Oecologia Australis
26(2):169–186, 2022
https://doi.org/10.4257/oeco.2022.2602.07

ANAEROBIC DIGESTION AS A TOOL TO REDUCE ANTHROPOGENIC IMPACTS ON AQUATIC ECOSYSTEMS

Thuane Mendes Anacleto[1,3], Helena Rodrigues Oliveira[1,3], Cristiane Fonseca Caetano da Silva[1,3], Rubens Perez Calegari[5], Mariana Erthal Rocha[6], Tiphane Andrade Figueira[3], Marcelo Côrtes Silva[8], Laura Shizue Moriga Masuda[7], Renato Paquet[4], Vinicius Peruzzi de Oliveira[3] & Alex Enrich-Prast[2]*

[1] Universidade Federal do Rio de Janeiro, Centro de Ciências da Saúde, Programa de Pós-graduação de Biotecnologia Vegetal e Bioprocessos, Av. Carlos Chagas Filho, 373, Cidade Universitária, Rio de Janeiro, RJ, Brasil, CEP: 21941-599.

[2] Linköping University, Department of Thematic Studies – Environmental Change, SE-581 83, Linköping, Sweden.

[3] Universidade Federal do Rio de Janeiro, Instituto de Biologia, Unidade Multiusuário de Analises Ambientais – UMAA. Av. Carlos Chagas Filho, 373, Cidade Universitária, Rio de Janeiro, RJ, Brasil, CEP: 21941-902.

[4] Polen - Solução e Valoração de Resíduos, Rua Praia de Botafogo, 440, Botafogo, Rio de Janeiro, RJ, Brasil, CEP: 22250-040.

[5] Universidade de São Paulo, Centro de Energia Nuclear na Agricultura , Av. Centenário, 303, Piracicaba, SP, Brasil, CEP: 13400-970.

[6] Universidade do Estado do Rio de Janeiro, Programa de Pós-graduação em Engenharia Sanitária, Rua São Francisco Xavier, 524, Rio de Janeiro, RJ, Brasil, CEP: 20550-013.

[7] Instituto Chico Mendes de Conservação da Biodiversidade, Diretoria de Pesquisa, Avaliação e Monitoramento da Biodiversidade - DIBIO, EQSW 103/104, Brasília, DF, Brasil, CEP: 70670-350.

[8] Instituto Federal de Educação, Ciência e Tecnologia do Amazonas, São Gabriel da Cachoeira campus, BR-307, km 3, São Gabriel da Cachoeira, AM, Brasil, CEP: 69750-000.

Email: thuaneanacleto@gmail.com (*corresponding author), helenaro3110@gmail.com, cristianecaetanobio@yahoo.com.br, rubenscalegari@usp.br, marianaerthalrocha@gmail.com, tiphane.figueira@gmail.com, marcelo.cortes@ifam.edu.br, shizuemm@yahoo.com.br, renato@brpolen.com.br, viniciusperuzzi@gmail.com, alex.enrich.prast@liu.se.

Abstract: The large global generation and improper management of waste lead to the pollution of the environment and efforts toward reducing the impacts of anthropogenic activities on aquatic environments should be prioritized. The United Nations (UN) declared 2018-2028 as the international decade for action on "Water for Sustainable Development" and integrated management of water resources. Several international initiatives, such as the UN 2030 Agenda, the Sendai Framework for Disaster Risk Reduction and the Paris Agreement, have highlighted and strongly recommended the development of new technologies to reverse the current environmental scenario of global water bodies. The use of anaerobic digestion (AD) for treating organic wastes can minimize and avoid several adverse effects on aquatic environments while promoting nutrient cycling and the production of biogas, a renewable energy source that can replace fossil fuels and therefore decrease the emission of greenhouse gases. We performed a systematic review to evaluate the contribution of AD in preventing and reducing human impacts on aquatic ecosystems. China (15.1%), Spain (7.3%) and Italy (7.3%) are countries with a pronounced research focus on this topic, indicating their awareness on the importance of managing and preserving their water resources. The integration of co-digestion and pretreatment methods into AD improved the production of byproducts (especially energy and biofertilizer). Thus, this review highlights the success of AD technology as a waste treatment strategy, while reducing the damage inflicted to aquatic systems and its consequences to human health and aquatic biodiversity.

Keywords: Biogas; circular economy; sustainable development; waste management; water pollutants.

INTRODUCTION

The non-management or mismanagement of waste is one of the major global barriers in reducing the direct and indirect impacts of human activities on aquatic ecosystems (Ferronato & Torretta 2019). Current global consumption patterns generate huge amounts of waste, and the application or development of new tools to mitigate environmental pollution is beneficial not only to the environment, but also to human health and well-being (Hu *et al.* 2017, Dhanya *et al.* 2020, Hussain *et al.* 2020). Pollution in aquatic ecosystems is a serious worldwide problem that causes up to 14000 deaths and diseases every day (Chaudhry & Malik 2017). Considering the magnitude of the effects caused by this problem, solutions must cover not only ecological, but also social and economic aspects.

A large amount of organic waste constantly reaches water bodies, whether by leaching, runoff or sewage discharge. This may not be the situation in many high-income countries, but it is the reality of most countries in the world (FAO 2017). These inputs increase organic pollutants and nutrient concentrations, resulting in a decrease in water quality (Revitt & Ellis 2016) soluble reactive phosphorus (PO_4-P, and contributing to eutrophication, which can lead to a decrease in aquatic biodiversity (da Costa *et al.* 2018).

The United Nations declared 2018-2028 as the international decade for action on "Water for Sustainable Development", motivated by the foreseen worsening lack of access to water and sanitation due to population growth, the development of global economy and climate change (Levia *et al.* 2020). The goals for the decade focus on sustainable development and integrated management of water resources, aiming to achieve targets such as the Sustainable Development Goals (SDGs) presented in the 2030 Agenda (especially SDG 3- Good health and well-being, 6- Clean water and sanitation, 14- Life below water and 15- Life on land). Several studies pointed out a demand for the development of technologies in order to achieve these goals (Arif *et al.* 2018, Jarvis 2020, van Vliet *et al.* 2021).

Anaerobic Digestion (AD) is a biochemical process of organic matter degradation driven by microorganisms such as bacteria and archaea in the absence of oxygen (Batstone & Virdis 2014) that occurs both in natural environments, such as animal intestines, aquatic sediments and wetlands, as well as in anthropogenic environments such as landfills and rice fields (Arif *et al.* 2018). This complex process converts biomass into gases (*i.e.*, CH_4 and CO_2) which, once produced in the controlled environment of a bioengineering system, can not only avoid greenhouse gases (GHG) emissions but also recover them as energy through biogas technology (Manyi-Loh *et al.* 2019).

Several sources of organic waste – such as sewage, algae, animal, agricultural, municipal and industrial wastes – can be used as substrates, either alone or combined (Sarker *et al.* 2019). AD reduces the waste pollution potential while producing biogas and digestate (residual material from the process), which can be used as a biofertilizer (McCabe *et al.* 2019), bio-oil (Barbanera *et al.* 2018) or biochar (Hung *et al.* 2017). Biogas is a renewable energy source that can replace natural gas to generate heat and electricity (Angelidaki *et al.* 2019). Furthermore, the use of the digestate as a biofertilizer or soil conditioner promotes nutrient cycling, decreasing the demand for mineral fertilizer and improving soil quality (Sahoo *et al.* 2013, Drosg *et al.* 2015). We argue that an increase and spread in the application of AD technology to degrade organic waste could mitigate several adverse human impacts on aquatic environments. Aside from the waste treatment perspective, the use of AD technology can contribute to preserving several aquatic ecosystem services and directly promote a positive impact on the environment, saving freshwater for the production of electricity by hydroelectric plants and irrigation, reducing the eutrophication of freshwater bodies, climate change and ocean acidification (IRENA 2018, Baena-Moreno *et al.* 2019, Slorach *et al.* 2019, Jiménez-Benítez *et al.* 2020).

In this context, a systematic review, which is a structured and unbiased methodological tool and qualified to provide up-to-date summaries of relevant topics (Higgins & Green 2011), can synthesize the effect of applying this biotechnological tool to mitigate environmental damages as well as to elucidate its contribution in the current scenario. Therefore, this study aims to show the role of AD technology in preventing adverse impacts of anthropogenic activities on aquatic environments while generating valuable products from potential pollutants.

MATERIAL AND METHODS

Literature search and study selection

A systematic review was performed, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA, http://www.prisma-statement.org/) (Figure 1) on the Web of Science database. The literature search was constrained to articles in English published between 2010 and November 2020, given the fact that AD has been more widely used over the last years (Table S1). We used Boolean logic (NOT, AND, OR), wildcard ($ or *) and the list of search keywords: "anaerobic digestion" OR "anaerobic biodigestion" AND biogas AND aquatic OR water OR freshwater OR ocean* AND "persistent organic pollutant$" OR "emerging contaminant$" OR wastewater OR "heavy metal$" OR "organic waste" OR "organic residue$" OR sewage OR "solid residue$" OR "solid waste" OR eutrophication OR bloom.

The eligibility criteria to include articles in the review were: a) application of Anaerobic Digestion technology; b) mention of the source of pollution and; c) solution to the environmental problem. Articles that did not meet any of the criteria were classified as excluded, while articles that insufficiently met the criteria were excluded with reasons. Data collected from the selected articles were grouped in an Excel spreadsheet.

Data Analysis

Information compiled from the articles were: year of publication, polluting source, country of study and outputs of the AD process. The country of study considered the site where the waste source originated and the AD technology was applied. The possible outputs were classified as biofertilizer, reuse water, bioplastic (polyhydroxyalkanoate - PHA), biochar and bio-oil. Furthermore, the main sources of waste identified were classified as rural and municipal, according to the origin of the residues. Agricultural and animal residues, as well as manure, were grouped as Rural Waste, while food waste, industrial residues and Organic Fraction of Municipal Solid Waste (OFMSW) and sewage were classified as Municipal Waste.

