WASTEWATER TREATMENT PLANTS IN THE CONTEXT OF CIRCULAR ECONOMY

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Abstract: Regarding sanitation systems, the application of circular economy has great potential, especially when aligned with sustainability concepts. Considering that domestic sewage treatment plants generate a large amount of waste while simultaneously being extremely important for public and environmental health, applying circular economy strategies to these systems is a promising alternative. This work aimed to analyze how circular economy is being established in domestic wastewater treatment processes, identifying factors that directly influence this implementation. Considering the large amount of waste generated and its intrinsic value, whether in the form of nutrients, energy or water resources, the adoption of circular practices by these systems presents itself as a way of adding economic value to the waste produced, while also contributing to proper disposal and reducing the emission of pollutants. Aspects such as the lack or deficiency of legislation, the need to invest in certain technologies, the lack of government incentives and resistance on the part of companies and the public still hinder the application of these practices in wastewater treatment. However, the tendency is for the search for a transition from linear to circular models to increase, driven by the need to promote sustainable development.

Keywords: circular economy, wastewater, sewage sludge, biogas recovery, water reuse.

1. Introduction

The search for sustainable production and consumption alternatives in various economic sectors has become a growing necessity, especially in the face of climate change and the scarcity of resources. Two concepts that can be applied in various segments to generate positive impacts are circular economy and sustainability.

Circular economy aims to transform materials at the end of their useful life into new resources to close cycles (STAHEL, 2016), rethinking them from the beginning. It can be defined as a regenerative process, represented by minimizing resource input and waste, as well as reducing pollution emissions and wasting energy resources (GEISSDO-ERFER et al., 2017). This concept is in opposition to the linear model of extraction, manufacture/production and disposal/waste of materials, and has the potential to promote sustainable development by generating positive impacts, generating income and minimizing the consumption of finite resources and the generation of waste (IWA, 2016; TBC, 2016).

In turn, the sustainability tripod aims to integrate the social, environmental and economic dimensions in the various sectors of society. This concept aims to help governments, institutions, companies and non-governmental organizations evaluate their projects and policies in a more balanced way, through the lens of sustainability (SLAPER; HALL, 2011). In this way, sustainability actions can generate positive impacts in the following dimensions: environmental, by reducing the use of virgin raw materials and renewable energy sources, as well as reducing waste and emissions; economic, by reducing expenses generated by using the value of resources more fully, by reducing spending on environmental taxes and by creating a positive image for organizations; and social, by creating new jobs, social justice and strengthening the sense of community and cooperation (KORHONEN; HONKASALO; SEPPÄLÄ, 2018).

In this sense, a relevant recent example was the adoption of the Circular Economy Action Plan by the European Commission in March 2020, which is one of the main bases for the European Green Deal, the new European agenda for sustainable growth. The plan considers the entire life cycle of products, with changes in production, the encouragement of more sustainable consumption and circular practices, as well as the reduction of waste generation and the maximum possible permanence of resources within the economy (EC, 2021a). With great environmental, social and economic importance, the water industry is included in this plan, with an emphasis on new regulations related to water reuse, with a focus on agricultural applications. The document also considers that, in the future, there will also be a focus on revising directives for wastewater treatment and sewage sludge management (EC, 2021b).

Specifically regarding sanitation systems, the application of circular economy has great potential, especially when aligned with sustainability concepts. For example, increased revenue generation and reduced waste disposal help to make circularity projects in these systems financially and economically viable, in order to achieve more sustainable systems (TBC, 2016). Thus, water, sewage and sanitation services have the potential to become drivers for circular economy (IWA, 2016). Considering that domestic wastewater treatment plants (WWTPs) generate a large amount of waste, while at the same time being extremely important for public and environmental health, applying circular economy strategies to these systems is a promising alternative.

In addition, there is a diversity of actors who are (or potentially should be) involved in the context of sewage treatment systems and their interfaces (public and private institutions and organizations, legal framework, processes and people), which consequently implies the complexity of the process of their transition to circular economy.

This range of networked members that need to act synergistically (sometimes collaborating, sometimes competing) and establish robust governance, in order to generate value and minimize the overall use of resources, waste generation, pollution and emissions, is called a circular ecosystem (KONIETZKO et. al, 2020; MOORE, 2006; PARIDA et al., 2019).

