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Review

A Review on Dry Anaerobic Digestion: Existing Technologies, Performance Factors, Challenges, and Recommendations

Umer Hayyat [1], Muhammad Usman Khan [1,*], Muhammad Sultan [2,*], Umair Zahid [3], Showkat Ahmad Bhat [4,5] and Mohd Muzamil [6]

1 Department of Energy Systems Engineering, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad 38000, Pakistan; umerhayyat850@outlook.com
2 Department of Agricultural Engineering, Bahauddin Zakariya University, Multan 60800, Pakistan
3 Department of Food Engineering, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad 38000, Pakistan; umair.zahid@uaf.edu.pk
4 Institute of Communication Engineering, National Tsing Hua University, Hsinchu 300044, Taiwan; showkatbhat1994@gmail.com
5 Center of Innovative Incubator, Department of Computer Science, National Tsing Hua University, Hsinchu 1300044, Taiwan
6 Division of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Shalimar, Srinagar 190025, J&K, India; muzamil4951@gmail.com
* Correspondence: usman.khan@uaf.edu.pk (M.U.K.); muhammadsultan@bzu.edu.pk (M.S.)

Abstract: With the increase in the growing rate of municipal solid waste throughout the world and due to the high moisture and organic components of the organic fraction of municipal solid waste, dry anaerobic digestion has become the future direction to cope with this waste while reducing the impact on the environment, including climate change. Dry anaerobic digestion has become a promising technology that converts the organic fraction of municipal solid waste into combustible biogases, which can be used as an alternative energy source. However, the technology faces several challenges that must be addressed to enhance its performance and adoption. This paper provides a comprehensive analysis of the current technologies used for dry anaerobic digestion in OFMSW and delves into the various factors that influence the performance of these technologies. This review paper also identifies and discusses the challenges faced in optimizing and scaling up these technologies, such as feedstock pretreatment requirements, characteristics of inoculum, and other crucial parameters.

Keywords: dry anaerobic digestion; organic fraction municipal solid waste; AD technologies; performance influencing factors; sustainable waste management

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Citation: Hayyat, U.; Khan, M.U.; Sultan, M.; Zahid, U.; Bhat, S.A.; Muzamil, M. A Review on Dry Anaerobic Digestion: Existing Technologies, Performance Factors, Challenges, and Recommendations. *Methane* **2024**, *3*, 33–52. https://doi.org/10.3390/methane3010003

Academic Editor: Silvia Fiore

Received: 2 October 2023
Revised: 19 December 2023
Accepted: 9 January 2024
Published: 15 January 2024

1. Introduction

Each year, various sources, such as agriculture, industry, and municipalities, contribute to the generation of solid waste, producing millions of tons of waste. The global management of this waste poses a significant concern due to its elevated water content, which results in the natural decomposition of the organic component of the waste over some time [1]. Moreover, the uncontrolled degradation of the organic part of municipal solid waste can also contaminate the air, soil, and water [2]. Municipal solid waste comprises two distinct components: a biodegradable organic fraction and a non-biodegradable fraction, as depicted in Figure 1. Based on the data presented in the figure, it is evident that a significant proportion of municipal solid waste (MSW) consists of organic materials. Specifically, paper and paperboard represent the most significant fraction, accounting for 28% of the total waste composition. Following closely, food and yard trimmings constitute the second largest fraction, comprising 14% of the waste composition [3]. The organic fraction of municipal solid waste, particularly food and yard waste, contains significant potential energy and nutrient content. These valuable resources can be efficiently used to generate bioenergy, thereby reducing the carbon footprint associated with waste management procedures [4]. Various technologies are currently being used to manage the organic fraction, which are discussed in the following section.

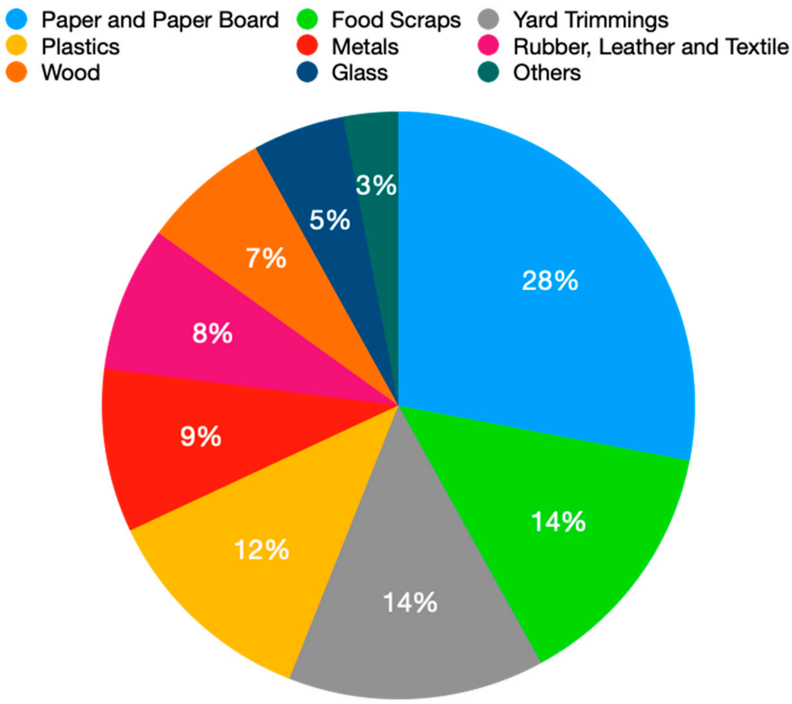

Figure 1. Different fractions for MSW (USEPA. 2009).

In the United States, the most frequently used technology or procedure for solid waste disposal is landfilling. The current method of waste management accounts for approximately 54% of the total waste volume, leading to the deposition of an estimated 243 million tons of municipal solid waste in landfills in 2009 [3]. Landfilling is known to be a significant human-caused contributor to methane emissions in the United States, accounting for approximately 17% of the total methane emissions released into the atmosphere [5]. The decomposition of one metric ton of organic solid waste in landfill results in the release of methane and carbon dioxide in the range of approximately 90–140 m^3 and 50–110 m^3, respectively [6]. The effect of methane gas as a greenhouse gas is 23 times more potent compared to CO_2. Moreover, the gas recovery systems of landfills will never be able to capture all methane emissions, and a significant fraction of gas will escape during energy recovery in landfills, giving rise to GHG emissions to the atmosphere [7]. The amount of solid waste being landfilled can be minimized by diverting the organic fraction of MSW away before landfilling, while using this fraction as a feed material for generating valuable products such as methane.

Composting is used to a certain degree in the United States for the purpose of handling the organic component of municipal solid waste. The economic value of compost obtained from the OFMSW is frequently negligible, with an average of approximately $13 US per cubic meter. As a result, numerous composting facilities do not generate revenue through the sale of compost; instead, they distribute it to local residents free of charge [8]. Furthermore, the process is energy consuming and does not unravel the potential of this waste. Hence, the development of a sustainable, effective, and economically viable strategy is crucial for effectively managing the significant amount of municipal solid waste. This approach is expected to produce energy output that significantly exceeds the energy required for its operation [9].

