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The Integral Management of the Wastewater Treatment Sector in Mexico Using a Circular Economy Approach

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Abstract: Wastewater treatment must be proactive and sustainable to facilitate an increase in the circularity of water. Therefore, the current approach, based on a linear cycle, must be replaced with a circular economy concept that implements strategies to address the different byproducts in the wastewater treatment sector. In recent years, Nuevo León, Mexico, has encountered high water stress levels, with its main water bodies presenting their lowest levels ever recorded. This study was focused on the wastewater treatment plant Monterrey, which treats the largest volume at the state level. Throughout its operation process, it generates different potential byproducts that are yet to be harnessed to fully. This study developed three proposals using a circular economy approach: the treatment of water for the industrial sector, the use of residual sludge as an organic fertilizer, and the cogeneration of energy from biogas. These proposals can potentially generate benefits regarding the three pillars of sustainability, yielding a closed cycle in the wastewater treatment sector at the national level.

Keywords: biogas; circular economy; sewage sludge; wastewater treatment; WWTP

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Citation: Ochoa Garza, J.A.; Gómez Urquijo, M.; Paredes Figueroa, M.G. The Integral Management of the Wastewater Treatment Sector in Mexico Using a Circular Economy Approach. *Recycling* **2024**, *9*, 84. https://doi.org/10.3390/recycling9050084

Academic Editor: Julio Sacramento Rivero

Received: 3 August 2024
Revised: 6 September 2024
Accepted: 18 September 2024
Published: 22 September 2024

1. Introduction

The scarcity of fresh and clean water, along with climate change, is expected to affect the water security of the world and potentially result in a crisis in the coming years. This has highlighted the importance of water as a vital resource. Consequently, there is an urgent need to implement mechanisms for its appropriate reuse and recycling [1].

Water stress occurs when the water demand exceeds the available quantity during a specific period, or when its use is restricted owing to poor quality [2]. In recent years, numerous organizations have voiced concerns regarding the escalating water stress worldwide. According to reports from the United Nations, water consumption is projected to double by 2050 [3]. Moreover, at least half of the world's population and the 25 countries that hold a quarter of the world's population are expected to experience extreme water stress; 4 billion people will live in conditions of water stress for at least one month per year [2]. Water stress is projected to continue to increase owing to inadequate water management, population growth, and economic development in industries such as agriculture, cattle raising, and manufacturing [2].

Wastewater, a critical component of the water cycle, must be managed appropriately during its generation, treatment, and distribution, as well as during its reuse and final return to the environment. The most common wastewater treatment involves a linear system that removes contaminants present in the water. The goal is to convert the wastewater from domestic and industrial use into a final effluent that is environmentally acceptable in an esthetic, organoleptic, and healthy manner [4].

A wastewater treatment plant (WWTP) typically involves three stages. During the primary stage, the water is retained in a container wherein the wastewater is settled. This enables the heavier solids to sediment at the bottom [5]. During the secondary stage, after approximately 40–60% of the solids have been removed, a biological process occurs, which eliminates the biological matter that has been dissolved or suspended. This is facilitated through a balance between the bacterial communities, organic waste, and dissolved oxygen. The tertiary stage involves the elimination of the pathogenic agents and fecal bacteria still present through a chemical process that utilizes methods such as chlorination, filtration, and precipitation [5]. At the end of the treatment, treated water complying with a series of regulations is obtained for discharge into a water body or for a certain type of reuse. However, it is the final quality level and regulatory standards that determine the situations and requirements under which it can be reused. In addition, throughout these operations, various byproducts are generated, such as sludge, sand, gravel, biogas, etc.

The concept of a circular economy model is based on the principle of maximizing the value of previously used materials and providing them with a second life. It is defined as a restorative and/or regenerative system by intention and design. Thus, it replaces the concept of "end-of-life" [6]. In the context of a circular economy, water would retain its complete value after each use and eventually return to the system. For this reason, a closed system that permits cyclical use should be considered, and not just in terms of the cleansing of water [1]. The inclusion of water in a circular economy model can be approached by employing different methods with the purpose of benefiting innovation. Nutrients and energy can also be extracted from the cycle, ushering in benefits such as the enhancement of agricultural productivity and providing a new energy source through biogas production [7].

The wastewater treatment plant in Ridgewood, New Jersey, is a notable example of an enterprise undertaken to integrate wastewater into a circular economy model. The plant allied itself with an energy provider (Ridgewood Green) and achieved a successful co-digestion system project that produces sufficient biogas to satisfy the plant's energy consumption needs [8]. Once the biogas is collected, cleaned, and compressed, it can be injected into a cogeneration system to produce electricity. Excess thermal energy is used to heat the anaerobic digesters, which increases the energetic efficiency of the process. Ridgewood Green invested the initial capital required to modernize the cogeneration system, and Ridgewood WWTP buys the electricity generated at a lower cost than the grid price to facilitate its operations [8].

Furthermore, in Madrid, Spain, an investment of 200 million euros was allocated for the treatment and regeneration of 70 million cubic meters of water. This impacted 2.5 million inhabitants in the region. The initiative also covered the irrigation of 6500 public green areas and the management of waste from the Isabel II canal through its agricultural and energy-related valorization. The process utilizes thermal drying operations with cogeneration to satisfy the energy demands of the wastewater plant. This is coupled with composting for agricultural and gardening purposes [9].

