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Review

Circular Economy, Eco-Innovation and a Business Model for the Operation of Wastewater Treatment Plants in Mexico

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Abstract: Wastewater treatment plants face enormous economic, environmental, technical, and regulatory challenges, including the high energy costs of their operation, waste generation, and the destination of treated water. In this regard, a proposal was made for the operation of municipal WWTPs in Mexico, based on the symbiosis of the circular economy and eco-innovation as strategies for sustainable change in their operation. As a result, it was possible to obtain an updated diagnosis of the situation of the WWTPs, a proposal for their operation was made, and a circular and innovative business model was established for these plants in order to channel decision-making and visualize the path for the transition of these facilities to sustainable operation.

Keywords: sewage sludge; water reuse; circular economy

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1. Introduction

Currently, municipal wastewater treatment plants (WWTPs) in Mexico face great challenges in their operation. Among these are the reduction in negative environmental impacts and the operation costs involved, as well as transitioning to an operation based on the circular economy (CE), which allows for the sustainable management of sewage sludge and its use as a source of energy, nutrients and water reuse, as well as the necessary regulatory conditions for its use [1–3]. It has been determined that municipal governments do not have the necessary solvency for this management; consequently, the management of their plants is not prioritized, and priority is given to the drinking water supply and sewerage services rather than sanitation [4]. Sanitation is, in fact, the aspect with the least investment, representing only 15% of the resources allocated to water management [5].

WWTPs are designed and built with the purpose of eliminating pollutants and generating treated water that complies with federal and state regulations in terms of discharge. This water can then be used for agricultural irrigation, watering parks, gardens and environments with aquatic life. It can even be supplied for direct human use depending on the quality of the treatment received [6]. WWTPs belong to the public services sector [7], and municipal governments are fully responsible for their operation and maintenance [4]. The typical configuration of a WWTP includes a series of physical, chemical and biological processes that are used in four different stages (pre-treatment, primary, secondary and tertiary treatment) to obtain both treated water and sewage sludge [8,9].

1.1. Treatment and Use of Sewage Sludge

Managing the sewage sludge generated in WWTPs has posed a huge challenge. Initially, the only option contemplated was disposal in landfills; nowadays, alternatives are being sought that allow a more sustainable management model, taking maximum advantage of its potential [10]. With regard to the treatment and final disposal of the sludge generated in water treatment, it represents between 25 and 60% of the infrastructure and total budget of the plant operation. The most common treatment of this residue is gravity thickening, belt filter dewatering and aerobic stabilization [11].

Currently, the following four main trends can be identified in the end-use of the sludge generated in the WWTPs: final disposal in landfills and discharges into the sea, which is decreasing; its use as fertilizer, which is the predominant use; as a base product for the extraction of different materials, which is also increasing; and finally, the use as an energy recovery source, which has remained stable [12,13]. Also, tests have even been carried out to use the sludge as a building material [14]. The destination of sludge has changed over time, and it also changes with each country. As a reference, we have the European Union, where the most widespread sewage sludge disposal practices are its application in agricultural use (67%), energy production (27%) and final disposal (6%) [10].

Regarding treatments to use the energy potential of sludge, various processes can be implemented, including co-digestion, anaerobic digestion and biogas production, pyrolysis and fuel production, gasification, as well as incineration. Each of them have different benefits and implementation conditions [15,16]. Optimal treatment depends on costs, changes in technology, physicochemical properties of sludge and utilization potential [10,12,13]. Regarding anaerobic digestion and biogas production, it has been proven to be a consolidated strategy for energy self-sufficiency and consequently for the economic viability of WWTPs, as it is estimated that the use of sludge for biogas production can cover up to 70% of their electricity consumption [17].

1.2. Reuse of Treated Water

The reuse of water is important for the benefits it brings, such as the water supply to agricultural production systems and a reduction in the scarcity of this vital resource. This has been achieved through implementation of the circular economy approach, which has still been little explored but could accelerate these benefits [2,18]. Regarding water reuse, the 2019 water statistics from Mexico show that 31% of the treated water is reused and only 5.8% of water is reused to replace first-use water [5].

1.3. Sustainability Strategies in the Operation of WWTPs

Transforming the operation of wastewater treatment plants involves generating resources from waste as well as reusing treated water to deal with water scarcity [19]. To transition to this form of operation, WWTPs require a sustainability framework that allows them to seek economic prosperity and protect natural systems and quality of life for people [20]. In this regard, the CE is a model that aims to contribute to the sustainability of production and consumption processes through principles such as reducing waste generation and promoting its use, keeping resources in use, regenerating nature and moving towards the use of renewable energies and materials [21–23]. In addition, it has been possible to identify a clear relationship between some CE indicators and the Sustainable Development Goals (SDGs); therefore implementing CE initiatives contribute to the achievement of the SDGs [24,25]. Thus, many companies, institutions, regions and citizens have stressed the importance of the transition to CE as a way to contribute to sustainability [24].

