



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

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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 (PO₄-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.*, CH₄ and CO₂) 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, Drosig *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).

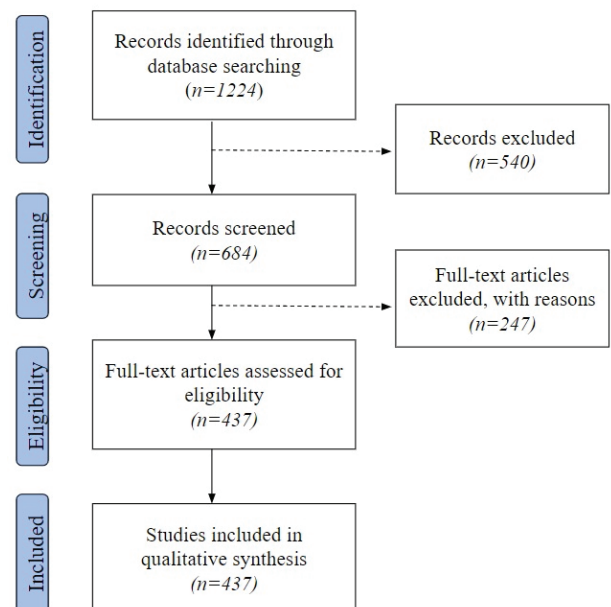


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram, showing the steps for the study selection in the systematic review, according to the eligibility criteria (adapted from <http://www.prisma-statement.org/>).

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

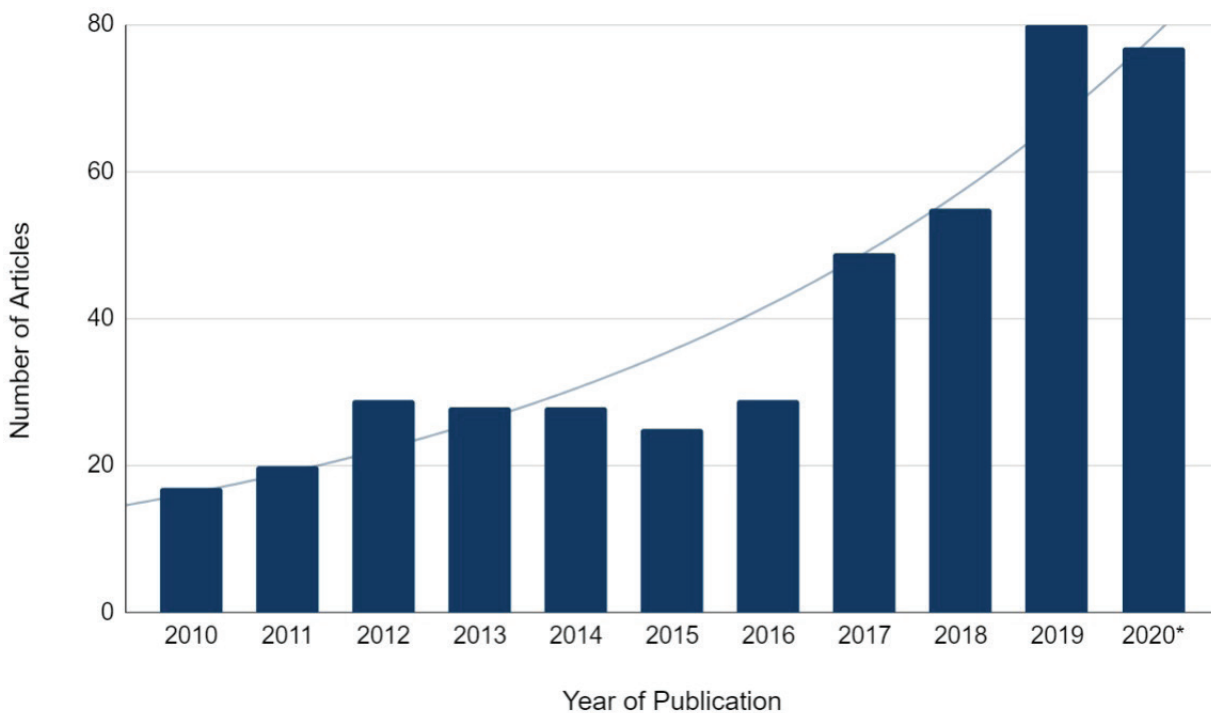


Figure 2. Publications of articles per year. *Articles included until November 2020.