A Latin American example includes the WWTP "La Farfana" in Santiago, Chile. In 2005, only 3.6% of the wastewater from the city of Santiago was treated, and the rest was discharged into the Mapocho River, an important source of irrigation and drinking water for the region. A few years after its opening, "La Farfana" was able to treat up to 50% of the wastewater from the metropolitan region, which required the construction of infrastructure at various points in the city over approximately 10 years. Most of the work involved building collectors to prevent wastewater discharge into the Maipo River, the Zanjón de la Aguada, and the Mapocho River, which are now directed to the plant. Since 2018, 604 million cubic meters of water have been treated in order to irrigate 130,000 hectares of green areas. Meanwhile, the sewage sludge is stabilized through an anaerobic digestion process and dried to generate six million cubic meters of biogas that are used for self-consumption by the digesters. Additionally, dehydrated sludge is used as agricultural fertilizer on 4300 hectares per year, thanks to the 137,000 tons of organic fertilizer produced by the biofactories [10].

In Peru, an alliance was formed between regional and local governments, development agencies, and the largest copper mine in the country, Sociedad Minera Cerro Verde (owned by Freeport-McMoRan), to create a water resource recovery facility that would benefit the mine's operations and the local population's needs. The WWTP "La Enlozada" was designed, financed, and built, and it is currently operated by Cerro Verde under a public–private partnership (PPP) agreement. In exchange, Cerro Verde receives a percentage of the treated water, while the remaining treated wastewater is returned to the Chili River. Before the WWTP, the Chili River received untreated sewage water; this solution allowed the reuse of wastewater generated by the population, decontaminated the river, and created benefits for the region related to health, the environment, tourism, and agriculture [11]. Economically, the WWTP "La Enlozada" has generated more than 3000 permanent jobs and an additional 3000 temporary jobs. It has also enabled over 350,000 new users to gain access to drinking water [12].

In Mexico, specifically in the metropolitan area of the Valley of Mexico, the federal government developed the Atotonilco WWTP to benefit more than 10.5 million people in the Mexico City Metropolitan Area [13]. The Atotonilco WWTP is the largest wastewater treatment plant in Latin America and one of the largest in the world, being located in the municipality of Atotonilco de Tula in the state of Hidalgo. Its goal is to treat 60% of the wastewater from the Valley of Mexico, and it is designed with two treatment processes: a physical–chemical process train based on chemically enhanced primary treatment (CEPT), which cleans stormwater discharged into the river, and a high-flow activated sludge biological treatment for water intended for reuse in irrigation. This treatment scheme meets the plant's resource needs and significantly reduces operational costs [13]. Wastewater treated for irrigation meets quality standards and can be used to irrigate up to 90,000 hectares in the Mezquital Valley. The biogas generated during the sludge stabilization process in the anaerobic digesters is used to produce electricity for self-consumption and to heat the digesters through a combined heat and power (CHP) system. The installed capacity is 32.4 megawatts, which is around 60% of the plant's electricity. Another process within the plant involves methane capture, which is used to generate energy. This reduces the plant's greenhouse gas (GHG) emissions by approximately 145,000 tons of carbon dioxide (CO_2) per year, allowing the Atotonilco WWTP to earn and monetize carbon credits. Additionally, the biosolid (stabilized sludge) produced meets the quality standards required to be classified as a type C sludge, which, according to NOM-004-SEMARNAT-2002 [14], is suitable for application in forests, soil improvement, and agriculture.

Nevertheless, in Mexico, there is a prevalent national water distribution problem. This is primarily due to its geographical location, as certain regions experience constant droughts while others are subjected to high levels of rainfall. Without an intervention in water infrastructure and better governance, water stress is expected to increase in Mexico along with its growing population and economy [2]. Mexico experienced water stress at a level of 45% in 2021 [15]. This figure is alarming because Mexico is close to having only half of the water required to meet all the needs of a growing population [16]. The situation is aggravated by climate change, agricultural use, water pollution, the overexploitation of aquifers, and deficiencies in water management.

Conversely, water issues in the state of Nuevo Leon (in the north of the country) go beyond the local level. Nuevo Leon, specifically the Monterrey Metropolitan Area (MMA), is the third largest urban center in Mexico and an industrial and commercial powerhouse of national importance. There is a substantial risk of a water crisis in the MMA due to climate threats and the vulnerability of its water supply system, while the continued growth in the MMA will keep amplifying the consequences of such a crisis [17].

As evidence of this, in 2022, the state of Nuevo León entered a state of emergency owing to an extreme drought that resulted in critically low levels of water in its dams, the main source of water for the population. The numbers revealed in January 2022 (Cerro Prieto, 9.88%; La Boca, 25.28%; and El Cuchillo, 53.98%) stirred uncertainty regarding the water supply for the coming months [18]. Nuevo Leon has a very high water stress level (4.44 out of 5) [2] and is placed 12th among the 32 entities comprising Mexico [19].