According to the Ellen MacArthur Foundation, CE involves three principles: preserving and enhancing natural capital through the use of renewable energy sources; optimizing resource yields through maximum utility of materials; fostering system efficiency through the elimination of negative externalities [26]. The principle of maximizing the utility of materials involves two main cycles to maintain a circular economy system: the biological and the technical cycles. The biological cycle applies the principles of regeneration, nutrient recovery and anaerobic digestion; the technical cycle uses the principles of sharing, maintaining, reusing, redistributing, renewing, remanufacturing and recycling [27].

Six levers are required, according to the Ellen MacArthur Foundation, in order for governments and companies to transition to CE, which they have defined in a framework called ReSOLVE. This corresponds to the following six actions: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange; it is considered that the implementation of these actions increases the use of physical assets, extends the useful life of materials and replaces energy sources with renewable ones [28].

In addition to the ReSOLVE framework there is also the International Water Association (IWA) framework that proposes a set of pathways for water utilities from the CE. The necessary aspects this framework considers are the connection with interested parties, leadership, innovation and new business models. WWTPs are still considered to be part of the old paradigm, i.e., only the elimination of pollutants rather than the reuse of their waste. According to this framework, WWTPs are part of a large closed loop in which three CE routes are proposed: the water route, the materials recovery route and the energy route [29].

In addition to CE, another tool that contributes to the achievement of sustainability is innovation, in particular eco-innovation (EI). This involves innovative practices that combine economic benefits with the care of natural resources [30]; the object of innovation can be a product, process, service or method, reducing the resources used and consequently the negative impact on nature [31,32]. The link between CE and EI is still being researched; however, it is considered that they have a close relationship and, in order to transition to CE, innovations compatible with this approach are required [32–34]. However, innovation is one of the fundamental barriers to overcoming to move to the circular economy [18,35,36]. Innovation can have a positive impact on WWTPs through changes in processes, regulations and management.

Many innovations have been generated, in addition to traditional options such as energy generation, related to the sustainable use of sewage sludge from variations in the anaerobic digestion process [37]; pyrolysis processes have become more efficient [38], and sewage sludge has been used as construction material [14,39]. In water treatment issues, different and more efficient technologies have been developed, e.g., membranes, economic microalgae systems and advanced oxidation, among many others [40].

However, from a business point of view, it is important to know the role of business models in the circularity approach. A business model provides the logic for creating, retaining, and delivering value [41,42]. When that business model considers circularity instead of a linear chain for value creation, the company or organization contemplates the use of loops and networking in production. The objective is to reduce the impact of linear alternatives so as to increase the value and useful life of both raw and processed materials; in other words, a circular business model (CBM) [41].

A process or service can adopt any of the above approaches and, in the case of WWTPs, they could improve economically, environmentally, and socially. However, the union of these approaches is unclear, so a way must be sought to unite the coincidences and find a form of operation that is both unifying and sustainable. In this regard, the purpose of this research is to make a proposal for the operation of the WWTPs based on the CE, the EI and the CBM so that they converge towards a common objective and a proposal to achieve the sustainability of the WWTPs can be obtained.

2. Methods

2.1. Diagnosis of the WWTP Situation in Mexico

An exploratory descriptive study was carried out, with its main focus being on qualitative methods, in order to obtain a diagnosis of the current situation of wastewater treatment plants in Mexico. The most recent official government documents were taken as inputs, such as the National Censuses of Municipal Governments and Territorial Demarcations of Mexico City, by the National Institute of Statistics and Geography (INEGI); the National

Inventories of Municipal Water Treatment and Wastewater Treatment Plants in Operation, from the National Water Commission (CONAGUA); the reports of the Water Statistics in Mexico, from CONAGUA, and the Report on the Environment in Mexico by the Ministry of Environment and Natural Resources (SEMARNAT). The information collected in these documents was analyzed using descriptive statistics, which allowed us to obtain the current situation of WWTP operations in Mexico.

2.2. Symbiosis of Theories for the Sustainability of WWTPs

A search was carried out for theories regarding sustainability and possibilities of application in watercourse management, in particular in the operation of WWTPs. Three main approaches that maintain coincident elements in the search for sustainable processes were taken into account. These are (a) the CE and ReSOLVE framework, as it includes actions and principles that governments and companies can take to transition to CE and increases the use of physical assets, extends the useful life of materials, and replaces energy sources with renewables [28,43]; and the IWA framework, in which the water, materials recovery and the energy routes are proposed [29]; (b) EI, as a strategy of change that seeks to reduce the environmental risks and pollution caused by resources, processes, services, products, businesses or methods [32]; and finally, (c) the CBM, which allows for the creation, capture and delivery of value, not only taking economic aspects into account but also the social and environmental ones, in this case, Bocken's Circular Business Model Innovation (CBMI) [44]. Figure 1 shows the theoretical symbiosis proposal for the operation of WWTPs, which includes the approaches mentioned above.

