameters influencing the AD process, including temperature, pH, organic loading rate (OLR), carbon to nitrogen ratio (C/N), and total solid content (TS(%)). Further, the paper highlights the inhibition caused by the excessive accumulation of volatile fatty acids (VFAs) and ammoniac, which exhibits the positive effects of co-digestion, pretreatment methods, and mixing techniques for maintaining process stability and enhancing biogas production. We analyze some current mathematical models explored in the literature, such as distinct generic, non-structural, combined, and kinetic first-order models. Finally, the study discusses challenges, provides some possible solutions, and a future perspective that promises to be a highly useful resource for researchers working in the field of household waste recovery for the generation of biogas.

Keywords: anaerobic digestion (AD); household waste; co-digestion; pretreatment; inhibition; mathematical modeling; biogas; compost; bio-fertilizer

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Citation: Benyahya, Y.; Fail, A.; Alali, A.; Sadik, M. Recovery of Household Waste by Generation of Biogas as Energy and Compost as Bio-Fertilizer—A Review. *Processes* **2022**, *10*, 81. https://doi.org/10.3390/pr10010081

Academic Editor: Jose Manuel Gomez Montes de Oca

Received: 26 November 2021
Accepted: 28 December 2021
Published: 31 December 2021

1. Introduction

The development of renewable energy is one of the most well-researched topics globally. It has gained worldwide attention, with thousands of papers published annually providing new strategies and technologies to support the improvement of clean energy. At the end of this decade, the energy policy of the Kingdom of Morocco expects 42% of total electric power to be provided by diversification of green energy sources at a total capacity of 4000 MW; the target is a 15% saving in energy consumption by 2030 [1]. This policy focuses on constructing solar power plants, wind energy farms, and hydraulic energy plants as sustainable strategies, despite the availability of green energy contained in organic material.

In addition, the growth of the world population currently stands at between 1% and 2% annually [2], and is expected to increase to over 9 billion by 2050 [3] with an increase in industrial activity that is expected to lead to a growth in a wide range of waste products, such as industrial waste, municipal solid waste, and animal waste (manure). Food waste, as the main component of municipal solid waste, has recently experienced rapid growth due to population growth, which has also accelerated the construction and competition of numerous food restaurants. Globally, around 1.3–1.6 billion tons of food waste (FW) are generated every year [4]. At present, the European Union generates 89 million tons of

FW and China generates 82 million tons annually. In comparison, the United States and Morocco produce 35 million tons and 5.2 million tons of FW every year, respectively [2,5]. In fact, to reduce the enormous volume of waste, countries face a significant challenge in finding the appropriate management tools to dispose of waste safely. Generally, conventional disposal methods which include landfill, open dumping, and burning are still applied by most countries to treat most waste produced [6]. Moreover, the demand for available land outside cities continues to rise, despite environmental damage from greenhouse gas emissions and other harmful toxic effects [7]. Composting is considered one of the treatment processes utilized to recycle food waste efficiently. It improves soil health and reduces environmental risks [8], but also requires a large treatment surface. On the other hand, with the continuous augmentation of energy requirements, many of the treatment practices of FW are utilized to recover clean energy, reduce waste volume, and maintain environmental protection. For this reason, thermal treatment processes are applied as alternative waste disposal techniques [9], with the popular types being mostly pyrolysis, gasification, and incineration. They are also known for the use of oxygen and heat in order to convert biomass into bio-oil, bio char, and other valuable products [10].

Additionally, pyrolysis is a comfortable thermal process that degrades different waste types at temperatures above 400 °C. Moreover, the simplicity, low cost, the ability to treat a wide range of waste, energy recovery, and reduction in greenhouse gas emissions are some of the benefits of pyrolysis [8]. In spite of these numerous advantages, especially in the operation's initial drying, a considerable amount of energy is lost [9]. Gasification is limited by recovering energy from specific types of waste, such as plastic and agricultural residues [11]. In addition, energy can be produced through FW incineration in the form of electricity and heat. However, certain residue nutrients cannot be recovered in the process, including nitrogen that can be lost in the atmosphere as a result of nitrogen oxide, and phosphorus that cannot be recycled [12].

An environmentally friendly process can extract energy located in FW as biogas [13] and exploit the residue to produce bio-fertilizer [14]. Anaerobic digestion is the appropriate operation that can combine sustainable energy production presented by biogas [15] generating heat and electricity and nutrient-rich digestate recovery in the form of bio-fertilizer [16] (Figure 1).

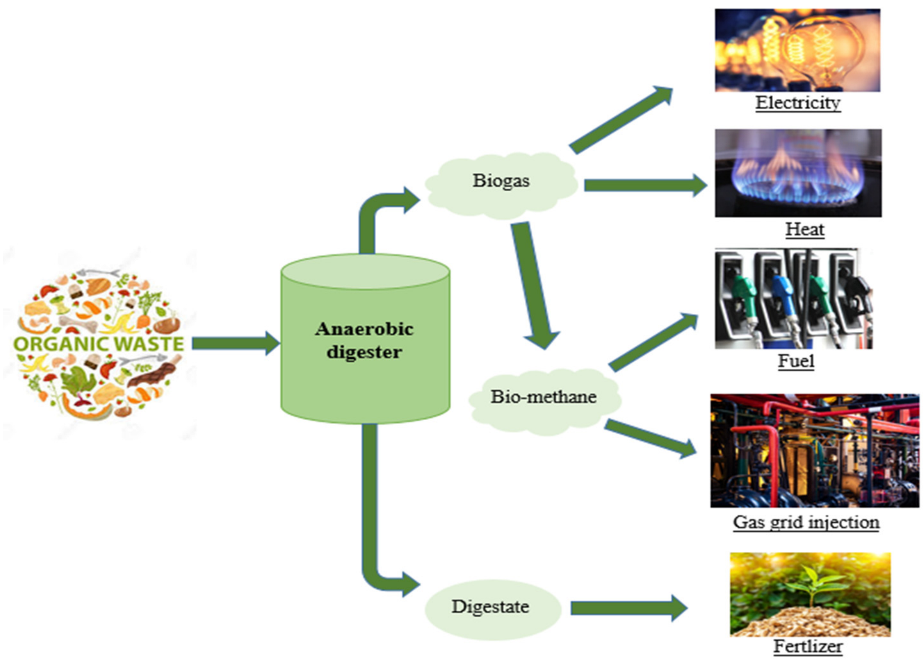

Figure 1. Principles of anaerobic digestion.

The anaerobic digestion process can be subdivided into four main processes (Figure 2) [17]; the first process is comprised of two extracellular stages which include disintegration and hydrolysis, in which sugar, amino acids, long-chain fatty acids, and other associated compounds are collected by the breakdown and solubilization of complex organic matter such as carbohydrates, proteins, and fats [18]. Usually, hydrolysis is considered the slowest step in the overall process and is regarded as the rate-limiting step in the degradation of organic matter.

