Conclusions report on investment in circular water treatment and renewable energy systems for Latin America and the Caribbean with the Nexus approach

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1 PRESENTATION

In accordance with the objective of the contract relating to "Support for research on investment in circular water treatment and renewable energy systems for the Americas", this document presents the conclusions report on investment in circular water treatment and renewable energy systems for Latin America and the Caribbean with the Nexus approach.

2 THE ISSUE OF WASTEWATER IN LATIN AMERICA AND THE CARIBBEAN

In this chapter we present a description of the issue of wastewater in Latin America and the Caribbean (LAC) (section A). Below is an analysis of the targets agreed on and set by the different countries in the region to make progress in urban wastewater treatment, in the framework of nationally determined contributions (section B).

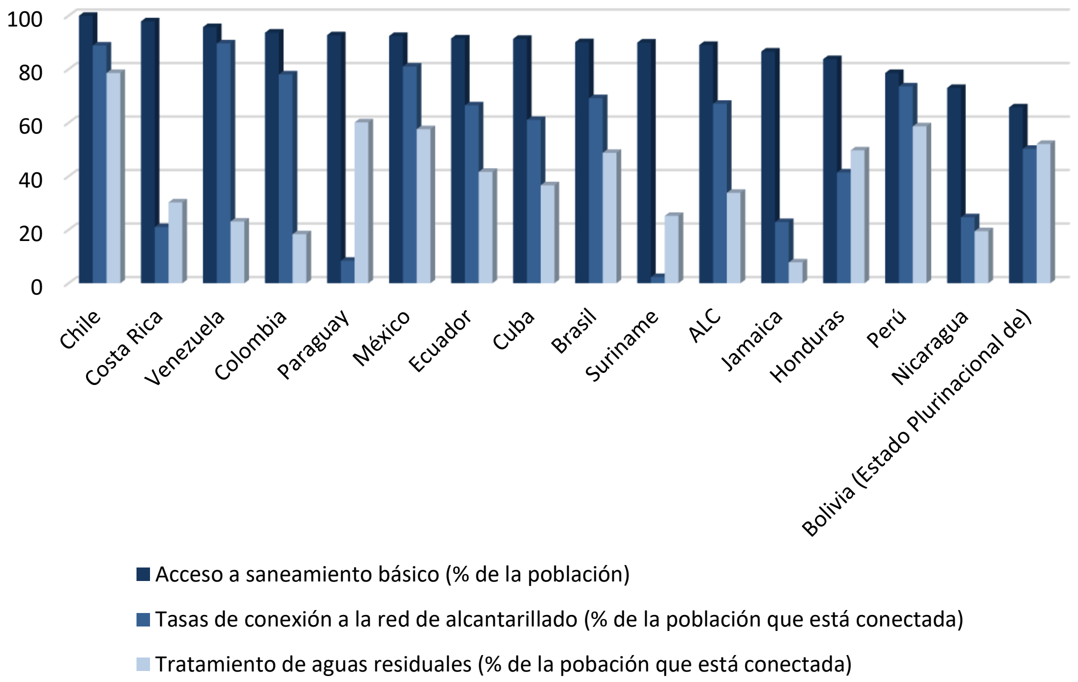
2.1 Wastewater treatment in LAC: situation

In Latin America and the Caribbean one of the main sources of water contamination is inadequate treatment of domestic water. Typically, in small and medium-sized populations there is no specific regulation in this regard, and many wastewater treatment plants (WWTPs) are in poor condition or abandoned due to their lack of financial resources and operating capacity. Only a low proportion of rural municipalities have wastewater collection systems, and fewer still have WWTPs (Peña, 2016).

In 2020, around 7 in 10 people in the region did not have access to safely-managed sanitation and up to one quarter of sections of rivers were affected by severe pathogenic contamination, with monthly concentrations of faecal coliform bacteria of more than 1000cfu/100ml, with a substantial increase of almost two thirds being observed between 1990 and 2010. This water contamination mostly originates in domestic wastewater from sewers (UNEP, 2016).

As shown in Graph 1, wastewater treatment and management levels vary greatly between the different LAC countries, and the regional averages mask this wide variation.

Graph 1
Access to sanitation and water treatment services in selected LAC countries, 2020
(In percentages)

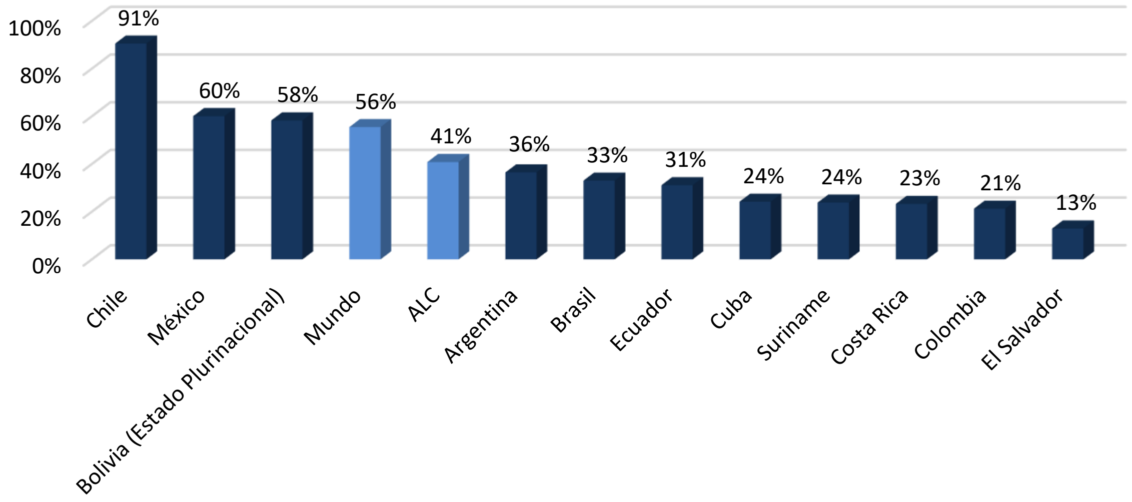


Source: Developed in-house, on JMP (Programa Conjunto de Vigilancia del Abastecimiento de Agua y el Saneamiento), 2021.

With regard to the indicator of target 6.3 of the Sustainable Development Goals (SDG) relating to water body quality, most LAC countries have not provided information for monitoring them and only 11 of the 33 ECLAC member countries have provided data on the percentage of wastewater treated safely (indicator 6.3.1).

The marked lack of available information highlights a major and clear lagging behind on the subject; however, when the statistics of the countries that did provide information are assessed, we can observe the lag in the region. Indeed, in eight of the eleven countries that provide data, treatment (adequate/safe) of wastewater of domestic origin does not exceed 40% of the total (Graph 2). El Salvador reported the lowest safe treatment coverage: only 12.95%, below Colombia, Costa Rica, Suriname and Cuba, which reported coverage below 25%.