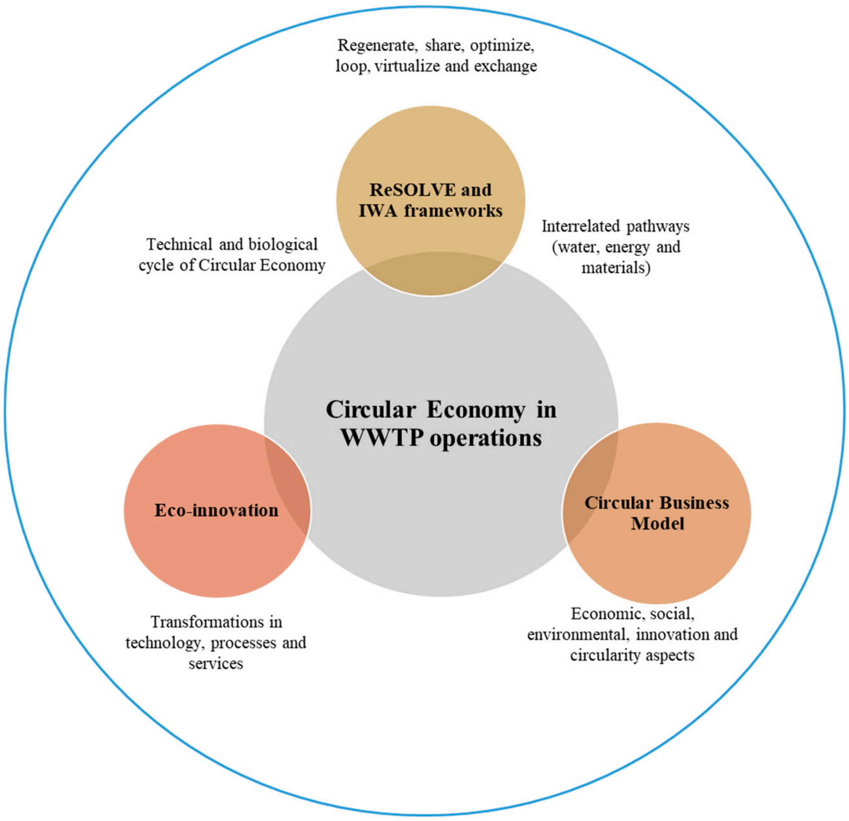

Figure 1. Symbiosis of theoretical approaches for the operation of municipal WWTPs.

2.3. Proposal for the Sustainable Operation of WWTPs

Based on the information obtained from the diagnosis of WWTPs in Mexico and the theoretical symbiosis proposed, a WWTP operation strategy was established. This proposal was based on two aspects; on the one hand, Ellen MacArthur's CE system model and the ReSOLVE framework were adapted to visualize the applicable circular economy strategies, while, on the other, those eco-technological, environmental and social innovations that have been identified as key were adopted. In addition, a CBMI was established to show the way forward in wastewater treatment and sewage sludge management.

The CE system, which shows the continuous flow of materials in CE, can be studied from two main cycles, the technical and the biological. The technical cycle refers to non-biodegradable materials, while the biological cycle refers to materials that can biodegrade and safely return to the soil. Materials from these cycles can be used in different ways before they become waste. The stages considered in the technical cycle are: sharing, to increase the utilisation of many products; reuse, which maintains products in use in their original form and for their original purpose; redistribution, another way to keep products in use and prevent them from becoming waste; renewal, returning products to their proper working order and remanufacturing products so that they can remain in circulation; and recycling, the ultimate way to keep using the materials from which the product is made [45]. The biological cycle includes regeneration as its main principle, which refers to the construction of natural capital; other principles of this cycle are agriculture, composting and anaerobic digestion, the use of loops and the extraction of biochemical materials as raw material [43].

Within the framework of ReSOLVE, Regenerate involves recovering ecosystems, switching to the use of renewable energies and materials and returning biological resources to the biosphere. Sharing involves maximizing the use of products through exchange, repair, and design with greater durability. Optimization involves increasing product yields and eliminating waste. Looping involves keeping components and materials in closed loops through remanufacturing, recycling, anaerobic digestion and nutrient extraction, both from inorganic and biological products, respectively. Virtualizing involves delivering utility virtually. Finally, Exchange involves replacing old materials, applying new technologies, and choosing new products and services [26,28].

According to the IWA framework, the water route consists of actions involving rainwater harvesting, graywater recycling and water reuse in agriculture, aquaculture, industry and direct water reuse. The materials route involves resource efficiency and the utilization of sewage sludge. The energy route involves reducing carbon-based energy consumption and increasing renewable energy consumption; this requires optimization of operations in WWTPs, energy production in distribution systems, as well as energy production from sewage sludge. Different approaches are proposed for this transition, including integrated resource management, connection with interested parties, leadership, innovation and new business models. The use of regulatory levers, key to the transition to CE, is also considered [29].