Based on this assumption, this work aimed to analyze how circular economy is being established in domestic sewage treatment processes, identifying factors that directly influence this implementation. After the literature review, to synthesize the knowledge obtained, a SWOT matrix was constructed to contribute to the analysis of the factors surrounding the implementation of circular economy in such processes.

2. Methodology

The studies analyzed in this paper were obtained from the Scielo, ScienceDirect, Scopus and Web of Science databases and the key question used to find them was: "How can circular economy be applied in conventional domestic wastewater treatment plants?". The search strings "circular economy" AND "sewage treatment" OR "wastewater treatment" were used. In the case of the Scielo database, the expressions in Portuguese were also used.

Publications whose characteristics were not in line with the proposed research were excluded, such as studies dealing with the treatment of industrial sewage, which promoted new structures for the treatment of domestic sewage or which only mentioned sewage treatment and circular economy, without focusing on their relationship.

Due to its scientific importance, the so-called gray literature was also considered. This type of literature includes term papers, handouts, manuals, reports, website content, standards and technical specifications, which are produced by government agencies, academic institutions, companies, industries, associations and non-governmental organizations (BOTELHO; OLIVEIRA, 2015).

After analyzing the main points made by the authors of the selected documents, a SWOT (Strengths - Opportunities - Weaknesses - Threats) matrix was structured, which is a simple way of laying out factors related to strategic issues and, therefore, adheres to the purpose of this work.

3. Results

3.1. Conceptualization of circular economy and its inclusion in wastewater treatment systems

Circular economy is seen as an effective alternative to the linear economic model, based on cradle-to-cradle implications (FISHER et al., 2020), presenting itself as a sustainable development strategy to reduce environmental degradation and control problems related to resource scarcity (KISELEV; MAGARIL; RADA, 2019). In addition, this alternative aims to promote the efficient production and use of material, energy, financial and labor resources in such a way that waste disposal is reduced or, in certain cases, eliminated (KAYAL et al., 2019). It is also seen as an alternative for increasing the resilience of processes by reducing the number of cases of interrupted resource availability (FISHER et al., 2020; LIPIŃSKA, 2018), a situation that occurs in many parts of the world (KAYAL et al., 2019; LÓPEZ; SANZ; MORENO, 2019).

Circular economy and its principles can be implemented, in addition to the waste and recycling sector, in sectors such as electricity, heating, renewable energies and trade and services (LIPIŃSKA, 2018). Within this group, the following stand out: agricultural; industrial; and municipal sectors (TAHIR et al., 2018). From this premise, the crucial role of WWTPs in policies to implement this model in the most diverse cities and towns in the world stands out (KISELEV; MAGARIL; RADA, 2019). These systems are waste producers with a large amount of energy, just as the treatment processes require a large amount of energy for their operations, which makes resource recovery an attractive option (ZOUBOULIS; PELEKA, 2018).

Thus, contributions to resilience can also be observed in the water industry. As stated by Casiano Flores et al. (2018), López, Sanz and Moreno (2019) and Mavhungu et al. (2020), the positive effects of circularity in these systems should be considered from the point of view of water availability, in addition to the issue of increasing water quality in surface watercourses. López, Sanz and Moreno (2019) also point out that the development of new water sources has a positive social impact through the creation of new jobs.

Furthermore, it is worth highlighting the relationship between wastewater and environmental and human health problems, which makes the management of this product a global rather than regional concern. In this context, alternatives that generate the least possible negative impact, combined with collection, transportation and disposal operations, are essential (VILLARÍN; MEREL, 2020). The transitions advocated here can be made, for example, through changes in processes, such as the reuse of biosolids and the recovery of thermal energy from effluents (TAHIR et al., 2018; TIAN et al., 2020).

Another key aspect in the introduction of circular economy practices in WWTPs is the large amount of nutrients present in sewage, since the substances ingested by the human body are not fully absorbed (ELLEN MACARTHUR FOUNDATION, 2017a). In general, these nutrients are extracted, used and remain concentrated in cities, being disposed of incorrectly and unsustainably, not following the natural flow back into the soil (ELLEN MACARTHUR FOUNDATION, 2018). However, nutrient recovery is possible from effluent digestion and it is a valuable justification for implementing circular models in these sectors (PAIHO et al., 2021).