In order to evaluate the evolution of the interest in the application of AD technology to solve water quality issues, temporal trends of the publications concerning the number of studies published per year since 2010 were analyzed. Moreover, the global distribution of the studies was also analyzed.

Our search in the Web of Science database resulted in 1224 articles published between 2010 and 2020. Following the eligibility criteria, 540 articles were excluded in the first screening and 247 were excluded during full-text assessment (Figure 1). In the end, 437 articles matched the eligibility criteria and were selected for the systematic review (Table S1).

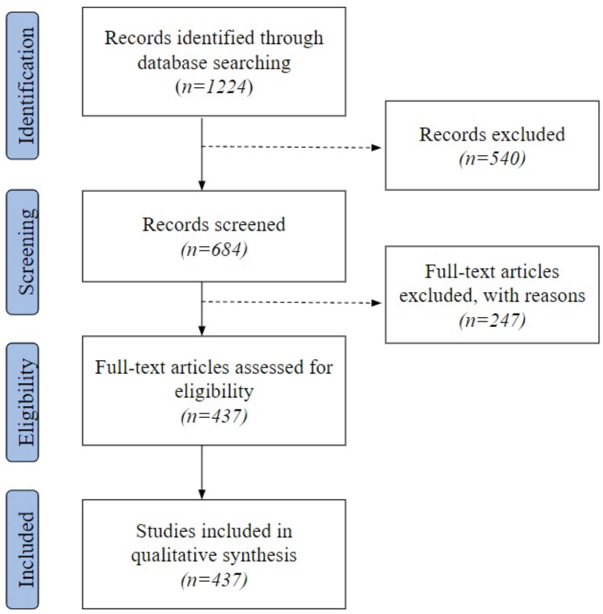

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram, showing the steps for the study selection in the systematic review, according to the eligibility criteria (adapted from http://www.prisma-statement.org/).

An upward trend in the number of articles over the years was identified, showing an increasing interest in mitigating the impacts of human activities through AD technology (Figure 2). The number of publications on AD presented a steadfast increase since 2017, with the 2020 records being 5 higher than at the beginning of this study series.

China presented the highest number of publications, with 15.1% of the analyzed articles – which corresponds to more than twice the number of papers from Italy and Spain (7.3% each), the following most prominent countries (Figure 3). Two other Asian countries, India and Iran, also demonstrated a great interest in understanding AD effects on environmental quality, representing 5.9% and 2.7% of the publications, respectively.

However, the combined contribution of European countries gives this the continent with the highest participation, with 41.0% of the published papers. Conversely, the contribution of Africa and Oceania were the lowest (3.2% and 2.3%, respectively). In the American continent, the United States dominated the publications in the North (6.2%) while Brazil was the country with the most substantial scientific production in Latin America (5.3%).

Different sources of organic pollutants and their treatment with AD processes were reported in the studies (Figure 4). Sewage, which includes municipal wastewater and waste from the sewage treatment process (such as waste activated sludge – WAS, and primary sludge – PS), was the most frequently reported polluting source (43% of the studies). The second most common polluting source, reported in 20% of the studies, was industrial residues, comprising solid waste and wastewater from different industries, such as food, pulp and paper mill, textile, tanning and ethanol.

Residues from rural activities, namely manure and agricultural residues, were also important sources of waste, each contributing with 14% of the studies, while other animal residues were reported in only 5% of the studies. The interest in studying AD of food waste (FW) and OFMSW, two important sources of urban solid waste, seemed to be relevant since they were reported in more than 24% of the studies. Overgrown macrophytes and macroalgae can be harmful to aquatic ecosystems, and the application of AD to manage these biomasses was reported in 5% of the studies. Pharmaceutical residues and organic contaminants were the least reported polluting sources, being the subject of less than 2% of the studies.

The most important reported wastes were classified into rural and urban and distributed according to the countries where the studies took

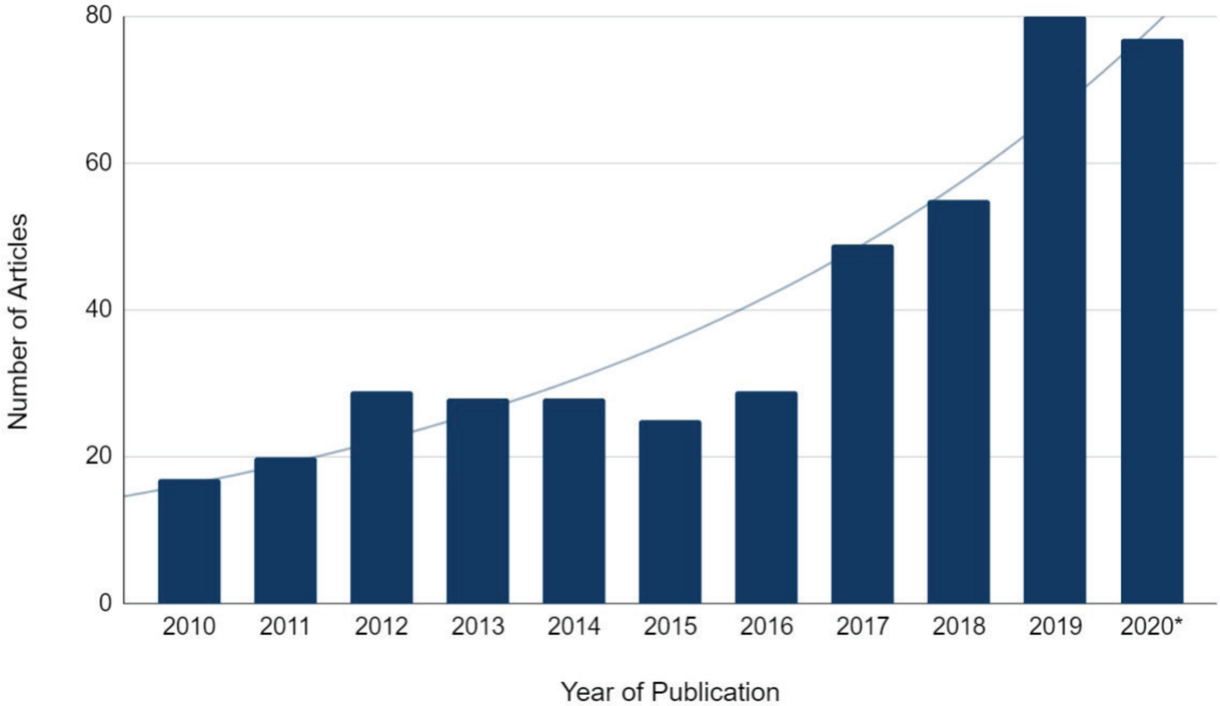

Figure 2. Publications of articles per year. *Articles included until November 2020.

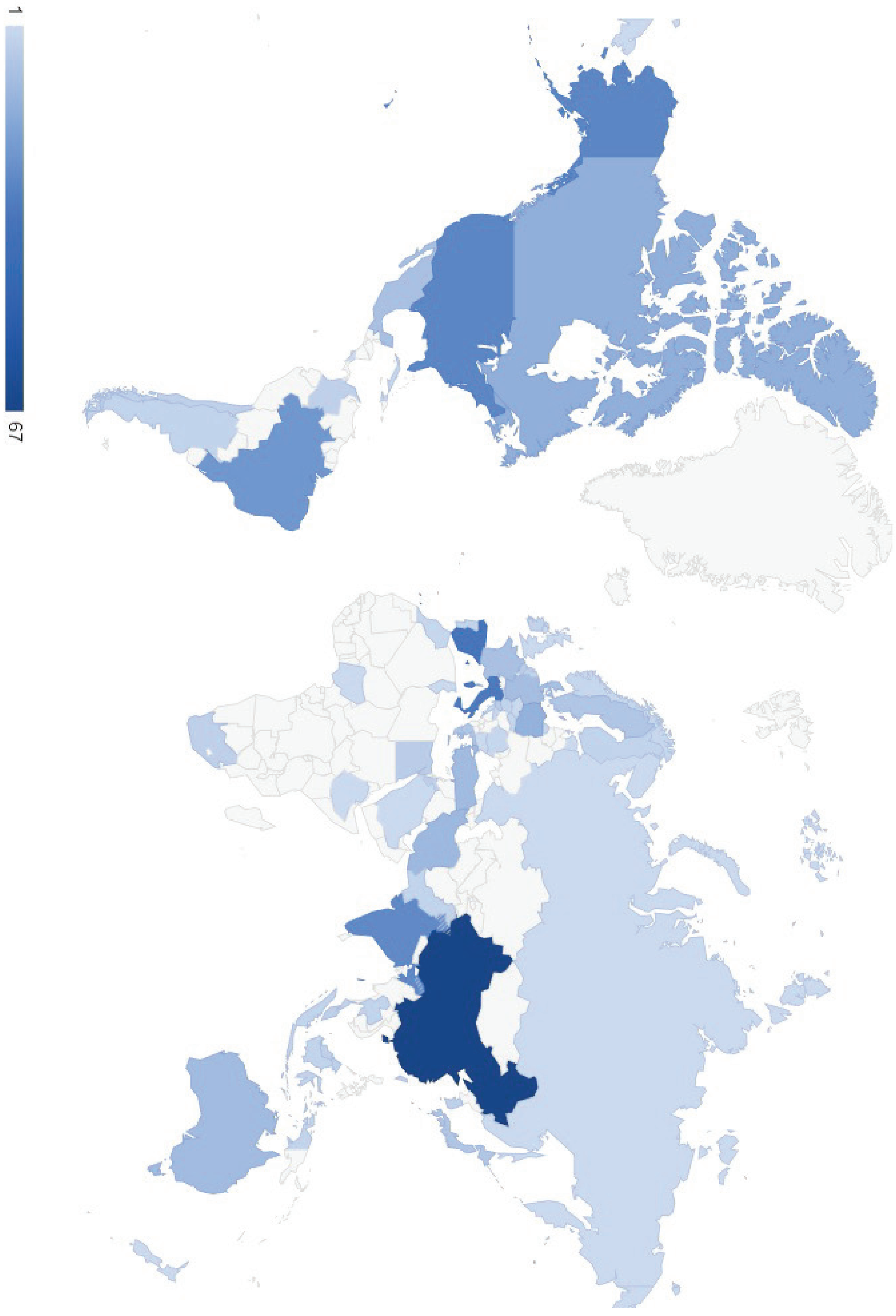

Figure 3. Global distribution of studies using Anaerobic Digestion (AD) technologies to mitigate environmental impacts in aquatic ecosystems. The blue scale represents the number of publications; color intensity was determined by the number of publications.