By the end of May 2024, the water levels of two dams were reported to be even lower, with Cerro Prieto at 5.8% and El Cuchillo at 32.9% [20]. It was not until the arrival of Tropical Storm Alberto in June 2024 that the situation improved, as the heavy rainfall replenished the reservoirs and brought temporary relief to the region [21]. However, despite the dams now being full, this event highlights the vulnerability of relying solely on short-term weather events to solve long-term water challenges. There is a clear and pressing need for adaptation measures. Recent government initiatives, such as the Nuevo Leon's $1.2 billion water management master plan, aim to address water needs by expanding infrastructure like aqueducts and dams [22]. However, sustainable solutions are essential to ensuring long-term water security in the face of recurring droughts.

Thus, it is crucial to innovate and move toward non-linear models that can bring about a sustainable future. Therefore, this study aimed to evaluate the implementation of a circular economy model in the wastewater treatment sector in Mexico, considering the three pillars of sustainability: social, environmental, and economic.

2. Results and Discussion

2.1. Proposal for Reuse of Treated Wastewater for the Industrial Sector

The agricultural sector consumes 61% of the water available for use in Nuevo León (1.2 billion m^3). This renders it the largest water consumer in the state. The second largest source of water consumption is urban usage (28%), followed by water use in multiple ways (5.75%) and the industrial sector (5.25%) [23]. According to the Public Registry of Water Rights of CONAGUA (National Water Commission) [24], the industries with the most demanding activities in terms of water are steel, paper, glass, and food production.

Table 1 presents the price ranges for the industrial clients of the Monterrey WWTP (Mty WWTP). The ranges are based on their monthly water consumption in m^3. Considering an average selling price of $0.50 USD/m^3, the yearly revenue provided by the sale of treated wastewater in 2022 was $7,112,546 USD.

Table 1. Prices of treated water sold by the Mty WWTP [25].

Monthly Water Consumption	Price ($USD/m^3)
1–131,999	0.77
131,000–389,000	0.75
391,400–777,600	0.72
Over 777,600	0.47

To increase the income of the Mty WWTP and reduce water stress in the region, a proposal to increase the percentage of treated wastewater sold from 10% to 50% was examined. This approximately equated to increasing the sale of treated wastewater to 116,300,000 m^3, which would provide a yearly revenue of $58,150,000 USD.

Treated wastewater can be sold to industries for their own garden irrigation and fire-fighting systems, as these uses are permitted under NOM-003-ECOL-1997, which states that treated wastewater meeting the established LMPs can be used to fill recreational and non-recreational lakes, artificial canals for navigation and water sports, and ornamental fountains. It can also be used for vehicle washing, hydraulic barriers, and the irrigation of parks, gardens, golf courses, boulevards, and cemeteries [26]. By focusing on these industrial uses, water stress in the region could be further reduced and the costly modifications that would be required for more stringent industrial processes may be avoided. If industries wish to use the treated wastewater for other purposes, they would be responsible for additional treatment (if necessary), as some potential industrial uses, such as in cooling systems, do not require compliance with potable water standards [27].

Another viable opportunity is the sale of treated wastewater to golf courses for irrigation purposes. In the state of Nuevo León, there are at least 10 golf courses, many of which still use potable water despite the severe drought conditions that have led to water supply restrictions. The Public Water Rights Registry lists concessions granted to several golf clubs across the country, including two in Nuevo León, which are allowed to extract 349,200 and 160,000 cubic meters per year, respectively [24]. Using treated wastewater instead of potable water is an attractive alternative for private clubs, which are increasingly facing public scrutiny for their water consumption practices.

Table 2 lists potential clients to whom the Mty WWTP could sell treated wastewater. To protect the privacy of the companies, the clients were grouped based on their respective business sectors. The annual water consumption was estimated based on the water consumption of previous clients of the Mty WWTP.

Table 2. Potential clients of Mty WWTP for the sale of treated wastewater.

Business Sector	Number of Companies	Annual Water Consumption (m^3)
Construction and materials	6	22,035,500
Industrial gasses	3	14,332,400
Chemical products	1	2,905,900
Paper	4	18,415,100
Textiles	1	4,056,500
Steel and aluminum	4	16,654,800
Agroindustrial	1	6,735,100
Manufacturing	4	19,156,700
Golf clubs	4	1,200,800
Total	28	105,492,800

These proposals are viable without requiring significant modifications or additional costs to ensure compliance with regulatory standards. The Mty WWTP could use its existing pipeline infrastructure, which extends up to a 15 km radius, to supply nearby industrial parks, and water trucks could be used for areas where pipeline construction is not feasible.

The use of treated wastewater could reduce operating costs and increase the competitiveness of companies, as employing treated wastewater for non-potable uses is more cost-effective than current practices. Adopting innovative water reuse practices can demonstrate a commitment to environmental responsibility and sustainability, potentially gaining support from regulators and the community. The social benefit of this proposal is based on increasing the availability of potable drinking water for human consumption by replacing potable water with treated wastewater in industrial uses. The state of Nuevo León is still encountering high levels of water stress; however, it is simultaneously experiencing exponential growth in the number of companies moving their operations to the area [28]. The environmental benefit of this is similar because it implies a reduced water demand from sources of potable water, such as rivers, streams, lakes, or aquifers, thereby preserving these natural resources that are vital to the ecosystem. The increased use of treated water in industry would also facilitate a reduction in the greenhouse gas emissions associated with the extraction, treatment, and transport of potable water.