The importance of water as a resource for maintaining life makes it an essential point for discussions involving the application of circular economy alternatives (CASIANO FLORES et al., 2018), and the transition to a circular model in WWTPs is considered inevitable (ABU-GHUNMI et al., 2016). This is because wastewater treatment systems are highly relevant to sustainability, through practices that are less aggressive towards the climate and more efficient in terms of energy and resource use (WAGNER et al., 2020).

These systems are of great importance for this transition as a whole, based on the premise that circular economy can be effectively implemented in this sector (KALEMBA, 2020), and are also important for the development of circular cities, based on the establishment of urban bioeconomies (ELLEN MACARTHUR FOUNDATION, 2017b). Wastewater treatment plants are systems that are naturally destined for circular economy (KAYAL et al., 2019), and the management objectives of the water-sewage-sludge sector are already closely linked to this model (LIPIŃSKA, 2018). In this way, these systems are fundamental in the transition from a linear model to a circular reality, being carriers of energy and resources of great value (DUCOLI; ZACCO; BONTEMPI, 2021).

Despite this importance, the current model on which WWTPs are based is not sustainable (KISELEV; MAGARIL; RADA, 2019). Therefore, in order to reinforce the primary ideas of circular economy, this transition must prioritize the recovery of nutrients and energy resources in the plant itself, with the remaining waste going to sustainable alternatives (SMOL, 2020). In this way, biological materials should return to their natural metabolic cycles and non-recyclable waste should be used in energy recovery processes (BIEŃ; BIEŃ, 2019). Sewage treatment becomes part of the idea of "closing the loop" by changing the view from waste to resources (ABU-GHUNMI et al., 2016). Circular economy practices, in this context, would transform wastewater treatment plants into manufacturing centers (FISHER et al., 2020).

Society as a whole needs to understand that sewage represents a rich stream of different valuable substances, capable of generating positive economic impacts (GUERRA-RODRIGUES et al., 2020). Considering this importance, there is a recent belief that the WWTPs of the future need to be designed, from the outset, as biorefineries to promote the recovery of resources from sewage (GUERRA-RODRIGUES et al., 2020). In this sense, especially in large systems, Kacprzak et al. (2017) believe that the main objective should be to maximize energy recovery.

For these transitions, the introduction of the private sector in engagement is a necessity (ABU-GHUNMI et al., 2016). Businesses are being pressured to seek, in addition to economic sustainability, environmental and social sustainability (FISHER et al., 2020), in order to "do more with less", and circular economy practices are aligned with these ideas (KAYAL et al., 2019). In this context, in addition to engagement, partnerships with private companies to implement circular economy alternatives are important, as well as cooperation with universities and research institutes (CHRISPIM; SCHOLZ; NOLASCO, 2020).

3.2. Important advantages

Wastewater is considered to be one of the means of proliferation of some viruses and, through the correct management of this waste, such as the incineration of sewage sludge at high temperatures, it is possible to promote the inactivation of these agents. The ash obtained, in turn, can be used as a component of construction materials (DUCOLI; ZACCO; BONTEMPI, 2021).

It is also important to highlight the interdependencies and beneficial relationships created by these practices. The organizations responsible for the WWTPs can benefit from the marketing of their products, just as, for example, farmers are provided with quality inputs at a lower cost (MAASS; GRUNDMANN, 2016). In this way, there is the possibility of creating relationships between rural and urban areas, making it possible, for example, to reduce transport costs for the purchase of fertilizers (JEDELHAUSER; BINDER, 2018). In some cases where circular models are applied to WWTPs, part of the added value ends up remaining within the communities in which these systems are located, which not only reduces the extraction of virgin resources, but also keeps capital within the region (MAASS; GRUNDMANN, 2016).

Finally, the growing volume of wastewater and the need to promote more sustainable wastewater management is another justification, as well as an advantage, for the introduction of circular practices (MAVHUNGU et al., 2020). Maintaining water flow in scarce regions and minimizing costs are also considered important advantages (HAGENVOORT et al., 2019).

