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Utilization of anaerobic digestion for the organic fraction of municipal solid waste treatment in Sri Lanka in the direction of circular economy

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Abstract

Solid waste management remains a major concern in Sri Lanka due to unavoidable and unmanageable waste generation. Various treatments have been initiated and implemented in Sri Lanka to manage this rising waste. Among these, anaerobic digestion is a treatment that is ideal for the treatment of Municipal Solid Waste (MSW) due to its higher amount of organic content. Although anaerobic digestion has been identified as a key strategy for the circular economy, it is only used by a few local authorities in Sri Lanka. Thus, it is critical to discover and be concerned more about the anaerobic digestion of the Organic fraction of Municipal Solid Waste (OFMSW) in Sri Lanka. The present study intended to review the utilization of anaerobic digestion for managing OFMSW in the circular economy. The published secondary data on global and local contexts in anaerobic digestion were utilized and reviewed to assess their applicability in the Sri Lankan scenario. The results revealed that energy and nutrients could be recovered from the OFMSW using anaerobic digestion, which is crucial for easing Sri Lanka's present energy and economic crisis. Accordingly, the anaerobic digestion of OFMSW creates both positive and negative impacts on the environment. The favourable impacts can be

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improved by upgrading the nutrient recycling and energy recovery facilities. Therefore, there is a high potential to utilize anaerobic digestion for managing waste in Sri Lanka. Thus, it is an environmentally friendly approach. Finally, these findings will help to make decisions and put these technologies into practice in the field of waste management to cater to the current and future needs of Sri Lanka.

Keywords: Anaerobic digestion, circular economy, municipal solid waste, organic fraction

Introduction

Waste generation has increased drastically over the last few decades due to the rising population, unplanned urbanization, rapid industrialization, improvement of living standards, and economic growth (Laurent et al., 2014; Samarasiri et al., 2021). As Pavi et al. (2017) reveal, 1.3 billion tonnes of municipal solid waste (MSW) was generated, estimated to reach 2.2 billion tonnes by 2025. Accordingly, the generation of MSW increased drastically from 0.64 kg per person in 2002 to 1.2 kg per person in 2012 (Samarasiri et al., 2021). This unavoidable and uncontrollable waste generation has caused severe social, economic, health, and environmental issues. (Nishanthi et al., 2021; Saja et al., 2021). To eliminate or reduce those negative impacts, it is necessary to find efficient and effective MSW management strategies. Different traditional and novel treatment methods have been initiated and implemented for managing waste globally. Composting, anaerobic digestion, landfills, sanitary landfills, incineration, gasification, pyrolysis, open dumping, and burning are frequently used in waste management (Behrooznia et al., 2020). Although the objective of MSW management is to reduce the consequences of waste, there are unavoidable impacts associated with those management strategies. Therefore, selecting a suitable management practice is critical to having a sustainable MSW management system. These strategies should be environmentally safe, economically viable, and socially acceptable.

Following the global scenario, MSW management is crucial for Sri Lanka since they are facing significant issues related to waste, such as unbearable stench, diseases, fire hazards, air pollution due to toxic gases, water contamination, aesthetic nuisance together with social and economic losses (Dharmasiri, 2019). Therefore, the focus is identifying the most viable options for managing MSW in Sri Lanka. Though numerous sustainable waste management strategies are available, open dumping has become the most common method of waste disposal (Maheshi et al., 2015). Despite this, a few local authorities have deployed composting, recycling, anaerobic digestion, and landfills to manage their waste (Menikpura et al., 2012). Though composting and anaerobic digestion are recognized as economic approaches and viable solutions for managing organic waste, much attention is still not focused on utilising those treatments in Sri Lanka, except for a few local authorities (Jayathilake et al., 2021). With the introduction of the circular economy approach, which is an economic system based on the reducing, reusing, recycling and recovering materials in the production, distribution and consumption process (Abad et al., 2019), anaerobic digestion and composting are rapidly gaining attention in managing waste all around the world as well as in Sri Lanka. The anaerobic digestion of Organic Fraction of Municipal Solid Waste (OFMSW) is a practical approach to lowering greenhouse gas emissions and enhancing energy security (Behrooznia et al., 2020).