2.2. *Proposal for the Application of Sewage Sludge as Biosolids*

For the following proposals, an ideal scenario was considered wherein the sewage sludge from an optimal anaerobic digestion process complied with the required environmental regulations. In addition, the reactivation of the Ecological Sludge Treatment Plant (ESTP), which has an integrated thermal drying plant, would also improve the quality of the sewage sludge up to an "A" classification, thereby broadening the sales scope of the byproduct. The estimated cost for repairing the ESTP was based on the cost of replacing the broken communication equipment and the labor costs for its installation, totaling $33,000 USD. The maintenance cost of the ESTP is much higher, at around $835,000 per year. This includes the salaries of four operators, the cost of the natural gas required to operate it (based on the gas invoices from the Mty WWTP), and a 10% contingency fund.

With the operation of ESTP, the sewage sludge could be processed into biosolids. This is among the oldest methods of using sludge as a fertilizer. It is spread or injected into the soil, thereby reducing demand for conventional fertilizers [29]. Sewage sludge could also be used as a raw material in different industries, such as construction [30], where it is used as a component in cement mix or as an additive in concrete and mortar [1].

Under the ideal scenario, approximately 99,700 tons of digested sludge would be generated annually. Following the thermal drying process, it is expected that only 55,800 tons of biosolids would be produced, based on the average volume reduction percentage (56%) [31]. An analysis of the prices and positioning of similar products indicated the presence of significant competition within the market. Therefore, the amount expected to remain following the ESTP would be sufficient for commercial sales. Moreover, any excess sludge produced would be donated to government institutions or non-governmental organizations (NGOs).

Two types of markets for the sale of biosolids were analyzed: retail and wholesale. Currently, the retail market offers similar products ranging from $3.23 to $11.85 USD, whereas the wholesale market has products ranging from $12.43 to $27.80 USD.

The retail sector comprises NGOs, businesses dedicated to reforestation, plant nurseries, environmental consultants, universities with reforestation programs, and the average user. For this market, a packaging presentation of 15 kg of biosolids was proposed. The wholesale market is considerably larger (80% of the total market) and comprises construction companies, municipal services, concrete companies, industrial parks, universities, apartment complexes, public and private schools, commercial areas, agriculture, and farming (45% and 40%, respectively) [32]. In this case, a packaging presentation of 50 kg was proposed.

The cost of transportation was estimated based on a quote from a national company dedicated to merchandise transportation. The costs of the acquisition of two packaging machines and packaging material, and of the operation of the ESTP (factoring in its maintenance and labor costs), were also considered. Table 3 presents the breakdown of the production costs for the different packaging presentations, outlining their selling prices and utility. Considering the overall costs, both presentations were highly competitive.

Table 3. The breakdown of biosolid production costs.

	Retail (15 kg)	**Wholesale (50 kg)**
Transport (USD/unit)	$1.06	$0.49
Packaging (USD/unit)	$1.18	$0.90
Machinery (USD/unit)	$1.74	$0.72
ESTP (USD/unit)	$1.12	$0.94
Total production costs (USD)	$5.10	$3.05
Selling price (USD)	$6.65	$7.65
Utility margin (USD)	$1.55	$4.60
Total annual cost (USD)	$2,088,900	$2,944,400
Annual revenue (USD)	$4,944,700	$6,825,900
Annual utility margin (USD)	$2,855,800	$3,881,500

By selling sewage sludge as biosolids, at least thirty types of markets are expected to benefit, including public and private sectors. It would also impact the general population through improvements in parks, municipal gardens, and recreational areas in the region containing trees and native vegetation. The payback period for purchasing the machinery needed to package the biosolids and repairing the communications infrastructure (total of \$1,327,000 USD) is less than a year.

In addition, thermal drying with flue gas only generates 77 kg CO_2 eq/ton. In contrast, the disposal of sludge in a landfill site produces 1564 kg CO_2 eq/ton (Table 4) [33]. Considering the annual generation of 99,700 tons, the reduction in GHG emissions is estimated to amount to approximately 148,254 tons of CO_2 eq/year. Thus, the proposed scenario is highly environmentally favorable.

Table 4. The breakdown of the kg CO_2 eq/ton emissions generated by the current and proposed scenarios for biosolids [33].

Scenario	Electrical Use	Use of Additional Chemicals	On Site Emissions	Total Emissions
Thermal Drying	56.26	20.64	-	77
Landfill	36.47	12.66	1515	1564

2.3. Proposal for the Implementation of a Biogas-Based Cogeneration System

The Mty WWTP has long been interested in the reactivation of its biogas-based cogeneration system. However, owing to a lack of the financial means necessary to realize this, this study proposed a bilateral alliance with a private company. This was based on the successful example of Ridgewood Green in the United States [8].

The intervention of the private sector would involve the operation and maintenance of the cogeneration system. In return, they would gain access to electrical power for their energy demands, which would be of benefit because the company considered for this proposal possesses a production unit near the WWTP. However, the Mty WWTP would be able to harness the methane generated and reduce their energy costs. This is because the private company would sell the electricity back to them at a lower price than the Federal Electricity Commission (a governmental organization that provides electricity to the country). In addition, the heat generated could be used to warm the digesters, thereby facilitating their operation at an ideal constant temperature for optimal sludge and biogas production.