Graph 2
Domestic wastewater treated safely in LAC, 2020
(In percentages)



Source: Developed in-house, based on UNSTAT (División de Estadística de las Naciones Unidas , 2021).

The situation is similar with respect to indicator 6.3.2, regarding the proportion of bodies of water that have good environmental quality and that do not pose a risk to the environment or human health. In this regard, the lack of data and close monitoring creates an additional concern, since contamination of bodies of water is one of the main external environmental factors that can result in complete ecosystems being destroyed, their benefits being removed (freshwater and food provision, regulation of the climate and cultural services) and their sustainability being hindered (Saravia Matus et al., 2020).

In most Latin American and Caribbean countries, it is common to discharge wastewater into lakes, rivers and streams without appropriate treatment, which poses serious problems for homes located along these waterways that depend on them for drinking water supply (Schady, 2015). For this reason, many river systems such as the Medellín river in Colombia and the Matanza Riachuelo river in Argentina, responsible for supplying drinking water to the populations of these municipalities and for irrigating products for human and animal consumption, which are the environment of many aquatic animal and plant species, are highly contaminated.

The discharge of nutrient loads with compounds from nitrogen and phosphorus is, furthermore, a precursor of "harmful algal blooms" (HAB), which proliferate when there is high solar radiation and high temperatures. These blooms often have regrettable toxic effects on organisms such as fish and birds and, therefore, on people who consume them, whose result may range from allergies to death if the toxin is lethal for these organisms (for example, the red tide) or for humans (cyanotoxins produced by microalgae, a microscopic biological component of water). HAB coincide with population increase in these coastal regions, since more urban water is discharged into the sea (Guzman, 2019).

Moreover, the lack of wastewater treatment correlates with outbreaks of diseases as severe as hepatitis A (González et al., 2019). The hepatitis A virus (HAV) is a dangerous pathogen transmitted via the faecal-oral route. The epidemiology of the infection is directly involved in the population's access to drinking water and in sewage infrastructure (Báez et al., 2016). A study carried out at Universidad de Concepción in Chile concludes that in a sea floodplain analysed, which was very contaminated with human faecal matter, there was a space-time correlation with a hepatitis A outbreak in the coastal population. Furthermore, in other Latin American countries the circulation of HAV has previously been highlighted in environmental samples in cities such as Córdoba in Argentina, Caracas in Venezuela and Río de Janeiro in Brazil (Ibid). It is important to mention that faecal human contamination is potentially more risky than that of animal origin, because in it there is a proliferation of all the specific human pathogens, such as the abovementioned hepatitis A virus (González et al., 2019).

All of the above is more concerning against the backdrop of climate change. According to the 2021 IPCC report, LAC is one of the regions in the world most affected by climate-related disasters. Hydrometeorological phenomena, such as floods, storms, droughts and heatwaves represent 93% of all disasters that have occurred in the last twenty years. In a scenario of water scarcity, when flows decrease, the dilution capacity of river systems is minimised and therefore the resilience of ecosystems to absorb changes is affected, thereby decreasing their ability to preserve biodiversity and increasing concentrations of contaminating materials. Likewise, during torrential rainfall, septic tanks can flood, creating a high-risk situation for public health.

Glacier retreat and saltwater intrusion, along with uneven precipitation, are reflected in the reduction in available water. Droughts may have severe negative impacts on the quality of water necessary for irrigation farming (Peña-Guerrero et al., 2020). In periods of drought there is intensification in the use of untreated wastewater for irrigation, a practice extensively used in some LAC countries. This leads to the risk of children and adults who work in farming, as well as those who consume their products, contracting various gastrointestinal tract infections and diseases due to bacteria, viruses or contact with protozoa, and diseases in livestock such as brucellosis, due to the intake of wastewater and food irrigated with untreated water, which naturally affects those who consume its meat (Cisneros, 2015).

2.2 Targets and agreements for progress in wastewater treatment in LAC

To observe progress in wastewater treatment in LAC, the nationally determined contributions (NDC) of the countries of the region were reviewed. They take into account the agreements and targets set by the different countries and they were set to make progress in wastewater treatment. The information analysed was obtained from the provisional registry of nationally determined contributions [Secretariat of UNFCCC (UN Climate Change), 2021].

It is important to mention that all LAC countries have reported their first NDC and only three (Argentina, Grenada and Suriname) out of 33 states have reported their second NDC, and they must do so before 2025 in accordance with the Paris Agreement.

Following the review of documents, it could be verified that 12 of the 33 countries (36%) included in their NDC related to wastewater treatment (domestic and industrial). Moreover, eight countries (24%) reported forecasts specifically related to domestic wastewater treatment in their NDC.

Table 1 presents a summary of each country's NDC proposals. In the commitments undertaken, the role of wastewater treatment to reduce methane emissions in the atmosphere and the strengthening of resilience in the sector are notable.

Table 1

Summary of proposals linked to NDC wastewater treatment in LAC by country

Country/report year[a]	Detail
South America	
Bolivia (Plurinational State of) (2016)	Actions to achieve water-related results: Domestic and industrial wastewater treatment plants to reduce their methane emissions into the atmosphere.
Chile (2020)	Measures considered in the projected scenarios 2030 and 2050: Use of sludge from wastewater treatment plants as a forest biostabiliser. In a neutral carbon scenario: New treatment plants in Gran Concepción and Gran Valparaíso by 2035, with sludge use and methane management.
Colombia (2020)	Target: Achieve 68% of domestic urban wastewater treatment in 2030. Goal: Increase coverage and quality in the treatment of wastewater flow in order to protect the most contaminated basins and sources supplying aqueducts, and strengthen the processes involved in executing the Discharge Sanitation programme (SAVER) with criteria for adaptation to climate change. Planned use, impact and estimated results: Based on the prioritisation through the SAVER programme, optimise or build sustainable infrastructure capable of facing the challenges of climate change; as well as managing information on technology that facilitates adaptation
Mexico + Central America	
Costa Rica (2020)	Costa Rica's contribution to the subject area of waste is focussed on comprehensive waste management, particularly organic waste, and on the modernisation of its sewage and wastewater treatment system, particularly in urban areas. Contribution: Target 8.4: In the year 2030, at least 50% of wastewater in high population density areas will be treated, while incorporating climate change resilience criteria. Target 8.2: By 2026, the base amount of the fee for water use, wastewater discharge and environmental services will have been updated, considering climate change and use efficiency criteria. Wastewater Sanitation National Policy
Guatemala (2017)	Mitigation: Implementation of Wastewater Regulation - Government Agreement 236-2006-, as an instrument for treating emissions produced by this sector.
Mexico (2020)	Line of action D3. Increase industrial and urban wastewater treatment, ensuring the amount and good quality of water in human settlements greater than 500,000 inhabitants
Nicaragua (2020)	Mid-term actions to consider in future NDC (2025 - 2030): Biodigesters in municipal and industrial wastewater treatment plants. Since 2007 wastewater treatment systems have increased significantly; in 2010, 13 departmental administrative centres provided wastewater treatment. Since the start of operations of the Managua Wastewater Treatment Plant the percentage of wastewater collected in the city that was treated improved significantly from 35.22% in 2007 to 98.19% by 2011, and the treatment index increased from 19.66% to 57.63% nationally.
The Caribbean	
Santa Lucía (2021)	Objective: Reduce emissions throughout the sector, using 2010 as a base year, covering the energy sector. Co-benefit: Reduction of emissions from wastewater management and introduction of renewable energy technologies into the water sector;

Source: developed in-house based on NDC per country.