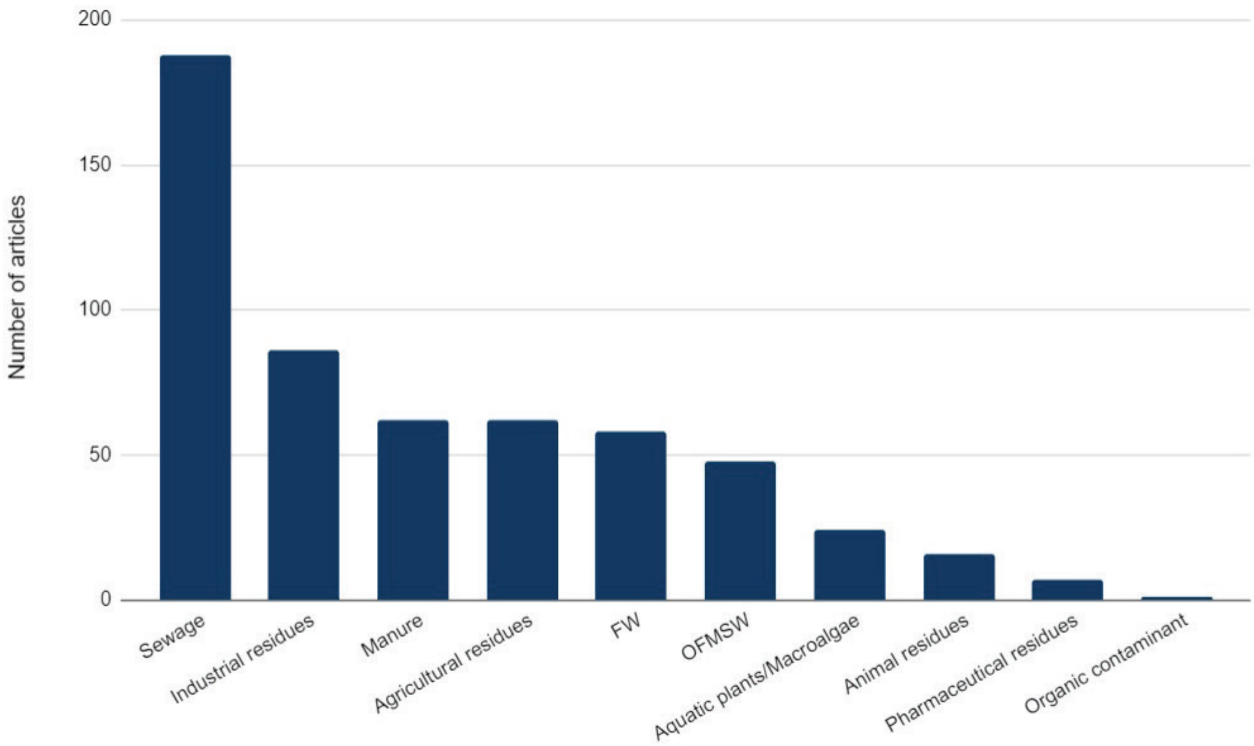

Figure 4. Number of publications per polluting source. FW: Food waste; OFMSW: Organic fraction of municipal solid waste.

place (Figure 5). Municipal waste was the focus of the studies in most countries; in six of them, this was the only waste source reported. In contrast, Ireland was the only country that presented exclusively studies treating rural waste.

Most studies have focused on the use of AD alone (52.4%), but there was a large proportion that performed a pretreatment (14.0%) or co-digestion (31.1%) of different substrates along with AD. The most common pretreatments were thermal and hydrothermal (29.8% and 26.3%, respectively); microwaves and ultrasound accounted for almost 28% of the applied pretreatment.

Amongst the studied polluting sources, aquatic plants/macroalgae presented the highest percentage of studies with pretreatments (33.3%)

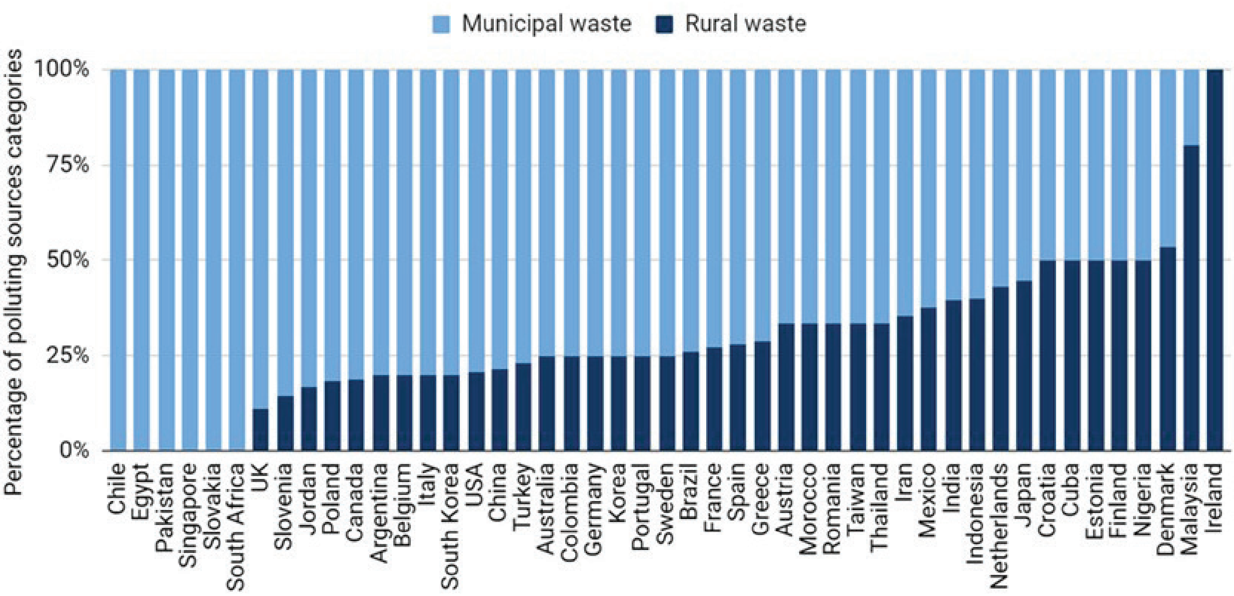

Figure 5. Evaluation of publications by country, related to the main sources of pollution: Rural Waste (agricultural residues, manure and animal residues), Municipal Waste (food waste, industrial residues, organic fraction of municipal solid waste and sewage).

followed by sewage (19.1%) and agricultural residues (17.7%) (Figure 6). The biggest percentage of co-digestion use was found for FW (67.2%) and agricultural residues (66.1%). On the other hand, animal residues were the source with the lowest participation of co-digestion studies (25.0%).

Even though the main focus of the studies was reducing the pollution potential of organic waste via AD while producing energy, several byproducts of economic value were indicated as byproducts of AD, namely biofertilizers, reuse water, PHA, biochar and bio-oil. Among those, 76% considered biofertilizer production, showing the importance of nutrient recovery in AD processes. Regarding the substrates used for AD, sewage, manure and agricultural residues were the main organic sources for biofertilizer production, corresponding to 32, 18 and 15% of those studies, respectively. Reuse water was also an important outcome of AD, representing 14% of the products reported, while biochar, PHA and bio-oil were reported only a few times.

DISCUSSION

The impact caused by anthropogenic activities in aquatic ecosystems is a global concern. The disposal of poorly managed wastes into aquatic environments leads to ecosystem impairment, jeopardizing endemic species and ecosystems services (Marotta *et al.* 2012). AD technology can be a valuable tool to prevent the impacts of human activity in freshwater ecosystems, as shown by this study.