Besides landfilling and composting, a small portion of municipal solid waste is also being incinerated (13%) and recycled (14%). Incineration will, however, produce exhaust gases, which need to be further treated to avoid contamination of the environment, as well as a solid residue, which will be high in heavy metals and other pollutions [10]. Incinerators are effective in fast volume reduction of MSW and to further produce energy. However, high investment costs along with social and environmental concerns about air pollution and residues have limited the use of these technologies in Western Europe [11]. Other technologies, such as gasification and pyrolysis, are less mature technologies compared to anaerobic digestion and incineration. These technologies' capital and operational costs are higher [11].

Considering the facts as mentioned earlier, there is a dire need for sustainable waste management technologies that not only reduce the landfilling of waste but are also cost-effective, environmentally friendly, and helpful in resource recovery from waste during processing. In this regard, anaerobic digestion is an effective renewable energy technology that is not only helpful in energy generation from organic waste but also minimizes GHG emissions [12]. The extensive use of anaerobic digestion to treat organic waste has been steadily growing over the past decade, and about 1.94 billion cubic meters of biogas were produced in Europe in 2017 from 5% of the biodegradable waste [13].

The degradation of lignocellulosic materials and the organic fraction of municipal solid waste in the absence of oxygen demands a significant quantity of water in traditional wet AD. Hence, dry anaerobic digestion is regarded as a more favorable alternative for managing these waste materials due to its ability to be conducted at elevated levels of solid concentration, typically ranging from 20% to 40% [14]. The popularity of dry anaerobic digestion has increased in recent years, but some companies are still reluctant to adopt this technology due to its complexity and lack of adequate knowledge. However, during the years 2010–2015, there was a 50% increase in dry anaerobic digestion biogas plants in Europe, and about 35% of the waste being treated by the AD process is processed using this technology [15]. Besides Europe, China has also encouraged the use of dry anaerobic digestion and found it an effective way of treating 0.9 billion tons of available lignocellulosic material [16]. Several aspects of dry anaerobic digestion technology have been discussed previously. These include the advantages of dry anaerobic digestion over wet anaerobic digestion, the potential for treating organic wastes with high total solid contents, and the challenges associated with excessive solid content. However, this paper aims to present a critical overview of the fundamental aspects of dry anaerobic digestion, covering specific characteristics, operational conditions affecting process stability, and recommendations for improving its performance. This review paper focuses on the technologies that have been developed for dry anaerobic digestion and provides an overview of the different aspects of improving these technologies. In Section 2, the review offers a general overview of the technologies working on the dry anaerobic digestion of municipal solid wastes, providing insights into the existing knowledge in this area. Section 3 delves into the parameters crucial for enhancing and optimizing the performance of dry anaerobic digestion, aligning with previous research while also shedding light on untapped potential areas for further investigation. Furthermore, in Section 4, the review discusses the challenges encountered in dry anaerobic digestion and provides recommendations for improvement, bridging the existing knowledge gaps. Lastly, Section 5 explores the future directions of development for dry anaerobic digestion technology, emphasizing the need for further research and the potential for advancements in this field.

2. Dry Anaerobic Digestion Technologies for OFMSW

The process of anaerobic digestion (AD) is currently being used for the management of the organic fraction of municipal solid waste (OFMSW) within the European region, and different processes have been developed for the enhanced degradation of this waste. These processes include Valorga, Dranco, Kompogas, Bekon, Aiken, Linde BRV, BioPercolate, and Iska. These methods can be used to manage the organic fraction of municipal solid waste (OFMSW) with total solids (TS) ranging from 20% to 40%. The OFMSW can be treated under mesophilic, thermophilic, single-, and double-stage conditions in all of these processes. Approximately 50–120 cubic meters of biogas are generated through the anaerobic decomposition of one metric ton of the organic fraction of municipal solid waste (OFMSW), with the specific amount varying based on the waste composition and the chosen method of processing. The anaerobic digestion of OFMSW can be performed under continuous or batch conditions, depending on the process used for the treatment. The plug flow reactors are commonly used for the treatment of OFMSW, and the substrate is not mixed generally, and it moves from the inlet towards the outlet. In two-phase dry AD systems, dry waste is inoculated in the percolation system. The water-based waste generated during the initial stage of anaerobic digestion is then transferred to the next phase, and the mixture from the subsequent phase is recycled back to the initial reactor. This recirculation of inoculum allows for better mixing of the waste and anaerobes engaged in the AD process [17].

During the year 1991–1995, around 38,800 tons of MSW were treated annually by anaerobic digestion. During the year 1996–2000, the AD treatment of MSW was further increased and around 223,500 tons of MSW/year were treated by this process. About 415,590 tons/year of MSW were treated using an anaerobic digestion process from 2001 to 2005. During the year 2006–2010, the anaerobic digestion of MSW was further increased, with an annual increase of 345,540 tons of MSW. The ability to handle waste is growing each year, and we are seeing the addition of 11 new biogas plants annually. These anaerobic digestion plants have the potential to process municipal solid waste of 32,000 tons each year [7].

An anaerobic digestion unit for OFMSW has six main components. The tipping floor is the first part of the AD facility, and the organic waste is unloaded from the trucks at this part. The second phase involves a facility where all the inorganic pollutants are eliminated from the waste, and the waste is prepared for additional processing. The third phase involves the anaerobic reactor, where the process of anaerobic digestion takes place for the pretreated waste. The management of solid waste occurs during the fourth phase, while the enhancement of biogas quality takes place during the fifth phase of the anaerobic digestion facility. A bio-filter is also provided in the facility to remove odor from all the ventilation air from the facility, as well as for purifying the final biogas [18].

2.1. Dranco

Dranco (Dray anaerobic digestion system) was used for the first time in 1983 to treat OFMSW in Belgium. There are currently approximately 20 Dranco plants operating worldwide for the purpose of treating organic fraction of municipal solid waste (OFMSW). The initial preparation of the organic fraction of municipal solid waste (OFMSW) involves reducing the size of particles to less than 40 mm [19]. Following this, the temperature of the waste material is raised to 50 °C by introducing steam. The Dranco is a single-stage thermophilic process in which the feed material is added into the reactor from the top and removed from the bottom. Mixing of the material is not performed in this system and the material is moved downward by a plug flow movement [20]. The process of anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) is conducted with a mechanical (hydraulic) retention period ranging from 15 to 30 days. The amount of biogas produced is approximately 80–120 cubic meters per metric ton of feedstock. The input material used for the reactor consists of one portion of the newly generated waste and six portions of the processed material. The digested material obtained during this process is dewatered by using a screw press to about 50% TS and then the material is composted for approximately two weeks [21]. Figure 2 shows the schematic diagram of Dranco anaerobic digestion [19].