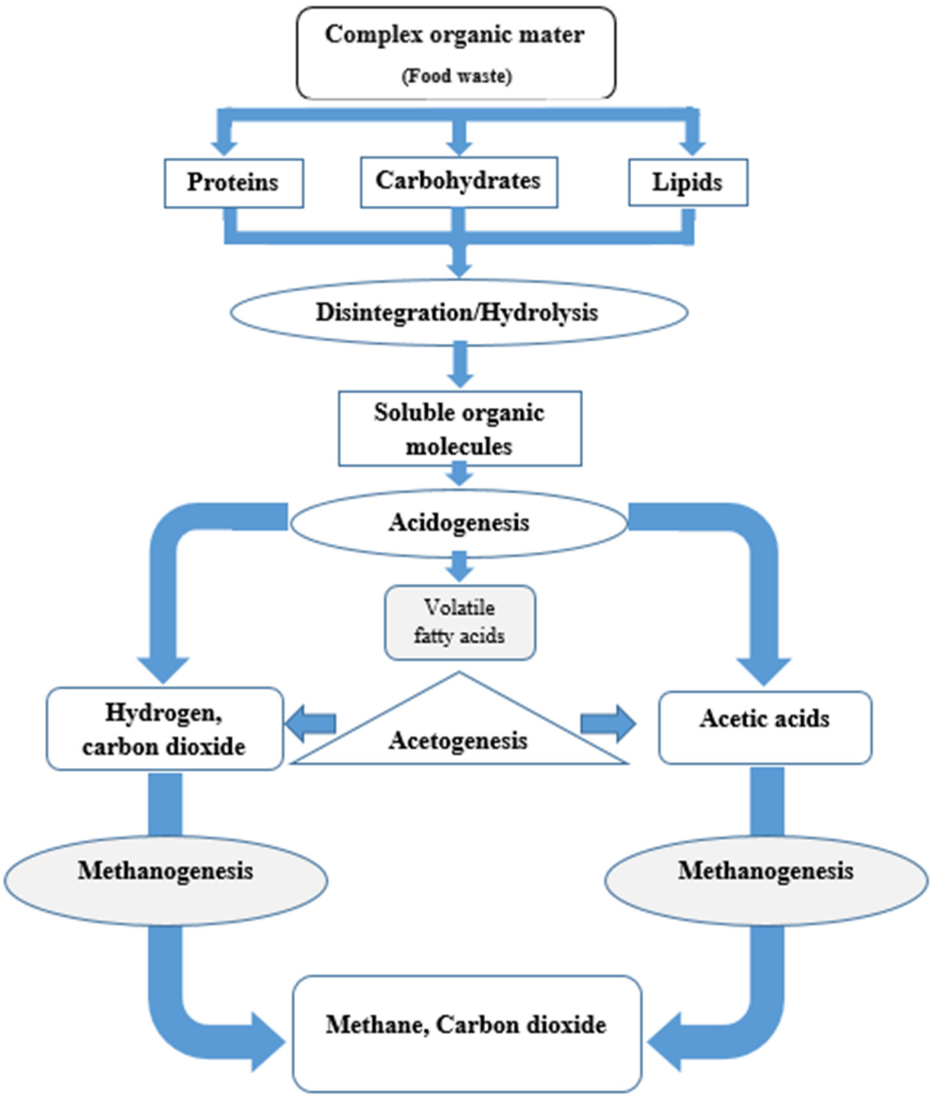

Figure 2. Different phases of anaerobic digestion.

The second part of the process includes three intracellular stages: acidogenesis or fermentation, the next step after hydrolysis, in which hydrogen (H_2) and carbon dioxide (CO_2) are produced, and the final stage which converts long-chain fatty acids (LCFAs) into volatile acids (VFAs) such as acetic acid, propionic and butyric by acidogenic bacteria [19]. In the acetogenesis phase, acetate is produced by the transformation of VFAs by acetogenic bacteria into hydrogen and carbon dioxide [16]. In the final phase, i.e., methanogenesis, methane is produced through two major metabolism pathways: acetate decomposition and hydrogenotrophic methanogenesis, by using the intermediate products (H_2 and CO_2). In addition, for the AD process, FW is considered an attractive feedstock because it contains highly biodegradable organic solids, high moisture content, and various types of organic matter, making it more suitable for the system of AD (Table 1). In theory, one ton of FW can potentially be converted into 847 kWh of electricity with 98.78 GJ of potential heating power [20].

Table 1. Different FW feedstock with methane generation.

Feedstock	pH	TS (%)	VS (%)	Moisture (%)	C/N Ratio	Organic Loading Rate (OLR)	Operating Temperature °C	Methane Yield	Ref.
Sweet potato vine	ND	91.8	78.7	ND	15.1	30 (g-VS/L)	37	200.22 (mL/g VS)	[21]
Food waste	5.2	18.5	17	ND	21.1	8 (g-VS/L)	35	2624 mL	[22]
Orange bagasse	4.0	19.2	95.2	80.7	30.1	ND	37	299 NmL	
Passion fruit Peel	3.7	18.5	94.0	81.4	51.6	ND	37	115 NmL	[23]
Cashew bagasse	4.2	29.0	96.0	70.9	28.3	ND	37	186 NmL	
Food waste	7.3	16.83	82.9	81.1	11:1	ND	26–32	16.308 mL	[24]
Food waste	4.3	9.11	8.53	ND	ND	0.24 $(kg\ VS\ m^{-3}d^{-1})$	36	0.06 $(L\ g\ VS^{-1})$	[25]
Sweet lactoserum	7.2	96	65	ND	ND	ND	37	0.34 $(Nm^3CH_4kg^{-1}COD^{-1})$	[26]
Acidic lactoserum	4.1	95	72	ND	ND	ND		0.06 $(Nm^3CH_4kg^{-1}COD^{-1})$	

The AD operation is a complex and sensitive process, and it needs adequate control and monitoring. It is a biological process that is affected by environmental factors such as temperature and pH. In addition, it can be inhibited by the accumulation of ammonia and VFA during the process, leading to the problem of low methane yield. Moreover, carbon to nitrogen ratio (C/N), moisture or total solid content (TS), volatile solid (VS), and organic loading rate (OLR) are the operational feedstock parameters. They also play a significant role in either the enhancement of the process or its termination. Additionally, the mathematical modeling of the AD process is key to estimating the quantity of biogas production [4,27], the concentration of VFA [28], and other continents. In this paper, we provide a comprehensive review of the AD process, including attractive issues concerning this process. We explore the impact of the various factors influencing the anaerobic digestion process while focusing on the mathematical models developed by the scientific community and presenting their advantages and limitations. The rest of the paper is organized as follows:

The Section 2 presents the parameters influencing the AD operation, the VFA, and ammonia inhibitions; in Section 3, we highlight the role of co-digestion, pretreatment methods, and mixing techniques, and their impact on biogas production; in Section 4, we illustrate the different mathematical models of the AD process (dynamic models, non-structural models, combined models, and simple kinetic models); in Section 5, we give some guidelines and identify future issues.

2. The Key Factors of Anaerobic Digestion and Their Impacts

2.1. Temperature

One of the most critical parameters influencing the performance of any AD process is temperature [29]. Methanogenic bacteria and volatile acid-forming bacteria are affected by temperature, and the enzyme activity that is secreted by these bacteria changes according to the temperature [30]. Thereby, it influences methane formation [7,31].

There are three temperature operating conditions for the AD process: psychrophilic (∼ 20 °C), mesophilic (∼ 35 °C), and thermophilic (∼ 55 °C) [32]. Most of the anaerobic digestion process happens in mesophilic and thermophilic conditions, and many studies have occurred under mesophilic conditions [33] due to its process stability, low energy consumption, and high bacteria diversity [34]. Several benefits can be gained by the thermophilic processes, such as enhancement of methane production, low retention time, fast degradability, and a high rate of pathogen destruction [35]. On the other hand, plenty of the consequences are negative for the thermophilic process, which is considered more energy-intensive, with low-process stability, five-fold greater accumulation of VFAs compared to mesophilic carried out at a low pH value, and high free toxic ammonia concentration [33]. In a study of co-digestion of meat, vegetables, fruit, and dairy, a maximum biogas yield $\left(740.4\ cm^3\ g\ ODM^{-1}\right)$ was achieved under mesophilic conditions compared to thermophilic conditions $\left(274.7\ cm^3\ g\ ODM^{-1}\right)$ [36]. Other research studies support two-stage anaerobic digestion systems; the concept is to isolate the hydrolytic-acidogenic phase from the methanogenic phase to alleviate the drawbacks of the single-stage process [3]. Additionally, the digestion of FW in a two-stage psychrophilic reactor generated a higher amount of biogas (0.800 $m^3 Kg_{VS}^{-1}$) than the single-stage mesophilic digester (0.751 $m^3 Kg_{VS}^{-1}$) [37]. On the other hand, the temperature presents a heating technique for the fermentation reactors. The use of electromagnetic microwave radiation can precisely control the temperature inside the reactors and permit energy to be directed at the feedstock [38]; this also decreases the energy losses caused by absorption by the reactor components [39]. It gives a positive energy balance (9.2 $Wh\ d^{-1}$) compared to a convection heating method ($-112\ Wh\ d^{-1}$) in a study of methane fermentation of expired food products [40].