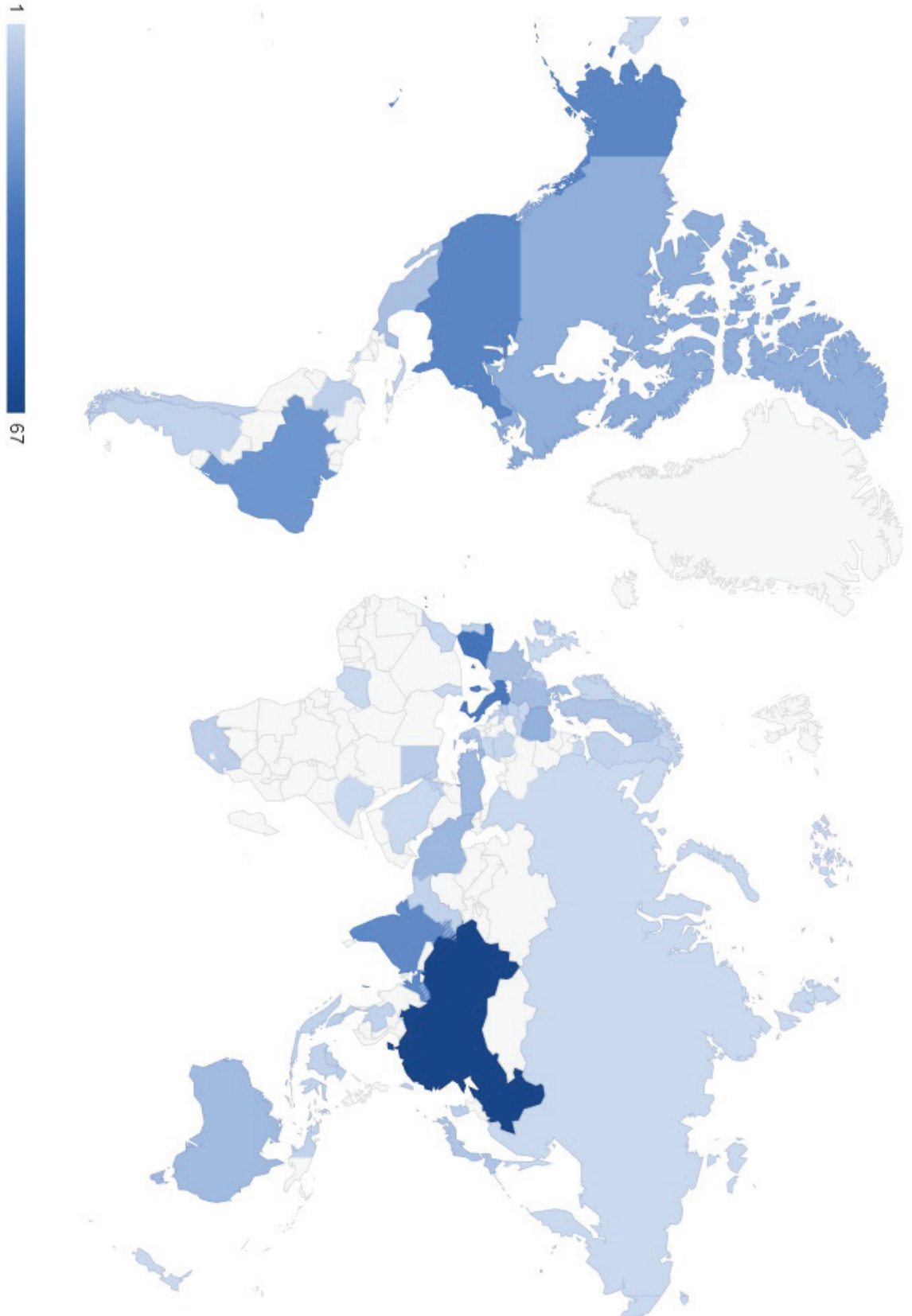


Figure 3. Global distribution of studies using Anaerobic Digestion (AD) technologies to mitigate environmental impacts in aquatic ecosystems. The blue scale represents the number of publications; color intensity was determined by the number of publications.