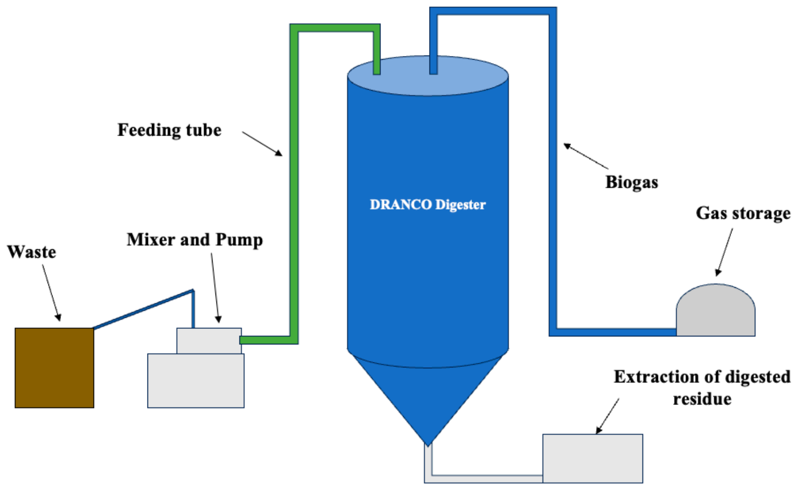

Figure 2. Schematic representation of Dranco digester.

2.2. Valorga

This system was developed in 1981 and the first plant was built in France in 1982. The process contains an automatic separator/baffle that removes the non-biodegradable parts of the MSW such as glass and plastic bags [22], as shown in Figure 3. Particles larger than 40 mm are eliminated, and the substance is heated using steam prior to being introduced into the reactor. The MSW is handled by using specially designed high-solid pumps and conveyor belts. The anaerobic digestion of OFMSW is carried out in a single stage under dry conditions. Valgora can be operated under thermophilic as well as mesophilic conditions. The TS content of the feed material is kept in the range of 25–32% by recirculation of the process water, and it is introduced in the reactor from the bottom. The biogas is circulated again from the lower part of the reactor to ensure thorough mixing of the substances within the reactor [23]. The duration for which Valgora retains information is between 18 and 25 days. The typical methane concentration of the biogas generated during the process is approximately 55%. The digested material is screw pressed to remove water and solids. The solid material obtained by the dewatering process usually has up to 40% solid content, which is stabilized by composting. The methane yield obtained by this process is 80–160 m^3/tone of the waste material added [24].

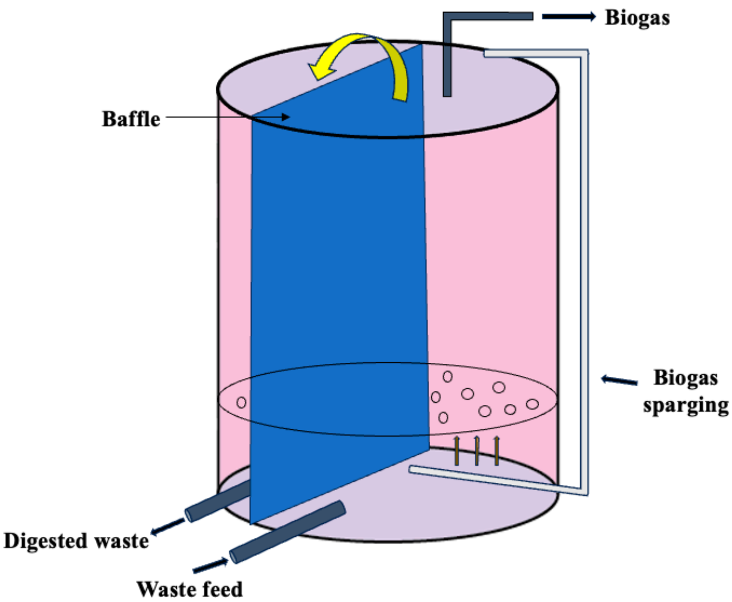

Figure 3. Schematic representation of Valorga design.

2.3. Kompogas

The Kompogas process was founded in Switzerland in 1980 by W. Schmid and the first plant was installed in 1991. The inorganic materials present in MSW are removed by mechanical pretreatment. After that, the organic waste is shredded by using a shredder in such a way that the particle size of the feed material should be 30 mm. The shredded feed material is then mixed with processed water and then it is mixed properly. After mixing, the homogeneous material is preheated by passing it through a heat exchanger before feeding it into the anaerobic reactor. The preheated feed material is introduced into the horizontal plug flow anaerobic reactor in which the material is agitated by a slowly rotating agitator, as shown in Figure 4. The substance undergoes anaerobic digestion in a single phase with high temperatures between 55 and 60 degrees Celsius [24,25]. This occurs over a period of 15–20 days, known as the hydraulic retention time. The processed substance is dehydrated using a screw press until it reaches a moisture content of up to 50% [22]. The water extracted from the processed substance is then combined with the feed material to regulate the overall concentration of solid components in the feed material, which falls within the range of 23–28% [26]. The Kompogas reactor is of smaller capacity and the many reactors are operated in parallel to increase the capacity of the reactor. The Kompogas reactors are available in two sizes that are 25,000 and 15,000 metric ton capacity. The total number of Kompogas units in the world is about 70 and most of these units are working in Europe. The biogas yield of the reactor is about 100–150 m^3/metric ton of the feed material and the biogas produced contains 60% CH_4 and 40% CO_2.

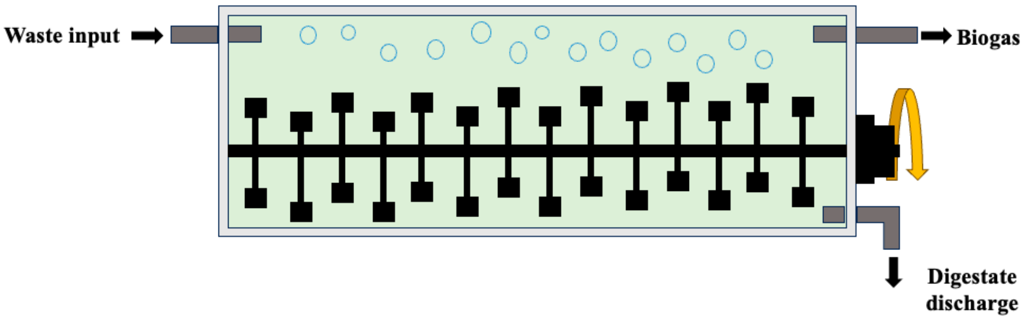

Figure 4. Schematic representation of Kompogas digester.