2.2. pH

pH is an essential parameter that impacts the process's efficiency, indicating and controlling its stability [41]. In addition, microorganisms are extremely sensitive to pH because different bacteria communities require various pH ranges [31]; for example, acidogenic bacteria performed well in the pH range between 4.0–6.0 helping in AD acidification and VFA production [3]. Methanogens are responsible for the production of methane gas; their pH range is narrow, around neutral value which is the optimal range for an efficient AD process. Maximum methane production was achieved at pH 7, while an 88% reduction of methanogen production was observed at pH 5.5 in continuous anaerobic digestion of waste-activated sludge [42]. In a study of the pH effect in anaerobic digestion of citrus waste, Eryildiz confirmed high methane production with a pH value equal to 7 [43]. At an exceeded value of pH, the activity of methanogens is inhibited [44]. In addition, this high value raises ammonia concentrations and is displaced by free toxic ammonia [45]. Pretreatment methods and co-digestion have a positive effect in controlling the pH value within the optimal range. El Gnaoui found that in the application of thermal pretreatment of FW, in a temperature value between 60–100 °C, the pH fluctuated in the range of 7.29–7.76 [46]. In addition, adding 0.5 g/L-COD into fruit waste resulted in neutralization of the pH value and improved the buffering capacity [23]. Sodium hydroxide can neutralize the pH of lactoserum acid [26]. Furthermore, the mixing method can neutralize the pH value; it passed from 6.84 for meat, 8.51 for fruit and vegetables, and 6.82 for dairy to 7.84 for the mixing together of 33.3% meat + 33.3% fruits and vegetables + 33.3% dairy [36].

2.3. Carbon to Nitrogen Ratio C/N

As a critical ratio that can appreciably affect the AD activity [47], the carbon to nitrogen ratio (C/N) was established as a feedstock character [48]. Several studies have found that an ideal C/N ratio of 20–30 results in an efficient AD process [49]. In a study of the co-digestion of orange bagasse and sewage sludge with a C/N ratio of 30.1 and 5.5, respectively, a high methane accumulation was observed (308 Nml) [23]. Other studies indicated that a ratio of less than 20 was acceptable in the AD system, and Zhang reported that the maximum methane yield (388 mL/g-VS) was achieved in co-digestion of FW and cattle manure at a C/N ratio of 15.8 [22]. Additionally, an optimal methane potential was observed in the co-digestion of dairy manure, chicken manure, and rice straw with a C/N value of 25:1 for mesophilic reactors and 35:1 for thermophilic reactors [50]. In a study of co-digestion of meat, fruit and vegetable waste, and dairy waste, the value of 9.77 was the most effective, and the range of operation was from 9.77 to 12.9 [36]. A high C/N ratio (high carbon content) caused acidification during the primary stages of the AD process, eventually conducted to process failure [49]. The amount of nitrogen was extracted from the breakdown of the proteins throughout the AD reactor, which is necessary for the growth of microorganisms [45]. A low C/N ratio highlighted an excessive ammonia concentration, which led to an increase in pH and inhibitory effects, further perturbing the process stability [51].

2.4. Organic Loading Rate (OLR)

OLR can typically be determined as a kilogram of the volatile solid (VS) loaded per volume of digester per day and can even be adjusted and regulated to maintain the stability of the AD process [52]. Additionally, different critical values are found in the literature. The process could operate at a value of ($32\ g - VS_{FW}/L + 16\ g - VS_{CM}/L$) of co-digestion of FW and cattle manure, while the optimum value in this study was $10\ g - VS_{FW}/L$ which increased the methane yield by 55.2% [22]. In a study of co-digestion of FW and garden waste, a maximum organic material conversion efficiency of 83% was achieved with an OLR of $0.54\ kg\ VS\ m^{-3}\ d^{-1}$. When OLR reached $0.63\ kgVS/m3/d$ the system was perturbed and finally showed some instabilities, such as an increase in VFA concentration [25]. Moreover, the allowed quantity of OLR was $2.53\ kg\ VS\ m^{-3}\ d^{-1}$ in a thermal pretreated food waste operated in a semi-continuous reactor under mesophilic conditions [46]. Additionally, an OLR value above $6\ g\ ODM\ dm^{-3}\ d^{-1}$ caused an inhibition of methane fermentation in the co-digestion of meat, dairy, and fruit and vegetables [36]. Furthermore, when the OLR increased, it led to a reduction in biogas productivity and therefore a decrease in the methane content [53]. In a study of anaerobic digestion of mixed supermarket waste under thermophilic conditions, the optimum OLR value was $3.6\ kg\ VS/m^3$ achieving up to 48.1% more methane production than other OLR values [54]. At an OLR value of $0.25\ Kg\ m^{-3}\ d^{-1}$, the highest total biogas yield $(0.674\ m^3\ Kg^{-1}VS\ )$ and methane percentage (62%) were recorded in anaerobic co-digestion of swine manure and corn stover [55].

2.5. Total Solids Content (TS %)

Generally, the AD process is divided into three ranges based on TS (total solid) percentages, i.e., wet ($\leq$ 10%), semi-dry (10–20%), and dry ($\geq$ 20%) [56]. However, these percentages vary in the literature. Dry AD had several limitations, such as the low connection between the microorganisms and substrates, and the accumulation of inhibited matter (VFAs and free ammonia) [57], which was considered to be related to the high concentration of the solids present in the process [7,45]. Furthermore, the daily yield of methane production was reduced by 81%, 66%, 23%, and 78% with the augmentation of TS% of 5.49–20.04% in the mono-digestion of sweet potato vine, pig manure, dairy waste, and chicken manure, respectively [21]. In addition, the potential methane yield decreased from $106.3\ ml\ g^{-1}\ VS^{-1}$ to $58.5\ ml\ g^{-1}\ VS^{-1}$ when TS% was augmented from 5% to 20% in the study of anaerobic digestion of poultry litter [58]. In the AD of pig manure at a TS content of 25% and above, the pH value was higher than 7.5, which is not the optimum value for methanogen activities [59], the specific methane yield was reduced at a TS content of 20% $\left(259.8\ NmL\ g^{-1}\ VS_{added}^{-1}\right)$ compared to the value recorded in a TS content of 15% $\left(291.7\ NmL\ g^{-1}\ VS_{added}^{-1}\right)$ [60]. According to some researchers, wet AD plants have a better energy balance than dry anaerobic digestion plants [61]. The methane yield was higher in the wet AD of chicken manure ($0.35\ m^3/kg\ VS$) compared with the dry process ($0.18\ m^3/kg\ VS$) [62], furthermore, the methane yield was greater in the wet AD of organic wastes $(320\ NLCH_4\ Kg^{-1}\ VS^{-1})$ compared with dry AD $(252\ NLCH_4\ Kg^{-1}\ VS^{-1})$ [63]. In contrast, a wet system is commonly used to treat municipal solid waste in co-digestion with another substrate, among them, animal manure, activated sludge, and sewage sludge.

A high methane content (64.6%) was achieved in the co-digestion of FW and piggery dung of $TS = 21.81\%$ [24]. Table 2 summarizes the effect of the parameters in the AD process.