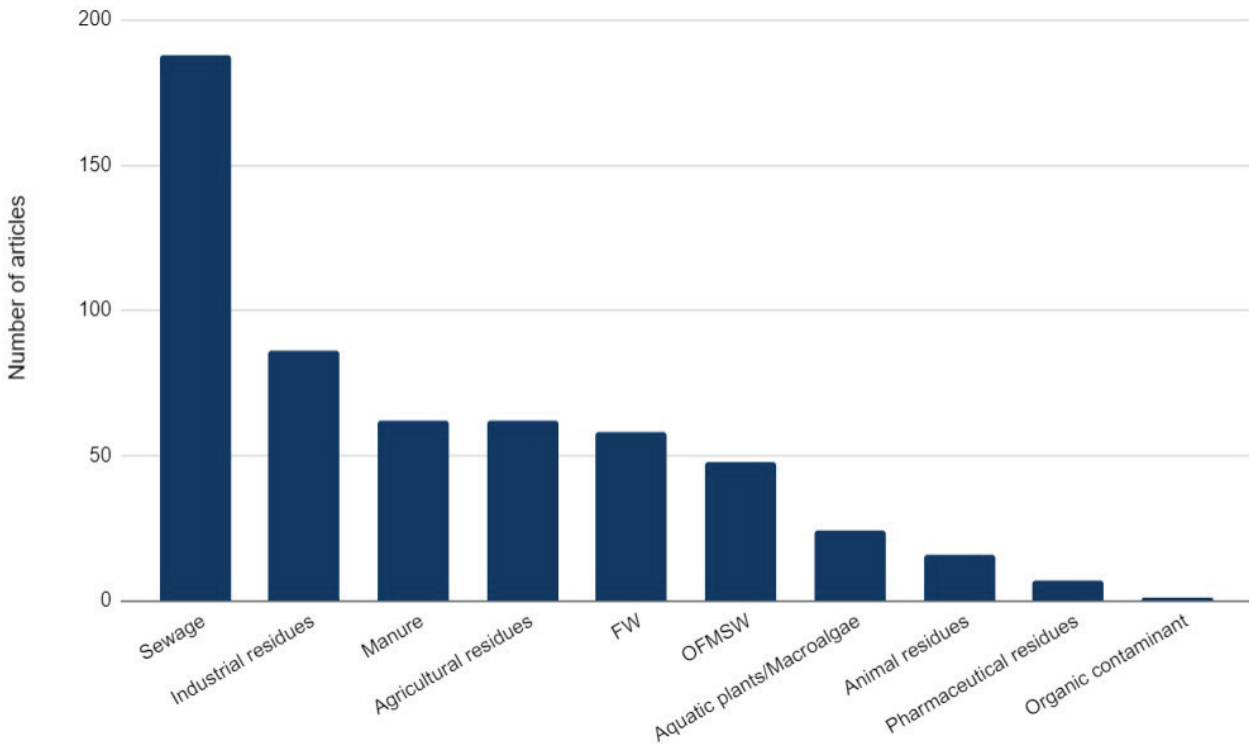


Figure 4. Number of publications per polluting source. FW: Food waste; OFMSW: Organic fraction of municipal solid waste.

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%)

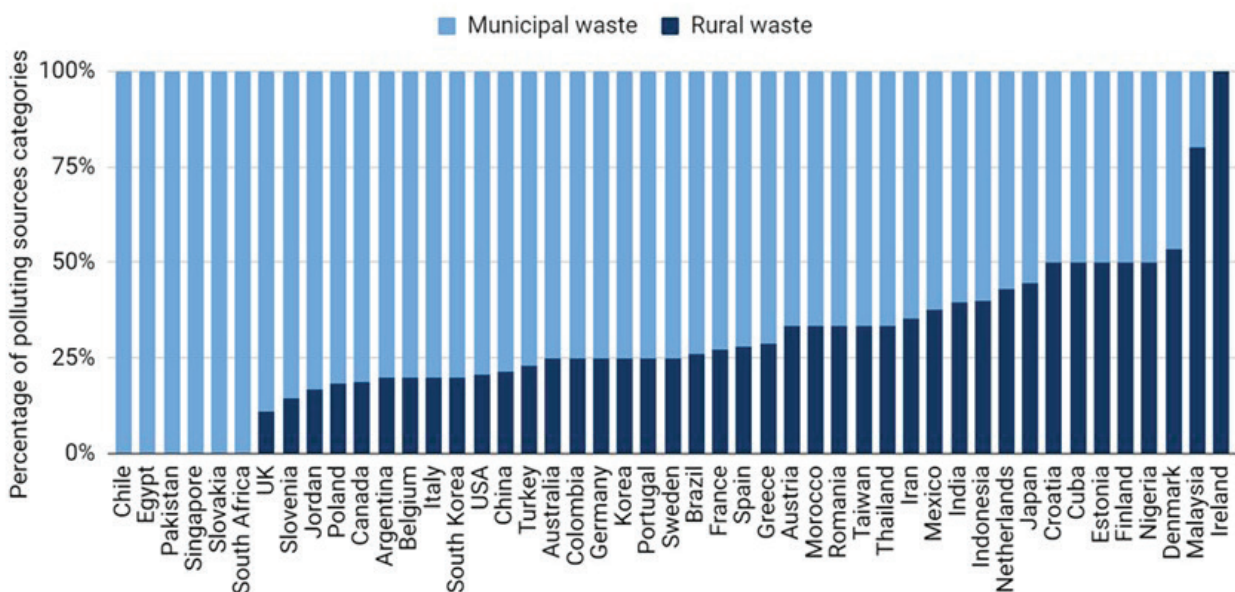


Figure 5. Evaluation of publications by country, related to the main sources of pollution: Rural Waste (agricultural residues, manure and animal residues), Municipal Waste (food waste, industrial residues, organic fraction of municipal solid waste and sewage).