2.4. Bekon

The Bekon anaerobic digestion system was founded in Germany in 1992. The first anaerobic reactor was installed in 2002. This method is used to facilitate the anaerobic decomposition of yard waste, the organic fraction of municipal solid waste (OFMSW), and energy crops in a moisture-free environment. The organic waste is anaerobically digested in garage-shaped reactors [27]. The air is usually removed from the reactor after loading it with biomass because the air can make an explosive mixture with methane if its concentration is around 15% or higher. The methane gas is removed from the reactor by introducing a CO_2-rich gas. The organic waste is anaerobically treated in the batch mode. Once the process of degradation is completed, the water and solids are removed from the digested material. Complete decomposition of the organic waste is achieved within a time frame of approximately four to five weeks. The wheeled loaders are used to load and unload the feedstock, which takes one day. About 50% of the digested material is mixed with the fresh feed material as an inoculum, as well as to adjust the solid contents of the material [28]. There is no stirring mechanism in these reactors and there is a percolation storage tank where the percolate is collected and returned to the reactor by a pump. The percolate collected is returned to the reactor in the form of a spray, which is helpful for the anaerobic digestion process of the newly added feed [16]. The drawback of the process is that VFAs can be accumulated due to non-availability of the stirring mechanism. The VFA accumulation can reduce the methanogenic activity by lowering the pH of the reactor [29]. The organic waste is treated under mesospheric conditions at 38 °C. The walls and floors of the reactors are heated to ensure the mesophilic temperature in the reactor. The schematic design of a Bekon digester is depicted in Figure 5.

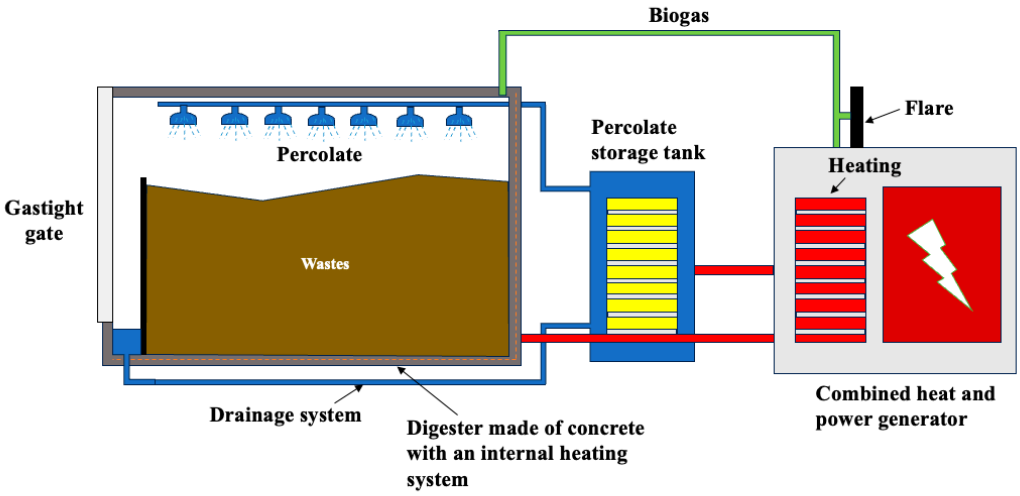

Figure 5. Schematic representation of Bekon digester.

2.5. Aikan

Aikan is a two-phase anaerobic process developed by Solum A/S, a Danish company. Figure 6 shows the schematic diagram of the Aikan digestion process. During the primary stage of anaerobic digestion, the organic waste is introduced into the reactor following its combination with woody biomass material. The total solid content of this mixture is 30%. After that, the effluent from the methanogenic reactor percolates in this reactor. The woody structural materials added are helpful in the percolation of OFMSW. The liquid waste that is gathered in the primary stage of anaerobic digestion is transferred to the methanogenic reactor. The addition of leachate is beneficial for the transformation of organic matter into methane during the secondary phase of the anaerobic digestion process. The anaerobic digestion process is continued until the methanogenic reactor reaches a point of methane production cessation, which is attributed to the introduction of leachate from the primary or initial stage. The first stage reactor is not heated in the Aikan process, whereas the second phase reactor is heated to attain a mesophilic temperature of 37 °C. The biogas yield in the Aikan reactor is 80 m^3 per ton of waste material and the retention time of the process is 15–21 days. The digested material is used for producing compost, and then it is used as a biofertilizer [30].

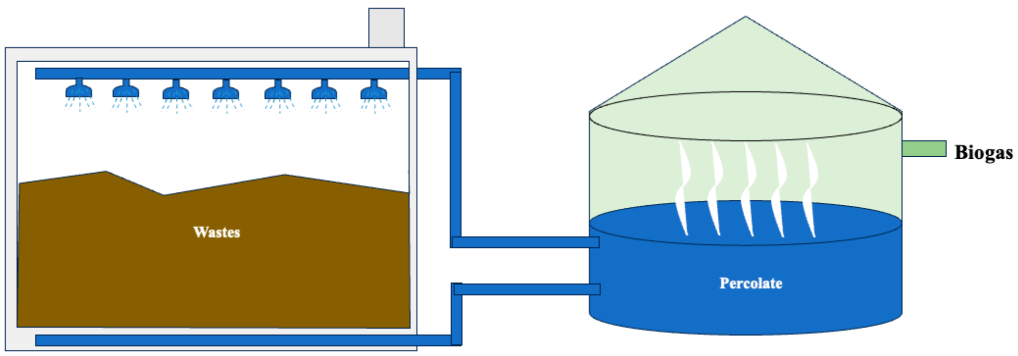

Figure 6. Schematic representation of Aikan.

2.6. Linde BRV

The Linde BRV process was founded in Switzerland in 1981 and the installation of the first plant started in 1989 for the management of manure through anaerobic digestion.

The company specializes in the operation of waste treatment plants that use both aerobic and anaerobic processes. The Linde BRV reactor operates in both moderate-temperature (mesophilic) and high-temperature (thermophilic) conditions. It is offered in two variations: a single-stage process known as dry AD and a two-stage process known as wet AD. The dry AD technology is used for the treatment of OFMSW with TS 15–45% [31,32]. The OFMSW is introduced in a horizontal plug flow reactor equipped with an agitator for the mixing of material during the AD process [33]. The anaerobic reactor yields an estimated volume of 100 cubic meters of biogas per metric ton of the organic fraction of municipal solid waste. The digested material obtained after the anaerobic digestion process is dewatered to separate solids and water fractions and then the solid part is aerobically treated to produce compost [34]. Figure 7 represents the schematic design of Linde BRV.

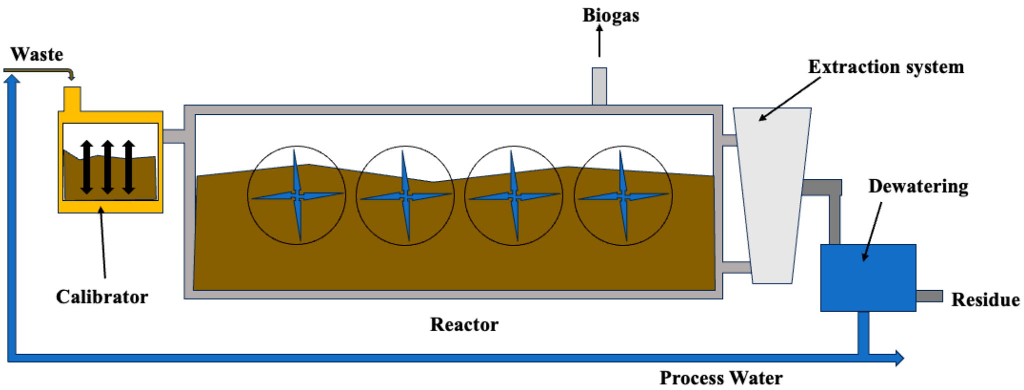

Figure 7. Schematic representation of Linde BRV digester.