An ideal scenario where the anaerobic digestion process is within optimal parameters, thus improving the quality of the digested sludge and the biogas, was considered. Therefore, for the ideal scenario, the anaerobic digesters must achieve a 65% vs. removal efficiency [34], producing 272.72 ton/day of digested sludge and 87,729 m^3/day of biogas. The methane content in the biogas is 65%, generating 57,024 m^3 of CH_4 per day. Biogas with similar concentrations of methane and carbon dioxide has the potential to generate 6.35 kWh per m^3 [35]. The calculations for these values considered a methane yield of 373 m^3/ton vs. [36].

The cogeneration system that is most common in wastewater treatment plants comprises an alternate motor that employs biogas as a fuel. Biogas generates a combustion reaction during which the released energy is subsequently transformed into mechanical and electrical energy [37]. To select the engine used in the cogeneration system, the electrical and thermal demands of the WWTP, as well as the amount of biogas generated, were considered. Table 5 presents the characteristics of the chosen model, the Caterpillar CG260-16 Biogas. Three engines of this type would match the required biogas production without the need for supplementary fuels. The cost for each engine is approximately \$2,200,000 USD [38].

Table 5. Characteristics of the proposed engine for the biogas cogeneration strategy (Caterpillar CG260-16 Biogas engine) [38].

Model	Electrical Power	Thermal Power	Electrical Efficiency	Thermal Efficiency	Total Efficiency
CG260-16 Biogas	3370 kW	3460 kW	42.9%	39.4%	82.3%

To determine the amount of energy the Mty WWTP could generate per year, first the energy content of the methane produced daily under ideal conditions was calculated. Considering that 1 m^3 of methane is equal to 36 MJ [39], the daily energy potential is 2,052,864 MJ/day. This is equivalent to 570,240 kWh/day, which is compatible with the total energy demand for the three engines (520,560 kWh/day). To calculate the electrical energy produced, the following equation was used (Equation (1)):

$$Ee = P_m \times e_e \times d \tag{1}$$

where Ee represents the electrical energy, P_m is the daily methane energy potential, e_e is the engine's electrical efficiency, and d represents the 365 days of the year. Continuous operation was assumed since the previously used CHPs (which are no longer operational) operated for 24 h every day of the year. The result is 89,291,030 kWh of electricity. This would satisfy the total electrical demand of the Mty WWTP (48,362,240 kWh/year) and leave 40,928,790 kWh/year for external sale by the private company.

Another primary component of the cogeneration system is the generation of thermal energy, for which a heat exchanger that allows heat utilization is required. The calculation of the thermal energy (Equation (2)) follows a similar formula:

$$Et = P_m \times e_t \times d \tag{2}$$

where Et represents thermal energy, P_m is the daily methane energy potential, e_t is the engine's thermal efficiency, and d represents the 365 days of the year. The result is 81,552,006 kWh/year. Thermal energy is crucial to this proposal because it will provide better treatment conditions for sewage sludge and, consequently, a better quality of biogas. When the cogeneration plant was operational, the Mty WWTP used the heat generated precisely for this purpose. If the proposal is successful, additional infrastructure could be added to use thermal energy to heat other parts of the WWTP and further reduce their dependence on other fuels.

To render this proposal viable, the established biogas quality requirements of a cogeneration system must be considered to avoid equipment deterioration. These requirements include a concentration of H_2S lower than 300 ppm and a concentration of siloxanes lower than 10 mg/Nm^3 [40]. As the biogas produced in the WWTP Mty is characterized by a high concentration of H_2S (2000–4000 ppm), first, a desulfurization process must be incorporated.

Certain methods used to achieve reductions H_2S concentrations include the injection of oxygen into the gasometer's interior, the use of external systems with desulfurization towers, the use of activated carbon filters, and the installation of a chemical desulfurization system with NaOH. After conducting a comparative analysis focusing on these desulfurization technologies, the first option, that is, the injection of oxygen, was found to be the most optimal at a price point of $58,400 USD. The oxygen supply (approximately 3–6% of air compared to the biogas) would be injected with an air pump with low operating costs. The reduction in H_2S can be attributed to the biological oxidation of H_2S to elemental sulfur and sulfates by Thiobacillus bacteria, which grows on the surface of the digester [41]. Based on this system, the H_2S in the biogas of the Mty WWTP can be reduced by between 80% and 99%, thereby achieving concentrations suitable for use in cogeneration systems. The desulfurized biogas would then be transported through a heat exchanger with the aim of reducing the temperature of the biogas to 5–10 °C. At these temperatures, the relative humidity value of <50% for required optimal functioning would be achieved [41].

The desulfurization technology would be financed by the savings earned by reducing the electricity costs of the Mty WWTP. This is because the private company's electricity price for the Mty WWTP would be $0.07 USD/kWh, which is 40% lower than the current rate ($0.12 USD/kWh) [42]. Previously, the Mty WWTP paid around $5,710,000 USD for their electricity costs. Under this scheme, the Mty WWTP would pay the private company $3,385,000 USD per year for the electricity generated by the biogas cogeneration system. Their yearly savings in electricity costs would amount to approximately $2,325,000 USD per year. These savings could be allocated to finance in situ oxygen injection desulfurization technology and the CG260-16 Biogas engines, which have an estimated total cost of $6,658,400 USD. Therefore, the time required for a return on investment for the Mty WWTP would be two years and nine months, while the private company would finance the operation and maintenance costs. This alliance allows the private company to sell energy directly to the Mty WWTP and to other clients.