Although anaerobic digestion is known as the best option for waste management under the circular economy concept, very few studies were conducted worldwide to assess the feasibility. In Sri Lanka, a few studies were conducted on anaerobic digestion to assess its feasibility and sustainability. Lokuliyana et al. (2016) conducted a feasibility study on anaerobic biogas plants in Sri Lanka and discussed all the aspects of biogas plants, including applications, raw material usage, installation, technologies, operation, problems, etc. Another study by de Alwis (2012) provided an overview of biogas and inspired people to consider using bio-based power generation and other advantages. The performance of Sri Lanka's use of renewable energy technologies was also reviewed by de Alwis (2002).

On the other hand, Weligama Thuppahige & Babel (2021) conducted a case study to assess the environmental impacts of anaerobic digestion of OFMSW. Also, a comparison study of the assessment of the environmental sustainability of solid waste volarization by anaerobic digestion and composting in Sri Lanka was conducted by Weligama Thuppahige & Babel (2022). As per the findings, anaerobic digestion has more favourable environmental impacts than composting. In the case of the circular economy approach, only a few studies were conducted in Sri Lanka. Samarasiri et al. (2021) conducted a study to evaluate the integrated circular system of waste management framework in Sri Lanka.

Therefore, it is much needed to assess the applicability of circular economy in waste management. As anaerobic digestion plays a significant role in the circular economy with the circulation of resources such as nutrients and energy to sustain human life, it is critical to consider the utilization of the anaerobic digestion of OFMSW in the circular economy for managing MSW. Therefore, the objective of the study is to review and analyze the utilization of anaerobic digestion for managing OFMSW in terms of the circular economy in Sri Lanka. The present study is intended to cater to the world energy crisis by ensuring energy and food security. In addition, it will help to support decision-making and policy formation in the field of waste management.

Municipal Solid Waste

In Sri Lanka, the MSW generation has been accelerated due to the increasing population, urbanization, rapid industrialization, and rising economies (Maheshi et al., 2015). As per the study conducted by Samarasiri et al. (2021), the total MSW generation was 10,768 tonnes/day, and only 3,458 tonnes/day was collected by the responsible local authorities. By 2025, the generation of MSW is predicted to exceed 1 kg/person/day due to the lack of efficient and effective MSW management practices (Saja et al., 2021). The MSW of Sri Lanka comprises biodegradable waste, plastic waste/shopping bags, metal waste, glass waste, and paper waste (Table 1). Among them, the major portion typically consists of organic matter, which is about 61.8% (Liyanage et al., 2015).

Table 1. MSW composition in Sri Lanka (Liyanage et al., 2015)

Composition	Amount (%)
Organic waste	61.8
Plastic waste	7.81
Paper waste	6.03
Metal waste	3.22
Glass waste	2.94
Other waste	18.2

Due to the higher portion of organic content of the MSW, handling remains a major challenge in Sri Lanka. Therefore, unavoidable and unmanageable waste negatively impacts public health, safety, and climate. In Sri Lanka, releasing greenhouse gases (GHGs), air pollution, soil contamination, aesthetic pollution, surface water contamination, and groundwater pollution are major environmental consequences of unmanageable MSW (Maheshi et al., 2015). GHG emissions such as methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and nitrous oxide (N_2O) during waste degradation contribute to global warming and result in severe climatic impacts (Giusti, 2009). Decomposition gases such as CH_4 and CO_2, volatile organic compounds (VOC), odour compounds, bioaerosols, and other gases such as sulfur dioxide (SO_2), nitrogen oxide (NO_x), ammonia (NH_3), and hydrogen sulfide (H_2S) impact on air quality and causes public health and environmental issues. Heavy metals, microbes, synthetic organic compounds, and other inorganic compounds present in the MSW cause significant impacts on soil and geology. Leachate that contains salts, heavy metals, biodegradables, and persistent organic compounds causes direct impacts on ground and surface water.

Municipal Solid Waste Management in Sri Lanka

To reduce and eliminate the detrimental consequences of MSW, such as air pollution, water pollution, soil contamination, and aesthetic pollution, an effective MSW management system is critical for ensuring the protection of the environment and quality of life. MSW management is a strategic framework for managing waste generation, transportation, treatment, and disposal (Baba et al., 2018; Joshi & Ahmed, 2016). An effective MSW management system improves the quality of the urban environment, ensures environmental protection, and improves public health by reducing air, water, and soil contaminants and creating job opportunities for the local community (Igbinomwanhia, 2011).