Table 2. The effect of different parameters on the biogas production.

Feedstock	Parameter	Observation	References
Meat, vegetables and fruits, dairy waste	Temperature	-A maximum biogas yield was achieved under mesophilic conditions $(740.4\ cm^3\ g/ODM)$ compared to thermophilic $(274.7\ cm^3\ g/ODM)$	[36]
Activated sewage sludge	pH	-A maximum methane production was achieved at pH = 7. -At pH = 5.5 a reduction by 88% of methanogens activity was recorded	[42]
Dairy manure, chicken manure, and rice straw	C/N ratio	-An optimal methane potential was achieved at C/N ratio = 25:1 for mesophilic reactors, and at C/N ratio = 35:1 for thermophilic reactors	[50]
Swine manure and corn stover	OLR	-the highest biogas yield was obtained $(0.674\ m^3\ Kg^{-1}VS)$, at an OLR value of, $0.25\ kg\ m^{-3}\ d^{-1}$	[55]
Food waste and pig manure	TS	-the specific methane yield was higher at TS = 15% $\left(291.7\ NmL\ g^{-1}\ VS_{added}^{-1}\right)$ compared to the value recorded at TS = 20% $\left(259.8\ NmL\ g^{-1}\ VS_{added}^{-1}\right)$	[60]

2.6. Volatile Fatty Acid (VFA) Inhibition

In the hydrolysis step, short-chain fatty acids are produced as a result of biodegradable, more complex organic matter such as long-chain fatty acids (LCFAs) and other soluble compounds. They are popularly known in the literature as volatile fatty acids (VFAs). The main types of VFAs widely found in the hydrolysis stage are acetic, propionic, butyric, and valeric acid [31]. In effect, because of the rapid breakdown of the organic matter in the hydrolysis step, a vast amount of VFA was accumulated, resulting in a drop in the resulting pH value, causing methanogenic inhibition [64], which confirmed the strong connection between pH and VFA generation. Besides that, the highest yield of VFA (632.2 $mgCOD/g\ VS_{fed}$) was reported in forced neutral pH, and a minimum yield in alkaline pH (31.4 $mgCOD/g\ VS_{fed}$), in a study of the effect of pH on VFA concentration [65]. Eryildiz realized a maximum VFA yield (0.793 g VFA/VS) when pH was adjusted to 6, and the substrate to inoculum ratio (S/I) was (1:1), whereas low methane generation was observed [43]. In another study, a maximum reduction of 73.2% and 67.5% in VFA production was reached in the co-digestion of FW and animal fat and vegetable oil batches, respectively [66]. In addition, Wu et al. discovered that an addition of 6–10% of fish residue to waste-activated sludge inhibited the system by the accumulation of VFAs due to the concentration of propionic acid that was indicated to be inhibitory above 1000 mg/L [67,68]. Another study found that a VFA concentration range of 50 to 250 mg/L was ideal for excellent anaerobic digester performance [69]. As a solution to the exceeded VFA generation, an increase in inoculum to substrate ratio (I/S) was frequently applied for batch processes [45]. Despite this, many published studies prefer to stop the AD process in VFA production due to the high valorization of the primary VFA acids and their significant prices [43]. Additionally, monitoring VFA concentrations has a significant effect on the avoidance of negative results. Actually, more advanced techniques have been developed to accurately track the efficiency of the reactor, including online monitoring-based GC, and titration [7].

2.7. Ammonia Inhibition

Nitrogen as a by-product of proteins is considered the main source for microbial growth. Furthermore, the distribution of nitrogen is necessary to the AD process because a high concentration of ammonia nitrogen leads to AD-process inhibition [57]. Additionally, in digesters, it can act as a natural buffer that helps tolerate acidification [70]. Meanwhile, it exists in two major forms in the AD process: ammonium ions (NH_4^+), and free ammonia commonly noted as (FA), that last one is more toxic than the ion form [71]. It is capable of penetrating the bacterial cell membrane, producing proton imbalances, raising maintenance energy needs, and blocking certain enzyme responses [72]. In addition, ammonia concentration is linked directly to the pH value and operating temperature. It increases with the temperature and pH; a concentration of FA of 600 mg-N/L can inhibit the system under thermophilic conditions. However, different studies reported different critical ammonia concentration ranges: free ammonia generally has inhibitory values ranging from 300 mg/L to 800 mg/L, whereas ammonium is tolerated at higher concentrations ranging from 1500 to 3000 mg/L [45]. The concentration of ammonia in a co-digestion of FW and cattle manure was less than the critical value of 700 mg/L under semi-continuous mesophilic conditions. In contrast, in a mono-digestion of cattle dung, the value was exceeded [22]. A considerable value of ammonia above 380 mg/kg led to a diminution of methane production of between 22% and 55% in the mono-digestion of pig manure, chicken manure, and co-digestion of sweet potato vine and chicken dung under dry conditions [21]. Thus, ammonia concentration has to be adequately controlled and monitored during the AD operation to avoid a toxic concentration that can allegedly lead to inhibition of the microbial community.

3. The Effect of Co-Digestion, Pretreatment Methods, and Mixing Techniques on the AD Process

3.1. Effect of Co-Digestion in the AD System

Typically, anaerobic co-digestion is defined as a strategy of mixing two or more substrates for simultaneous processing. This technique has been applied to overcome the potential limitations and problems of the mono-digestion process, such as system instability due to inhibitory factors, low methane yield caused by mono substrate characteristics (a notable example is FW, known for high carbon content, low alkalinity, high organic loads, and low nitrogen content) [31,73]. Numerous studies have supported anaerobic co-digestion of different feedstocks due to the numerous specific benefits that can be generated, such as good buffering capacity and process stability support by diluting inhibitory concentrations [74], leading to methane yield enhancement. Furthermore, animal manure, sewage sludge, and lignocellulosic wastes are the most adequate co-substrates that can be utilized in the anaerobic co-digestion of FW due to their high ammonia content, intense alkalinity, and other specifications that can balance the process nutrients and the AD operation [31]. Moreover, Zhang et al. reported that methane productivity was enhanced by 41.1% and reached a maximal value of 3725 mL compared to the mono-digestion 2624 mL; thereby an optimal C/N ratio (15.8) and neutral pH were obtained, concentrations of essential trace elements were improved, which had a significant effect in encouraging the methanogens' activities, and the process worked at a high OLR value [22]. Oladipupo et al. indicated a diminution of 57% in chemical oxygen demand (COD, which is the amount of oxygen required to oxidize an organic compound to CO_2, ammonia, and water) in a co-digestion of FW and piggery dung (PD); and a maximal value of biogas, a high mass equilibrium (0.38), and the most consumed rate of volatile solid (VS) (48%) were achieved with a high methane percentage (63%) in a co-digestion of FW, PD, and cow dung compared to the mono-digestion of FW [24]. Further, a proper co-digestion of 20% (OLR) of garden waste and FW conserved the pH at a neutral value, and the VFA concentrations were in the optimum range. There was also a reduction in VS by 83% and a high methane percentage (67%) was obtained in the co-digestion process [25]. On the other hand, the quantity of co-substrate added should be controlled, which was confirmed in a co-digestion of waste-activated sludge and fish waste: addition of 6% or more of fish waste reduced methane production to approximately (51 mL CH4/g VS) and inhibited the process by VFA and LCFA accumulation, whereas the addition of 3% of fish waste maximized methane production (683.8 mL CH4/g VS) [67].