[ha] To perform this analysis, the last available update was considered.

The review of these NDCs indicates that many of these countries are considering including circular economy principles in the improvement of their wastewater treatment. Thus, this study puts an economic, social and environmental value on the scenarios that are being considered by countries in order to contribute to fulfilling the Paris Agreement.

3 FROM WASTE TO RESOURCES: CIRCULAR ECONOMY OPPORTUNITIES IN THE TREATMENT OF MUNICIPAL WASTEWATER

The circular economy is a way of designing production processes as a system that is compatible with available resources. As such, to ensure the sustainability of this system, the intention is to use resources to the maximum and reduce waste through reuse, repair and recycling. Circularity allows resources to be managed more efficiently and it reduces the economy's dependence on the use of finite resources, and even improves productivity and provides long-term resilience.

Circular economy processes may be implemented in municipal wastewater systems, given that it is feasible to reuse treated wastewater so it returns to form part of the cycle. Likewise, instead of using energy from conventional sources in its treatment, it is possible to implement systems for emitting and capturing biogas, and cogenerating heat and electrical energy, with the direct effect being a limitation of fossil fuel use, since energy is recovered from the process. This is in line with one of the main appeals of the COP26, the "reduction in carbon use as an energy source and subsidies for fossil fuels". Lastly, by recovering nutrients from this wastewater, both greenhouse gas emissions and waste gas emissions can be limited and, in turn, profits can be generated from its sale.

In the following sections, we review the concept of the circular economy, its link to the sustainable development goals and its relevance in terms of water (section A). We will then review in detail the technological potential for implementing circularity schemes in wastewater treatment (section B), highlighting the possibilities provided by i) the reuse of wastewater, ii) the use of biogas to generate energy, amongst other options, and iii) nutrient extraction, identifying the main advantages and challenges in adopting them for each of these categories. Lastly, we demonstrate the benefits of adopting these circular economy techniques in municipal wastewater treatment (section C) in the economic, social and environmental fields, for Latin American and Caribbean countries.

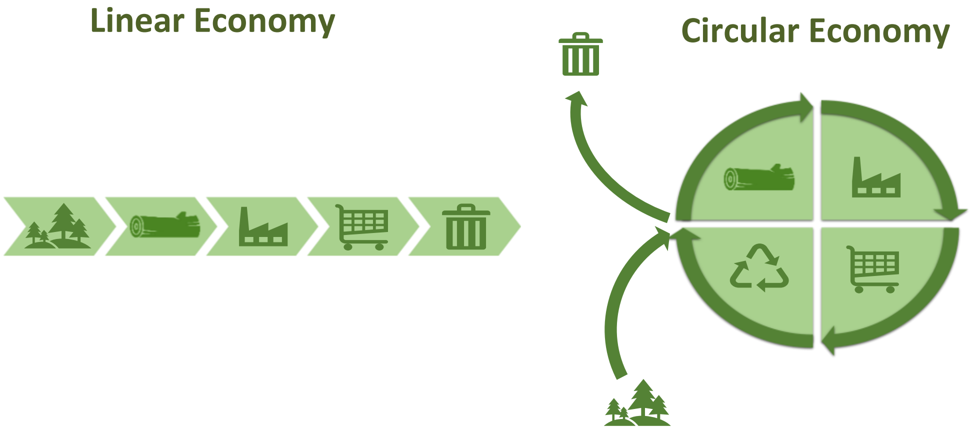
3.1 Scope of the Circular Economy

The circular economy is defined as a new paradigm that proposes to uncouple economic growth from the exploitation of finite natural resources and from energy use, based on regenerating resources and increasing efficiency in its use (Ellen MacArthur Foundation, 2013; Mulder y Albaladejo, 2020).

The circular economy is opposed to the linear economy concept, which defines the traditional production stream as an "extract-produce-waste" process in a linear fashion, as its name suggests (Diagram 1). The linear economy is the result of production, commercial and consumption practices that involve a constant supply of products from natural resources, which endangers the provision and sustainability of essential ecosystemic services. Here, the collection of raw materials leads to high energy and water consumption, the emission of toxic substances and the modification of natural capital. In terms of volume, it is estimated that around 82 billion tonnes of raw material entered the economic system in 2020, and this number is expected to continue rising in the future (Ellen MacArthur Foundation, 2013). Despite attempts to improve the situation, the linear economy is unsustainable in itself.

With the circular economy, the aim is, then, to minimise the impact on the whole service or production value chain so it is environmentally, socially and economically sustainable. They are production and consumption systems that promote the efficient use of materials, water and energy (Quirós, 2021). Likewise, they take into account the recovery capacity of ecosystems and the circular use of material flows (Ibid).

Diagram 1
Difference between the linear economy and circular economy



Source: EcoGreen Mundo (2015).

There are six circular economy system principles known as the 6Rs[1] (Quirós, 2021) because they include:

- **Rethink and reduce:** referring to using resources more efficiently;
- **Redesign:** considering the options of reusing, repairing and recycling before production;
- **Reuse:** promoting the reuse of products throughout the production chain;
- **Repair and remanufacture:** considering options of maintenance and review of products;
- **Recycle:** processing and reuse of materials from waste; and
- **Recover:** mainly focussing on obtaining energy from materials.

Likewise, the removal and incineration of waste is avoided before its maximum possible use is achieved. This involves a new approach in the design of products, which considers their durability and pre-fabrication, as well as reusing products and components, recycling materials and implementing regenerative land cultivation systems.

With circularity, the economy manages resources more effectively, which has many benefits, including the gradual systemic disconnection between the economic activity of consuming finite resources and improved productivity, thus providing long-term resilience to cities and countries.

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[1] The number of principles varies throughout the literature. Initially the so-called 3Rs of the circular economy were established. Reduce, Reuse and Recycle (King et al., 2006; Brennan et al., 2015; Ghisellini et al., 2016). The Waste Framework Directive of the European Union introduced 'Recover' as the fourth R. Since then, academics have proposed to go further than the 4R framework, and apply the 6Rs expressed here (Sihvonen and Ritola, 2015), the 9Rs (Van Buren et al., 2016; Potting et al., 2017), and even the 38Rs(Srinivas, 2021).