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

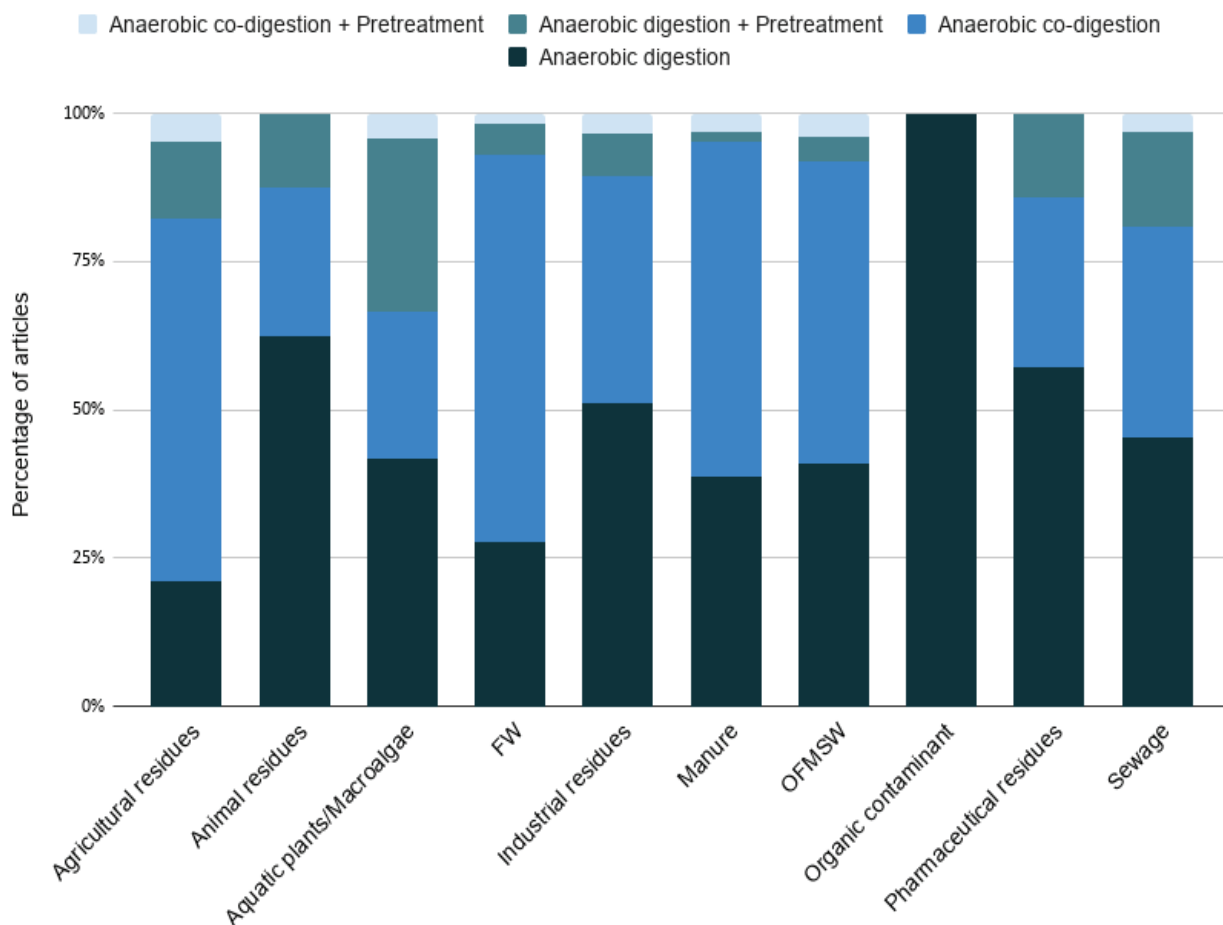


Figure 6. Proportion of studies considering co-digestion and pretreatment application as methods to improve AD during the treatment of wastes from the main pollution sources. FW: Food Waste; OFMSW: Organic Fraction of Municipal Solid Waste

(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-WATER2020). 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, SO_x and NO_x, 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, NO₃ 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 CH₄, N₂O, NO₂, NH₃ and CO₂ 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).

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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.

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SUPPLEMENTARY MATERIAL

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

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