3.2. Effect of Pretreatment Techniques in the AD System

The AD process has critical drawbacks due to its complexity and inhibitory factors. Among the adequate solutions that improve the process by increasing the rate of decomposition of the organic fraction and the generation of methane, otherwise improving process efficiency, is the application of pretreatment methods [75]. We distinguish a variety of techniques depending on the process used. Thus, we have chemical, physical, biological, and combined techniques [13]. Indeed, the choice of a more suitable method depends on its mechanism, substrate properties, and final requirements [7]. Various pretreatment techniques have been reported in the literature recently, to maintain process stability as a chemical pretreatment. An addition of ($0.5\ g\ NaHO_3\ g^{-1}\ COD^{-1}$) sodium bicarbonate kept the pH value at neutral [23], 3 M HCL and 3 M NaOH adjusted the pH value [67], NaOH neutralized the pH of lactoserum acid [26]. Moreover, an addition of salt (6 g/L) augmented the maximum VFA production by 14% (23.11 g/L) more than without salt (19.86 g/L), and alleviated inhibition caused by animal fats and vegetable oils [66]. The extraction of the inhibitor D-limonene from the orange peel by 70% in one hour was achieved by using steam distillation, which increased the biodegradability to 96.7% in COD in the thermophilic AD of orange peel [76]. While, physical pretreatment such as thermal techniques had several benefits, in the anaerobic digestion of swine manure, the methane production rate was enhanced by 390% [77]. In a study conducted by El Gnaoui et al., thermal pretreatment of FW at 100 °C for 30 min raised soluble COD by 43.41%, the methane yield was enhanced by 23.68%, and the biodegradability was increased by 9.8% compared with the untreated FW [46]. In another study, thermal pretreatment of kitchen waste produced a high hydrogen rate of up to 113 mL H2/g VSfed [4]. On the other hand, an intensification in methane production was observed in the application of energy of 90 KJ/KG during an ultrasound pretreatment on the inoculum presented by cow manure in the treatment of dairy waste [26]. The development of resilient microbiomes that can be acclimatized under thermophilic temperatures and resist the inhibitory concentrations by adjusting the substrate: inoculum ratio is one of the conventional pretreatments. Ghanimeh et al. indicated that by inoculating (digestate, manure, and activated sludge) thermophilic anaerobic digesters during the loading period, the pH decreased to 7.2 and gradually increased to stabilize at 7.8, confirming the acclimation of microbial flora [78]. Elsewhere, the co-digestion of different substrates has also been reported as a conventional pretreatment method, which can be implemented without any major modification in the system. In contrast, in the literature, emerging pretreatment methods have been reported: for example, the integration of microbial electrochemical systems to combine the microbial metabolism of electro-active bacteria with electro-chemistry; and the application of conductive additives so that electro-active bacteria directly transfer electrons to methanogens and reduce CO_2 to CH_4 in order to augment methane production and biogas quality. However, these techniques need a change in the process [33].

3.3. Effect of Mixing Methods on the AD Process

Mixing is one of the methods that can influence AD efficiency because it keeps microbes in contact with the substrate, promotes uniform conditions throughout the digester volume, and improves process kinetics and methane production [45]. It was found that reactors without any mixing failed with propionic acid inhibition [79], the production of CH_4 with mixing pretreatment was higher $\left(75\ L\ CH_4\ Kg^{-1}\ VS^{-1}\right)$ than that without mixing pretreatment $\left(60\ L\ CH_4\ Kg^{-1}\ VS^{-1}\right)$ in psychrophilic AD of swine manure slurry [80]. Moreover, there are three types of mixing: Gas recirculation [81], slurry recirculation [82], and mechanical (impeller) mixing [83]. It is critical to select the proper mixing technique to achieve efficient mixing and maximum biogas production while consuming the least amount of energy. Digesters fed with 10% manure slurry and mixed using biogas recirculation, slurry recirculation, and impeller produced 15%, 29%, and 22% more biogas than unmixed digesters in AD of animal manure [84]. Mechanical mixing is the most frequently utilized method and has been estimated to have the best power efficiency per volume unit mixed [85]. In general, there are two modes of mixing; intermittent and continuous mode [85]. A high specific methane yield was achieved $\left(437\ mL\ CH_4\ g^{-1}\ VS_{fed}^{-1}\right)$ in intermittent mixed reactors $(2\ min/h)$ compared to continuously and non-mixed reactors in the AD of FW [86]. An increase in biogas production by 7% was achieved with intermittent mixing compared to continuous mixing [87]. Therefore, it is considered an alternative strategy to reduce energy consumption. On the other hand, intense mixing strategies are known to have negative effects [45]. High shear forces can destroy microbial flocs and syntrophic interactions between methanogens and bacteria during start-up or high-load periods, resulting in negative impacts [88]. The cumulative biogas production at a mixing intensity of 80 rpm was higher by 18.3% compared to a mixing intensity of 160 rpm [89].

4. Mathematical Modeling of the AD System

The development of an appropriate mathematical model for the AD process has been the focus of much research due to its critical role in improving laboratory studies, more effective process performance through automated process control, and optimization of AD system design and control strategies [90]. In contrast, the AD process is a highly structured, complex, dynamic, non-linear system, making it difficult to model [91]. However, in 2002, the most predominant, highly structured, and generic model which described the overall AD process was established by the International Water Association (IWA) task group, i.e., ADM1. The reaction mechanism in the anaerobic digester ADM1 is complex and divided into two main types: biochemical reactions, which are catalyzed by intra- or extra-cellular enzymes and act on the reservoir of organic compounds available for biological use; and physico-chemical reactions which encompass ion association/dissociation, and gas-liquid transfer [92]. Moreover, it involved seven bacterial species. Indeed, ADM1 was classified in the field of white-box models, which were based on biochemical kinetics as well as physical and chemical balance. Furthermore, by adjusting the original structural and kinetic parameters, the ADM1 was used to simulate the AD performance of various feedstocks with the goal of predicting values of key factors (VFAs and ammonia concentrations, COD, etc.) which could be modified to achieve high methane production with accuracy [57]. In a study modeling carbon (C) fate to optimize biogas production and methane content, while nitrogen (N) and phosphorus (P) fates helped in the optimization of the AD process by recovering and reusing them from the excess degistate, a semi-continuous wet and high-TS AD process of pig manure was carried out under mesophilic conditions. An improved ADM1 model was constructed, in which the authors took into consideration an equation to describe the mechanism of solid precipitation, which was excluded in the standard ADM1, and an inhibition function of high TS was introduced in the hydrolytic process **(1).** The improved model considered the processes related to N and P. Subsequently, to determine the most sensitive kinetic parameters, a sensitive index was calculated (greater than 30%) **(2)**. On the other hand, to evaluate the improved model ADM1, the maximum value regression coefficient (R^2) and the minimum value of the mean absolute error (MAE) **(3)** were calculated, and the validation and calibration of the model were based on experimental data obtained from a semi-continuous reactor. Further, it was found that the improved model accurately predicted the methane production in wet and high-TS AD processes with an accuracy value of $\left(R^2 = 0.920\right)$, the predicted COD concentration, inorganic nitrogen, and phosphate concentration were in agreement with the experimental values with R^2 of 0.852, 0.728, and 0.685, respectively. Further, the improved ADM1 minimized the risk of high-TS inhibition in the hydrolysis process [57]. Due to the complexity and the non-linearity of the ADM1 model, many research studies developed simple mathematical models derived from ADM1, which took into consideration just two or three phases of the AD process in order to predict methane production, inhibition factors, and reactor design [93]. Loganath constructed a simplified AD mathematical model based on consecutive reactions, which analyzed the three-step process of AD (hydrolysis, acidogenesis, and methanogenesis), and could eventually predict the final substrate concentration in each stage by a simple solution procedure **(4)** [94]. In another study, a simplified model of the AD process was established based on the acidogenesis (whereby organic substrates are degraded into VFAs) and methanogenesis (whereby VFAs are converted to methane) phases. A sensitivity analysis was used to identify the most sensitive parameter after a sequential quadratic programming procedure was performed in order to estimate the relevant model parameters from experimental data. Finally, the validation and calibration of the model were analyzed by using the experimental data obtained from a pilot scale of AD in industrial wastewater. Thus, the results showed that the most sensitive parameters were VFA concentrations (0.228) and methane production (0.301), and the proposed model was capable of predicting methane production from a few key measures such as organic matter (gCOD/L) and VFAs (mmol/L) [95]. Many assumptions were made by Beevi et al. to simplify the complexity of the ADM1 model and simulate biogas production, pH, and VFA production, which were subsequently compared with experimental data of the AD of vegetable waste. The curves showed good accuracy between the predictions and experimental values [96].