In addition to the economics and ReSOLVE framework as approaches to the sustainable management of WWTPs, it is necessary to propose a business model for them, given that the application of CE could benefit the performance and finances of the plants [46]. In this regard, the model structure proposed by Bocken et al. [44] shows the ease of forming a sustainable business model, based on other relevant authors on the subject such as Osterwalder, Pigneur and Richardson. In this model, the social and ecological value is considered in addition to economic value. The canvas is systemic, based on CE as a driver of sustainability. It is composed of four values, considering that value is essential in the innovation of sustainable models. These values are creation, which includes resources and activities; proposition, which includes environmental and social aspects; capture, including costs and revenues and, finally, the value of delivery, which includes aspects of the customer relationship, segments and distribution channels.

The proposal of a business model canvas is a tool that allows for visualizing graphically the way to create, capture and deliver the value of an idea that creatively solves a problem [42]. The importance of this tool lies in the possibility of proposing strategies for companies or organizations that want to improve their economic situation while also protecting the environment and promoting social participation. This is shown in the case of the canvas proposal by Donner et al. [47], who made a first typology of the circular business model for the agricultural domain, which allows for experimenting with various creative business strategies based on CE and innovation.

3. Results

A generalized diagnosis of WWTPs in Mexico was obtained from two points of view, water reuse and sludge treatment and disposal. Two models were also obtained: one for the operation of WWTPs with respect to the applicable principles of CE and a circular and innovative business model which included all the strategies of circularity and innovation, thereby obtaining a sustainable and viable proposal for the operation of WWTPs in Mexico.

3.1. Diagnostics of Wastewater Treatment Plants

Regarding the situation of wastewater treatment plants in Mexico, it was found that, in 202,1 there was a record number of 4231 municipal WWTPs, of which 2872 plants were in operation, treating a flow of 145,341 L/s, which corresponds to a national coverage of 67.5% of municipal wastewater treatment. A total of 1359 plants were non-operational, representing 32% of the total [48]. To ascertain the behavior of the non-operational plants, data were reviewed for the year 2011, examining a total of 2719 plants; 2289 were in operation and 430 plants, or 15.8%, were non-operational [49]. In the behavior analysis of WWTPs in Mexico to discover the causes, it was observed that the percentage of non-operational plants had doubled over the course of 10 years (2011 to 2021); this means that about 929 plants stopped operations in that period. According to the latest census of municipal governments, when analyzing the results, it was observed that the main reported causes of non-operational WWTPs in Mexico were, firstly, operating costs; secondly, lack of maintenance and, thirdly, no water was received for treatment (water diversion) [50]. Also, unfinished construction of plants and, in other cases, theft of equipment and machinery were other elements [48,50]. Likewise, municipalities lack financial self-sufficiency for wastewater management [4,51].

Regarding the characterization of municipal wastewater in Mexico, the average concentration of contaminants is as follows: Biochemical Oxygen Demand (BOD5) of 220 mg/L, Chemical Oxygen Demand (COD) of 500 mg/L, Total Suspended Solids (TSS) of 220 mg/L, Total Nitrogen (Total-N) of 40 mg/L, Total Phosphorus (Total-P) of 8 mg/L and Oil and Grease of 100 mg/L [52]. According to Mexican regulations, wastewater effluent must not exceed certain permissible limits; in the case of discharge of treated water into water bodies, it must be COD of 100 mg/L, Total-N of 15 mg/L, Total-P of 5 mg/L, TSS of 20 mg/L and Oil and Grease of 20 mg/L [53].

An important aspect in the operation of municipal wastewater treatment plants is the type of process used for biological treatment. In this regard, the main biological processes used in Mexico in 2021 were stabilization lagoons (843 plants), corresponding to 29.3% of the total; activated sludge (818 plants), corresponding to 28.4%; upstream anaerobic reactors (390 plants), corresponding to 13.5%; artificial wetlands (230 plants), corresponding to 8%, and septic tanks (143 plants), corresponding to 4.9% [48].

3.1.1. Reuse of Treated Water

Regarding the destination of the treated water from the WWTPs in Mexico, 89.7% of the plants discharge it into a body of water (stream, canal, river, lake, etc.); in 7.8% of the plants, the treated water is used for irrigation (both agricultural and green areas) and 2.5% is used for infiltration [48].