3.3. Limiting factors

One of the limiting aspects pointed out for the implementation of circular economy is the top-down perspective. In this configuration, decision-makers at lower hierarchical levels have their actions subordinated to managers at higher levels (CASIANO FLORES et al., 2018), which can lead to slow processes and reduced implementation of effective solutions. The authors also believe that the time it takes to observe the results and the need for high initial investments, as well as, in many cases, the absence of polluter-pays principles and the resistance to change generated by the existence of well-established models are other limiting factors.

Another barrier cited, both for implementing circular models and for carrying out studies in this area, is the unavailability of data (ABU-GHUNMI et al., 2016). Lack of knowledge of practices and technologies is another limiting factor. For example, in a study carried out with various stakeholders on the use of biogas from WWTPs in the transport sector in Stockholm (Sweden), it was noted that there was a lack of knowledge of solutions for these uses, making both the role of decision-makers and acceptance by customers difficult (AMMENBERG et al., 2018).

Another limiting factor is the lack of interest from industries in investing and seeking new technological solutions for the transition to circular systems, even though organizations are aware of the environmental problems generated by their activities. This limiting factor is due, among other reasons, to the lack of incentives from governments (DE BOER et al., 2018), as well as specific programs and legislation.

Public acceptance is cited as another stumbling block. For example, some people tend to refuse products obtained from crops irrigated by effluent from wastewater treatment plants (KISELEV; MAGARIL; RADA, 2019). The most cited aspect is water reuse, which is still hampered by many barriers (LIPIŃSKA, 2018), such as public perception (CHRISPIM; SCHOLZ; NOLASCO, 2020). Despite the diversity of technologies for converting sewage into high-quality water, social research efforts are needed in this area precisely to facilitate public acceptance (VILLARÍN; MEREL, 2020). This rejection, which sometimes occurs even on the part of other stakeholders, can be explained by public health concerns, although an inherent prejudice towards the use of these materials is also a justification (DE BOER et al., 2018; MAASS; GRUNDMANN, 2016).

Other difficulties include the need to invest in hydraulic works and the high-quality standards that are sometimes required (HAGENVOORT et al., 2019), and the dialogue with potential user sectors, such as agriculture (ANICIO et al., 2022).

3.4. The role of governance and public policies

Political factors are sometimes highlighted as some of the main factors in the implementation of circular models in wastewater treatment systems. Encouragement from governments for this transition is extremely important (ABU-GHUNMI et al., 2016; CASIANO FLORES et al., 2018), as well as from public organizations in general (AMMENBERG et al., 2018).

In addition to the role of governments, at their various hierarchical levels, the role of local governance, as well as members of environmental activist movements, is also highlighted, as it brings the importance of circular models to communities and facilitates the population's acceptance of the use of products from these alternatives (ABU-GHUNMI et al., 2016).

It can also be seen that circular alternatives are inserted into highly complex value chains (which can be structured into circular ecosystems), involving different interdependent governance structures, which need to be aligned in order to apply transitions efficiently (MAASS; GRUNDMANN, 2018). There is a need to promote synergy between these actors (CASIANO FLORES et al., 2018), considering all the integrated systems, and not just the processes that take place in the WWTPs (WAGNER et al., 2020). Thus, far beyond technological development, this transition needs to consider the participation of various stakeholders, and it is conditional on the decisions made by them (JEDELHAUSER; BINDER, 2018; PICARDO et al., 2019).

The regulatory issue is another key factor (ELLEN MACARTHUR FOUNDATION, 2017a). There is a need for laws and regulations that facilitate these changes, taking into account, for example, aspects relating to the health of users, quality parameters for products and services and the encouragement of effectively circular practices (ABU-GHUNMI et al., 2016). A recurring example of this issue is the reuse of effluent, which is sometimes hampered by restrictions relating to legal or health issues (CIPOLLETTA et al., 2021; KISELEV; MAGARIL; RADA, 2019).

Thus, regional and even international standards that regulate sustainable wastewater management, considering the high value of this resource and its role in generating conflicts of interest, are extremely important (VILLARÍN; MEREL, 2020). In this sense, legislators and regulatory bodies need to take into account the comprehensive aspect of actions related to the application of these practices, their intersectoral characteristics, and alignment with national projects and objectives (JEDELHAUSER; BINDER, 2018).