2.7. BioPercolat

BioPercolat is a two-phase anaerobic process that was patented by Wehrle-Werk in Germany. The process was developed to treat the whole MSW. The BioPercolat process which is used to treat the OFMSW is called mechanical biological treatment (MBT). The non-biodegradable fraction of MSW is separated before feeding the material into the reactor. Before feeding the material into the reactor, the percolation of the material is executed in aerobic conditions so that the degradation rate of the material can be enhanced, and the retention time of the material is also reduced. The percolation of the material is carried out during the first stage of the anaerobic process and the retention time of this process is 2–3 days [24,32]. The percolate obtained from the first stage is transferred to the Up-flow Anaerobic Sludge Blanket (UASB) reactor. The Up-flow Anaerobic Sludge Blanket reactor is the second reactor, which holds the substance for a period ranging from 4 to 5 days. The hydraulic retention time (HRT) of the organic fraction of municipal solid waste (MSW) within the BioPercolat system is determined to be 8 days. The process of anaerobic digestion occurs in the BioPercolat process at moderate temperatures (mesophilic). Approximately 70–80 cubic meters of biogas are generated through the anaerobic decomposition of one metric ton of the organic fraction of municipal solid waste (OFMSW). The processed substance is dehydrated using a screw press after the anaerobic digestion process in order to separate the liquid and solid components. The liquid portion is used for the process of percolation, while the solid residue is subjected to aerobic composting in order to generate biofertilizer [24].

2.8. Iska

The Iska process is designed for the treatment of the entire MSW. The initial stage of the Iska anaerobic digestion process involves the separation of organic elements from non-organic parts within municipal solid waste (MSW) [35]. After separation, the anaerobic digestion of the organic material is carried out by a two-stage wet process. In the initial phase of anaerobic digestion, the substance is passed through a horizontal plug flow reactor. In this stage, the processed water inoculum obtained from an anaerobic reactor is sprinkled on the OFMSW. During this stage, the OFMSW is hydrolyzed under aerobic conditions. The percolation of the material occurs at a temperature of 40–45 °C in a semi-continuous mode [24]. The feed material enters the percolator from one side and leaves the reactor from the other end after the hydrolysis. The retention duration of the percolation process is two days. The percolate obtained during the first stage of the process is introduced into the anaerobic reactor from the bottom. The anaerobic reactor works under mesophilic conditions. The biogas obtained during the anaerobic digestion contains 70% methane and 30% carbon dioxide [24]. Upon completion of the procedure, the substance that has undergone digestion is subjected to dewatering through the use of a screw press. The resultant solids are then subjected to composting in order to produce biofertilizer. The comparison of all the technologies is displayed in Table 1.

Table 1. Comparison of different commercial dry anaerobic digestion technologies.

	Dranco	Valorga	Kompogas	Bekon	Aikan	Linde BRT	BioPercolate	Iska
Year of Foundation	1983	1981	1991	2002	-	1981	-	-
Country of foundation	Belgium	France	Switzerland	Germany	Denmark	Germany	Germany	Germany
Feed Material	SS-OFMSW	SS-OFMSW	OFMSW	Biowaste	Biowaste	Biowaste	OFMSW	OFMSW
Operating Condition	Thermophilic (50–55 °C)	Mesophilic/ Thermophilic (37/55 °C)	Thermophilic (55 °C)	Mesophilic (38 °C)	Psychrophilic/ Mesophilic (25/37 °C)	Mesophilic/ Thermophilic (37/55 °C)	Mesophilic (37 °C)	Mesophilic (37 °C)
Biogas Yield/Ton waste	80–120	80–160	100–150	130	80	100	70–80	50
Type of Reactor	Vertical	Vertical	Horizontal	Vertical	-	Horizontal	Vertical	Horizontal
Mode of operation	Dry Continuous	Dry Continuous	Dry Continuous	Dry Continuous	Dry Batch	Dry Continuous	-	Semi Continuous
OLR (kg VS/m^3 day)	10–15	10–15	4.3	-	-	-	-	-
Recirculation	Digestate recirculation	Biogas recirculation	No	Liquid phase	-	-	-	-
Capacity of the Plant (tpy)	50 to 100,000	50 to 100,000 And >100,000	50 to 100,000		-	50 to 100,000 And >100,000	50 to 100,000	50 to 100,000
HRT/SRT	20	20	29	28–35	15–20	18–25	8	8
VS Removal Efficiency	40–70	60	60–70	65–70	-	-	50–55	-
Stages	1	1	1	1	2	2	2	2
CH_4 (%)	55	55–60	50–63	55–60	70	55	-	70
TS (%)	20–35	25–32	23–28	≤50	30	15–45	>20	-
Size of Feed material particles (mm)	<40	<40	<60	-	<80	-	-	-
Energy Used/Available Energy	20% use/80% net	25% use/75% net	25% use/75% net	-	-	30% use/70% net	20% use/80% net	-
No. of Plants	17	22	38	60	-	8	1	-

3. Parameters Influencing Dry Anaerobic Digestion Performance

There are several factors that directly influence the performance of dry anaerobic digestion. Certain factors are significant as they directly contribute to the improvement of dry anaerobic digestion, while other factors establish the conditions in which dry anaerobic digestion operates more effectively. Both types of factors are crucial for the overall performance enhancement of dry anaerobic digestion.

3.1. Feedstock Pretreatment Process

The feedstock pretreatment process has emerged as an essential process to improve the ability of dry anaerobic digestion to produce methane as it makes feedstock more amenable to chemical conversion. Pretreatment processes like thermal pretreatment, biological pretreatment, chemical pretreatment, and mechanical pretreatment are the most common processes that are used depending on the nature of the feedstock. At the same time, it has been noted that the pretreatment methods used for wet anaerobic digestion can also be applied in dry anaerobic digestion.

3.1.1. Thermal Pretreatment

The thermal pretreatment process is the most commonly used process at the commercial level to enhance the performance of anaerobic digestion [36,37]. Thermal pretreatments enable the removal of pathogens from feedstock, decrease the viscous level, and remove excess moisture from the feedstock, resulting in enhanced digestate processing [36,38]. In this process, the feedstock's organic component is dissolved, and the cell walls are broken down during the thermal pretreatment process. In the thermal pretreatment method, the heat is incrementally raised to a specific target, typically between 60 and 270 °C. Once achieved, this temperature is sustained for a set duration, which can range from minutes to hours [39]. The polymeric compounds of the substrate degrade and enter the liquid state during the thermal treatment process. By breaking down the substrate's chemical bonds, this method makes it more easily biodegradable [40]. Based on the temperature range being used, there are two main categories in the thermal pretreatment process: methods using high temperatures and methods using low temperatures.