Although it is precedence, MSW management in Sri Lanka has received less attention than in other developing countries (Saja et al., 2021). However, the National Strategy for Solid Waste Management was formulated in 2000 to have an effective MSW management system. Then the National Policy on Solid Waste Management was formulated in 2007 and has had many national-level plans and policies/strategies to prioritize the appropriate and sustainable MSW management in Sri Lanka (Japan International Cooperation Agency, 2016). In Sri Lanka, local authorities such as municipal councils, urban councils, and Pradeshiya Sabhas are the main responsible authorities for managing MSW. However, the performances of MSW management in those local authorities are still inefficient due to a lack of financial support, absence of technological advances, lack of expertise, poor public awareness, and political involvement.

Japan International Cooperation Agency (2016) revealed that the waste generation amount of Western Province is higher than other provinces of Sri Lanka, accounting for 33% of the total generated waste. The collection of MSW in the country is still uneven and very poor. Although the municipal councils of Colombo, Dehiwala-Mount Lavinia, and Kotte have the greatest collection rates, the rest of the country has a poor collection rate (Bandara, 2011). Municipal councils collect around 50% of solid waste generated in Sri Lanka, urban councils collect 17%, and pradeshiya sabhas collect 33% (Saja et al., 2021). Then the collected waste is transported for either treatment or final disposal by the responsible local authorities. Among all MSW disposal strategies, open dumping (85%) was found to be the most common and worst disposal MSW management strategy, while the remaining 15% of the collected MSW accounts for composting (10%) and recycling (5%) (Saja et al., 2021). The other remaining not collected waste is disposed of inappropriately by the community using dumping on streets, waterways, and backyards, dumping, and burning (Bandara, 2011).

Although open dumping is the most common method of waste disposal, it results in various health and environmental issues, including air pollution, soil, water, and groundwater contamination. Therefore introducing a sustainable and advanced waste management strategy is much needed to mitigate the detrimental consequences and sustain socio-economic, health, and environmental aspects. Limited local authorities have attempted to develop more sustainable MSW management systems using sanitary landfills, anaerobic digestion, composting, and thermal treatment (incineration, gasification, and pyrolysis). Nevertheless, most have failed due to inadequate facilities, including finance, knowledge, technology, etc. Among all MSW treatment methods, anaerobic digestion plays a vital role in reducing GHGs emissions, improving energy security, and improving nutrient recycling (Behrooznia et al., 2020).

Anaerobic digestion

Anaerobic digestion Process

Anaerobic digestion is a biochemical process that degrades organic waste into valuable products, mainly biogas and digested without oxygen with anaerobic microbes (Teferra & Wubu, 2018). It is a complex process that includes four different biochemical reactions performed by specific groups of microorganisms: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as mentioned in Figure 1 (Adekunle & Okolie, 2015; Nordahl, 2018).

During the hydrolysis phase, complex polymers such as carbohydrates, fats, and proteins are breakdown into monomers and oligomers such as sugars, fatty acids, and amino acids by hydrolytic bacteria (Nordahl, 2018). In the acidogenesis phase, acidogenic bacteria convert produced sugars, fatty acids, and amino acids into carbon dioxide, organic acids, hydrogen, and ammonia. Then, in the acetogenesis phase, acetogenic bacteria transform organic acids into methanogenesis substrates. Finally, methanogenic bacteria generate methane and carbon dioxide under strictly anaerobic conditions.

World context of anaerobic digestion

The anaerobic digestion of OFMSW is a vital tool to improve the sustainability of MSW management in the European Union. As a result of expanding anaerobic digestion rapidly in Europe, Germany has become the largest producer of biogas, while China follows in second place and Italy follows in third place producing biogas. Eventually, the expansion of biogas production has been spread to other continents (Fusi et al., 2016).