In this systematic review, we observed an increase in the number of published papers on AD technology over the last decade. That aligns with the creation of global environmental frameworks and governmental economic strategies, as those established by China, the leading country in publications (Figure 3). Biogas technology is not only in accordance with the SDGs goals, but also with circular economy principles, as suggested by the use of sewage waste as the main substrate and biofertilizer as the most reported byproduct

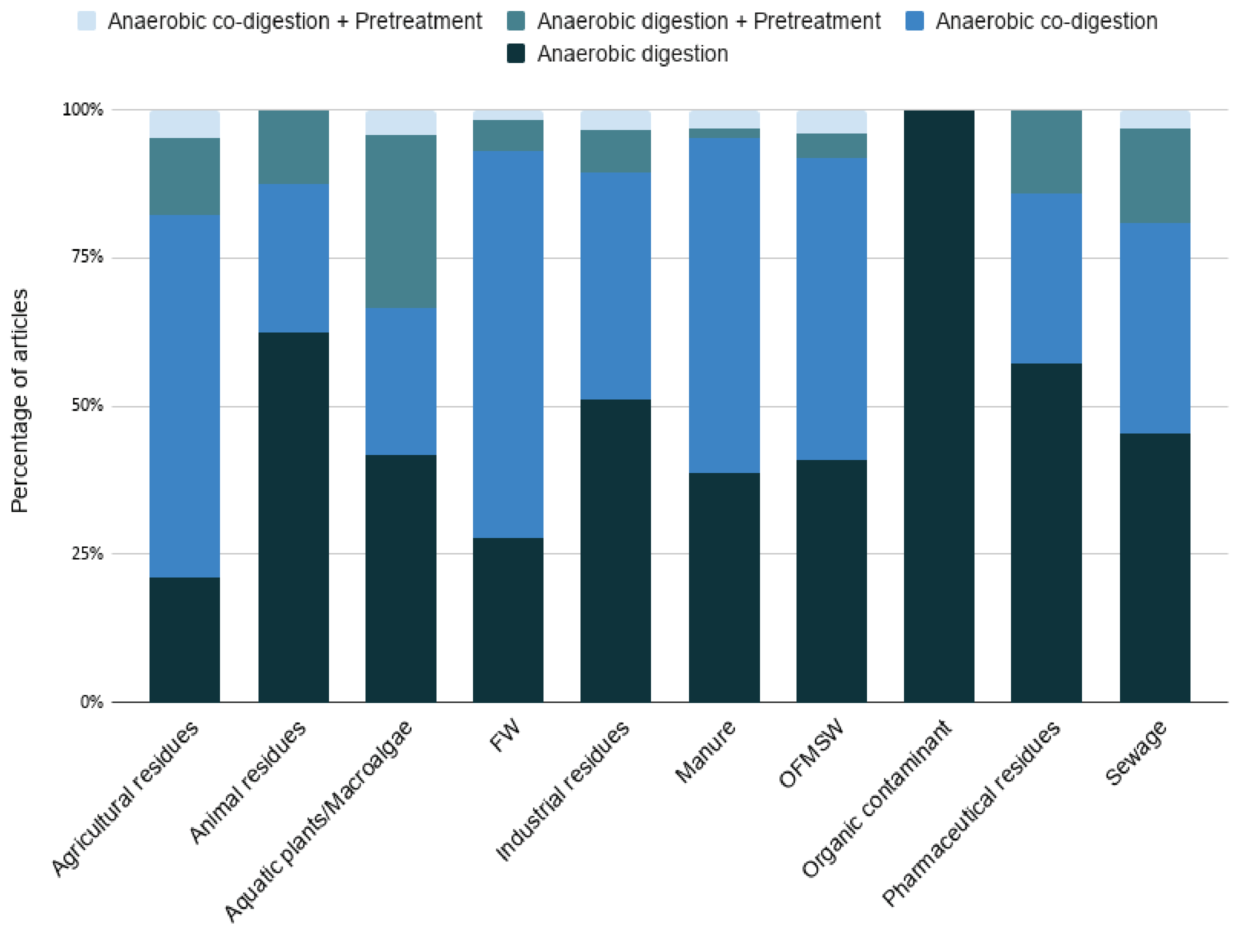

Figure 6. Proportion of studies considering co-digestion and pretreatment application as methods to improve AD during the treatment of wastes from the main pollution sources. FW: Food Waste; OFMSW: Organic Fraction of Municipal Solid Waste

(Figure 4). The input of sewage and output of biofertilizer allows the return of nitrogen (N) and phosphorus (P) to the technological cycle, reducing its discharge and, consequently, the eutrophication of soil and freshwater systems (Ma *et al.* 2017).

Global perspective

The implementation of international policies and agreements such as the 2030 SDGs Agenda encourages a sustainable economic development and the adoption of circular economy principles, leading to the application of technologies to mitigate ecosystem impacts (de Oliveira *et al.* 2020).

The continuous rise in the number of published articles focusing on AD since 2017 (Figure 2) suggests an increase in the concern towards the inadequate disposal of waste into aquatic systems. It could also indicate an increase in the interest in a circular economy approach to residue management since AD processes can provide not only waste treatment, but energy and biofertilizer, as well as other products with economic value, converting an environmental liability into an economic asset (Freitas *et al.* 2019).

China and India have the two largest populations in the world and face a severe energy deficit (Shar *et al.* 2018, Garg 2020), making them more prone to invest in research on alternative energies, such as AD. Although this effort is confirmed by the high number of studies published and performed in China (Figure 3), the same is not observed for India.

Fossil fuel combustion is strongly associated with the release of high levels of polycyclic aromatic hydrocarbons (PAHs), considered persistent organic pollutants (POPs) and some of the main sources of pollution in aquatic environments worldwide (Han & Currell 2017). The intensification of environmental impacts caused by anthropogenic activity increasingly exposes China's difficulty to meet international climate change goals while preserving its energy security (Richerzhagen & Scholz 2008). As a solution, the Chinese government has the goal to develop a non-fossil energy matrix that will account for 20% of the country's total energy consumption by 2030 (Chen *et al.* 2017).

The European Union (EU) is a leading actor in the application of AD technology to treat organic waste, which is represented by 35.9% of the studies focusing on the effect of AD on reducing human impacts on aquatic systems (Figure 3). Over the last decades, European countries have improved their waste treatment systems focusing on water reuse and generation of energy and biofertilizers. Italy and Spain were the two leading countries in the publications targeted by this study (Figure 3). Italy is the second largest biogas producer in the EU, using mostly rural waste as substrates for AD (Zhu *et al.* 2019), while Spain is one of the countries with the most incentives for biogas production and utilization in the EU, where most of the produced biogas comes from landfills (Capodaglio *et al.* 2016, Zhu *et al.* 2019).

Australia and the United States of America (USA) joined the AD scenario more recently when compared to European countries, with a specific focus on industrial effluent and wastewater treatment plants (WWTP), respectively (Edwards *et al.* 2015), as suggested by the smaller number of studies from these countries (Figure 3). In these nations, AD is primarily considered a solution to lessen environmental problems and mitigate climate change without neglecting its energy potential. The USA has a more established AD market, with energy gains of 1 billion kWh of electricity in 2019, mainly from sewage and industrial wastewater treatments (EIA 2020).

In terms of technology development, Brazil leads Latin America, with the highest number of publications (Figure 3). The application of this technology for animal waste treatment (especially bovine and swine) in Brazil is promising, due to the high potential of methane production, which can reach over 50 million cubic meters of methane per day (Piñas *et al.* 2018).

The African continent has one of the highest potentials for AD implementation but presents the lowest participation in the global scientific production on this matter, with only six out of its 56 countries represented in the screened literature (Figure 3). According to Kemausuor *et al.* (2018), the high initial costs, weak environmental policies, lack of coordination and linkage in biogas programs, poor institutional framework and infrastructure are among the main hindrances for the development of commercial plants, although family-size biogas installations can be found in many African countries. Despite its modest contribution to this review, Kenya possesses the first grid-connected AD plant in the continent, with an energy production potential of 2.2 MW, using local crop waste (BioenergyNews 2015).

Despite the increasing investments for the implementation of waste treatment technologies, they are highly uneven across countries, and in most of them, huge amounts of waste pollutants still reach aquatic environments and impact ecosystems (Bashir *et al.* 2020).

Impacts of different waste sources on aquatic environments

The increase in the global population leads to a proportional increase in the production of all forms of organic waste (Corcoran *et al.* 2010). We identified several pollutant sources that are liable to be degraded at AD treatment, instead of being released into the environment (Figure 4).

We found that sewage is one of the main polluting sources considered for treatment by AD (Figure 4). The lack of sewage management results in its infiltration in groundwaters or direct disposal into water bodies, causing oxygen depletion, eutrophication and affecting water potability due to the accumulation of pathogens (Fayomi *et al.* 2019, UN-WATER 2020). Primary and activated sludge waste are results of conventional sewage treatment processes and can have high levels of pathogens, heavy metals and organic contaminants posing a high potential impact on the environment (von Sperling & Gonçalves 2007).

The increase in global population will also increase the demand for food, and thus the production of agricultural residues. Although the organic waste from agriculture can potentially generate high incomes to the sector through energy production (Tamburini *et al.* 2020), the potential of AD to prevent the pollution of aquatic environments should be considered by stakeholders concerned about the degradation of such habitats. Especially in developing countries, in which economies are usually based on agricultural commodities, most of its waste does not receive treatment and is often left to rot in the field, potentially affecting water bodies (Sabiiti 2011). In these places, a commonly used strategy is the open burning of agricultural residues, which not only hinders nutrient cycling but also emits greenhouse gases, VOCs, SOx and NOx, among others, contributing to air pollution and acid deposition (IARI 2012). Moreover, ashes of burnt biomass can cause air and water pollution, via rainfall and dust fall (Xiao *et al.* 2020).

The application of animal manure directly to the soil to provide organic matter and nutrients to the crop is a widespread practice. However, overuse can cause nutrient export, leading to eutrophication, NO_3 contamination of groundwater, pathogen spreading and production of phytotoxic substances (Lory *et al.* 2006, Bayo *et al.* 2012, Kelleher *et al.* 2016, Luján-Facundo *et al.* 2019).

Another common manure management practice is its storage in stabilization lagoons (Cheng *et al.* 2002). This practice increases the risk of water contamination through leakage, overflow during rainfall, or runoff from recently irrigated fields (Xu *et al.* 2016). Furthermore, when mishandled, storage and soil application of animal manure can lead to CH_4, N_2O, NO_2, NH_3 and CO_2 emissions, contributing to global warming, water eutrophication and ocean acidification (Dinuccio *et al.* 2008).

Slaughterhouses produce waste with high pollution potential and high chemical oxygen demand (COD) and biochemical oxygen demand (BOD) levels mostly due to manure, oil, grease and blood (Vilvert *et al.* 2020), substances that show potential to induce water pollution, turbidity and eutrophication (Hernández *et al.* 2018). The liquid fraction of that waste is often discharged without proper treatment into municipal wastewater facilities or rivers, while the solid fraction is usually incinerated or buried, which facilitates the contamination of groundwater (Marcos *et al.* 2017). The use of these animal residues as a substrate for AD produces high amounts of biogas and biofertilizer, increases organic pollutants degradation rates and decreases the impact on aquatic systems (Tamburini *et al.* 2020).