3.1.2. Treatment and Disposal of Sewage Sludge

Regarding the management of sewage sludge, through an analysis with descriptive statistics of the data, it was determined that only 22.5% of the plants treated the sludge in some way, while, in the rest of the plants, no treatment was given or applied. As for the main methods used in the treatment of sludge, 493 plants use dewatering, 143 plants use sludge thickening and only 15 plants use cogeneration of electricity [50]. Successful examples in Mexico include the Atotonilco plant in Hidalgo, which produces 93 GWh/h from the sewage sludge-generated biogas, and the wastewater treatment plant in León, Guanajuato, which has an infrastructure for biogas use and electricity generation, leading to a 40% reduction in consumption [17]. It could be said that less than 1% of the plants in operation practice CE with respect to electricity generation.

Regarding the sludge generated, it is estimated that 32.5 million ton/year of sewage sludge are generated in Mexico [54]. In sludge digesters, the typical methane (CH_4) of biogas is 0.35 L CH_4/g COD or 0.75 to 1.12 m^3 CH_4 per Kg SSV removed. Based on the above data, it is estimated that, in Mexico, at least 104 WWTPs with flow rates greater than 200 L/s have the potential to take advantage of sludge through anaerobic digestion, which would generate 35, 300 kWh of energy from the biogas generated under their current operating conditions. The high electricity consumption can be covered up to 70% by generating electricity from biogas [11].

3.2. Operation of WWTPs under a Circular Economy Scheme

It was determined that the CE can be applied in the operation of WWTPs from the perspective of the biological cycle, which would involve the use of sewage sludge in agriculture, composting and anaerobic digestion to obtain biogas and nutrient extraction. In the case of water, this represents the product in the WWTPs, so it is not considered in either of the two cycles. However, the treated water can have different destinations according to the needs of the areas in which the WWTPs are located. These are irrigation, both of green areas and agriculture, water recharge and ecosystem conservation, either by infiltration or discharge to water bodies, and its reuse in industry [55,56].

Based on the proposal for adapting the EC to a production system, a circularity proposal was made in the WWTP. Figure 2 shows the three principles of CE in WWTPs: (1) preserving natural capital through regeneration, (2) the use of optimization strategies and loops in the life cycle applicable to the sewage sludge generated, and (3) the reduction in negative externalities [28]. Due to its nature, the sewage sludge adjusts to the biological cycle, and it can have different management options. In this example, anaerobic digestion is used as an energy generation process. The biological cycle of the CE and the levers of action that it includes were considered applicable; in addition to the ReSOLVE framework, the six strategies that could be applied in the WWTPs were taken into account, namely:

- Regenerate would be represented by sewage sludge with anaerobic digestion, the extraction of nutrients and their use in agriculture; in the case of treated water, it would be reflected in its reuse for irrigation and infiltration, contributing to the restoration of ecosystems and the integration of resources into the environment.
- Share would be reflected through reuse actions, such as agreements between WWTPs and local farmers to reuse water for irrigation or treated sludge as fertilizer.
- Optimize would be reflected in self-consumption actions, making the WWTP self-sufficient and avoiding the use of external energy requirements.
- Loop would be reflected in each of the principles applied in the process and the recovery of all materials and energy, as can be seen in Figure 2, 'Diagram of the operation with the CE model in the WWTPs'.
- Virtualize could be carried out through virtual sales strategies or digital applications for local farmers and merchants.
- Exchange would be reflected in the use of eco-innovations, as well as energy-efficient processes, equipment and inputs with lower environmental impacts [28,56].

These strategies go along with the strategies proposed in the IWA water utilities framework, such as water reuse, material and nutrient recovery, and energy recovery.