The temperature at high-temperature thermal pretreatment usually lies above 110 °C. Liu et al. [38] examined the impact of high-temperature pretreatment on biomass feedstock in relation to methane production. The conclusion was that subjecting biomass feedstock to high-temperature thermal pretreatment resulted in a 34.8% increase in methane production. This increase can be attributed to the potential reduction in both the moisture content and viscosity of the biomass feedstock. During high-temperature thermal pretreatment, the conversion of complex substances, such as lignin, into a soluble phase occurs as a result of the efficient breakdown of polymeric compounds and cell membranes [41]. However, subjecting the biomass feedstock to high temperatures can result in the formation of resistant compounds or harmful byproducts, which could potentially cause a reduction in the generation of biogas [40]. Therefore, thermal treatment at low temperatures (below 100 °C) has garnered significant attention from researchers. Ilanidis et al. [42] used a technique to improve the production of methane from swine manure by involving the application of thermal treatment at lower temperatures in anaerobic digestion. The findings indicated that proteins, cellulose, and hemicellulose experienced considerable degradation, leading to a 39.5% increase in methane production in anaerobic digestion.

3.1.2. Mechanical Pretreatment

The use of mechanical pretreatment methods has become essential in the processing of raw materials for anaerobic digestion as the dimensions and varied composition of the raw materials can significantly affect the digestion process [43]. Numerous studies have demonstrated that the application of mechanical pretreatment on biomass feedstock can significantly influence methane production during anaerobic digestion. Specifically, it has been noted that the presence of large particle sizes tends to lead to reduced methane production, whereas smaller particle sizes tend to enhance methane production [44]. Mechanical techniques, such as grinding and milling processes like rolling, chipping, and hammering, are primarily used for the preliminary treatment of raw materials before they are used in anaerobic digestion [45]. By using such techniques, the size of the particles in the feedstock is diminished. Following the implementation of milling pretreatments, the resulting particle size ranges from 0.2 to 2 mm, whereas chipping pretreatments produce particles with sizes that vary from 10 to 30 mm [46,47]. The mechanical crushing or shredding process has emerged as a recent advancement in the pretreatment of lignocellulosic feedstock, receiving significant attention in the industry for its ease of use and effectiveness in anaerobic digestion for methane production [48]. The application of mechanical pretreatment has the potential to enhance various properties of biomass feedstock intended for anaerobic digestion. These properties include improved flow characteristics, increased porosity, and enhanced bulk density [49].

3.1.3. Chemical Pretreatment

Chemical pretreatment of biomass feedstock involves the application of organic solvents, acids, and alkali solutions for anaerobic digestion. Both organic and synthetic acids are used for the initial treatment of biomass materials. These acids include hydrochloric, sulfuric, phosphoric, and nitric acids [42], whereas ammonia (NH_3), calcium hydroxide ($Ca(OH)_2$), calcium oxide (CaO), potassium hydroxide (KOH), and sodium hydroxide (NaOH) are among the alkali solutions predominantly used for pretreating biomass feedstock before initiating the anaerobic digestion process [50]. The primary objective of this pretreatment process is to improve the biodegradability of biomass feedstock further, thereby leading to enhanced production of methane during anaerobic digestion [51]. During the pretreatment process, the use of alkali solutions promotes the disruption of chemical bonds present in the primary constituents of biomass, namely lignin, cellulose, and hemicellulose. This phenomenon leads to the breakdown of specific components and alters the cellulose's structural composition, thereby enhancing the efficiency of anaerobic digestion [52]. Additional factors that can potentially impact the performance of the alkali chemical pretreatment technique include temperature and residence time in anaerobic digestion. Acids primarily target the hemicellulose portion of biomass during the pretreatment process. It has been demonstrated that pretreatments with acids can dissolve the hemicellulose and produce pentose sugars. These pretreatments, which are frequently used to obtain biomass feedstock ready for anaerobic digestion, have worked well [53]. The organic solvent or 'organosolv' pretreatment process can be performed either with the inclusion of a catalyst or solely. This method of using an organic solvent fully extracts the hemicellulose and lignin components from the biomass, enhancing its surface area and pore volume [54].

3.1.4. Oxidative Pretreatment

The use of oxidizing agents in the pretreatment procedure aims to optimize the efficiency of dry anaerobic digestion by treating biomass feedstock. The pretreatment process uses the oxidizing agent's capacity to break down the structure, speed up the elimination of lignin, and increase the quantity of soluble constituents [55]. The pretreatment process involves oxidative treatment, which is subsequently divided into two categories: one involving the addition of water and the other using advanced wet explosion techniques [56]. The pretreatment technique of wet oxidation involves the introduction of water into the system, along with substances such as oxygen or air. Subsequently, the biomass feedstock is subjected to extreme temperatures. Factors such as operating temperature and time of reaction can affect the performance of this pretreatment process. The impact of wet oxidation pretreatment on fruit branches utilized as feedstock for anaerobic digestion was investigated by Lee et al. [57]. The use of hydrogen peroxide was employed in the pretreatment procedure, resulting in a significant 49% increase in methane production. In the advanced wet explosion method, the biomass feedstock undergoes oxidative modifications and physical transformations through a particular patented pretreatment methodology. The efficacy of this approach relies on the manipulation of temperature, regulation of pressure, and identification of the duration of exposure. Once the reactor attains the target temperature, oxygen is introduced into it, followed by the treatment of the biomass for a predetermined duration. After the reactor has finished its operation, the pressure inside is promptly decreased, and the processed substance is transferred to a subsequent containment vessel, commonly known as a flash tank [58]. Ahring et al. [59] examined the impact of wet explosion pretreatment on biomass feedstock when it is used for anaerobic digestion. The researchers reached the conclusion that methane production exhibited a 4–5 times increase in comparison to the conventional pretreatment process.

3.1.5. Biological Pretreatment

The biological pretreatment process is an economically efficient and energy-saving method that employs enzymes and microbes to treat biomass feedstock before undergoing anaerobic digestion [60]. The high methane production in anaerobic digestion can be achieved through the utilization of various biological pretreatment processes, including bacterial pretreatment, fungal pretreatment, and microbial and enzymatic pretreatment techniques.

The hydrolysis process has been identified as the factor responsible for the deceleration of methane production during anaerobic digestion. The enzymatic pretreatment process possesses the capability to enhance the hydrolysis process in the context of anaerobic digestion. Despite being relatively costly in comparison to alternative methods, this particular process is not widely employed for pretreatment purposes [61]. White-rot fungi are commonly employed in fungal pretreatment procedures owing to their remarkable efficacy in the degradation of lignin linkages and subsequent lignin removal. Fungi possess potent enzymes that facilitate the degradation of lignin, thereby enhancing the degradability of biomass feedstock through fungal pretreatment [62]. The corn stover silage goes through fungal pretreatment prior to its use in the process of anaerobic digestion. The findings of the study revealed that the sample that underwent pretreatment exhibited a methane production rate that was 23% higher compared to the samples that did not undergo any pretreatment [63]. On the other hand, microbial pretreatment engages in the degradation of hemicellulose and cellulose using microbes derived from natural resources. In their study, Shah et al. [64] employed a microbial pretreatment process on rice straw biomass feedstock. Their findings indicated that this approach led to an enhancement in the feedstock's suitability for methane production. Specifically, the microbial pretreatment process resulted in a reduction in lignin content within the biomass feedstock, ultimately leading to a 76% increase in methane production.