Incentive policies are also considered an important aspect, in order to encourage management institutions to implement resource recovery practices and market acceptance of the use of the products obtained (CHRISPIM; SCHOLZ; NOLASCO, 2020), as well as being essential when considering problems with scarcity (PARDO; PÉREZ-MONTES; MOYA-LLAMAS, 2020), such as those with water and energy. These policies must be associated with a change of mindset on the part of society, governments and private companies, in order to facilitate the transition from a linear to a circular economy (GUERRA-RODRIGUES et al., 2020). In this context, the adoption of green technologies as mandatory for the construction or regeneration of WWTPs could be an alternative to enable such a transition (CASIANO FLORES et al., 2018).

In addition to the regulatory issue, encouragement through funding is also seen as a means of achieving more sustainable wastewater treatment systems, based on the idea that recovered products can be valuable to the market (DE BOER et al., 2018; SAIDAN et al., 2020).

3.5. Waste from wastewater treatment plants in circular economy

Some considerations about waste from WWTPs are presented below, as well as their inclusion in circular models.

3.5.1. Sewage sludge

Sewage sludge is a semi-solid or solid product, with humidity between 75 and 99% (CHEN et al., 2020), made up of a mixture of water, organic matter, microorganisms and organic and inorganic toxic contaminants (KACPRZAK et al., 2017), as well as pathogenic bacteria and heavy metals (CHEN et al., 2020). It is categorized as biomass, being a source of high-value substances for both the biological and technical cycles (LIPIŃSKA, 2018). It can also be used as an energy source for heat and power production and as a raw material for fertilizer production, making it an economically and environmentally viable alternative (KACPRZAK et al., 2017).

The management of this product represents a significant portion of sewage treatment costs (LIPIŃSKA, 2018), mainly due to the high cost of landfill disposal, a practice that is becoming less and less applicable due to regulatory restrictions and social pressure (CALLEGARI; HLAVINEK; CAPODAGLIO, 2018). The correct management of this product, in turn, can be aligned with the precepts of circular economy, based on the recovery of energy, heat and nutrients, allowing the cycles of certain resources to be closed (ROSIEK, 2020).

Considering the problems of climate change, the recovery of energy from organic matter in sludge is an alternative for reducing greenhouse gas emissions (ELLEN MACARTHUR FOUNDATION, 2018), by reducing the use of fossil fuels, as well as contributing to increasing soil quality (KACPRZAK et al., 2017).

Regarding the loss of valuable biological nutrients, given the current linear disposal of those related to sewage and other organic waste in most cities, the idea of their recovery becomes a viable alternative (ELLEN MACARTHUR FOUNDATION, 2018). Sewage sludge then needs to be seen as a reservoir of energy, compounds and nutrients, such as phosphorus and nitrogen (KACPRZAK et al., 2017), so that its processing and beneficiation become aligned with pro-ecological principles and with the idea of turning waste into products (KASZYCKI; GŁODNIOK; PETRYSZAK, 2021).

From a circular point of view, sludge should be seen as a raw material (KOMINKO et al., 2018), and its sustainable production can even be improved using adjuvants that improve the efficiency of the sludge in drying processes (GOMES et al., 2020). Examples of this are sludge pre-treatment processes that seek to boost biogas production for later recovery, with biological pre-treatment and co-digestion being the most economically viable and efficient (VOLSCHAN JUNIOR; DE ALMEIDA; CAMMAROTA, 2021).

Mechanical, thermal, chemical, biological and hybrid processes are used to process sewage sludge (KLEDYŃSKI et al., 2020), and the current availability of various technologies enables nutrient recovery to be in line with environmental quality standards (ROSIEK, 2020).

The use of thermally processed sludge is promising as it significantly reduces the volume of waste and destroys organic substances that are difficult to biodegrade, as well as pathogens. These methods include incineration, gasification and pyrolysis. Of these, the incineration process is considered the best according to financial aspects, and it is possible to use the ashes in the production of construction materials (DUCOLI; ZACCO; BONTEMPI, 2021; GUERRA-RODRIGUES et al., 2020; SMOL, 2020), as well as recovering phosphorus from the ashes and recovering the heat generated, which can be used, for example, in the sludge drying process (BIEŃ; BIEŃ, 2019), reducing the mass of the waste by 60 to 70%. Incineration can also produce around 555-1068 kWh/ton by generating electricity from the gas produced (SINGH; PHULERIA; CHANDEL, 2020). There is also the option of roasting sewage sludge with a high concentration of ash to produce organic fertilizers (PULKA et al., 2020).