Food waste or green waste, municipal waste and domestic sewage, animal waste and manure, and agricultural waste, including cassava, corn sugarcane, and agro-industrial waste, are potential feedstock sources for anaerobic digestion (Bhardwaj & Das, 2017). Many countries around the world use biogas mainly for cooking and lighting. It is a beneficial energy source for rural areas without access to other energy sources. Also, some countries use biogas as a source to generate electricity for their domestic and street lighting. Biogas is also used for heating processes using combined heat and power units (CHP). Compressed biogas uses in vehicles as a source of fuel.

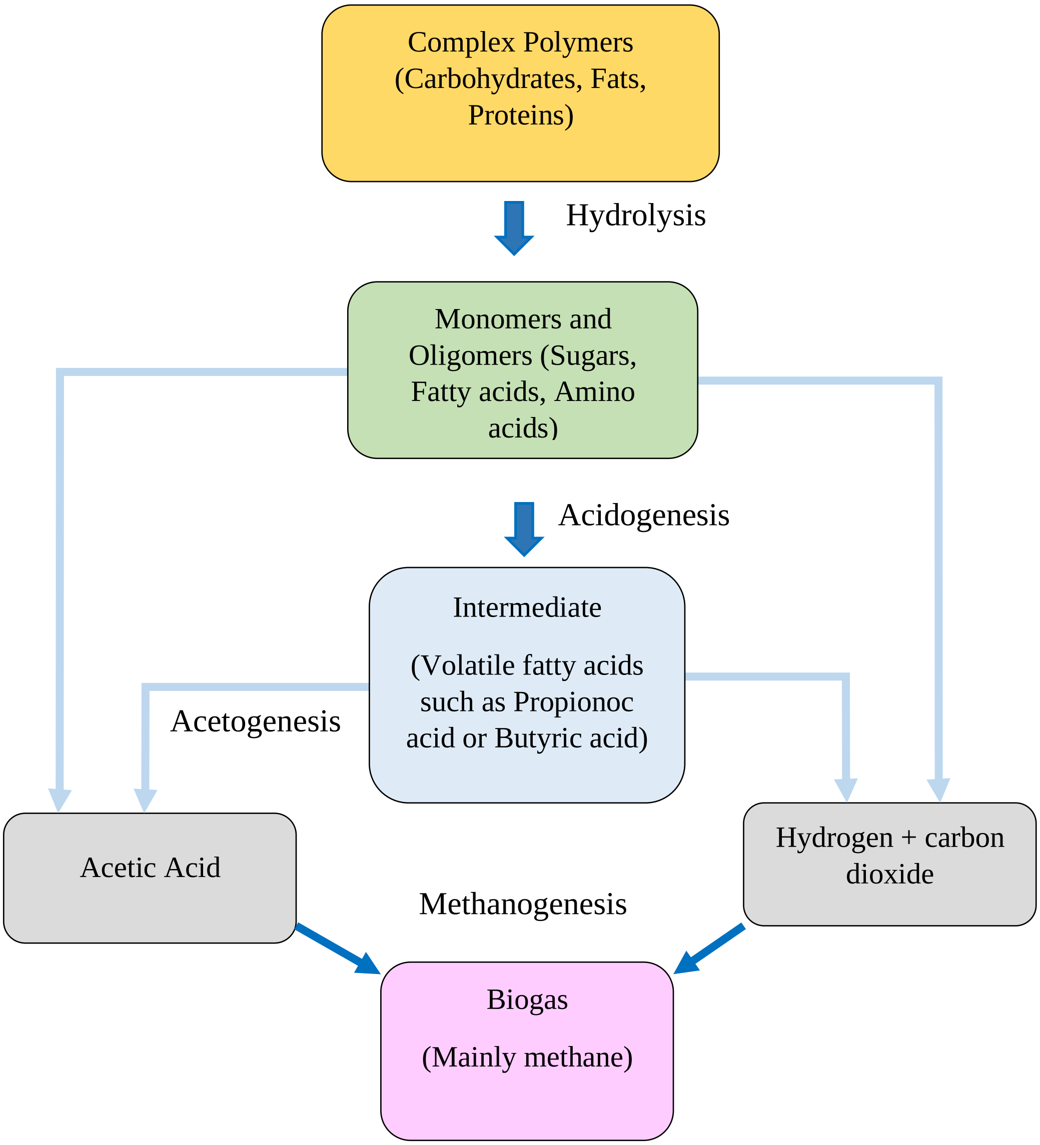

Figure. 1 Anaerobic Digestion Process (Abanades et al., 2022)

Anaerobic digestion in Sri Lanka

Although biogas production has been rapidly spread in the European Union, Sri Lanka too has had experience with the biogas system for a long time (Alwis, 2012). However, there has been limited popularization and applications of biogas in Sri Lanka (Mendis & Thayaparan, 2021). Then it was promoted for its capacity to provide lighting, cooking gas, energy, and biofertilizer. In Sri Lanka, manure, energy crops, and crop residues, municipal solid waste are widely used for biogas production (Lokuliyana et al., 2016).