With regard to its specific benefits, the circular economy leads to environmental improvements since it proposes to remove production systems that consume a lot of energy or water, as well as changing to use less toxic materials (Ellen MacArthur Foundation, 2013; UNEP, 2012). Both factors will be reflected in a decrease in greenhouse gas emissions, the correct use of water and the protection of biodiversity. Likewise, this new economic approach creates social benefits, such as job creation and a decrease in the cost of food and services, it reduces social externalities and promotes innovation (Ellen MacArthur Foundation, 2015; Gower y Schröder, 2016; Schröder y otros, 2019).

Adopting circular economy principles is perceived as a way to reduce exposure to commodity price shocks and mitigate the need to absorb waste disposal costs (Ellen MacArthur Foundation, 2013). For the European Union, it is estimated that the move to a circular economy could reduce net spending on resources by 700,000 million dollars per year and generate net profit of 2.1 billion dollars per year (Ellen MacArthur Foundation, 2015).

For these reasons, the circular economy practices are considered to be of great significance for transforming the traditional approach of the economy towards sustainable consumption and production systems.

3.2 Circular economy and sustainable development

There is a strong relationship between the circular economy and the Sustainable Development Goals (SDG) of the 2030 Agenda. Aspects such as recycling domestic waste, electronic waste and wastewater, use of renewable energy and greater efficiency in the use of resources are more than sufficient to support several of these goals.

The most solid relationships between circular economy practices and the targets of the different Agenda goals can be identified in SDG 6 on Clean Water and Sanitation, in SDG 7 on Affordable and Sustainable Energy, in SDG 8 on Decent Work and Economic Growth, in SDG 12 on Responsible Production and Consumption, and in SDG 15 on Life on Land(Schröder y otros, 2019). In particular, recycling and reuse of water directly contributes to targets 6.1, 6.2, 6.3, 6.4 and 14.1; waste reduction, to targets 12.3 and 12.5; and the industrial symbiosis created from cauterising activities around the use of energy and waste discarded by others, to targets 3.9, 6.3, 7.3, 8.2, 12.4, 9.4 and 17.7 (Montesinos & Martín, 2020).

Likewise, various indirect synergies have been identified that would arise from adopting the circular economy. These refer to the goals that promote economic growth and employment (SDG 8), eradicating poverty (SDG 1), eradicating hunger and sustainable food production (SDG 2), and protecting biodiversity in the oceans (SDG 14) (Schröder y otros, 2019; Velenturf y Purnell, 2021) These synergies are present, to a greater or lesser extent, in practically all the SDG (Diagram 2).

Diagram 2
Circular economy and Sustainable Development Goals
Fraction of each SDG that would be enabled through the circular economy and that would have a strong (red) or partial (orange) impact

Source: Velenturf and Purnell (2021).

Therefore, the circular economy practices, as well as extending to sustainable systems, can be applied to achieve a considerable number of SDG targets. In this regard, this approach is proposed as a solution and a support tool for governments if they aim to achieve the development targets they committed to.

3.3 Circular economy and water

Considering that the impacts of climate change directly affect water resources, it is crucial to carry out circular actions in the water sector to tackle them. For example, in light of water scarcity, climate action should include decreased water demand, reduced loss and the reuse of treated wastewater, to name only a few approaches. The increase in climate resilience in the water sector often goes hand-in-hand with potential collateral benefits related to the mitigation of greenhouse gases (GHG), sustainable development and the protection of ecosystems, including their biodiversity (Denton y otros, 2014). Water-related climate impacts also affect other sectors, such as farming (for example, due to their effect on irrigation) and energy (for example, water for cooling), which furthermore requires us to consider the water, energy and food nexus (Kerres y otros, 2020). All of the above can be achieved by adopting circular economy practices.

The circular economy recognises that water is a finite resource. This recognition fully involves seeking to decrease use of finite resources as a raw material, which is why water use will be avoided whenever possible; furthermore: through this approach the aim will be to reuse water to the maximum to overcome negative externalities generated by its scarcity or poor quality. In an economy with this approach the impact of production systems on natural sources is minimised, which promotes the restoration of basins and ecosystems.

The circular economy supports water security and resilience (Quirós, 2021) because:

- It improves water storage capacity and its preservation;

- It incorporates a great potential for nature-based solutions, promoting integrated and flexible approaches;
- It supports exploration of alternative water resource use, including the reuse of treated wastewater.

With regard to wastewater, the benefits of the circular economy are even more evident. The recovery of resources from wastewater facilities is achieved in the form of reusable water, energy, biosolids and nutrients. These represent an economic and financial benefit that contributes to the sustainability of water supply and sanitation systems, as well as of the companies operating them (Rodríguez y otros, 2020). In this way, by applying circular economy principles to wastewater management, the recovery and reuse of resources transforms sanitation, which changes from a costly service into a self-sustaining one and one which adds value to the economy (Ibid).

Below, we review the different techniques and opportunities to recover resources through municipal wastewater treatment including reuse of the same water, harnessing this waste in the form of energy and extraction of nutrients.

3.4 Technological potential of the circular economy in wastewater treatment

By adopting the circular economy approach in water sanitation, wastewater is redefined and is no longer waste but is considered a reusable resource. As such, in addition to reducing wastewater disposal in cities, new water sources are generated, which increases its supply. Moreover, by harnessing waste for energy generation (in the form of heat, gas and electricity) other energy sources are replaced, the result and economic sustainability of wastewater treatment improves and methane emissions, which are a major source of greenhouse gases, decrease, in line with the decreases applied by COP26.

The supply, transportation and treatment of water are energy-intensive processes, which contribute to carbon emissions when they are powered by fossil fuels. Energy use in water- and wastewater-related activities represent approximately 4% of international electricity consumption and this could double by 2040 (Kerres y otros, 2020). Likewise, wastewater treatment can generate methane (CH_4) and nitrous oxide (N_2O) emissions, with a global warming potential of between 80 and 300 times stronger than CO_2, respectively (EPA, 2021; Kerres y otros, 2020). Therefore, instead of generating waste in the form of dirty water, energy derivatives and gas emissions, it is possible to recover this water, produce energy and obtain nutrients.

It is estimated that more than 80% of global wastewater does not receive any type of treatment (Kerres y otros, 2020), mainly because investment needs in the water supply and sanitation sector are very high and, in most cases, very much lagging behind. Given that cities are continuing to grow, it is essential to ensure that investments in the sector are made in the most sustainable and efficient manner, incorporating circular economy technologies into their waste management systems. In this context, wastewater is and must be considered a valuable resource from which energy and nutrients can be extracted, as well as constituting an additional source of water (Rodríguez y otros, 2020).

Circular economy processes may be present at different stages and in different dynamics of wastewater systems. As we have mentioned, obtaining energy in the form of heat, biogas or electricity and recovering nutrients can promote reuse of wastewater. The detail of each of these processes is set out below and the benefits and opportunities of adopting these circular economy techniques in municipal wastewater treatment are highlighted.