Still about incineration, it is a safe option for health crisis situations where it is necessary to neutralize pathogens. In times like these, the amount of waste sent to landfill increases, as concerns about contamination risks reduce recycling processes. Therefore, incinerating sewage waste is also an option to reduce the volume of waste disposed of (DUCOLI; ZACCO; BONTEMPI, 2021).

From pyrolysis, a process in which there is thermal decomposition without the presence of oxygen gas, biochar, bio-oil (biodiesel) and gaseous products (syngas) can be obtained. Syngas, made up of hydrogen gas (H_2), carbon monoxide (CO), methane gas (CH_4), carbon dioxide (CO_2) and water (H_2O), among other compounds, is considered the least valuable product. Biochar, a solid waste product, can be used as a compound in cement (ROYCHAND et al., 2021), in chemical and metallurgical processes, water purification processes and in agricultural processes to correct the soil, improve aeration and water retention capacity. Finally, biodiesel can be used as a transportation fuel (CALLEGARI; HLAVINEK; CAPODAGLIO, 2018). It is therefore understood that the use of these biodegradable materials is promising, through the introduction of this waste into value chains (LIMA et al., 2020).

Considering agricultural use, the most expressive destination of this reused material (LIPIŃSKA, 2018), this product can be co-digested with other organic waste, making it possible to further minimize the loads dumped in landfills (TIAN et al., 2020). Mixtures from this codigestion can produce high-quality fertilizers (PECORINI et al., 2020), surpassing mono digestion (VOLSCHAN JUNIOR; DE ALMEIDA; CAMMAROTA, 2021), as well as being highly efficient in improving poor soils (CRISTINA et al., 2019). It is worth noting that certain limitations to this use still exist, generated by the risk of the presence of pathogens and the possibility of contamination and that, in order to guarantee its viability, it is necessary, for example, to have a market analysis that considers possible consumers for the fertilizers produced (KACPRZAK et al., 2017). For agricultural use of sewage sludge, Brazil and other countries, such as the United States of America, have well-established legislation, which is not the case for other uses of sludge, such as materials for construction (ANICIO; BEGA; MALHEIROS, 2023).

An estimate by the Ellen MacArthur Foundation, a leading organization in encouraging the transition to a circular economy, indicates that the recovery of sludge into biofertilizers in the city of São Paulo could save 4 million dollars in landfill costs and generate revenue of 2.8 million dollars a year from the recovery of nitrogen and phosphorus, with a generation of 202.005 tons of biofertilizers and a reduction of 40.000 tons of Greenhouse Gas (GHG) emissions, related to the avoidance of the generation of these gases after dumping in landfills (ELLEN MACARTHUR FOUNDATION, 2019).

More specifically, the recovery of so-called biogens, such as phosphorus and nitrogen, is important for various sectors of the economy (LIPIŃSKA, 2018). The phosphorus recovered from composting, in the form of phosphoric acid, can be used in anti-corrosion and rust-removing processes (JEDELHAUSER; BINDER, 2018). When obtained by precipitating the supernatant liquid after centrifuging the sludge, the phosphorus is in the form of struvite (KEHREIN et al., 2020), or magnesian ammonium phosphate, a heterogeneous material whose characteristics vary depending on the wastewater treatment plant (JEDELHAUSER; BINDER, 2018). The recovery of this material helps to minimize problems with fouling in pipes (ELLEN MACARTHUR FOUNDATION, 2017a), and it can be done, in addition to the commonly used precipitation process, from the liquor obtained after drying the sludge, which is even more efficient in recovering the nutrient (SIMOES et al., 2020).

The recovery of phosphorus from sludge, although still at an early stage of implementation (JEDELHAUSER; BINDER, 2018), is considered an easy alternative to implement, with various possibilities (EGLE; RECHBERGER; ZESSNER, 2015) and is an interesting alternative to the low natural availability of the nutrient, which is of great importance for food production and whose reserves are under pressure due to the increase in the world population (KLEDYŃSKI et al., 2020).