In addition, the use of biogas reduces dependence on fossil resources and promotes a transition toward renewable energy sources. The CHP would have lower environmental impacts because, during combustion, the emissions of carbon dioxide (CO_2) and nitrogen dioxide (NO_2) are reduced compared to traditional energy sources such as coal or oil [29]. The capture and use of methane as fuel, avoiding its direct release into the atmosphere, also contributes to the reduction in GHG emissions in the WWTP sector. Based on the national grid's emission factor (0.438 tCO_2eq/MWh) [43], we estimate that the Mty WWTP currently emits 21,180 tCO_2eq yearly by consuming energy from the Federal Electricity Commission (CFE). By consuming the same amount of energy from biogas-based electricity, the emissions of the Mty WWTP could be reduced by up to 90%, contributing to the improvement of air quality in the region. The production and sale of biogas would generate employment opportunities, contributing to the social and economic development of the community.

2.4. Comprehensive Summary of Circular Economy Initiatives at the Mty WWTP

The main challenges for each proposal are as follows: the sale of treated wastewater to a larger number of customers, aiming for a 40% increase in customers; the high initial investment required for the biogas-based cogeneration system and to implement the commercialization of biosolids; and the establishment of strategic sales points for biosolids. Figure 1 presents a visual summary of the proposals for treated wastewater, the use of sludge as a biosolid, and the biogas-based cogeneration system.

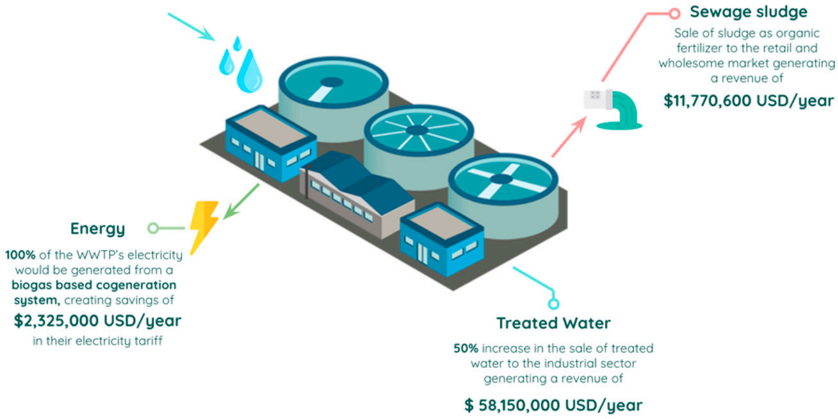

Figure 1. A comprehensive circular economy proposal for the Mty WWTP.

After conducting a technical analysis (Section 3.2), we confirmed that most of the current byproducts comply with the environmental standards established by federal and state institutions, and we proposed solutions for those byproducts that currently do not comply with them. The proposed solutions for ensuring compliance and incorporating these byproducts into a circular economy are technologically feasible and use a sustainable approach. Thus, we think that the proposals presented would lead to social, economic, and environmental benefits.

The increase in treated wastewater would result in a reduction in water stress in the state, generating a greater availability of drinking water for the areas surrounding the WWTP. Subsequently, the commercialization of biosolids would generate revenue from their sale as biofertilizers. Socially, this would lead to a reduction in the price of the fertilizers available to local customers. At an environmental level, CO_2 emissions would be reduced by decreasing the disposal of biosolids in landfills. On the other hand, the proposal for cogeneration from biogas would have economic benefits for both parties: WWTP and the associate company. The Mty WWTP would benefit from lower energy consumption costs, while the enterprise would generate direct revenue. Socially, air quality would improve, leading to a better quality of life for the areas surrounding the facility. On the environmental level, CO_2 emissions would be reduced by using biofuel.

Table 6 presents the multiple benefits that can be derived from the adoption of these strategies. The table highlights the relevance of these proposals and their potential for a positive impact on society and the environment.

Table 6. A summary of the economic, social, and environmental benefits of the various proposals for the Mty WWTP.

Proposal	Economic Benefits	Social Benefits	Environmental Benefits
Sale of treated wastewater	Increased annual income that can be used for maintenance costs and additional infrastructure ($47,957,000 USD).	Greater availability of drinking water for the community by allocating treated water to industries.	Reduction in water stress through the reuse of treated wastewater (116,302,886 m^3).
Biogas-based cogeneration system	A saving of 67% in electricity costs ($2,325,000 USD). The establishment of a business partnership with a private company.	Air quality improvement for the inhabitants of the surrounding areas due to the reduction in GHG.	A 90% reduction in the amount of CO_2 eq emitted annually compared to the current process (19,064 tCO_2eq per year).
Sale of biosolids from sewage sludge	Annual revenue that can be used for maintenance costs and additional infrastructure ($11,770,600 USD).	Availability of organic fertilizer at a lower cost for clients in the area (mainly farmers).	Reduction in tons of CO_2 eq produced annually, minimizing landfill stress (148,254 tCO_2eq per year).