$$I_{TS} = 1/\left(1 + \frac{S_{TS}}{K_{TS}}\right) \tag{1}$$

where S_{TS} is the concentration of TS $\left(kg/m^3\right)$ and K_{TS} is the inhibition constant.

$$\delta_{ij} = p_i/\left(OF_j(p_i)\right) \times \left(OF_j(p_i + \Delta p_i) - OF_j(p_i)\right)/\Delta p_i \times 100 \tag{2}$$

where $OF_j(p_i)$ is the objective function j estimated with p_i, Δp_i is the absolute variation of the parameter p_i, and δ_{ij} is the sensitive index.

$$MAE = \left(\sum_{i=1}^{n} |Y_{expi} - Y_{prei}|\right)/n \tag{3}$$

where Y_{expi} and Y_{prei} indicate the experimental and the predicted values, n was the number of observations.

$$\begin{cases} dS_H/dt = -K_H S_H X_H/\left(K_{S_H} + S_H\right) \\ dS_{LCFA}/dt = K_H S_H X_H/\left(K_{S_H} + S_H\right) - K_A S_{LCFA} X_A/\left(K_{S_A} + S_{LCFA}\right) \\ dS_{SCFA}/dt = K_A S_{LCFA} X_A/\left(K_{S_A} + S_{LCFA}\right) - K_M S_{SCFA} X_M/\left(K_{S_M} + S_{SCFA}\right) \\ dS_M/dt = K_M S_{SCFA} X_M/\left(K_{S_M} + S_{SCFA}\right) \end{cases} \tag{4}$$

where S_H is the hydrolysable substrate concentration, K_H is the maximum specific rate of hydrolysis, X_H is the hydrolytic microorganisms concentration, K_{S_H} is the half velocity constant for hydrolysis, S_{LCFA} is the concentration of long chain fatty acids (LCFA), K_A is the maximum specific rate of acidogenesis, X_A is the concentration of acidogenesis microorganisms, K_{S_A} is the half velocity constant for acidogenesis, S_{SCFA} is the concentration of short chain fatty acids (SCFA), K_M is the maximum specific rate of methanogenesis, K_{S_M} is the half velocity constant for methanogenesis, and X_M is the concentration of methanogenesis microorganisms.

Most black-box mathematical models were developed and constructed based on Artificial Neural Networks (ANN) as an alternative to white-box models, due to their simplicity, particularity [27], and appropriation for non-linear systems compared to dynamic models [97]. However, these models were purely empirical and based on the measurements carried out on the process. Additionally, Wang et al. proposed a prediction model of biogas production for the AD of FW based on the Back Propagation neural network (BP) improved by the Levenberg–Marquardt (LM) algorithm **(5)**, in which a combination of the gradient–descent method and the Gauss–Newton method were developed with the goal of enhancing the speed of convergence of the error function. Subsequently, the particle swarm optimization (PSO) algorithm, which was inspired by simulation of the simplified social model (birds, fish systems), was applied in order to optimize the parameters of the model, reduce the effect of human factors, and generate an efficient and accurate model. Subsequently, the root mean square error (RMSE) **(6)** was calculated with the goal of getting a smaller error. On the other hand, 140 sets of data were used to train the model and 40 sets of data were utilized for model validation; the results showed that the test error of the BP-LM algorithm was decreased by 17% compared with standard BP, and the BP-LP-PSO algorithm had a significant effect on improving the model accuracy [27]. In 2019, X. Li et al. conducted research for an on-line soft measurement of VFA concentration due to its importance for monitoring the AD process. They established an improved model based on a deep belief network (DBN) which was constructed with the trained RBM combination. Initially, the Gaussian mixture model (GMM) was used to classify the data sets, and ensemble empirical mode analysis (EEMA) was applied to decompose the input signal into many functions in intrinsic mode. Following that, the extreme learning machine (ELM) was utilized to develop and instruct the model in order to improve the training of the model and increase the accuracy of the prediction. (Figure 3) [28].

$$\Delta x = -\left[J^T(x)J(x) + \mu I\right]^{-1} J(x)e(x) \tag{5}$$

where x is the vector of weight, *e(x)* is the error, $J(x)$ is the jacobian matrix, the constant μ is the scale factor, and I is the unit matrix.

$$RMSE = \sqrt{\left(\sum_{i=1}^{n}\left(x_i^p - x_i^t\right)^2\right)/n} \tag{6}$$

where x_i^p and x_i^t are the predicted and the true values of the i-th data.

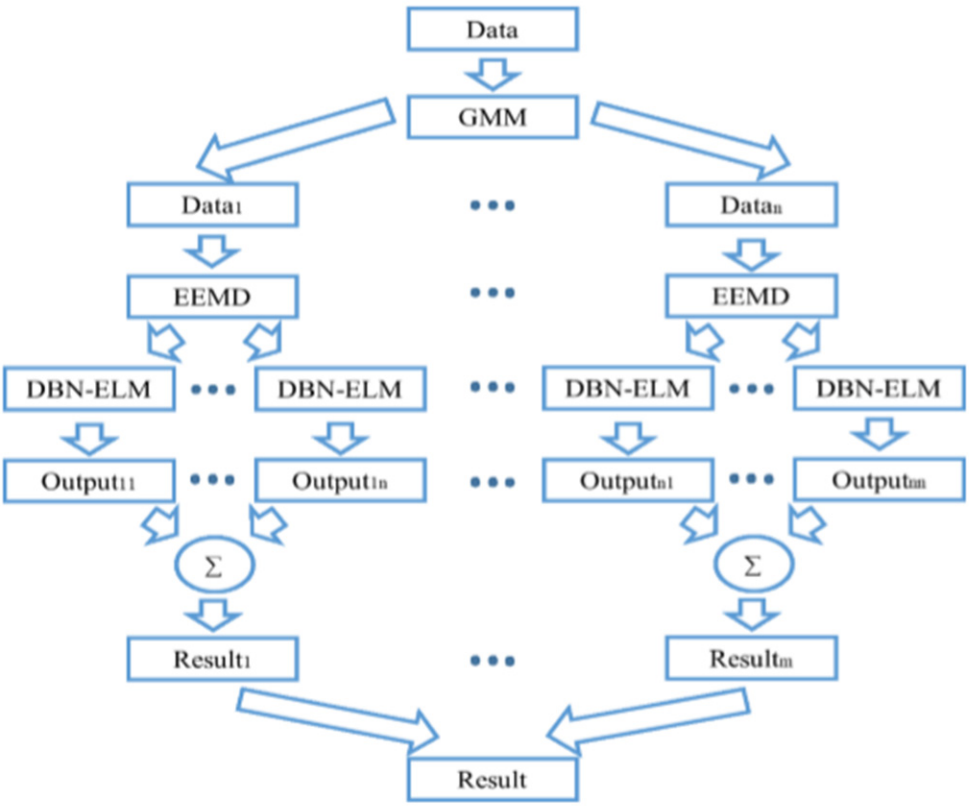

Figure 3. The flow of the improved DBN algorithm [28].