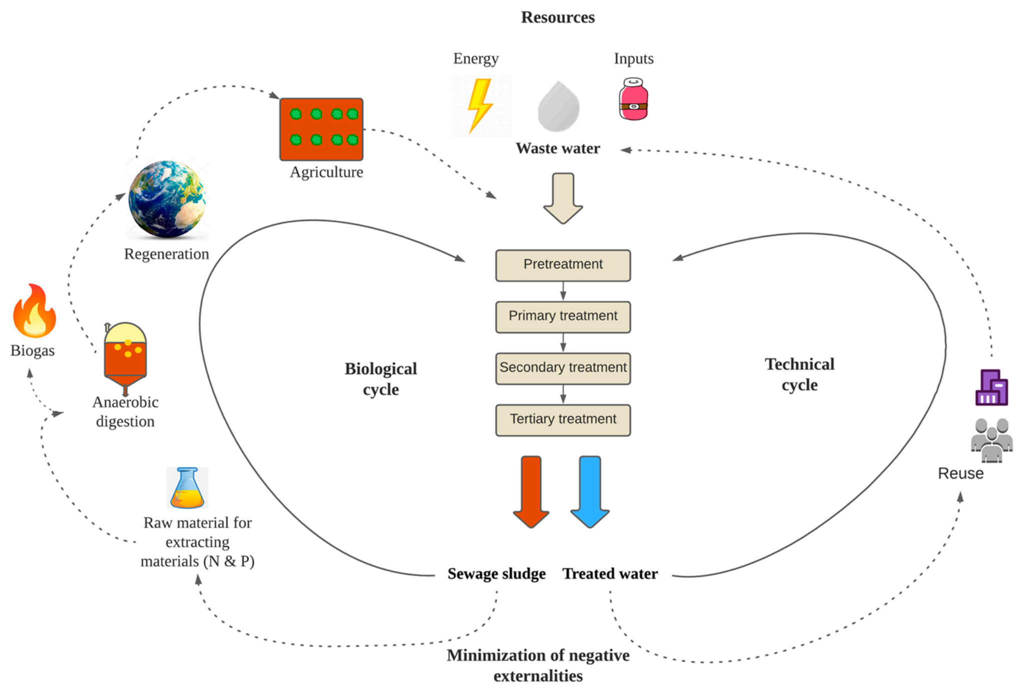

Figure 2. Diagram of the operation with the EC model in the WWTPs. Adapted from Ellen MacArthur Foundation [27].

3.3. Symbiosis of CE Frameworks, EI and CBM for Wastewater Treatment Plants

The principles that can be applied to the operation of WWTPs from each of the approaches were retrieved. Table 1 shows the works and authors that were taken as the main reference source.

Table 1. Main approaches considered.

Focus	General Principles	Authors
Circular Economy ReSOLVE framework	Levers of biological cycle: nutrient extraction, anaerobic digestion and biogas production, regeneration and agriculture. Principles of ReSOLVE framework: regenerate, sharing, optimization, looping, virtualizing and exchange.	[28,43]
IWA	Based on three interrelated pathways (water, energy and materials)	[29]
Eco-Innovation	Innovations of product, process, service or method, which contribute to mitigating negative externalities on the environment. Innovation may be carried out in the economic, social and environmental dimensions.	[30,32]
Circular and Innovative Business Model	Creation, proposal and delivery of value with elements of circularity and innovation.	[42,44,47]

As a last result, a proposal was made of the business model for a wastewater treatment plant through the CBMI canvas. In this proposal, the elements of the CE and EI were integrated as keys to benefit the operation of the WWTPs. Figure 3 shows this canvas proposal. The CBMI's proposal is aimed at the use of sewage sludge through anaerobic digestion and biogas generation, as well as water reuse for agricultural irrigation.

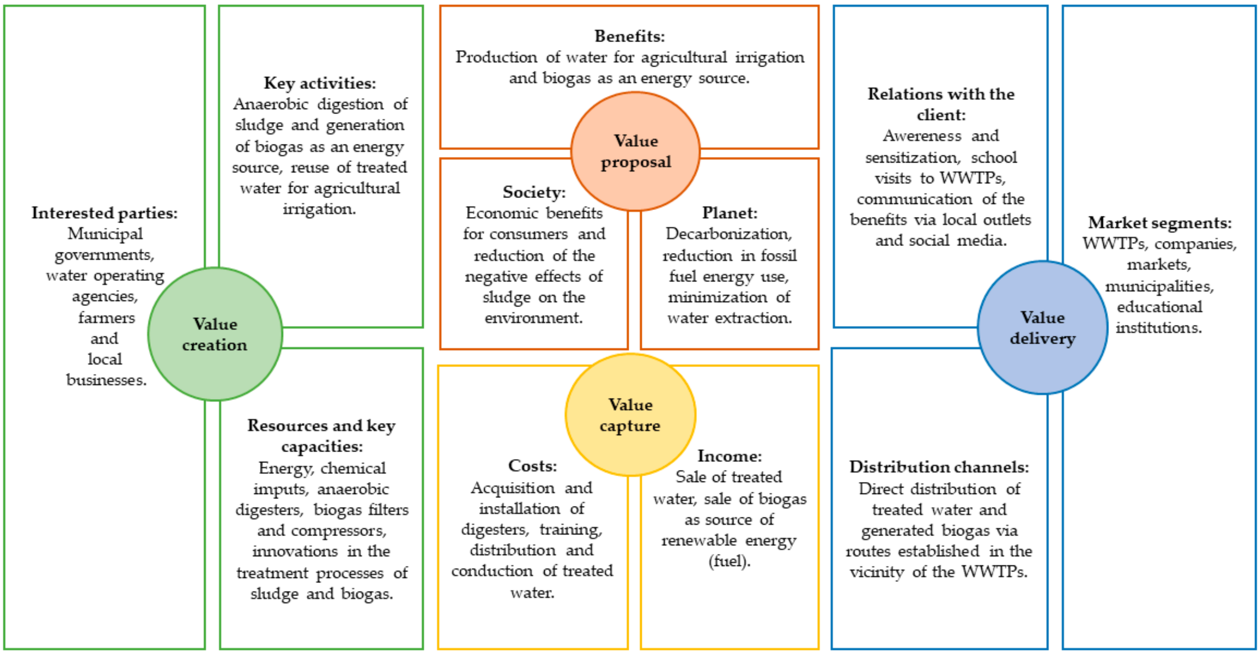

Figure 3. Canvas of the CBMI in the WWTPs of Mexico. Source: Authors' own elaboration based on Bocken et al. [44].