In this sense, implementing a circular economy model in the wastewater treatment sector not only allows for the sustainable management of resources, but also generates opportunities to maximize the value of byproducts, thus closing the cycle. In addition, it reduces operational costs, increasing financial viability and economic resilience. In summary, a circular economy framework provides a comprehensive strategy to maximize the use of available resources, reduce environmental impacts, and generate economic value, resulting in a more sustainable and efficient system.

2.5. Additional Byproducts for Future Circular Economy Integration

It is important to mention that this study is limited because the components such as sand, gravel, nutrients, and cellulose were excluded from our analysis due to a lack of technology and data, but their potential importance in circular economy strategies should be recognized. Therefore, it is recommended that future research focus on the development of technologies for the extraction of nutrients and cellulose in Mexican WWTPs, particularly given the limited scope of such research. Dedicated research and development for each byproduct would consequently provide a deeper understanding of the potential impacts and challenges of their use and their long-term feasibility under a circular economy approach. An overview of the potential roles these excluded components could play in future efforts is presented as follows.

Regarding the extraction of nutrients, in the current scenario, approximately 24.6 and 32.4 mg/L of nitrogen and phosphorus, respectively, are removed monthly in preliminary water treatment to comply with NOM-001-SEMARNAT-1996. This is equivalent to 295.2 and 388.8 mg/L of nitrogen and phosphorus annually, respectively, being available for extraction and use in valuable applications. The phosphorus and nitrogen fertilizer market are crucial to agricultural production and the demand for nutrients in the fertilizer industry is increasing [44]. Phosphorus is the second most important nutrient in Mexican and world agriculture [45]; however, it is among the least abundant elements in the composition of the Earth's crust. Although Mexico has soils that are rich in phosphorus, changes have been observed in the available amount of that element used by organisms [46]. Moreover, nitrogen in its reactive form (ammonium, nitrate, and nitrite) is also a limited resource that is essential for plant growth [45].

There are various techniques for nutrient recovery, including chemical, physical, and biological processes [47]. The most used method for the recovery of both nitrogen and phosphorus is the formation of struvite (magnesium ammonium phosphate) through crystallization or precipitation. Struvite is an excellent fertilizer due to its low water solubility and slow release. However, its crystallization is associated with problems such as high chemical costs and the unintentional formation of struvite, which causes the blockage of valves, pipes, and pumps. Nevertheless, the Mty WWTP could market the extracted phosphorus and nitrogen to fertilizer manufacturing companies. Consequently, they can generate income, providing a return on initial investment into the recovery technology. This measure entails both economic and environmental benefits. This is because the production of fertilizers with recovered phosphorus and nitrogen could prevent the water pollution and soil degradation associated with the traditional process of extracting and producing phosphate fertilizers.

A successful endeavor that employs this model is the Saskatoon WWTP, which works in alliance with the Ostara company. It is the first commercial nutrient recovery facility in Canada. Its pearl nutrient recovery reactor removes phosphorus and nitrogen from wastewater flows and converts them into high-value fertilizers [48]. Within the system reactor, the growth of struvite is facilitated by the addition of magnesium in a controlled pH environment. This facilitates the crystallization of nutrients into eco-friendly fertilizer granules, which are collected, dried, and subsequently distributed and sold by Ostara as Crystal Green Fertilizer, which is a certified enhanced-efficiency fertilizer. Furthermore, the treated effluent is discharged from the top of the reactor and returned to the plant with a significantly reduced nutrient content [48].

Two other components that are currently not reused are sand and gravel. Currently, the Mty WWTP generates 2 containers of 21 m^3/month each, which are then dumped in the internal landfill. This landfill is currently at its maximum capacity owing to the excessive generation of residual sewage sludge and waste. The key to minimizing waste discharge into the landfill is the extraction of the maximum number of components from the previous stages and their subsequent integration into a circular model.

Sand and gravel could be marketed through different strategies. First, these materials would necessitate processing and analysis to satisfy the quality standards required for use in specific applications and human contact. Further, additional infrastructure would be needed for the proper cleaning and processing of sand and gravel. This would imply an investment in separation and filtration equipment, as well as in quality control systems.

Moreover, the Mty WWTP could establish partnerships with local companies in sectors such as construction or manufacturing to identify business opportunities and develop sustainable supply chains for these recovered materials. The treated sand could be sold as a construction material for the manufacture of concrete. Furthermore, it could be sold as an aggregate for use in the construction of roads or in the filling of potholes, which are persistent urban development problems in the metropolitan area of Monterrey. Gravel could also be used in landscaping projects or as fill material in construction. The successful commercialization of waste sand and gravel would necessitate careful planning and collaboration between the public and private sector. Additionally, research is needed to fully understand the characteristics of the waste sand and gravel treated at the Mty WWTP.

Notably, no previous case study has integrated sand and gravel waste into circular economy models. The ways in which these byproducts could be reused in relation to Mexican regulations would also have to be explored, since the current regulations are limited to standards for water and sludge. This renders it difficult to identify the appropriate commercial opportunities and thus develop viable business models. Despite these challenges, the commercialization of sand and gravel in a WWTP offers significant potential benefits. These include the reduction in waste disposal costs, the generation of additional income, and the promotion of more sustainable practices in waste management.