1. Water reuse

Municipal wastewater consists 99.8% of water (López y otros, 2017). Once treated, this water can be used for different purposes, the most common being irrigation, industrial processes and replacement of groundwater. Its use for domestic purposes, particularly toilet waste discharge, already has various technologies and systems that enable it (Ibid).

In the urban setting, the main reuse for treated wastewater is residential irrigation. Given that human exposure is high in these processes, special care must be taken to avoid potential health issues. Due to the above, countries are developing and implementing specific regulatory bodies in this regard (Mo y Zhang, 2013). In line with these protocols, water may be used for irrigating gardens, discharging toilet waste, washing vehicles, and even for direct consumption. It is estimated that in the United States around 64,000 million litres per day of wastewater are reused, and this rate is increasing by 15% each year (Mo y Zhang, 2013).

Reuse of wastewater treatment plant (WWTP) water has the potential to provide many advantages. By establishing these systems it is possible to reduce uncertainty created by climate change regarding provision and increase the supply of available water. The foregoing results in energy savings by decreasing the requirement for energy that is used in obtaining and distributing water. Furthermore, the amount of water that can be reused is proportional to the initial or primary demand, and the system is sustainable over time. Lastly, it reduces the need to explore water sources that consume more energy, such as desalination.

The main limiting factors for widespread adoption of wastewater reuse systems is the cost associated with the initial investment in treatment infrastructure and variability in effluent quality. Furthermore, concerns about health and environmental safety continue to be major factors for a more extensive application of this practice.

When water has domestic purposes it can be reused in the drinking water network or system directly (Leverenz y otros, 2011). Amongst the positive aspects of this decision it is indicated that it may improve the general reliability of the water supply and, as such, neither a dual system (also connected to the network) nor water injection or sprinkling system are required, as are required by indirect systems (Ibid). However, water treatment for reuse as drinking water has high requirements, which may increase the operating cost, as well as there still being the large obstacle of its low public acceptance (Mo and Zhang, 2013).

Groundwater recharge as part of the reuse of this water would be the last of its applications and it generates many benefits. Due to this, it is possible to relieve land subsidence, ease saltwater intrusion in coastal areas, provide natural storage without the need to resort to works of infrastructure, with losses through evaporation that this entails, as well as functioning as a natural filter where water receives additional treatment that facilitates its subsequent recovery and reuse (Mo y Zhang, 2013). However, it has certain challenges, including the requirements of monitoring water quality and operating the facilities. Furthermore, recharging scarcely treated wastewater may increase the danger of aquifer contamination. Lastly, not all recharged water can be recovered, due to groundwater movement beyond the place of extraction or the potential contamination that occurs with poor quality groundwater.

2. Energy generation

Another component of wastewater that may be recovered or regenerated is energy. It is possible to obtain different forms of energy by harnessing WWTP waste: such as heat, biogas or electricity. Below we review each of these technologies, their benefits and challenges to achieving their widespread application.

a) Heat (and cold) generation

Extraction of heat energy from WWTP wastewater is usually performed using a heat pump, a mechanical device that transfers water from one place to another. As such, the water temperature is used to heat up or cool down an environment (GIZ, 2020). The system recovers the heat/coolness from the wastewater, making it pass through pipes, and uses this heat to heat up/cool down the same treatment process or industrial facilities, departments or particular houses in the vicinity of the wastewater treatment plant. Heat pumps are an efficient technology for self-consumption of renewable energy and comply with the circular economy's principles.

These systems have a special potential for use in the domestic sector, for which they are widely available and have various designs. They harness the temperature of wastewater, which remains constant throughout the year at around 20 degrees (Pistonesi y otros, 2010). These technologies enable their implementation both in residential buildings that require between 5kW and 30kW, and in large buildings and urban heating schemes of 100kW to 1000kW or more (GIZ, 2020), and the outlook for their demand is enormous if we consider that energy demand projections for space cooling are estimated to more than double by 2030 (IEA, 2016). As can be seen, these systems are highly versatile as regards their current application in the municipal sector, but will be even more so in the future.

One of the main benefits of heat pumps from WWTPs is that they are highly energy efficient systems: they deliver between 2 and 4 units of heat energy for each unit of electrical energy consumed (GIZ, 2020). Indeed, the International Energy Agency considers it to be the best air conditioning technology available, and it estimates that reduction of CO_2 emissions from heat pumps is 6% with the potential to reach 16% in the future (IEA, 2016). In addition, they are durable devices that require little maintenance. In terms of energy savings in the supply of hot water and heating to a block of residential buildings, a saving of 990 USD per year is estimated when compared to a gas boiler (Arnabat, 2017). As we can see, they have many advantages and yield significant financial savings.

Their main disadvantage is that the initial investment to implement them continues to be higher than that of conventional air conditioning systems. However, this is offset by operating costs, which are considerably lower. On the other hand, the pumps normally emit noise to levels that in some cases may be disruptive[2]. Furthermore, in very cold or very hot climatic zones the performance of the pumps may decrease considerably, since the wastewater's temperature is lost before entering the system (GIZ, 2020). Likewise, the places to be air-conditioned must be insulated, otherwise the systems will consume more energy than expected (Ibid). In this regard, in addition to the initial investment in the system, the fitting-out of the spaces and of the complete system must be considered.

b) Harnessing methane and cogenerating electrical energy

It is possible to harness WWTP waste to generate energy in the form of gas. This occurs when anaerobic (without oxygen) digestion of municipal wastewater is carried out, instead of using aerobic treatment. Gases generated in sludge digestion both in anaerobic and aerobic treatment plants may also be used. The anaerobic process of wastewater and sludge generates methane gas (CH_4) as a by-

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[2] There are systems that use radiant floor heating or radiators that generate practically imperceptible noise levels, which is not the case for those with fans (GIZ, 2020).

product. This gas can be used *in situ* for different processes inside the treatment plant, such as heating up the sludge digester and increasing the efficiency of the anaerobic digestion process itself, as well as drying and reducing the volume of sludge before its final disposal (López y otros, 2017). Likewise, this biogas, after being cleaned of impurities, can then be used directly as fuel for vehicle, industrial or residential purposes.

Total methane production per unit of time (m^3/day or similar) in a municipal WWTP mainly depends on the treatment technology, in addition to the concentration and composition of organic matter present in wastewater, which change in accordance with the availability of drinking water, the socioeconomic level of the population, the infiltrations of rainwater in the sewage network, the type of sanitary facility and the activities performed in the area where the wastewater is collected (Von Sperling, 2005). Likewise, the temperature of the process and the characteristics and efficiency of the technology influence it (López y otros, 2017).