Aquatic macrophytes and marsh plants are important members of the biotopes in water bodies (Bauer *et al.* 2018). However, eutrophication can lead to their overgrowth (Bucholc *et al.* 2014); removal can be costly and the harvested biomass is often left to decompose near the streams, causing nutrient leaching and increasing eutrophication (Zehnsdorf *et al.* 2017, Bauer *et al.* 2018). Their use as a substrate for biogas production can give this biomass a suitable destination while reducing costs and eutrophication issues (Kaspersen *et al.* 2016). Furthermore, aquatic plants and macroalgae can be used in phytoremediation strategies, biosorption and constructed wetlands (Lodeiro *et al.* 2005, Cohen *et al.* 2013, Fernandes *et al.* 2019), usually generating contaminated biomass, for which AD can also be a solution.

The organic fraction of municipal solid waste (OFMSW) is mostly composed of food waste (FW) (Ornelas-Ferreira *et al.* 2020), and its poor management can result in soil, water and air pollution (Khoshand *et al.* 2018). Leachate, which is composed of many substances toxic to human health and the environment, is produced in landfills and poses a risk for surface and groundwater contamination (Vaverková 2019).

In Brazil, as in many developing countries, 60% of municipalities do not have an adequate solid waste disposal system (Ornelas-Ferreira *et al.* 2020), increasing the necessity of finding sustainable waste management alternatives. The implementation of AD in the treatment of FW and OFMSW can be an alternative to reduce the impacts of inadequate disposal (Xu *et al.* 2015, Guven *et al.* 2019, Brenes-Peralta *et al.* 2020).

Industrial activities generate huge amounts of residues and wastewater that must be properly handled. Many industrial wastes are disposed of without treatment (Kavacik & Topaloglu 2010, Muthu 2015) or discharged into sewage treatment lines (Prazeres *et al.* 2012), posing risks to the environment and to the stability of the sewage treatment process. Many chemicals, such as dyes and aromatic compounds, are present in industrial residues, and their untreated discharge into the environment can threaten water quality of aquatic ecosystems (Muthu 2015).

For example, colored effluents can modify the physicochemical characteristics of the water, reducing sunlight penetration and impacting the photosynthetic process, while sulfur-rich effluents can cause odor problems and toxicity to aquatic life (Muthu 2015). The high organic content of many effluents, such as cheese whey (Kavacik & Topaloglu 2010), cassava wastewater (Peres *et al.* 2019), tannery wastewater (Achouri *et al.* 2017), among others (Fernández-Rodríguez *et al.* 2019, Khalid *et al.* 2019) can promote a decrease in dissolved oxygen levels, hindering the survival of aquatic organisms and unbalancing the whole ecosystem. Applying AD to industrial waste is a potential way to produce a more homogeneous waste and generate energy, which could reduce the economic costs of waste management. Moreover, co-digestion with other organic waste sources can make the AD process more economic and technically feasible (Kumar *et al.* 2020).

Improvements of Anaerobic Digestion

The advances in AD procedures, strategies and technologies, such as the simultaneous application of different pretreatments over the years promoted a reduction of toxic compounds, GHG emission and an increase in organic matter degradation (Paolini *et al.* 2018). Pretreatment of the substrate promotes further solubilization of the organic matter in simpler, bioavailable molecules for microorganisms' metabolism, leading to an increase in biogas production and methane yield (Agbor *et al.* 2011). Pretreatments are usually an investment to maximize the biogas yield and economic balance (Paolini *et al.* 2018). In this sense, the application of pretreatments in all kinds of organic substrates has the potential to, indirectly, benefit aquatic environments (Prabakar *et al.* 2018).

An alternative strategy is the co-digestion of different organic wastes. This technique can also optimize the nutrient balance, improve the energetic yield of the residues, decrease the risk of inhibition of methane formation while improving treatment performance and biogas production (Mata-Alvarez 2003, Borowski & Kubacki 2015).

FW and OFMSW were the most commonly used substrates for co-digestion (Figure 6), which can be attributed to the huge amount of this waste produced worldwide and the concern on their safe disposal (Talan *et al.* 2021). The high biodegradability of FW makes it an interesting substrate for co-digestion along with organic waste sources with lower degradability, such as manure (El-Mashad & Zhang 2010), sewage sludge (H. Cheng *et al.* 2021) and agricultural residues (X. Chen *et al.* 2015). Tyagi *et al.* (2018) reported that the most used co-substrates for OFMSW are sewage sludge, animal waste (manure and slaughterhouse waste), food and agro-industrial wastes.

Byproducts of economic value from Anaerobic Digestion

The production of biomethane is the main economic interest for the AD of organic waste. However, other byproducts can be produced from AD processes, *e.g.*, biofertilizer, reuse water, biochar, bio-oil and bioplastics (Hung *et al.* 2017, Barbanera *et al.* 2018, Ferrari *et al.* 2019, McCabe *et al.* 2019), reducing operating costs through their commercialization (Alrefai *et al.* 2020).

The digestate is the result of the AD process and the amount produced is equivalent to the amount of substrate non-degraded, meaning that a large production of biogas entails a large production of digestate. It can be used as biofertilizer in agriculture, due to its high amounts of essential nutrients (Alfa *et al.* 2014, Hamedani *et al.* 2020), being the most cited non-energetic output in the reviewed articles.

Biofertilizers can be an alternative to chemical fertilizers, contributing to reducing GHG emissions, with the potential to benefit small farms and family businesses that cannot afford mineral fertilizers, especially in developing countries (Audu *et al.* 2020, Padi & Chimphango 2020). The use of biofertilizer leads to a more efficient utilization of N and P, which otherwise could end up in aquatic environments, causing eutrophication (Audu *et al.* 2020, Ahmad *et al.* 2020). Particularly in the case of phosphorus, the use of biofertilizers can help prevent reserve insecurity, as phosphate rock is a limited resource (Battista *et al.* 2020).

Sewage, manure and agricultural residues were the main organic sources used for biofertilizer production. These wastes are the most widely used for biogas conversion and have the highest concentrations of N and P in their composition (Hamedani *et al.* 2020). Sustainable and efficient biogas and biofertilizer production is a promising process to achieve a circular economy and cleaner production (Padi & Chimphango 2020).

The treated effluent from AD, recycled as reuse water, meets the high demand for freshwater in response to increasing urbanization, is mainly used for irrigation of crops that, in addition to contributing to food production, support energy production through its waste, ending its life cycle (Batuecas *et al.* 2019, Ferrari *et al.* 2019). Furthermore, the recovered water can be applied in agro-industrial processes such as the ethanol fermentation process as a cheaper and eco-friendly alternative (Wang *et al.* 2014).

Other AD byproducts were also present, to a lesser extent, in the screened studies, namely biochar, bio-oil, and PHA. Bio-oil is a primary material capable to replace diesel in an internal combustion engine (Monlau *et al.* 2015), contributing to reduce the impact caused by the use of fossil sources. Biochar has multiple applications, improving soil quality, carbon sequestration and climate change mitigation, wastewater treatment, construction, metallurgy, cosmetic and food industry and energy production (Narzari *et al.* 2015). PHA is a biodegradable biopolymer that can substitute conventional plastic, reducing the impacts of their consumption (Pratt *et al.* 2019), such as bioaccumulation on aquatic life and blockage of the passage of food, resulting in reduced nutritional intake, hunger, malnutrition and even mortality (Lam *et al.* 2018).

CONCLUSION

AD is a biotechnological tool that allows the degradation of huge amounts of organic waste, with its efficiency in the treatment of several pollutants confirmed. Our results showed that although European countries have the highest application of AD (41%) reported in articles, China leads the total number of publications, having 15.1% of the total worldwide. AD can help prevent inadequate waste disposal. Aquatic ecosystems are highly affected by the introduction of organic waste and nutrients that lead to eutrophication and loss of water quality due to the accumulation of pathogens, causing a decrease in aquatic biodiversity. These impacts can be mitigated with the use of AD. Among the environmental damages avoided by the proper management of polluting sources, almost 50% are from sewage, followed by industrial (20%) and agricultural (14%) waste. The interest in the application of this technology has increased over the last years, especially since 2017. Approaches such as co-digestion and pretreatments have been applied in combination with AD as reported in 31% and 14% of the articles, respectively to increase treatment capacity and efficiency, with direct environmental effects.

ACKNOWLEDGMENTS

This study was partly financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, through PhD scholarships for T.M.A. and R.P.C.. H.R.O. thanks the Brazilian National Council for Scientific and Technological Development (CNPq) for the PhD scholarship. M.E.R. thanks the Departamento de Tecnologia e Inovação da UERJ for the funding through the Inova UERJ Qualitec scholarship. C.F.C.S. has a fellowship of the Support Program for the Insertion of Researchers in Companies from Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ). A.E.P. is a fellow researcher from CNPq and Cientista do Nosso Estado from FAPERJ.