3.1.6. Hybrid Pretreatment

In recent decades, researchers have explored new or hybrid pretreatment techniques to enhance the production of biomethane. In this regard, various researchers have employed hybrid or integrated pretreatment techniques, yielding favorable outcomes [65]. Chemical pretreatment processes are commonly integrated with other processes to enhance their efficacy in pretreating biomass feedstock. One such combination involves the integration of thermochemical and biochemical pretreatment processes, with thermochemical pretreatment being the most widely recognized hybrid approach [66]. Nevertheless, recent research has revealed that the implementation of an integrated thermal and chemical pretreatment process results in reduced methane production. This is primarily attributed to the susceptibility of this process to chemical properties, such as pH levels and the presence of potentially harmful elements. The integration of physical and biological pretreatment techniques represents an effective strategy that enhances methane production efficiency and simultaneously reduces energy requirements in the pretreatment process. The combined application of wet oxidation and alkali pretreatments results in a reduction in the formation of challenging substances. The use of wet oxidation and steam explosion in conjunction proves advantageous in addressing the issue of significant biomass particle dimensions. The effective treatment of challenging biomass, particularly those with high lignin content, can be achieved through the combination of wet oxidation and steam explosion techniques [67,68].

3.2. Operating Temperature

Operating temperature plays a crucial part in the management of organic waste during anaerobic digestion. The presence of various microorganisms, the rate and energy balance of biochemical reactions, and the routes through which feedstock and their byproducts are transformed are all influenced by it [69]. Dry anaerobic digestion can be categorized into mesophilic or thermophilic processes, depending on the temperature at which they are conducted. During the process of mesophilic digestion, the temperature typically ranges between 35 and 40 °C. In contrast, thermophilic digestion takes place within a temperature range of 50 to 57 °C [70]. Currently, mesophilic digestion is the favored approach owing to its inherent stability and cost-efficiency [71], whereas thermophilic digestion is commonly employed in more giant commercial anaerobic digesters [72]. Thermophilic digestion possesses various benefits compared to its mesophilic equivalent, such as an increased organic matter destruction rate, improved liquid–solid separation during dewatering, and enhanced microorganism development rate [73]. Fernandez-Rodriguez et al. [74] examined the speed at which mesophilic and thermophilic digestion occurred at a 20% TS. They discovered that the microorganisms exhibited a notable increase in their specific rate of growth ranging from 27% to 60% when subjected to thermophilic conditions. Sun et al. [75] concluded that the highest methane production during the process of dry anaerobic digestion of beer lees exhibited a 21% increase when the temperature was raised from 35 °C to 55 °C. Despite the advantages mentioned, the thermophilic dry AD process does have some disadvantages in terms of both technical and economic factors. These include a lack of stability and reliability, which necessitates careful monitoring and precise operational controls. Additionally, the process requires a significant amount of energy for heating [76,77]. Dry thermophilic digestion is generally considered to be superior in efficiency compared to mesophilic digestion when it comes to methane production and organic compound degradation. However, it does require stricter operational controls to ensure the stability of the process. When using dry anaerobic digestion in practice, it is crucial to balance the efficiency of methane production with the cost of operation and energy consumption [78,79].

3.3. Carbon to Nitrogen (C/N) Ratio

The C/N ratio is an essential and crucial determinant in increasing the effectiveness of anaerobic digestion. The presence of an unbalanced carbon-to-nitrogen ratio has the potential to generate volatile fatty acids and induce a low pH, thereby potentially compromising the effectiveness of the process of anaerobic digestion [80]. A recent study has suggested that the optimal C/N for anaerobic digestion lies within the interval of 20 to 30 [81,82]. However, it is evident that achieving the optimal C/N ratio value is dependent upon using the appropriate biomass feedstock. The development of a more equitable carbon-to-nitrogen (C/N) ratio can be accomplished through the careful blending of substrates possessing varying C/N ratios, ensuring appropriate proportions are maintained. A possible reason for implementing co-digestion in anaerobic digestion is to improve operational stability in practical applications [69].

3.4. pH Level

The pH level in anaerobic digestion is crucial for both the efficiency of the process and the state of the microbes that are involved. The pH level shows whether the environment inside the digester is acidic or alkaline. Hence, it is very sensitive to changes in pH level inside anaerobic digestion. Study on the influence of pH and its impact on the AD process is currently limited despite its considerable importance. The impact of pH on dry AD can be concluded by examining investigations conducted on wet AD, as both processes share similarities in terms of their bioprocesses and the involvement of anaerobic bacteria. Methane production happens between pH 5.5 and 8.5, but the best pH for an excellent anaerobic digestion process is usually between 6.8 and 7.2 [83].

3.5. Retention Time

The term "retention time" relates to the average period during which the substrate, also known as feedstock, remains within the digester. The duration of interaction between microorganisms and the feedstock in dry anaerobic digestion processes is determined by the retention time [84]. During anaerobic digestion, it is crucial to have proper retention times to allow the microbial community enough time to decompose organic materials and generate biogas. Insufficient retention time may result in incomplete digestion, causing a decrease in biogas production and potential problems with digester stability. However, if the retention times are excessively long, it could indicate that the digester is not being utilized to its maximum potential, which may not be economically viable [85].

3.6. Microbial Community

The microbial community plays a crucial role in anaerobic digestion by breaking down complex organic matter into simpler compounds, such as volatile fatty acids (VFAs), hydrogen, and carbon dioxide, through a series of biochemical reactions. The microbial community is responsible for the conversion of organic matter into biogas, which is a mixture of methane and carbon dioxide, and the stabilization of the digestate. Different microbial groups, such as acidogens, acetogens, and methanogens, work together in a complex metabolic network to achieve efficient and stable anaerobic digestion [86]. The knowledge of microbial community dynamics can be used to optimize the performance of anaerobic digesters by developing tools to design, operate, and control the AD process. By understanding the relationship between functional microbial community and process conditions, it is possible to select targeted anaerobes, realize stable operation, and enhance the process stability and performance [87]. Additionally, the microbial community indicators of digesters' performances can be used to assess the dynamic behavior of community composition and improve the process efficiency [88].

4. Challenges and Recommendations

The anaerobic digestion technology has been extensively researched since 1980 and has been widely implemented in the industrial sector, particularly for the purpose of treating the OFMSW. Hence, this technology has undergone significant development and has become firmly established within the market. The use of dry anaerobic digestion for the organic fraction of municipal solid waste has increased over the last 15 years, and most of the reactors using this technology are operating under continuous mesophilic conditions. Most of the plants operating under dry anaerobic digestion systems are working in Europe, which are using advanced high-tech systems. Besides Europe, some decentralized dry AD systems are also working in China and India, which are utilizing cheaper and simpler technologies for treating organic municipal solid waste. Dry anaerobic digestion has many benefits, like higher biogas yield at a lower cost for the materials with TS = 20–50%. The VS reduction efficiency of dry anaerobic digestion is 40–75%. However, the OLR of dry AD systems is higher at 12–15 kg VS/m^3 per day compared to wet anaerobic digestion, in which the OLR is <5 kg VS/m^3 per day [72].