Obtaining energy in the form of biogas has a series of positive impacts. The main one is the reduction of local energy requirements. For example, an aerobic WWTP that has an average energy expenditure of 100kW/h throughout the year may achieve production of close to 285kW/h with an anaerobic system that harnesses methane (Hernández, 2021)[3]. Likewise, these processes significantly reduce waste in the form of sludge. Whereas common aerobic processes generate between 30 and 60kg of sludge per 100kg of material that is vulnerable to rust, by implementing anaerobic processes this waste can reduce significantly down to 5kg of sludge (Hernández, 2021). This means that these technologies are particularly in line with circular economy concepts, since they reduce and repurpose production process waste and transform it into resources that are available for other processes.

Likewise, it is possible to recover energy from the sludge resulting from the aerobic treatment of wastewater through anaerobic digestion of it, since it enables the emission, capture and subsequent harnessing of methane in the generation or cogeneration of energy. This technique has demonstrated that it decreases greenhouse gas (GHG) emissions in treatment plants by 21% and that it is possible for it to provide up to 14% of the energy required by the plant, in addition to the environmental benefits it entails (Aguilar & Blanco, 2018).

The main challenge to its large-scale implementation are the initially high costs compared to those of the aerobic procedures currently employed. Adopting this technology industrially requires the system to be fitted out for processing the gas, in addition to the purchase of a reactor or anaerobic digesters. These systems include gas holders, compressors, desulphators and engine generators[4], amongst others (Linares, 2020). In summary, despite this system having undeniable energy benefits and the possibility of future benefits, it requires a high initial investment if there is no previous or minimal infrastructure from the start.

Lastly, combined heat and energy systems use methane from wastewater and from sludge to obtain heat and electricity. Biogas is the fuel that moves turbines and generates around 1,300kW/h of electrical energy per million litres of treated wastewater (Burton, 1996 in Mo and Zhang, 2013). One study on this indicates that if all WWTPs in Texas utilised these systems, a 26% reduction in electricity

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[3] This information is only a referential example, since efficiency and production depend on the size/capacity of the plant, its geographic location and other abovementioned characteristics.

[4] The use of engines is 1.5 times more efficient than that of turbines (Felca y otros, 2018).

use could be achieved throughout the state (Stillwell y otros, 2010). Electricity produced in this way is reliable and consistent, but installation requires relatively high capital costs, around 4,500 USD/kW (Mo y Zhang, 2013). Moreover, these systems require high gas volumes and, as such, they are only viable for WWTPs with a flow higher than 231l/s, that is 20 million litres per day (Ibid), which is generated by a population of around 135,000 inhabitants[5]; however, more recent studies that use information from countries in the region refer to the existence of methane-harnessing systems in plants that serve populations greater than 300,000 inhabitants (Silva et al., 2016; Nolasco, 2010). Lastly, technical and professional ability is necessary to operate these systems. Therefore, despite these systems being highly efficient, their limiting factors are the high costs of initial investment, the abovementioned high volumes of treated water and the requirement for trained professionals.

c) Other forms of electricity generation

Anaerobic treatment of wastewater and anaerobic digestion of sludge may result in the by-product of electricity and heat generation, for which there are different processes, with the most common of them using the same biogas in the form of methane. Other methods include bioelectrochemical systems, microalgae, hydroelectricity and the incineration process. Below, we summarise each of these and assess the potential for them to be adopted in a circular economy[6].

Bioelectrochemical systems: Bioelectrochemical systems use biological catalysts to cause chemical reactions from the enzymes or microorganisms contained in wastewater. These may store energy in microbial fuel cells or microbial electrolysis cells. In the first case the enzymatic or microbial energy is directly converted into electricity (McCarty y otros, 2011; Mo y Zhang, 2013). Energy thus obtained varies between 10 and 100MW/m^2 (Liu y otros, 2004). These systems, in addition to producing energy more efficiently, even more than in the anaerobic approach, reduce sludge excess by around 20% when compared to conventional treatment (Foley, 2010; McCarty y otros, 2011). Its most notable disadvantages are energy loss during the electricity generation process, low rates of organic use and capital costs 800 times higher than an anaerobic system (Liu y otros, 2004; McCarty y otros, 2011). In microbial electrolysis treatments, energy is recovered in the form of biochemicals, particularly hydrogen and methane. It is a more recent system and there are fewer studies on it that corroborate its efficiency (Mo y Zhang, 2013).

Microalgae: The microalgae technology recovers energy by growing these small algae in wastewater and subsequently converting them into energy products. This technique has the potential to generate 2,600kWh of energy per tonne of dry algae (Aresta y otros, 2005). During cultivation, microalgae absorb carbon and nutrients from the wastewater, which reduces the waste load to be treated. Moreover, microalgae use carbon dioxide quicker than conventional organic crops, resulting in negative emission of greenhouse gases of the equivalent of 51kg CO_2 for each kWh generated, with the consequential reduction and mitigation of carbon dioxide emissions (Groom y otros, 2008; Kumar y otros, 2010). Its challenges to greater integration include the costs of growing the algae, the high energy levels required to collect, dehydrate and extract lipids, and the identification of species of microalgae with optimum yields (Kumar y otros, 2010; Mo y Zhang, 2013).

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[5] For an average discharge of 150 l/h/d

[6] Other existing systems include the use of solar concentration to accelerate the effluent-drying process and the installation of solar panels for WWTP electricity self-consumption. However, these systems will not be analysed in this document.

Effluent hydroelectric energy: Effluent hydroelectric energy uses turbines or other devices installed in pipes, channels and ducts to generate electricity from moving water. In WWTPs, these technologies use conduit systems and the effluent of wastewater itself. In addition to generating energy, this type of hydroelectric system can increase the concentration of oxygen dissolved in treated wastewater, thus promoting aerobic treatment processes (Gaius-Obaseki, 2010). Their main limitation is that they require the effluent to have sufficient kinetic energy or movement, which demands a significant height or flow (Ibid).

Incineration to obtain electricity: A way of obtaining this type of energy is incineration, linked to a combustion plant, which limits atmospheric waste. The process consists of transporting sludge to an oven so this sludge can be used as fuel to generate electricity, which simultaneously minimises waste (Mo y Zhang, 2013). This sludge is subject to prior drying treatment, since it needs to be dehydrated so it is easier to store and use as fuel (Linares, 2020; Mo y Zhang, 2013). A great advantage of this technique, which requires little initial investment, is that, in addition to recovering energy instead of using it, it allows minerals to be extracted from the ashes: approximately 90% of phosphates and other metals (Hao y otros, 2020). It is calculated that by incinerating the biosolids in all wastewater treatment plants in Texas, electricity consumption in the wastewater sector in the whole state would reduce by around 57% (Stillwell et al., 2010). However, this procedure has a significant negative impact since it harnesses the emission of volatile organic compounds, such as sulphur dioxide (SO_2) and carbon dioxide (CO_2), derivative compounds of nitrogen dioxide (NO_2) and heavy metals (Linares, 2020). Due to the above, despite it being a waste reuse technology, these environmental disadvantages must be resolved for it to be in line with circular economy principles.