REFERENCES

Achouri, O., Panico, A., Bencheikh-Lehocine, M., Derbal, K., & Pirozzi, F. 2017. Effect of Chemical Coagulation Pretreatment on Anaerobic Digestion of Tannery Wastewater. Journal of Environmental Engineering, 143(9), 04017039. DOI: 10.1061/(asce)ee.1943-7870.0001235

Agbor, V. B., Cicek, N., Sparling, R., Berlin, A., & Levin, D. B. 2011. Biomass pretreatment: Fundamentals toward application. Biotechnology Advances, 29(6), 675–685. DOI: 10.1016/j.biotechadv.2011.05.005

Ahmad, T., Belwal, T., Li, L., Ramola, S., Aadil, R. M., Abdullah, Xu, Y., & Zisheng, L. 2020, May 1. Utilization of wastewater from edible oil industry, turning waste into valuable products: A review. Trends in Food Science and TechnologyElsevier Ltd. DOI: 10.1016/j.tifs.2020.02.017

Alfa, M. I., Adie, D. B., Igboro, S. B., Oranusi, U. S., Dahunsi, S. O., & Akali, D. M. 2014. Assessment of biofertilizer quality and health implications of anaerobic digestion effluent of cow dung and chicken droppings. Renewable Energy, 63, 681–686. DOI: 10.1016/j.renene.2013.09.049

Alrefai, R., Alrefai, A. M., Benyounis, K. Y., & Stokes, J. 2020. Enhancing the Economic Viability of Anaerobic Digestion by Exploiting the Whole Biomass of Mango Waste and Its Residues after Digestion. Energies, 13(24), 6683. DOI: 10.3390/en13246683

Angelidaki, I., Xie, L., Luo, G., Zhang, Y., Oechsner, H., Lemmer, A., Munoz, R., & Kougias, P. G. 2019. Biogas Upgrading: Current and Emerging Technologies. In: S. R. Ashok Pandey, Christian Larroche, Claude-Gilles Dussap, Edgard Gnansounou, Samir Kumar Khanal (Ed.), Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels. pp. 817–843. Cambridge: Academic Press.

Arif, S., Liaquat, R., & Adil, M. 2018. Applications of materials as additives in anaerobic digestion technology. Renewable and Sustainable Energy Reviews, 97(September), 354–366. DOI: 10.1016/j.rser.2018.08.039

Audu, I. G., Barde, A., Yila, O. M., Onwualu, P. A., & Lawal, B. M. 2020. Exploring biogas and biofertilizer production from abattoir wastes in nigeria using a multi-criteria assessment approach. Recycling, 5(3), 1–24. DOI: 10.3390/recycling5030018

Baena-Moreno, F. M., Rodríguez-Galán, M., Vega, F., Reina, T. R., Vilches, L. F., & Navarrete, B. 2019. Synergizing carbon capture storage and utilization in a biogas upgrading lab-scale plant based on calcium chloride: Influence of precipitation parameters. Science of the Total Environment, 670, 59–66. DOI: 10.1016/j.scitotenv.2019.03.204

Barbanera, M., Pelosi, C., Taddei, A. R., & Cotana, F. 2018. Optimization of bio-oil production from solid digestate by microwave-assisted liquefaction. Energy Conversion and Management, 171(May), 1263–1272. DOI: 10.1016/j.enconman.2018.06.066

Bashir, I., Lone, F. A., Bhat, R. A., Mir, S. A., Dar, Z. A., & Dar, S. A. 2020. Concerns and Threats of Contamination on Aquatic Ecosystems. In: K. R. Hakeem, R. A. Bhat, & H. Qadri (Eds.), Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation. pp. 55–73. Cham: Springer.

Batstone, D. J., & Virdis, B. 2014. The role of anaerobic digestion in the emerging energy economy. Current Opinion in Biotechnology Elsevier Ltd. DOI: 10.1016/j.copbio.2014.01.013

Battista, F., Frison, N., Pavan, P., Cavinato, C., Gottardo, M., Fatone, F., Eusebi, A. L., Majone, M., Zeppilli, M., Valentino, F., Fino, D., Tommasi, T., & Bolzonella, D. 2020. Food wastes and sewage sludge as feedstock for an urban biorefinery producing biofuels and added-value bioproducts. Journal of Chemical Technology and Biotechnology, 95(2), 328–338. DOI: 10.1002/jctb.6096

Batuecas, E., Tommasi, T., Battista, F., Negro, V., Sonetti, G., Viotti, P., Fino, D., & Mancini, G. 2019. Life Cycle Assessment of waste disposal from olive oil production: Anaerobic digestion and conventional disposal on soil. Journal of Environmental Management, 237(February), 94–102. DOI: 10.1016/j.jenvman.2019.02.021

Bauer, A., Moeller, L., Wedwitschka, H., Stinner, W., & Zehnsdorf, A. 2018. Anaerobic digestion of mixed silage of waterweed biomass and wheat straw in a production process. Energy, Sustainability and Society, 8(4). DOI: 10.1186/s13705-017-0145-9

Bayo, J., Gómez-López, M. D., Faz, A., & Caballero, A. 2012. Environmental assessment of pig slurry management after local characterization and normalization. Journal of Cleaner Production, 32, 227–235. DOI: 10.1016/j.jclepro.2012.04.003

BioenergyNews. 2015. Africa's first grid-connected AD plant fires up. (Retrieved on March 22nd, 2021, from https://www.europeanbiogas.eu/kenya-africas-first-grid-connected-anaerobic-digestion-plant-fires-up/).

Borowski, S., & Kubacki, P. 2015. Co-digestion of pig slaughterhouse waste with sewage sludge. Waste Management, 40, 119–126. DOI: 10.1016/j.wasman.2015.03.021

Brenes-Peralta, L., Jiménez-Morales, M. F., Campos-Rodríguez, R., De Menna, F., & Vittuari, M. 2020. Decision-making process in the circular economy: A case study on university food waste-to-energy actions in Latin america. Energies, 13(9). DOI: 10.3390/en13092291

Bucholc, K., Szymczak-Zyła, M., Lubecki, L., Zamojska, A., Hapter, P., Tjernström, E., & Kowalewska, G. 2014. Nutrient content in macrophyta collected from southern Baltic Sea beaches in relation to eutrophication and biogas production. Science of the Total Environment, 473–474, 298–307. DOI: 10.1016/j.scitotenv.2013.12.044

Capodaglio, A. G., Callegari, A., & Lopez, M. V. 2016. European framework for the diffusion of biogas uses: Emerging technologies, acceptance, incentive strategies, and institutional-regulatory support. Sustainability (Switzerland), 8(4), 1–18. DOI: 10.3390/su8040298

Chaudhry, F. N., & Malik, M. F. 2017. Factors Affecting Water Pollution: A Review. Journal of Ecosystem & Ecography, 07(01), 5–8. DOI: 10.4172/2157-7625.1000225

Chen, L., Cong, R. G., Shu, B., & Mi, Z. F. 2017. A sustainable biogas model in China: The case study of Beijing Deqingyuan biogas project. Renewable and Sustainable Energy Reviews, 78, 773–779. DOI: 10.1016/j.rser.2017.05.027

Chen, X., Yuan, H., Zou, D., Liu, Y., Zhu, B., Chufo, A., Jaffar, M., & Li, X. 2015. Improving biomethane yield by controlling fermentation type of acidogenic phase in two-phase anaerobic co-digestion of food waste and rice straw. Chemical Engineering Journal, 273, 254–260. DOI: 10.1016/j.cej.2015.03.067

Cheng, H., Li, Y., Hu, Y., Guo, G., Cong, M., Xiao, B., & Li, Y. Y. 2021. Bioenergy recovery from methanogenic co-digestion of food waste and sewage sludge by a high-solid anaerobic membrane bioreactor (AnMBR): mass balance and energy potential. Bioresource Technology, 326(January), 124754. DOI: 10.1016/j.biortech.2021.124754

Cheng, J., Bergmann, B. A., Classen, J. J., Stomp, A. M., & Howard, J. W. 2002. Nutrient recovery from swine lagoon water by Spirodela punctata. Bioresource Technology, 81(1), 81–85. DOI: 10.1016/S0960-8524(01)00098-0

Cohen, M. F., Hare, C., Kozlowski, J., Mccormick, R. S., Chen, L., Schneider, L., Parish, M., Knight, Z., Nelson, T. A., & Grewell, B. J. 2013. Wastewater polishing by a channelized macrophyte-dominated wetland and anaerobic digestion of the harvested phytomass. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering, 48(3), 319–330. DOI: 10.1080/10934529.2013.726896

Corcoran, E., Nellemann, C., Baker, E., Bos, R., Osborn, D., & Savelli, H. (Eds.). 2010. Sick Water?

The central role of wastewater management in sustainable development. United Nations Environment Programme. GRID-Arendal. DOI: 10.1007/s10230-011-0140-x

da Costa, J. A., de Souza, J. P., Teixeira, A. P., Nabout, J. C., Carneiro, F. M., Estadual, U., & Ueg, D. G. 2018. Eutrophication in aquatic ecosystems. Acta Limnologica Brasiliensia, 30(2014), 245–253.

de Oliveira, F. R., dos Santos, R. F., França, S. L. B., & Rangel, L. A. D. 2020. Strategies and challenges for the circular economy: A case study in Portugal and a panorama for Brazil. Brazilian Archives of Biology and Technology, 63. DOI: 10.1590/1678-4324-2020180646

Dhanya, B. S., Mishra, A., Chandel, A. K., & Verma, M. L. 2020. Development of sustainable approaches for converting the organic waste to bioenergy. Science of the Total Environment, 723, 138109. DOI: 10.1016/j.scitotenv.2020.138109

Dinuccio, E., Berg, W., & Balsari, P. 2008. Gaseous emissions from the storage of untreated slurries and the fractions obtained after mechanical separation. Atmospheric Environment, 42(10), 2448–2459. DOI: 10.1016/j.atmosenv.2007.12.022

Drosg, B., Fuchs, W., Al Seadi, T., Madsen, M., & Linke, B. 2015. Nutrient Recovery by Biogas Digestate Processing. IEA Bioenergy.p. 40.

Edwards, J., Othman, M., & Burn, S. 2015. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renewable and Sustainable Energy ReviewsElsevier Ltd. DOI: 10.1016/j.rser.2015.07.112

EIA. 2020. Biomass explained: Landfill gas and biogas. (Retrieved on March 20th, 2021, from https://www.eia.gov/energyexplained/biomass/landfill-gas-and-biogas.php#:~:text=Thermochemical conversion of biomass to,biomass gasification for hydrogen production.&text=Nearly all of the biogas,and used for electricity generation.).