4. Discussion

The main results obtained from this review work are the following: (1) the construction of a diagnosis of WWTPs in Mexico and at the municipal level, from water reuse and sludge treatment and disposal; from the symbiosis of the elements of CE, the IWA and ReSOLVE frameworks and IE, it was obtained: (2) a model for the operation of WWTPs and, (3) it was applied to a circular business model innovative, more sustainable in the operation and possible energy generation of WWTPs in Mexico.

Regarding the diagnosis of WWTPs in Mexico, it could be summarized that the problems of municipal WWTPs in Mexico are centered on the economic aspect due to the high costs of operation and maintenance; the environmental aspect, due to the negative impacts on the environment due to the lack of alternatives for the management and utilization of the waste generated; and the technical-administrative aspect, due to the technical and operational difficulties, the age of the equipment, as well as the constant change in plant operators with the changes in government representatives.

Therefore, proposals and actions are required so that municipal WWTPs can improve their technical, economic, regulatory and environmental aspects [4,57]. In particular, CE proposes a cyclical flow of materials and energy so that the disposal of waste in landfills becomes the last option [23]. CE strategies in WWTPs would allow for the recovery of resources and materials, bringing economic, environmental and, consequently, social benefits to the plant environment [2,3,58]. Sewage sludge could be used [59] and treated water reused [18].

According to the principles of the CE, sewage sludge can have several destinations, which are nutrient extraction, anaerobic digestion and biogas generation, composting and agricultural use [12,13]. However, in Mexico, the final destination of sewage sludge is not clear, as such information is not reported.

Some of the studies identified in this context report that at least 17 WWTPs in Mexico used anaerobic digestion and generated biogas [50,60]. However, biogas is only used as an energy source in 53% of these plants, while in the rest it is burned, although about one hundred plants are estimated to have the potential to generate biogas and produce electricity. The methods of calculating the amount of sludge that can be generated by plants, as well as the estimation of biogas and energy production, are well studied [11,17].

To achieve this, it is necessary to provide subsidies and carry out feasibility studies for the installation of biodigesters and power plants in existing WWTPs as well as to provide finance for investment in biodigesters and power plants [11].

The use of biodigesters for biogas generation has shown that treatment plants can achieve energy self-sufficiency by improving carbon sequestration, in which good progress has been made [61]. It can be observed that anaerobic digestion and biogas production is an attractive and, perhaps, the most outstanding alternative; however, agricultural use or nutrient extraction are other alternatives worth studying, leading to another enormous area of possible research in this field.

About 90% of WWTPs in Mexico do not apply reuse options for treated water. This may be due, on the one hand, to the fact that current Mexican regulations do not require the reuse of treated water, as they are focused on regulating discharges to water bodies for water recharge. This is a great area of opportunity for updating Mexican regulations in terms of treated water reuse. On the other hand, the reuse of treated water may imply the need to improve its treatment quality, which would be reflected in an increase in WWTPs' operating costs [2]. CE can be particularly useful in this regard, given that studies have been carried out that show that the circular economy has an influence on environmental legislation, guidelines for the management of water resources and environmental factors [62].

There are also other consolidated actions of the CE in the water sector, such as the recovery of nutrients and energy; this means it is necessary to change society's vision of wastewater, to consider it as a rich source of valuable substances with economic impacts and associated value, in addition to promoting the appropriate public policies [63].

Some frameworks have been developed that focus on helping organizations to transition to the CE model; for example, the Ellen MacArthur Foundation's ReSOLVE framework and the IWA's water utilities framework. It was found that these frameworks converge on principles that can be applied to help such a transition. Among these are the adoption of actions that take advantage of the different properties of the waste generated, the optimization of processes and the use of renewable energy sources, as well as the maintenance of resources in use and regeneration of nature.

The Ellen MacArthur Foundation proposed an approach to apply CE by means of a series of actions, carried out in two cycles, the biological and the technical, depending on the nature of the waste to be treated [27]. This can be a benefit, as it brings greater clarity when looking for options for the management of waste generated in any process. This approach, together with the ReSOLVE framework, which has been studied and applied to various aspects of wastewater management, can contribute to sustainability [56].

As can be seen in the ReSOLVE and IWA frameworks, eco-innovation is a key tool in the transition to CE [42]. Ideas, processes, teams and actions are required to improve the current situation, from the technological, regulatory, social and business perspectives, as long as the environmental impacts decrease and the social and economic benefits increase. In this respect, there are advances in the relationship of these approaches through the development of indicators [32].