3. Nutrient extraction

A process that has been gaining momentum recently regarding use of wastewater in line with circular economy principles involves harnessing the nutrients it provides. This may be done directly and simply by discharging WWTP sludge onto soil, or doing this through unconventional toilets that allow urine to be separated for it to be applied to soil, or with more sophisticated wastewater treatment technologies that enable recovery of the phosphate it contains, or through struvite crystallisation to obtain the valuable phosphate. Below we review each of these techniques and present their advantages and disadvantages to achieving their widespread use.

The first way of extracting nutrients from wastewater consists of spreading biosolids on the soil, following its treatment through digestion, alkaline treatment, composting or drying. Its use in this form is mainly as fertiliser, which decreases dependence on fossil fertilisers. However, it can also be used to prepare the soil and landfill cover (Mo y Zhang, 2013). Use of biosolids in this manner is a simple and quick way of obtaining nutrients, but it leads to some major social and environmental concerns related to health and the smell produced (Ibid).

A second way of recovering nutrients from wastewater involves separating the urine, which is already done in some rural areas on a low scale. This procedure consequently reduces the waste load of water on WWTP, given that urine contains around 75% of the nitrogen and 50% of the phosphorus of domestic wastewater. It is calculated that around 70% of these nutrients could be recovered through collector toilets (Mo y Zhang, 2013). Urine separation is highly efficient from the energy point of view compared to other nutrient-recycling technologies. It also offers the possibility of recovering costs through its direct sale (Benetto y otros, 2009; Flores y otros, 2009; Larsen y otros, 2009). Given that separation usually occurs in the domestic habitat, these systems are installed in homes, which requires the support and participation of local communities, as well as involving the challenge of avoiding cross contamination with faeces (Mo y Zhang, 2013; Verstraete y otros, 2009). The recovery of nitrogen and phosphorus from urine would then be reflected in the decrease in WWTP labour and resources, but it requires coordination and a solid local community system.

A third way to recover nutrients from wastewater is controlled struvite crystallisation, which enables nutrients from sludge digester liquor to be recycled. This technique shows high rates of nutrient recovery, particularly for phosphate (Mo y Zhang, 2013), since its concentration in sludge digestion liquids is usually quite high, to the extent that the theoretical crystallisation potential may be up to 67,000 tonnes of fertiliser per year in the United Kingdom alone (Gaterell y otros, 2011). However, due to phosphate sources being limited and many of them being located in countries where there is constant political and social unrest[7], there has been an increase of more than 30% in its prices since 2011 (and particularly in 2022 with the war in Ukraine), which makes the prospect of a cost-effective recovery of this nutrient from wastewater economically attractive (Ellen MacArthur Foundation, 2013; Kerres y otros, 2020; Rodríguez y otros, 2020), since despite the fact that obtaining phosphate from wastewater is between 2 and 8 times more costly than extracting it from rocks, and that investment in this technology is high, the recovery rates through selling the material can balance these costs, and there would be the added social and environmental benefits of reducing them in the form of waste.

4 EXPECTED BENEFITS OF THE CIRCULAR ECONOMY IN WASTEWATER TREATMENT PLANTS

Based on the different technologies presented, it is evident that wastewater must be considered as a resource and not as waste. When seen like this, and when adopting the principles of the circular economy with regard to municipal wastewater treatment, it is possible to perceive multiple benefits, which are detailed below, classified by their economic, environmental or social nature.

4.1 Direct economic benefits

The following economic benefits can be listed:

- The sale of treated water. It is possible to directly sell partially treated wastewater at a lower price than that of fully treated wastewater. And although the low cost of freshwater makes it difficult for an adequate price to be charged for recovered water, there is an example of a successful practice in this regard carried out in Honolulu, Hawaii (Lazarova y Asano, 2013). There, two types of water are sold depending on the intended user. The first type is sent to the industrial sector of the island, which includes refineries, factories and energy companies, all located near the facilities where it is treated. These users receive the water, which is treated and then processed by reverse osmosis, producing water of high purity and quality. A second type is sent to golf courses, gardens and irrigation, and is sold cheaper since it is not subject to the reverse osmosis process. The volumes of water produced by this system and sold since its creation in 2000 have continuously increased, to the extent that in

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[7] Morocco, Western Sahara, China, Egypt, Algeria, Syria, Brazil, South Africa and Saudi Arabia have 91% of the global reserves **Invalid source specified.**.

2012 its volume was 11.5 million m^3, of which 17% was high purity water for industrial purposes and 83% was allocated to irrigation. As expected, considering the growing scarcity of water and the uncertainty about its availability, the requirement for this water and its value have a growing potential.

- <u>Inter-sectoral water swaps or transfers</u>. Unlike with sales, a commercial exchange of water supply sources is performed here, which results in savings or a direct economic benefit. For example, it is possible to make agreements between producers of water treated for irrigation and producers of freshwater for domestic and industrial use (Winpenny y otros, 2010). This model can be applied in water exchanges between users with a low water quality demand and users who consume more, with specific requirements, who may pay a higher price for it (WWAP, 2017). With this scheme, despite these swaps not increasing the total availability of the resource, they allow savings to be made compared to the cost of resorting to other water sources such as the treatment and filtering of scarce surface water, as well as the deepening of wells, with all the energy costs involved in the use of groundwater sources.
- <u>Sale of biogas.</u> It is possible to sell biofuels obtained from microalgae and organic processes, or else in the form of biogas. These biofuels can be used for transportation, the development of bioplastics and biochemicals, as nutritional supplements for humans and animals, and as antioxidants and cosmetic ingredients (WWAP, 2017). In the La Farfana wastewater treatment plant in Santiago, Chile, profits of 1 million USD per year have been generated by the direct sale of methane (Rodríguez y otros, 2020). The plant annually treats between 222 and 289 million cubic metres of wastewater and produces an average of 25 million cubic metres of biogas (World Bank, 2020b). Through its sale alone it is estimated that in less than three years they will recover the investment of 2.7 million USD used to modernise the plant and incorporate this technology (Rodríguez y otros, 2020). The reduction of GHG emissions is an additional benefit. Here, it is calculated that the system reduces the equivalent emission of CO_2 by 19.788 tonnes per year, a potential source of additional income if the sale of carbon credits is considered (World Bank, 2020b). Likewise, the gas company with which the sale agreements were signed saved an estimated 1.6 million USD by buying this biogas instead of buying from their conventional sources (Ibíd.).
- <u>Sale of fertilisers and waste savings.</u> The sale of by-products is the way commonly used by WWTPs to recover their costs, and it includes fertilisers such as phosphorus, nitrogen and biosolids. The New Cairo, Egypt, water company sells sludge to the cement industry and to farming, thereby obtaining an additional revenue stream (World Bank, 2020a). The La Farfana plant in Chile, with a production of 800 tonnes/day of sludge, delivers these biosolids to farmers free of charge, thereby saving it the costs of depositing biosolids in landfill sites, which are 40 USD/tonne, which would annually amount to 11.6 million USD (World Bank, 2020b).
- <u>Sale of phosphate.</u> The extraction and sale of phosphate has a growing economic potential, since in the next fifty to one hundred years the mineral sources from which the mineral is extracted will be scarce or will have been exhausted (Van Vuuren y otros, 2010). The Ostara Company of Canada recovers phosphate as granules, called crystal green, and the income obtained through the sale of this fertiliser is shared with the city to offset the costs of the facilities.
- <u>Cost reduction.</u> Firstly, and as mentioned above, promoting the circular economy in WWTPs results in a cost reduction due to the decrease in waste and the consequential minimisation of the costs of its disposal. Likewise, anaerobic treatments, in addition to using less energy, generate it, also enabling consequential energy savings. Lastly, they reduce the costs linked