El-Mashad, H. M., & Zhang, R. 2010. Biogas production from co-digestion of dairy manure and food waste. Bioresource Technology, 101(11), 4021–4028. DOI: 10.1016/j.biortech.2010.01.027

FAO. 2017. Water pollution from agriculture: A global review. Executive Summary. p. 35. Rome. (Retrieved on from http://www.fao.org/3/a-i7754e.pdf).

Fayomi, G. U., Mini, S. E., Fayomi, O. S. I., Owodolu, T., Ayoola, A. A., & Wusu, O. 2019. A Mini Review on the Impact of Sewage Disposal on Environment and Ecosystem. In: IOP Conference Series: Earth and Environmental Science. DOI: 10.1088/1755-1315/331/1/012040

Fernandes, K. D., Cañote, S. J. B., Ribeiro, E. M., Thiago Filho, G. L., & Fonseca, A. L. 2019. Can we use Cd-contaminated macrophytes for biogas production? Environmental Science and Pollution Research, 26(27), 27620–27630. DOI: 10.1007/s11356-018-2318-2

Fernández-Rodríguez, M. J., de la Lama-Calvente, D., Jiménez-Rodríguez, A., Borja, R., & Rincón-Llorente, B. 2019. Anaerobic co-digestion of olive mill solid waste and microalga Scenedesmus quadricauda: effect of different carbon to nitrogen ratios on process performance and kinetics. Journal of Applied Phycology, 31(6), 3583–3591. DOI: 10.1007/s10811-019-01858-x

Ferrari, F., Pijuan, M., Rodriguez-Roda, I., & Blandin, G. 2019. Exploring submerged forward osmosis for water recovery and pre-concentration of wastewater before anaerobic digestion: A pilot scale study. Membranes, 9(8). DOI: 10.3390/membranes9080097

Ferronato, N., & Torretta, V. 2019. Waste mismanagement in developing countries: A review of global issues. International Journal of Environmental Research and Public Health, 16(6). DOI: 10.3390/ijerph16061060

Freitas, F. F., De Souza, S. S., Ferreira, L. R. A., Otto, R. B., Alessio, F. J., De Souza, S. N. M., Venturini, O. J., & Ando Junior, O. H. 2019. The Brazilian market of distributed biogas generation: Overview, technological development and case study. Renewable and Sustainable Energy Reviews Elsevier Ltd. DOI: 10.1016/j.rser.2018.11.007

Garg, P. 2020. Energy Scenario and Vision 2020 in India., 3(August 2002), 7–17.

Guven, H., Wang, Z., & Eriksson, O. 2019. Evaluation of future food waste management alternatives in Istanbul from the life cycle assessment perspective. Journal of Cleaner Production, 239, 117999. DOI: 10.1016/j.jclepro.2019.117999

Hamedani, S. R., Villarini, M., Colantoni, A., Carlini, M., Cecchini, M., Santoro, F., & Pantaleo,

A. 2020. Environmental and economic analysis of an anaerobic co-digestion power plant integrated with a compost plant. Energies, 13(11). DOI: 10.3390/en13112724

Han, D., & Currell, M. J. 2017. Science of the Total Environment Persistent organic pollutants in China' s surface water systems. Science of the Total Environment, 580, 602–625. DOI: 10.1016/j.scitotenv.2016.12.007

Hernández, S. C., Jiménez, L. D., & García, J. A. B. 2018. Potential of energy production from slaughterhouse wastewater. Interciencia, 43(8), 558–565.

Higgins, J. P. T., & Green, S. 2011. Cochrane Handbook for Systematic Reviews of Interventions. Wiley.

Hu, Y., Cheng, H., & Tao, S. 2017. Environmental and human health challenges of industrial livestock and poultry farming in China and their mitigation. Environment International, 107(July), 111–130. DOI: 10.1016/j.envint.2017.07.003

Hung, C. Y., Tsai, W. T., Chen, J. W., Lin, Y. Q., & Chang, Y. M. 2017. Characterization of biochar prepared from biogas digestate. Waste Management, 66, 53–60. DOI: 10.1016/j.wasman.2017.04.034

Hussain, Z., Mishra, J., & Vanacore, E. 2020. Waste to energy and circular economy: the case of anaerobic digestion. Journal of Enterprise Information Management, 33(4), 817–838. DOI: 10.1108/JEIM-02-2019-0049

IARI. 2012. Crop Residues Management with Conservation Agriculture : Potential , Constraints and Policy Needs. Indian Agricultural Research Institute.

IRENA. 2018. Biogas for road vehicles: Technology brief.

Jarvis, P. 2020. Environmental technology for the sustainable development goals (SDGs). Environmental Technology (United Kingdom), 41(17), 2155–2156. DOI: 10.1080/09593330.2020.1772547

Jiménez-Benítez, A., Ferrer, F. J., Greses, S., Ruiz-Martínez, A., Fatone, F., Eusebi, A. L., Mondéjar, N., Ferrer, J., & Seco, A. 2020. AnMBR, reclaimed water and fertigation: Two case studies in Italy and Spain to assess economic and technological feasibility and CO2 emissions within the EU Innovation Deal initiative. Journal of Cleaner Production, 270. DOI: 10.1016/j.jclepro.2020.122398

Kaspersen, B. S., Christensen, T. B., Fredenslund, A. M., Møller, H. B., Butts, M. B., Jensen, N. H., & Kjaer, T. 2016. Linking climate change mitigation and coastal eutrophication management through biogas technology: Evidence from a new Danish bioenergy concept. Science of the Total Environment, 541, 1124–1131. DOI: 10.1016/j.scitotenv.2015.10.015

Kavacik, B., & Topaloglu, B. 2010. Biogas production from co-digestion of a mixture of cheese whey and dairy manure. Biomass and Bioenergy, 34(9), 1321–1329. DOI: 10.1016/j.biombioe.2010.04.006

Kelleher, B. P., Leahy, J. J., Henihan, A. M., O'Dwyer, T. F., Sutton, D. C., & Leahy, M. J. 2016. Advances in poultry litter disposal technology – a review. Journal of Failure Analysis and Prevention, 16(2), 302–309. DOI: 10.1007/s11668-016-0088-z

Kemausuor, F., Adaramola, M. S., & Morken, J. 2018. A Review of Commercial Biogas Systems and Lessons for Africa. Energies, 11(11), 1–21. DOI: 10.3390/en11112984

Khalid, Z. Bin, Siddique, M. N. I., Nasrullah, M., Singh, L., Wahid, Z. B. A., & Ahmad, M. F. 2019. Application of solar assisted bioreactor for biogas production from palm oil mill effluent co-digested with cattle manure. Environmental Technology and Innovation, 16, 100446. DOI: 10.1016/j.eti.2019.100446

Khoshand, A., Kamalan, H., & Rezaei, H. 2018. Application of analytical hierarchy process (AHP) to assess options of energy recovery from municipal solid waste: a case study in Tehran, Iran. Journal of Material Cycles and Waste Management, 20(3), 1689–1700. DOI: 10.1007/s10163-018-0736-3

Kumar, P., Samuchiwal, S., & Malik, A. 2020. Anaerobic digestion of textile industries wastes for biogas production. Biomass Conversion and Biorefinery, 10(3), 715–724. DOI: 10.1007/s13399-020-00601-8

Lam, C. S., Ramanathan, S., Carbery, M., Gray, K., Vanka, K. S., Maurin, C., Bush, R., & Palanisami, T. 2018. A Comprehensive Analysis of Plastics and Microplastic Legislation Worldwide. Water, Air, and Soil Pollution, 229(11). DOI: 10.1007/s11270-018-4002-z

Levia, D. F., Creed, I. F., Hannah, D. M., Nanko, K., Boyer, E. W., Carlyle-Moses, D. E., van de Giesen, N., Grasso, D., Guswa, A. J., Hudson, J. E., Hudson, S. A., Iida, S., Jackson, R. B., Katul, G. G., Kumagai, T., Llorens, P., Ribeiro, F. L., Pataki, D. E., Peters, C. A., Carretero, D. S., Selker, J. S., Tetzlaff, D., Zalewski, M., & Bruen, M. 2020. Homogenization of the terrestrial water cycle. Nature Geoscience, 13(10), 656–658. DOI: 10.1038/s41561-020-0641-y

Lodeiro, P., Cordero, B., Barriada, J. L., Herrero, R., & Sastre De Vicente, M. E. 2005. Biosorption of cadmium by biomass of brown marine macroalgae. Bioresource Technology, 96(16), 1796–1803. DOI: 10.1016/j.biortech.2005.01.002

Lory, J. A., Massey, R., & Joern, B. 2006. Using Manure as a Fertilizer for Crop Production. In: Gulf Hypoxia and Local Water Quality Concerns Workshop. DOI: 10.13031/2013.24247

Luján-Facundo, M. J., Iborra-Clar, M. I., Mendoza-Roca, J. A., & Also-Jesús, M. 2019. Alternatives for the management of pig slurry: Phosphorous recovery and biogas generation. Journal of Water Process Engineering, 30(August 2017), 100473. DOI: 10.1016/j.jwpe.2017.08.011

Ma, Y., Yin, Y., & Liu, Y. 2017. Bioresource Technology New insights into co-digestion of activated sludge and food waste: Biogas versus biofertilizer. Bioresource Technology, 241, 448–453. DOI: 10.1016/j.biortech.2017.05.154

Manyi-Loh, C. E., Mamphweli, S. N., Meyer, E. L., & Okoh, A. I. 2019. Microbial anaerobic digestion: process dynamics and implications from the renewable energy, environmental and agronomy perspectives. International Journal of Environmental Science and Technology, 16(7), 3913–3934. DOI: 10.1007/s13762-019-02380-w

Marcos, A. C., Al-Kassir, A., Cuadros, F., & Yusaf, T. 2017. Treatment of slaughterhouse waste water mixed with serum from lacteal industry of extremadura in Spain to produce clean energy. Energies, 10(6). DOI: 10.3390/en10060765