Thus, transforming the flow of phosphorus in the environment into a circular system has been spreading (NENOV et al., 2020), closing the cycle between food, people and soil, as well as being economically attractive, especially given the growth in the price of the nutrient in recent years (ELLEN MACARTHUR FOUNDATION, 2017a). In addition to reducing the amount of phosphorus discharged into watercourses and contributing to better sludge management (NENOV et al., 2020), recovery technologies are also attractive because they can be incorporated into existing processes at WWTPs (DE BOER et al., 2018).

Another alternative for the inclusion of this product in circular economy is its use as a raw material for adsorbents (WERLE; SOBEK, 2019) and bioplastics (GUERRA-RODRIGUES et al., 2020), as well as the extraction of nanocellulose from toilet paper waste present in wastewater networks (ESPÍNDOLA et al., 2021). Cellulose can also be used to obtain fibers to be used in mortars, being able to increase the water vapor permeability and buffering capacity of the final product (PALMIERI, 2019).

Finally, it is worth noting that even sustainable product recovery options are not emission-free. Thus, the trade-off between maintaining the current disposal and the options of making the sludge useful for fertilizer production and for other alternatives must be analyzed (SVANSTRÖM et al., 2017), for example from the perspective of life cycle analysis.

3.5.2. Biogas

The biogas generated by sewage treatment processes consists of CH_4, hydrogen sulfide (H_2S), H_2 and CO_2. Its production is proportional to the reduction of volatile solids in the sludge, being generated in the range of 0,75 to 1,1 Nm^3/kg (0º C and 1 atm) of material (PICARDO et al., 2019). Anaerobic digestion of sludge can generate around 315-608 kWh/ton of product (SINGH; PHULERIA; CHANDEL, 2020).

This product can be transformed into electricity or injected into natural gas networks (ELLEN MACARTHUR FOUNDATION, 2018), as well as being used for the joint production of heat and energy (CHANG et al., 2019) and to produce biomethane from anaerobic digestion (MICHAILOS et al., 2020). In this way, harmful gases can be used as a useful energy source (ELLEN MACARTHUR FOUNDATION, 2018), contributing to the reduction of greenhouse gas emissions, the reuse of resources and pollution control, while also being sustainable by replacing the use of fossil fuels (CHANG et al., 2019).

Although the treatment processes carried out in WWTPs are responsible for reducing water pollution, they also consume a large amount of energy and produce waste that can intensify climate problems (KISELEV; MAGARIL; RADA, 2019). Using biogas to produce electricity, for example, could be an option for minimizing significant expenses (CASIANO FLORES et al., 2018; SINGH; PHULERIA; CHANDEL, 2020). Sludge can be processed continuously to produce biogas, generating a smaller carbon footprint than other methods (TAHIR et al., 2018).

As an example, at a WWTP located in Valencia, Spain, the production of electricity from biogas is responsible for supplying 65% of the plant's electricity needs (HAGENVOORT et al., 2019). Similarly, some WWTPs that produce energy from biogas can meet all their needs and even generate surplus quantities that can be sold (ELLEN MACARTHUR FOUNDATION, 2018). In this way, there is the possibility not only of improving energy efficiency, but also of promoting self-sufficiency (LIPIŃSKA, 2018) and generating economic benefits (ELLEN MACARTHUR FOUNDATION, 2017b).

3.5.3. Reuse water

The reuse of effluent treated in WWTPs is another alternative for inserting them into circular models. The use of this alternative can generate greater water availability and reduce the discharge of contaminated water (LÓPEZ; SANZ; MORENO, 2019), and when it is of high quality, reuse water is considered the most valuable product in this chain (ELLEN MACARTHUR FOUNDATION, 2017a). The practice of circular economy is already more widespread in the use of this effluent, with water reuse already being adopted in locations experiencing problems of low water availability. However, this use is also recommended in regions that do not experience such issues, due to the environmental benefits generated, especially when considering the reduction in pressure on water bodies (GUERRA-RODRIGUES et al., 2020; LIPIŃSKA, 2018).