Changes in WWTP operation must be reflected in the environmental, social and economic aspects; therefore, integrating CE and EI in the WWTPs allows for them to be visualized from the perspective of CBM. This means generating value from the plant's waste and the treated water. The proposal of a canvas to model the circular and innovative business in WWTPs can serve as a blueprint for water operating agencies in Mexico. It will enable them to experiment with different options for water reuse, such as reuse in irrigation and its different destinations or reuse in industrial or domestic settings, as well as the use of sludge in agriculture, biogas generation or nutrient extraction, according to the characteristics of the plant under study. Water operators in Mexico require tools that will help them improve WWTP management.

Bocken's CBMI proposal was chosen. As it has elements of circularity and innovation in the business model, the objective is to convert businesses to sustainable models. An additional advantage of this model is that CE and EI could be applied as key components of sustainable business [44]. The levers of the CE and the principles of the ReSOLVE framework were taken into consideration for the proposal of the CBMI in the WWTPs, and several other innovative strategies are proposed, such as the anaerobic digestion of sewage sludge and the generation of biogas.

With regard the theoretical and methodological implications of this work, it is established that the main contribution in this respect is the integration of various theoretical frameworks in the line of CE, which contributes to confirming the necessary elements for WWTPs to operate under the CE model. Both the plant operation proposal and the innovative circular business model can support the sustainable management of such facilities in developing countries such as Mexico.

With regard to the limitations in carrying out this work, it was identified that the main one is the lack of information regarding the management of sludge and treated water in WWTPs. This is due to the fact that, in most of the plants, the managers do not register the information that is generated by the operation of the plants; as a consequence, no information is reported in the Census of Municipal Governments, the annual WWTP Inventory nor the official reports on the environment. This gives rise to an important opportunity to promote the collection and dissemination of this information by the corresponding agents.

The effects of the linear model on the management of water resources are observed in the inefficient use and waste of water. Due to the greater use of material and energy in water extraction and distribution, this also increases vulnerability and social inequality in the face of water scarcity. The circular model of water resources proposes the use of different socio-technical tools for a comprehensive solution of these problems [64]. However, the transition of WWTPs to a CE is still seen as a long and complex process which requires both technical knowledge and overcoming the economic, social and regulatory barriers [3]. The lack of resources and the lack of a legal framework are among the constraints on transitioning to a circular economy in water treatment plants [65].

5. Conclusions

In Mexico, one third of municipal WWTPs are non-operational; the main reason for this is the high cost of operation and maintenance, an unaffordable situation for municipal governments. WWTPs generate waste that can be used through CE and EI to generate energy or nutrients, reduce negative externalities and conserve ecosystems. It is considered that a WWTP operating under these sustainability strategies can be energy self-sufficient and have both economic and environmental benefits.

According to the CE, any production process can transition to this model instead of the traditional linear economic model. Consequently, a proposal for the operation of the WWTPs was made based on the diagram of the Ellen MacArthur Foundation's CE system. It was considered that the biological cycle was the most relevant due to the nature of the waste generated, which can follow different paths such as nutrient extraction, anaerobic digestion and biogas production, composting and agricultural use, as well as regeneration in ecosystems.

Likewise, it was identified that the final destination of sewage sludge in Mexico is not clear, being an aspect that is not included in the main government reports. However, regarding waste treatment, it was found that the most used method is dehydration, while anaerobic digestion for the generation of electricity is less common. Regarding the reuse of water, the recharge of water bodies is the main destination, followed by agricultural or green area irrigation, while the least used is infiltration. Reuse as first-use water, or reuse in industry, is not yet significant.

In addition to CE, EI strategies can also be applied in WWTPs, focusing on innovations that allow changes in processes, equipment, services or methods, to reduce negative impacts on the environment. It was determined that there are intersecting elements between CE, the ReSOLVE framework, the Water Utilities Pathways of IWA framework and EI; these approaches aim to reduce the negative externalities of production and consumption processes in order to provide options that allow for balancing the economic, social, political and environmental aspects, which are the engine of sustainability.

Another contribution of this work is the adaptation of the municipal WWTPs operations to a circular and innovative business model, which takes elements of CE and innovation and incorporates them in the search for a sustainable business; in this case, proposing the use of the generated sludge. This proposal may represent a useful tool for decision-making in the administrative and governmental sectors of WWTPs in Mexico.

One of the options of circularity in WWTPs was established as an example of CBMI, the use of sludge in anaerobic digestion and the generation of biogas as an energy source. In the case of water, its reuse is proposed for irrigation in agriculture. Both proposals are based on the diagnosis made of the WWTPs in Mexico. EI can be applied to any of the levers of the life cycle and to the principles of the ReSOLVE framework.

As for recommendations and future work, a socio-environmental cost–benefit evaluation of the possibilities for the use of sludge and destination of the wastewater is proposed, as well as a study of the feasibility of the different options for WWTPs in Mexico. Additionally, evaluations of the long-term effects of the proposed strategies and improvements to determine their sustained effectiveness and potential environmental and economic impacts are also suggested.

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