to the use of water from natural sources. In a rural sanitary system of San Pedro de Potosí, in Mexico, a 33% reduction was estimated in the costs due to reuse of water, representing savings of 3 million USD per year on energy, which helped cover the water company's operating and maintenance costs (Rodríguez y otros, 2020).

- GDP and trade. Contaminated water can directly affect economic activities that use water, such as industrial production, fishing, aquaculture and tourism (UNEP, 2016). Furthermore, it may indirectly limit the exportation of certain goods due to restrictions, and even prohibitions, on selling contaminated products (WWAP, 2017). It is calculated that for every 1 USD spent on sanitation the return is 5.5 USD (Hutton and Haller, 2004, at WWAP, 2017). In this regard, in addition to promoting trade, investment in water treatment systems based on the circular economy principles can generate GDP gains and country development.

4.2 Environmental Benefits

In addition to the economic benefits mentioned, promoting a circular economy in wastewater treatment has environmental benefits. The most significant benefits include:

- Mitigation of climate change. When wastewaster is disposed of in bodies of surface water, it increases the amount of nutrients and organic matter in its flow, which brings about the emission of even more GHG (Kerres y otros, 2020). The application of the circular economy in its treatment decreases these emissions. In the same vein, when liquefied gas is replaced by methane and the use of wood as fuel is reduced it is possible to substantially decrease these emissions (Cornejo and Wilkie, 2010). In short, the expansion of water treatment capacity with the circular economy approach has a positive effect on GHG emissions, particularly methane, because the contributions of organic matter and nutrients to surface water bodies and of GHG to the atmosphere is reduced. This is an effective contribution to the national efforts to mitigate climate change.
- Protection of water quality. The discharge of untreated wastewater into the atmosphere has a negative impact on water quality. This, in turn, affects the amount of quality water resources available for direct use.
- Safeguarding of aquatic systems. When wastewater is treated based on the paradigm of the circular economy, the waste discharged into bodies of water is minimised. Eutrophication[8], driven by an excess of nitrogen and phosphorus, can cause blooms of potentially toxic algae, as well as a decrease in biodiversity (WWAP, 2017). When the waste from these nutrients going into natural sources is reduced and instead is reinserted into farming processes, the risk of the blooming of these algae formations decreases. Discharges into seas and oceans is estimated to have affected 245,000km^2 of marine ecosystems, with repercussions for the fishing industry, livelihoods and food chains (Ibid). By extracting these nutrients from

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[8] In the region there are 31 areas with eutrophication and 19 areas with hypoxia (known as "dead zones", because the oxygen deficiency has extinguished local biodiversity), with a greater concentration in the Atlantic than in the Pacific. **Invalid source specified.**

treated water, the immediate effects of this contamination are reduced along with the resulting deterioration of aquatic ecosystems.

- Increase in energy sustainability. By increasing the use of methane from wastewater and given that its availability is proportional to population growth, the sustainability of the system is reinforced. Likewise, the energy grid is diversified and there is a reduction of environmentally harmful energy participation, such as that deriving from coal and wood.

4.3 Social Benefits

The positive effects of adopting a circular economy approach in the treatment of wastewater are reflected significantly in society. The main benefits of this type include:

- Improvements in public health. The efficient management of human waste provides unquestionable benefits to society, particularly in terms of public health. By reducing the waste discharged into bodies of water there is decrease in the diseases transmitted by contaminated freshwater supply (WWAP, 2017), such as cholera, various diarrhoea, dysentery, hepatitis A, typhoid fever and poliomyelitis. Indeed, it is estimated that around 842,000 people die each year from diarrhoea as a result of the unhealthiness of the water (Mills and Cumming,2016).
- In 2014 it was estimated that, in the region, 5.7 million years of life, adjusted for disability, had been lost due to these diseases, which were assessed at 1,800 million dollars (Dalal & Svanström, 2015). Indeed, this has a long-term impact on the wellbeing of the communities and on their livelihoods.
- Generation of green jobs. There is an initial beneficial effect on job creation when activities are begun to implement the circular economy in wastewater treatment. In countries with different development levels there is always a relationship between water management in general and employment opportunities. In other words, water plays a key role in the generation and continuation of direct jobs in a wide range of sectors and all those that emerge due to its multiplying effect (WWAP, 2017).

5 CONCLUSIONS

A review of the literature proposed in this chapter, and the multiple options that have been documented for implementation of circularity in wastewater treatment, demonstrate the extensive potential of the subject, particularly in LAC, if the current situation of wastewater treatment in the region is taken into account.

Of the possibilities set out, that which has the best prospects for LAC is energy generation that takes into account methane use. Firstly, this technology can be less costly than bioelectrochemical systems and can involve fewer challenges than energy generation from microalgae. In turn, although alternatives such as incineration to obtain electricity may have economic and technical viability, their impact on the emission of volatile organic compounds entails major environmental impacts that are opposed to circular economy principles. With regard to nutrient extraction, the urine separation systems have significant restrictions that hinder achieving economies of scale. Likewise, the controlled struvite crystallisation system involves high costs that are reflected in the financial unsustainability of its implementation in the region.

By contrast, there is significant literature that has documented the financial feasibility of implementing methane-harnessing and energy cogeneration systems in WWTPs that serve populations greater than 300,000 inhabitants, which has a broad potential for the implementation of this type of technology in mid-sized cities.

In turn, the implementation of circularity by harnessing methane has significant social, environmental and economic benefits, insofar as this scheme is not exclusive and allows circularity to develop in other wastewater treatment areas, such as the use of waste sludge as a source of nutrients for farming activity (such as in the WWTP of La Farfana in Chile and Nuevo Cairo in Egypt) and the sale of treated wastewater for irrigation or heat and cooling generation. Also, as a central component it decreases GHG emissions through reduction of methane emissions generated in WWTPs and the energy cogeneration that can be used by the WWTPs in internal processes. Surpluses may even be generated, which implicitly have the benefit of replacing energy from the national energy grid (which usually contains non-renewable energy sources), with renewable energy.

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