The reuse of wastewater in agricultural processes is also considered a strategy for the transition advocated in this work, applying circular economy concepts to both the water industry and agriculture (MAASS; GRUNDMANN, 2018). As a solution to low water availability in the countryside, this effluent can be used in irrigation processes, machine cooling, street cleaning, centralized heating (KISELEV; MAGARIL; RADA, 2019), cooling power generators and sanitary appliances (KLEDYŃSKI et al., 2020). Its use in agriculture can be a financially viable option, meeting the needs of crops in times of drought and avoiding the expense of pumping groundwater, as well as helping to reduce fertilizer costs due to the presence of nutrients in the effluent (HAGENVOORT et al., 2019).

It is believed that correct control of the risks associated with this practice, such as the presence of pathogens and emerging micro-pollutants, will increase the use of this effluent as valuable water (GUERRA-RODRIGUES et al., 2020). As a result, faced with the problems of scarcity and the growing water demand, this effluent can stop being a waste product and become a valuable resource for various uses, including, in certain cases, the production of drinking water (VILLARÍN; MEREL, 2020).

In addition to biosafety factors, analysis of the nutrients present in the effluent is important, since excess quantities can lead to excessive concentrations of these substances in the soil and nearby water reserves. Therefore, it is important to consider the dependence of the volume of reuse water for irrigation on the characteristics of the soil and crop in question, evapotranspiration rates and rainfall (MAASS; GRUNDMANN, 2018).

It should also be considered that the reuse of wastewater can generate environmental and economic-financial impacts, whether due to the use of chemical products, energy consumption in advanced treatments, the need to invest in new facilities (LÓPEZ; SANZ; MORENO, 2019) or even the need for these reuse waters to have a lower commercial value than treated water from the water treatment plants, in order to become attractive to users (SAIDAN et al., 2020). Another relevant aspect to be considered is the impact on cities and communities downstream of the point of reduced discharge of treated sewage (VILLARÍN; MEREL, 2020), whether from a quantitative or qualitative point of view.

3.7. SWOT matrix

Based on the analysis of the texts considered in this review, the SWOT matrix shown in Chart 1 was drawn up.

Chart 1: SWOT matrix for the application of circular economy practices in WWTPs

Strengths	Weaknesses
- High availability of waste and nutrients; - Natural cycles inherent to wastewater treatment products; - Possibility of effective implementation.	- Presence of pathogens and emerging micropollutants; - Old installations in WWTPs; - Concerns about the by-products that can arise from the use of products derived from sewage treatment and their correct destination within a circular ecosystem.
Opportunities	**Threats**
- Great search for research and new technologies; - Scarcity of water resources and climate change; - Change in mindset and pressure from society for more sustainable alternatives; - Loss and scarcity of nutrients in cultivated soils, especially in monocultures; - Market interest for investments in a promising market.	- Weak legislation; - Little public acceptance; - Few government incentives; - Difficulties in changing well-established structures; - High initial investment requirements; - Incorrect disposal of by-products generated from the use of wastewater treatment products.

Source: Authors (2024).

4. Conclusions

Problems related to climate change and the scarcity of resources are driving the search for sustainable alternatives that, in addition to reducing pressure on the environment, generate economic benefits that facilitate the implementation of these practices. In this sense, circular economy has become a strategy for creating cycles in ecosystems and promoting the use of the value of materials.

Sewage treatment is an extremely important activity for human health, and its relationship with the environment reinforces the need for more sustainable practices applied to these systems. Considering the large amount of waste generated and its intrinsic value, whether in the form of nutrients, energy or water resources, the adoption of circular practices by these systems presents itself as a way of adding economic value to the waste produced, while also contributing to proper disposal and reducing the emission of pollutants.

Wastewater treatment plants are considered to be systems that are naturally suited to the adoption of circular models. Despite the advantages offered, aspects such as the lack or deficiency of legislation, the need to invest in certain technologies, the lack of government incentives and resistance on the part of companies and the public still hinder the application of these practices in wastewater treatment. However, the tendency is for the search for a transition from linear to circular models to increase, driven by the need to promote sustainable development.

Legislative and governmental changes, as well as changes in the mindset of various sectors and stakeholders, are therefore necessary in order to encourage the application of circular technologies and practices in the context of WWTPs.

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