In contrast, traditional dynamic models were robust enough to simulate the AD process, which was characterized by complexity, nonlinearity, and the affection of uncertain factors. On the other hand, the black-box models avoided the mechanism structure, the parameters, and the dynamic performance of the process [98]. As a solution, Hu et al. suggested a combination model (ADSM) which took into consideration ADM1 and systems-thinking methodology in order to decrease the stiffness of the structural model, and improve the model's accuracy [98]. However, they made certain modifications to the ADSM model, such as the simplification of valerate, butyrate, and propionate as VFAs; the function graph expressed the pH and ammonia inhibition, and the self-learning function was introduced to develop the sensitive parameters of the self-adjusting procedures. To evaluate and compare the ADM1 and ADSM simulations with the experimental data results, the coefficient of determination (R^2) **(7)** and the relative absolute error (rAE) **(8)** have been calculated. Subsequently, they found that the simulation results predicted by ADSM and ADM1 had high accuracy and great coefficient of determination (88.6%) and (84.9%), with rAE values of (25%) and (32.3%) respectively, compared with experimental data of a lab-scale digester. As expected, the ADSM predicted with higher accuracy than ADM1. Moreover, in comparison between the full-scale measured results and the ADSM simulated results, they provided a predicted biogas production with $R^2 = 98.1\%$ and rAE = 11%.

$$R^2 = 1 - \left(\sum_{i=1}^{n} \left(y_{mi} - y_{pi}\right)^2\right) / \left(\sum_{i=1}^{n} y_{mi}{}^2\right) \tag{7}$$

$$\text{rAE} = \left(\sum_{i=1}^{n} \left(\left|y_{mi} - y_{pi}\right|\right) / y_{mi}\right) / n \tag{8}$$

where y_{mi} and y_{pi} are the measured and the simulated output values.

Additionally, kinetic models were applied to estimate biogas production, substrate biodegradability, methane production potential, and other applications. Zhang et al. used a mathematical modified first order model **(9)** to estimate the substrate biodegradability, and the methane potential. They reported a value of R^2 (indicated by the conversion constant and the methane production potential) ranging between 0.9715–0.9966, and a value of k (representing the substrate biodegradability and the hydrolysis efficiency) between 0.003–0.0953 in wet, semi-dry, and dry AD with an augmentation in the values in the co-digestion [21]. In another study, Andréa fitted and predicted methane production by applying a comparison between the first order model **(10)** and the modified Gompertz model **(11)**, and noted that all configurations fitted well with the modified Gompertz model with a coefficient of determination (R^2) ranging from 0.96 to 0.99, and the estimated cumulative methane yield obtained by the Gompertz model was closer to the experimental value. Further, the hydrolysis constant ($K_h d^{-1}$) in the first order kinetic model fluctuated from 0.02 to 0.10 d^{-1} indicating that the degradable compounds were hydrolyzed. In addition, the value of λ ranged between -5.04 and 9.40 [23]. Meanwhile, Wu et al. utilized the modified Gompertz model **(11)** to predict AD performance, after which a value of R^2 above 0.964 was found indicating accordance between the experimental and predicted results, while the lag time (λ) increased to 7.9 and 20.1 days [67]. In another study, the first order kinetic model **(12)** was used to estimate the value of the hydrolysis constant (K) and coefficient of determination (R^2), in order to ensure the applicability of sweet and acid lactoserum as feedstock to generate biogas. The authors noted a value of R^2 between 0.98 and 0.99, and a value of K from 0.07721 to 0.09001 and from 0.3206 to 0.3641 of sweet and acid lactoserum, respectively [26].

$$Y = Y_0[(1-\beta) - (1-\beta)exp(-kt)] \tag{9}$$

where Y is the cumulative methane yield, Y_0 is the ultimate methane yield, β is the non-degradable function, k is the rate constant, and t is the digestion time.

$$B(t) = L_0 \times \left(1 - e^{k_h - t}\right) \tag{10}$$

$$B_t = L_0 \times exp\{-exp[((R_b \times e)/L_0) \times (\lambda - t) + 1]\} \quad (11)$$

where B (t) is methane cumulative production, L_0 is methane maximum production, k_h is the hydrolysis constant, R_b is the methane maximum production rate, and λ is the lag phase.

$$B(t) = B_0 \times \left(1 - e^{k.t}\right) \quad (12)$$

where k is the apparent kinetic constant, B_0 is the maximum methane yield.

5. Discussion and Challenges

The anaerobic digestion process is an appropriate procedure for the treatment of municipal solid waste for further generations of bioenergy. It is an adequate method for treating food waste. According to Regulation No. 852/2004 of 29 April 2004 on the hygiene of foodstuffs, food waste, and non-edible byproducts from manufacturing and food trading, facilities must be stored in closed containers that are appropriately designed and preserved in good condition and are easy to clean and disinfect. Moreover, according to the provisions of the Act of 7 June 2001, on collective water supply and sewage removal, it is illegal to dispose of solid waste through the sewage system [99]. However, this still requires adequate control and further in-depth research to broaden knowledge about the parameters influencing the performance of reactors. Most studies have been conducted under mesophilic conditions due to the stability of the system, but a long retention time has been reported [45]. Under thermophilic conditions, an enhancement in biogas generation, and short retention time were observed, but VFA and free ammonia accumulations were mentioned [7]. A few studies have been conducted under psychrophilic conditions due to the slow degradation speed and the long retention time; despite the benefits of the two-stage psychrophilic digester [37], it requires more space and is more costly. On the other hand, the co-digestion of two substrates or more has been reported as an efficient method to maintain pH value [100], to reduce VFA accumulation [101], and ammonia inhibition [102], and to increase the AD performance in high TS which ultimately improves methane production. It is difficult to determine an appropriate ratio for diverse feedstock since the best mix of feedstock is influenced by a variety of characteristics such as feedstock type, composition, trace element concentration, and biodegradability, among others [103]. Even if a common ratio such as C/N has been reported to influence energy recovery [101], we cannot ignore the effect of moisture and other environmental factors. In addition, the pretreatment methods have a good ability to maintain pH value [46], enhance methane generation [104], and other important features. In spite of these benefits, pretreatment methods can negatively affect process efficiency if the appropriate method has not been selected. Thermal pretreatment decreases the digestion time by hastening the AD hydrolysis phase, and high refectory compounds such as hemicellulose and lignin are dissolved [105]. However, a higher temperature or a longer heating duration requires more energy consumption and may form inhibitor compounds and reduce biodegradability. After thermal pretreatment of kitchen waste, methane accumulation is reduced by 8% [4]. A wave pretreatment displays good performance when treating a variety of fat-based substrates [106] but has high operating costs owing to energy consumption and needs periodic maintenance. A high-intensity ultrasound pretreatment could reduce methane production [26]. An addition of 6 g/l of salt enhanced VFA generation [66], but reduced the biogas generation. An addition of zero-valent iron and biochar has a significant effect on methane enhancement and the stability of the process [104], but the residual digestate was constructed from toxic components and needed extra treatment. By removing the toxic effects, ozone pretreatment improves the anaerobic biodegradability of polluted organic solid waste [107], but it requires high operating costs and depends on biological stability. Recently, studies of LCA techniques for the assessment of environmental impact have gained more attention. They can be performed with two approaches: attributional LCA, which is useful for consumption-based carbon accounting because it offers information on the average unit of a product; and consequential LCA, which provides information about the consequences of changes to a product, including effects inside and outside the life cycle of the product [108]. A reduction of 42% in the carbon footprint of the electricity produced from the biogas plant can be recorded by substituting about 9900 t of corn silage with 6600 t of FW in a study of combined LCA (attributional and consequential) analysis [109]. In a study of the LCA of the AD of pig manure coupled with different digestate treatments, it was found that the direct use of digestate under controlled conditions is the most environmentally favorable [110]. Despite the interesting information that LCA provided about the AD process, studies on it have been very limited [111], which will increase the overall cost of the AD process. Combined pretreatments such as thermal microwave and autoclave enhanced pollutant contaminant removal can boost the degradability of high refactory substances in the initial stages of digestion [9] but have poor energy gain compared to process demand. Thermochemical pretreatments can help kill some pathogenic infections, decrease organic pollutants, and reduce antibiotic resistance [112], but sometimes it can negatively affect the soil with the compounds of the digestate [7]. Furthermore, the requirements for the cleaning and upgrading of produced biogas and residual digestate [113] after the AD process in the post-treatment procedure are a significant challenge and require more research in large-scale studies [114].