According to the study conducted by Lokuliyana et al. (2016), biogas is mainly used for cooking (71.4%), lighting (4.8%), and electricity generation (6.3%). Still, anaerobic digestion has a higher possibility to produce electricity and cater to the current energy crisis in Sri Lanka.

Resource Recovery from MSW

In the current economy, materials are taken from the earth; products are made from excavated materials and eventually thrown away as waste. It is a linear process known as "take-make-use-dispose". Due to the use of indefinite resources, non-renewable and polluting sources of energy, and the generation of waste materials, the world has recognized it as unsustainable. Therefore, the world has shifted to a more sustainable "circular economy" (Mancini & Raggi, 2021). In contrast, the circular economy promotes the elimination of waste, safe use of natural resources, harnessing of renewable energy, and replenishing of natural resources (Pan et al., 2015). Ellen MacArthur Foundation defines it as "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models. Consumables in the circular economy are largely made of biological ingredients or 'nutrients' that are at least non-toxic and possibly even beneficial and can be safely returned to the biosphere directly or in a cascade of consecutive uses" (Mancini & Raggi, 2021).

Waste-to-energy is a viable circular economy model that helps towards achieving energy demand. Different technologies are available for waste-to-energy, including anaerobic digestion, incineration, combustion, gasification, and pyrolysis (Pan et al., 2015). Therefore, anaerobic digestion is a bioenergy and bioresource recovery technique based on circular economy principles (Mancini & Raggi, 2021). For Sri Lanka, the circular economy is a relatively new concept as it is unfamiliar in developing countries. This method of resource recovery creates a cyclic system. It converts OFMSW into energy and nutrients. Nutrients, energy, and water can be extracted from OFMSW. Among these three, nutrients and energy are most important resources that can generate revenue in Sri Lanka.

The potential of Energy Recovery from OFMSW

The produced biogas from the OFMSW degradation is converted into electricity and thermal energy. According to Samarasiri et al. (2021), potential electricity generation was 10.31 W per kg of OFMSW based on the currently available data from 2012. Therefore, the total revenue from the generated electricity cost was 21,155,926 USD per annum (Samarasiri et al., 2021). This recovered energy from OFMSW will be an alternative solution to today's energy crisis in Sri Lanka. This alternative energy will help reduce fossil fuel consumption, known as a finite and non-renewable energy source. Therefore, it will help reduce the impacts of fossil fuel combustion. Therefore, this will be vital resource to generate electricity with low cost and environmentally friendly manner. Nowadays, Sri Lanka is also facing with financial crisis due to the lack of financial resources to purchase fossil fuel for transportation, electricity generation and etc. Thus power generation from anaerobic digestion will be the most effective way to cater this problems. Therefore, the energy produced by anaerobic digestion process will be contributed to energy security too.

The Potential of Nutrient Recovery from OFMSW

The anaerobic digestate is a byproduct of the anaerobic decomposition, which can be converted into inorganic fertilizer. It is known as struvite production by chemical production (Samarasiri et al., 2021). Nutrients such as nitrogen, phosphorous can be recovered from the treatments. According to Samarasiri et al. (2021), the minimum struvite generation potential was 3.839 per kg of OFMSW. This nutrient recovery process is known as a value addition for anaerobic digestion. These recovered nutrients from OFMSW will be recirculated once after food consumption and back for the OFMSW. Nutrients recovered from OFMSW will be a resource to the agriculture sector. This will be a great solution for Sri Lankan agricultural sector, as the lack of imported inorganic fertilizers severely impacts it. This recovered nitrogen and phosphorous fertilizers can be used instead of those banned inorganic fertilizers. This fertilizers will help to food production and to ensure the food security in Sri Lanka as well as world.