Marotta, H., Duarte, C. M., Guimarães-Souza, B. A., & Enrich-Prast, A. 2012. Synergistic control of CO 2 emissions by fish and nutrients in a humic tropical lake. Oecologia, 168(3), 839–847. DOI: 10.1007/s00442-011-2131-9

Mata-Alvarez, J. (Ed.). 2003. Biomethanization of the organic fraction of municipal solid wastes. Vol. 34IWA Publising. DOI: 10.1002/chin.200313271

McCabe, B. K., Antille, D. L., Marchuk, S., Tait, S., Lee, S., Eberhard, J., & Baillie, C. P. 2019. Biosolids-derived organomineral fertilizers from anaerobic digestion digestate: Opportunities for Australia. 2019 ASABE Annual International Meeting, 3–18. DOI: 10.13031/aim.201900192

Monlau, F., Sambusiti, C., Antoniou, N., Barakat, A., & Zabaniotou, A. 2015. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. Applied Energy, 148, 32–38. DOI: 10.1016/j.apenergy.2015.03.024

Muthu, S. S. (Ed.). 2015. Environmental Implications of Recycling and Recycled Products. Springer. Hong Kong: Springer: p. 31–50. DOI: 10.1007/978-981-287-643-0_2

Narzari, R., Bordoloi, N., Chutia, R. S., & Borkotoki, B. 2015. Chapter 2- Biochar: An Overview on its Production, Properties and Potential Benefits. Biology, Biotechnology and Sustainable Development, (August). DOI: 10.13140/RG.2.1.3966.2560

Ornelas-Ferreira, B., Lobato, L. C. S., Colturato, L. F. D., Torres, E. O., Pombo, L. M., Pujatti, F. J. P., Araújo, J. C., & Chernicharo, C. A. L. 2020. Strategies for energy recovery and gains associated with the implementation of a solid state batch methanization system for treating organic waste from the city of Rio de Janeiro - Brazil. Renewable Energy, 146, 1976–1983. DOI: 10.1016/j.renene.2019.08.049

Padi, R. K., & Chimphango, A. 2020. Commercial viability of integrated waste treatment in cassava starch industries for targeted resource recoveries. Journal of Cleaner Production, 265, 121619. DOI: 10.1016/j.jclepro.2020.121619

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., & Cecinato, A. 2018. Environmental impact of biogas: A short review of current knowledge. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering, 53(10), 899–906. DOI: 10.1080/10934529.2018.1459076

Peres, S., Monteiro, M. R., Ferreira, M. L., do Nascimento Junior, A. F., & de Los Angeles Perez Fernandez Palha, M. 2019. Anaerobic

Digestion Process for the Production of Biogas from Cassava and Sewage Treatment Plant Sludge in Brazil. Bioenergy Research, 12(1), 150–157. DOI: 10.1007/s12155-018-9942-z

Piñas, J. A. V., Venturini, O. J., Lora, E. E. S., & Roalcaba, O. D. C. 2018. Technical assessment of mono-digestion and co-digestion systems for the production of biogas from anaerobic digestion in Brazil. Renewable Energy, 117, 447–458. DOI: 10.1016/j.renene.2017.10.085

Prabakar, D., Suvetha K, S., Manimudi, V. T., Mathimani, T., Kumar, G., Rene, E. R., & Pugazhendhi, A. 2018. Pretreatment technologies for industrial effluents: Critical review on bioenergy production and environmental concerns. Journal of Environmental Management, 218, 165–180. DOI: 10.1016/j.jenvman.2018.03.136

Pratt, S., Vandi, L.-J., Gapes, D., Werker, A., Oehmen, A., & Laycock, B. 2019. Polyhydroxyalkanoate (PHA) Bioplastics from Organic Waste. Biorefinery, 615–638. DOI: 10.1007/978-3-030-10961-5_26

Prazeres, A. R., Carvalho, F., & Rivas, J. 2012. Cheese whey management: A review. Journal of Environmental Management, 110, 48–68. DOI: 10.1016/j.jenvman.2012.05.018

Revitt, D. M., & Ellis, J. B. 2016. Urban surface water pollution problems arising from misconnections. Science of the Total Environment, 551–552, 163–174. DOI: 10.1016/j.scitotenv.2016.01.198

Richerzhagen, C., & Scholz, I. 2008. China's Capacities for Mitigating Climate Change. World Development, 36(2), 308–324. DOI: 10.1016/j.worlddev.2007.06.010

Sabiiti, E. N. 2011. Utilising Agricultural Waste to Enhance Food Security and Conserve the Environment. African Journal of Food Agriculture, Nutrition and Development, 11(6).

Sahoo, R.K., Bhardwaj, D., Tuteja, N. 2013. Biofertilizers: A Sustainable Eco-Friendly Agricultural Approach to Crop Improvement. In: Tuteja, N., Singh Gill, S. (eds) Plant Acclimation to Environmental Stress. pp. 403 – 432. New York: Springer.

Sarker, S., Lamb, J. J., Hjelme, D. R., & Lien, K. M. 2019. A review of the role of critical parameters in the design and operation of biogas production plants. Applied Sciences (Switzerland), 9(9). DOI: 10.3390/app9091915

Shar, A. M., Mahesar, A. A., & Memon, K. R. 2018. Could shale gas meet energy deficit: its current status and future prospects. Journal of Petroleum Exploration and Production Technology, 8(4), 957–967. DOI: 10.1007/s13202-017-0399-y

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. 2019. Environmental sustainability of anaerobic digestion of household food waste. Journal of Environmental Management, 236(January), 798–814. DOI: 10.1016/j.jenvman.2019.02.001

Talan, A., Tiwari, B., Yadav, B., Tyagi, R. D., Wong, J. W. C., & Drogui, P. 2021. Food waste valorization: Energy production using novel integrated systems. Bioresource Technology, 322(December 2020), 124538. DOI: 10.1016/j.biortech.2020.124538

Tamburini, E., Gaglio, M., Castaldelli, G., & Fano, E. A. 2020. Biogas from agri-food and agricultural waste can appreciate agro-ecosystem services: The case study of Emilia Romagna region. Sustainability (Switzerland), 12(20), 1–15. DOI: 10.3390/su12208392

Tyagi, V. K., Fdez-Güelfo, L. A., Zhou, Y., Álvarez-Gallego, C. J., Garcia, L. I. R., & Ng, W. J. 2018. Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. Renewable and Sustainable Energy Reviews, 93(May), 380–399. DOI: 10.1016/j.rser.2018.05.051

UN-WATER. 2020. The United Nations World Water Development Report 2020: Water and Climate Change. Paris: UNESCO: p. 219.

van Vliet, M. T. H., Jones, E. R., Flörke, M., Franssen, W. H. P., Hanasaki, N., Wada, Y., & Yearsley, J. R. 2021. Global water scarcity including surface water quality and expansions of clean water technologies. Environmental Research Letters, 16(2). DOI: 10.1088/1748-9326/abbfc3

Vaverková, M. D. 2019. Landfill impacts on the environment— review. Geosciences (Switzerland), 9(10), 1–16. DOI: 10.3390/geosciences9100431

Vilvert, A. J., Saldeira Junior, J. C., Bautitz, I. R., Zenatti, D. C., Andrade, M. G., & Hermes, E. 2020. Minimization of energy demand in slaughterhouses: Estimated production of biogas generated from the effluent. Renewable and Sustainable Energy Reviews, 120(March 2019), 109613. DOI: 10.1016/j.rser.2019.109613

von Sperling, M., & Gonçalves, R. F. 2007. Sludge characteristics and production. In: C. V. Andreoli, M. von Sperling, & F. Fernandes (Eds.), Sludge Treatment and Disposal. pp. 4 – 28. London: IWA Publishing.

Wang, K., Zhang, J., Liu, P., Cao, H., & Mao, Z. 2014. Reusing a mixture of anaerobic digestion ef fl uent and thin stillage for cassava ethanol production. Journal of Cleaner Production, 75, 57–63. DOI: 10.1016/j.jclepro.2014.04.007

Xiao, Q., Chen, W., Tian, D., Shen, F., Hu, J., Long, L., Zeng, Y., Yang, G., & Deng, S. 2020. Integrating the Bottom Ash Residue from Biomass Power Generation into Anaerobic Digestion to Improve Biogas Production from Lignocellulosic Biomass. Energy & Fuels, 34, 1101–1110. DOI: 10.1021/acs.energyfuels.9b01898

Xu, C., Shi, W., Hong, J., Zhang, F., & Chen, W. 2015. Life cycle assessment of food waste-based biogas generation. Renewable and Sustainable Energy Reviews, 49, 169–177. DOI: 10.1016/j.rser.2015.04.164

Xu, J., Adair, C. W., & Deshusses, M. A. 2016. Performance evaluation of a full-scale innovative swine waste-to-energy system. Bioresource Technology, 216, 494–502. DOI: 10.1016/j.biortech.2016.05.089

Zehnsdorf, A., Moeller, L., Stärk, H.-J., Auge, H., Röhl, M., & Stinner, W. 2017. The study of the variability of biomass from plants of the Elodea genus from a river in Germany over a period of two hydrological years for investigating their suitability for biogas production. Energy, Sustainability and Society, 541, 1124–1131. DOI: 10.1016/j.scitotenv.2015.10.015

Zhu, T., Curtis, J., & Clancy, M. 2019. Promoting agricultural biogas and biomethane production: Lessons from cross-country studies. Renewable and Sustainable Energy Reviews, 114(June), 109332. DOI: 10.1016/j.rser.2019.109332

SUPPLEMENTARY MATERIAL

Table S1. List of articles included in the systematic review.

Submitted: 15 May 2021
Accepted: 12 March 2022
Invited Associate Editors: Rayanne Setubal, Reinaldo Bozelli and Vinícius Farjalla