A number of dry anaerobic biogas plants are operating globally, but this technology is still facing many challenges that hinder its full adoption for different types of waste. These challenges include the longer SRT of this technology compared to wet AD because of lower mass transfer [89]. Moreover, improvements in conversion efficiency, as well as the economics of dry anaerobic systems, are also essential for its full adoption for different types of wastes. Besides this, the dry AD technology also requires reactors which can be used for other types of waste besides MSW like crop residue, dewatered sludge, and manure. The improvements in the stability of the reactors as well as pretreatment of the feed can further increase with the application of this technology.

The characteristics of inoculum and feed materials are the main contributing factors that determine the efficiency and performance of a dry anaerobic digestion system. The total solid of the feed material, as well as the solid retention time (SRT) and organic loading rate (ORL) of the dry anaerobic digestion system, are also influenced by these two parameters. The robustness and operational characteristics of the dry AD system are affected by physical properties, as well as the impurities present in the feed material. The performance of the dry AD system decreases with increased heterogeneity of the feed material [90]. The characteristics of the inoculant, including its type, ratio, and flow pattern, can have a significant impact on the amount of biogas produced during the dry anaerobic digestion of organic waste. Optimizing the flow pattern of the inoculum can lead to increased gas production in municipal waste digestion processes. Using a 1:1 mixture of anaerobic sludge and cow manure as an inoculant generates higher gas yields. Implementing a multilayer flow pattern for the inoculum, with layers placed at intervals of 4–5 cm, improves mass transfer between the inoculum and biomass [91]. In the face of challenges such as solid retention time (SRT) and lower mass transfer in dry anaerobic digestion, several solutions have been proposed. Optimization techniques such as improving the feedstock and inoculum could potentially manage the SRT and boost the mass transfer rate. Co-digestion and pretreatment processes could be implemented to increase biogas production, potentially managing both longer solid retention times and lower mass transfer [92,93].

The collection and conversion of feed material is the primary factor for maintaining the continuous operation of a dry anaerobic digestion system. The collection and storage of the feed material without loss of organic fraction and transportation is still a challenge in dry anaerobic digestion systems [94]. However, there are possible solutions to address the challenge of the collection and storage of feed material in dry anaerobic digestion systems. One approach is to optimize the operational parameters such as temperature, pH, solids retention time, and substrate composition. By finding the right balance of these parameters, it is possible to maximize the system's performance and process stability. Another solution is to implement modern reactors with enhanced biomass retention capacity. These reactors can effectively retain the biomass during the digestion process, ensuring that the organic fraction is not lost. This not only improves the overall efficiency of the system but also helps in obtaining higher methane yields and productivity. The stability issue in dry anaerobic digestion is a significant obstacle that can be overcome by developing efficient techniques for monitoring alterations in organic matter and microbial cells throughout the anaerobic digestion procedure [95]. Moreover, the online methods for pH monitoring, gas composition, and gas production may also help monitor the stability of the process. The enhancement of energy balance and energy consumption in dry anaerobic digestion systems can be achieved through integration with complementary renewable energy technologies such as solar energy. This integration has the potential to decrease system costs and enhance overall efficiency [96]. Besides this, the two-stage dry anaerobic digestion systems can help obtain higher overall energy compared to single-stage AD because the hydrogen and ethanol production during the first stage is an additional benefit of the two-stage process [97,98].

Enhancement of industrial-scale dry anaerobic reactors' performances can be achieved through the optimization of inoculation, thereby facilitating a reduction in the lag phase [99]. Modification of the mechanical properties of the digested material is expected to improve the mass transfer within the dry anaerobic digestion system, thereby resulting in improved system performance [100]. Besides this, the sedimentation of heavy particles is also a challenge during biogas recirculation in dry anaerobic digestion systems [100]. The inhibition caused by ammonia is a significant challenge that must be addressed when undertaking anaerobic digestion of manure and sludge within a dry anaerobic digestion system. Controlling ammonia inhibition, as well as the removal and recovery of ammonia from the substrate, will be key to success for dry anaerobic digestion systems [101]. The life cycle analysis (LCA) of the dry aerobic digestion system serves as a valuable tool for obtaining comprehensive insights into the operational efficiency and overall reliability of dry anaerobic reactors [102].

Besides all the above-mentioned facts, the dry anaerobic digestion system still has many technological and research gaps regarding their optimization including inoculation, process monitoring, and the pre- and post-treatment techniques of substrates, as well as the factors that may cause inhibition of the dry AD system. Laboratory-scale dry anaerobic digestion studies can be helpful to overcome all the above-mentioned challenges and improve the performance of dry AD systems.

5. Future Directions

To ensure the sustainability and success of dry AD for the OFMSW, future trends focus on integrating new reactor designs, pretreatment methods for substrates, advanced modeling techniques, and innovative conductive materials. Additionally, membrane-based anaerobic digestion systems present a promising development as they selectively retain biomass and improve the interaction between microorganisms and substrates [103]. It is advantageous to explore various pretreatment techniques in order to optimize methane production. Integrating different pretreatment methods can further enhance the synergy between them. Utilizing advanced modeling and simulation approaches, such as CFD, LCA (GaBi), and artificial modeling, can offer valuable insights into mass transfer dynamics in complex AD systems both from a fluid dynamics and biological perspective. Utilizing these models can assist in optimizing digester configurations, identifying possible limitations, and forecasting performance under different operational circumstances. The association between CFD-predicted parameters and biological effects should be investigated further in future studies. The use of new stable carbon-based nanoparticles with a significant surface area has the potential to improve biochar absorption and expedite bonding within microbial communities, ultimately enhancing digestion efficiency.

6. Conclusions

Dry anaerobic digestion (AD) presents numerous benefits in managing the organic fraction of municipal solid waste. These benefits include reduced water usage, increased capacity for organic waste processing, enhanced biogas generation, and elimination of wastewater production. Moreover, recent advancements in research have demonstrated the potential of using dry anaerobic digestion (AD) as a means to extract additional value-added products from municipal solid waste. These products include hydrogen, ethanol, methane, and VFA, which can be obtained from different types of waste materials characterized by higher solid contents, such as lignocellulosic waste, dewatered sewage sludge, and cattle manure. However, dry anaerobic digestion for methane production is the only technology that has been commercialized yet. The increasing growth of dry anaerobic digestion plants indicates that continuous single-stage dry anaerobic digestion technology has the potential for dominance in the near future. Moreover, the pretreatment of feed material, co-digestion of different wastes, and acclimation of microbes can further improve the methane yield efficiency of the dry anaerobic reactors. However, further research is necessary in dry AD technology to reduce the reactors' cost, SRT, and easy process control of the dry anaerobic reactors.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All relevant data are included in the paper.

Acknowledgments: The authors would like to extend their gratitude to the *Methane* Journal for their invaluable support and for providing the opportunity to publish their review in their esteemed journal.

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

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