Environmental Impact of OFMSW Treatment by Anaerobic Digestion

The life cycle assessment study conducted by Weligama Thuppahige & Babel, (2021) evaluated the environmental impact of a full-scale anaerobic digestion plant. Accordingly, environmental burdens regarding global warming potential, ozone formation on human health, freshwater eutrophication, freshwater ecotoxicity, human carcinogenic toxicity, land use, and water consumption were found. However, environmental benefits were identified in the stratospheric ozone depletion, fine particulate matter formation, ozone formation in terrestrial ecosystems, terrestrial acidification, marine eutrophication, ecotoxicity (terrestrial and marine), human non-carcinogenic toxicity, mineral resource scarcity, and fossil resource scarcity. The avoided impacts from the anaerobic digestion plant were mainly due to the electricity production. On the other hand, Weligama Thuppahige et al. (2021) conducted a life cycle assessment to assess the environmental impact of a full-scale composting plant in Sri Lanka. The study results (Table 2) show that the composting system created burdens for global warming, stratospheric ozone depletion, fine particulate matter formation, terrestrial acidification, and fossil resource scarcity. While freshwater eutrophication, ozone formation (human health and terrestrial ecosystems), human carcinogenic toxicity, ecotoxicity (freshwater, terrestrial, and marine), marine eutrophication, human non-carcinogenic toxicity, land use, water consumption, and mineral resources scarcity were avoided due to compost production.

Table 2. Environmental impact comparison of OFMSW treatment between composting (Weligama Thuppahige et al., 2021) and anaerobic digestion (Weligama Thuppahige & Babel, 2021)

Impact categories	**Unit**	**Anaerobic digestion**	**Composting**
Global warming	kg CO_2 eq	2.30E+02	2.18E+02
Fine particulate matter formation	Kg $PM_{2.5}$ eq	-1.04E-03	7.5E-01
Terrestrial acidification	kg SO_2 eq	-3.30E-03	6.17
Fossil resource scarcity	kg oil eq	-1.58E-01	6.13E-01

Terrestrial ecotoxicity	kg 1,4 DCB	-1.74E-01	-1.33E+01
Marine ecotoxicity	kg 1,4 DCB	-3.31E-05	-1.00E-01
Human non-carcinogenic toxicity	kg 1,4 DCB	-4.02E-03	-2.71
Land use	m^2a crop	1.32E-04	-2.26
Water consumption	M^3	2.23E-02	-2.22E-01

In the comparison of these two studies, the impact assessment results indicated that both composting and anaerobic digestion systems highly influence global warming impact categories, whereas fine particulate matter formation and terrestrial acidification are highly influenced by the composting system. The utilization of liquid slurry as an organic fertilizer could contribute to the reduction of the unfavourable environmental impact and enhance the environmental performance of the anaerobic digestion systems.

Therefore, anaerobic digestion can be used as a viable option for the circular economy in the field of waste management in Sri Lanka. Although energy recovery from anaerobic digestion is mainly practised, it can recover nutrients from those organic waste. The study mainly discussed the potential of energy and nutrient recovery towards the circular economy in Sri Lanka. Finally, the reviewed and assessed data on anaerobic digestion will be encouraged to assess and be concerned about using anaerobic digestion for managing MSW in Sri Lanka.

Conclusions

In this study, the utilization of anaerobic digestion of OFMSW treatment was reviewed and assessed regarding the circular economy. The anaerobic digestion of OFMSW contributes more to the circular economy approach. The anaerobic digestion converted OFMSW into biogas and produced electricity or heat. This produced energy can be harnessed and used for electricity and heat generation while contributing the resource recycling. The anaerobic digestate, produced as a byproduct of digestion, contains nutrients such as nitrogen and phosphorus. These nutrients can be extracted using chemical treatments and used as inorganic fertilizers for crop production. These recovered nutrients contribute to the circular economy without wasting those materials. Also, this resource recovery in terms of circular economy will facilitate enhancing the performances of anaerobic digestion plants. This resource recovery or circular economy positively contributes to anaerobic digestion, improving the positive environmental impacts. Finally, these reviewed results can be used for decision-making in waste management shortly.

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