In general, different mathematical models have been constructed to describe AD performance, control the AD procedure, and predict the biogas production rate [92]. However, the complexity of some models and the accuracy of their predictions are the challenges that require further study. ADM1 is the most standard model that describes the AD process, but it was conducted for wastewater simulation, and the lack of the identifiability of heavy parameterization made its use for monitoring more difficult [115]. Manjusha et al. developed a simplified ADM1 that predicted VFA, pH, and biogas production and showed similar trends [96], but the curves of the predicted and experimental results were not close. An improved ADM1 was developed to accurately predict methane production in high TS conditions, and the prediction of inorganic nitrogen was reasonable with the experimental values [57], but it failed in the simulation of phosphorus fluctuation trends, the inorganic nitrogen predicted did not present the experimental trend, and there was difficulty in the prediction of COD. Therefore, more studies are required to enhance the accuracy of these models. A simplified mathematical model was constructed and showed an easy-to-solve procedure [94], but the simplification of substrate concentration facing the half-velocity constant could affect the accuracy of the solution. In addition, the ADSM model was created in order to predict VFA, pH, Alk, and methane with greater accuracy than ADM1 [98], but some deviations were observed in the simulation of the full-scale AD, and it was fitted only to simulate wastewater treatment. A modified Gompertz model followed experimental trends with an accuracy of 98% [116], but it failed to predict the first value of the specific methane yield. Delgadillo et al. predicted methane production with a few key measurements [95] but, due to the non-linearity of the model, the identification of the parameters was difficult. The LM-BP neural network and partical swarm algorithm had significant advantages, such as fast minimization of the error function, accurate prediction of methane production, and a few input variables were introduced to the model [27], but it required an overly large number of datasets for the training and the test procedure. An improved DBN model could predict VFA concentration with high accuracy and could automatically extract data features [28], but the random initialization of the RBM could slow down the research target. In addition, the basic kinetic models are easy to implement, but it is difficult to provide direct practical knowledge for full-scale implementation [117]. Table 3 summarizes the different mathematical models.

Table 3. Discussion of different mathematical models.

Model	Description	Results	Observation	Ref
Simplified ADM1	-The hypotheses were cited in order to reduce the hydrolysis constants. -Using Euler method solver ODE15 for differential equation systems.	-Simple procedure for solving. -Similar trends between the predicted VFA, pH and biogas production and the experimental values.	-The accuracy was not calculated. -The curves of the predicted and experimental results were not close.	[96]
AM2	-Taking into consideration just two steps of the AD (acidogenesis and methanogenesis).	-Predicted methane production with a few key measurements (organic matter and VFA).	-The identification of the parameters was difficult due to the non-linearity of the model.	[95]
ADSM	-ADSM was constructed based on ADM1 and systems-thinking methodology.	-Predicted with accuracy VFA, pH, Alk, and methane better than ADM1 under different conditions.	-Some deviations were observed in the simulation of the full-scale AD. -It was fitted only to simulate the wastewater treatment.	[98]
Improved ADM1	-Addition of precipitation equation. -Addition of high TS inhibition function.	-Predicted with accuracy methane production in high TS conditions. -The prediction of inorganic nitrogen was reasonable with the experimental values. -Simulated the change in phosphorus.	-Difficult prediction of COD. -The inorganic nitrogen predicted did not present the experimental trend. -Failed in the simulation of phosphorus fluctuation trends.	[57]
Simplified Mathematical model	Four main differential equations describing the four main sub-processes of the AD.	-Simple procedure for solving.	-The simplification of substrate concentration facing the half-velocity constant could affect solution accuracy. -The model did not present the development of other parameters.	[94]
LM-BP Neural Network and partical swarm algorithm	-The BP neural network was improved by LM algorithm. -The PSO algorithm was introduced to optimize the parameters of the model.	- Fast minimization of the error function. - High accuracy in the prediction of methane yield was achieved. -Few input variables were introduced to the model (the daily feed volume, TS, VS, pH, VFA, Alk, and the average flow rate of ammonia	-Requirement of a large number of data sets prepared for the training and the test.	[27]
Improved DBN	-Classification of data by GMM. -The decomposition of the input signal using EEMD. -The combination of DBN and ELM in order to measure VFA concentration.	-High accuracy of the prediction compared to other models based on partial least squares (SVM, PB). -Automatic extraction of data features.	-Requirement of a large number of data sets and the random initialization of the RBM could slow down the research target.	[28]
Adaptive network-based fuzzy inference system (ANFIS)	-few input parameters: C/N ratio, temperature, and retention time.	-Predicted with accuracy 99.96% of the biogas production of AD of spent mushroom compost with wheat straw.	- Requirement of a large number of data sets	[118]
Modified model based on ADM1	- Simulates the disintegration of OFMSW. -Takes into account the peculiarities of a co-digestion process.	- Process failure could be predicted using the combined influence of particle size distribution and OLRs.	- Large particle size = higher OLR to reach digester failure.	[119]
BSM2 and ADM1 based model	-A plant-wide simulation. -Co-substrate characterization for ADM1.	-Addition of solid precipitation improve the accuracy. - Revealed the importance of protein loading limit & NH3 inhibition prevention in the digester.	-Using principal component analysis, identify two significant failure modes: NH3 and LCFA inhibition.	[120]

6. Conclusions and Perspectives

According to legal regulations, the AD process is considered one of the best techniques for efficiently managing household waste, and it is an adequate operation contributing to the sustainable production of biogas composed of mixed gases including carbon dioxide and methane, which have different uses. Further, the remainder of the residue after appropriate treatment can be utilized as bio-fertilizer. Despite its numerous advantages, AD is more susceptible to by-product inhibition, such as VFA and ammoniac, which have a negative impact on the process and cause system failure. However, the monitoring and the adjustment of the parameters, such as temperature, pH, OLR, TS (%), and C/N ratio can be efficient for both process stability and biogas generation. Furthermore, there are other significant parameters that are not included in this paper, such as volatile solid removal (%), TVFA/alkalinity ratio, soluble COD percentages, substrate/inoculum ratios, etc. We will give a critical review of the impact of these parameters on the AD system and their relationship with the biogas enhancement methods in the next review paper. Moreover, we are looking to analyze different post-treatment techniques of the residual digestate in order to convert it into an efficient bio-fertilizer, as well as different methods of conversion of biogas into electricity and heat. Additionally, we will study the LCA technique which gives an environmental impact of AD in different categories. Furthermore, co-digestion, pretreatment methods, and mixing techniques have excellent effects on the enhancement of biogas production and process efficiency, but the study of their effects on the residual digestate requires more research. On the other hand, the application of different mathematical models which can accurately estimate and predict biogas potential and other by-products is also important for the control and adjustment of process efficiency, but more research is required in order to apply them at plant scale.

Author Contributions: Writing—original draft preparation, Y.B.; reviewing, supervision and editing, M.S.; supervision, A.F., A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Moroccan Ministry of Higher Education and Scientific Research–National Centre for Scientific and Technical Research (CNRST).

Institutional Review Board Statement: Not applicable.

Acknowledgments: We are grateful to the guest editor and the anonymous reviewers for their valuable comments that substantially improved the presentation of this research.

Conflicts of Interest: The authors declare no conflict of interest.

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