The final byproduct that the Mty WWTP could incorporate into its future circular economy model is cellulose, which originates from sources such as toilet paper and agricultural waste. The treatments for the extraction of cellulose are classified into physical, chemical, and biological treatments, and are also categorized as advanced technologies [49]. The methods available for physical treatment include sedimentation and flotation. Chemical treatments include coagulation, flocculation, and oxidation. Further, biological treatments involve aerobic and anaerobic digestion processes. Finally, the advanced technologies for the extraction of cellulose are precipitation, enzymatic hydrolysis, and membrane technologies [49]. Similar to the sand and gravel byproducts, a public–private partnership could be established to market the cellulose and consequently sell it to the construction industry. This is because recovered cellulose can be used in the construction of pavements [50]. There are currently no data regarding the amount of cellulose present in the water treated at the WWT sector at the national level, meaning that studies would first have to be dedicated to studying the composition of the wastewater in the Mty WWTP.

A primary advantage of adopting a circular economy model in the WWTP sector is the transformation of the expensive sanitation service into a self-sustaining system. Thus, throughout this case study, we discussed various sustainable circular economy strategies applicable to the WWTP sector in Mexico. Figure 2 presents the circular economy flow of the Mty WWTP under the proposed scenarios: the byproducts in the black text represent those from the current process of the Mty WWTP, the byproducts in the blue text denote the additional circular economy proposals, and the byproducts in the gray text indicate those that could be incorporated into a circular economy model in the future.

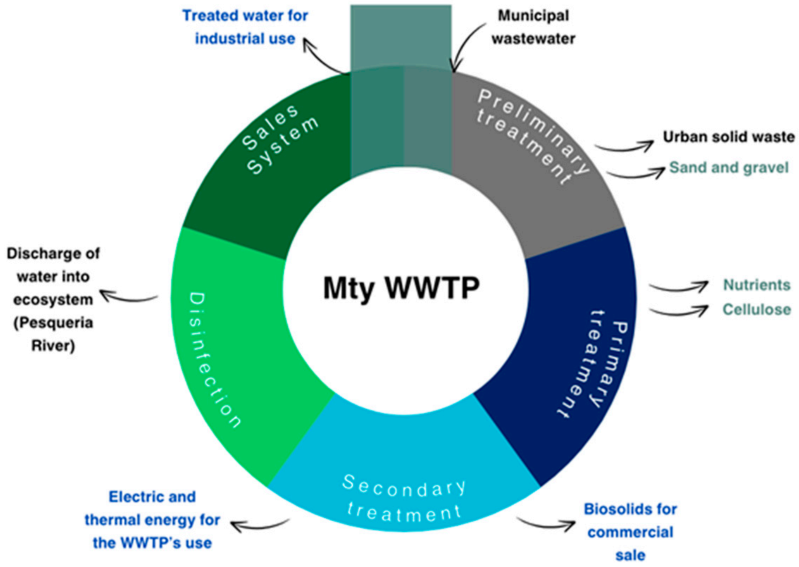

Figure 2. Proposed circular economy strategies for the Mty WWTP.

2.6. Challenges and Future Perspectives for Circular Economy in WWT Sector

Owing to the limited availability of freshwater and its growing demand, wastewater has become a valuable resource. Consequently, it must be conserved and used in a sustainable manner. As part of a circular economy model, water must retain all its value after each use and be returned to its cycle. Further, pollution must be prevented, and water should circulate in a system with closed circuits. However, the use of water within industry is based on a linear model of "taking–consuming–disposing". As a result, water becomes increasingly contaminated as it moves through the system, rendering its future use impossible [51].

Current WWTPs also operate under a linear economy model, wherein the goal is to produce quality effluents without the incorporation of the recovery of energy and byproducts. Circular economy models are expected to play an important role in the future of municipal wastewater management, maximizing the recovery of freshwater, energy, and resources in a move toward urban sustainability [51]. The need for more sustainable WWTPs is particularly relevant for 50–90% of the developing countries in Asia, Africa, and Latin America [52], wherein integrated water resource management is largely inadequate.

Wastewater treatment consumes four times more energy than supplying drinking water. This is largely owing to sewage sludge management, which represents 50% of the total operating cost and 40% of total greenhouse gas emissions from wastewater treatment [53]. Efforts to improve effluent quality typically exhibit a trade-off relationship between the cost of increased energy demand for treatment and the increased amounts of sewage sludge produced, a byproduct of major concern to the sanitation industry.

However, the significant barriers that exist in Mexico must be recognized for the effective implementation of the strategies presented. Among them, the lack of adequate infrastructure, particularly in rural and peri-urban areas, where the coverage of WWTPs and sewage systems is limited, is of concern. Similarly, there is a lack of awareness and education regarding the importance of wastewater treatment, as well as a lack of policies and proposals for its promotion. Securing investment necessary to build and maintain the infrastructure is also a significant challenge. This is the case with the Mty WWTP, where the lack of investment has halted the operations of biogas cogeneration system and the ESTP. Currently, 33.5% of wastewater treatment plants nationwide suffer from a deficiency in their processes due to a lack of maintenance [36]. Consequently, this has resulted in the inadequate management of the different byproducts generated.

Water scarcity and environmental challenges highlight the importance of improving and promoting the technology used in the WWTP sector at the national level. To promote a circular economy model, there is a need for a comprehensive approach that involves investment in research and the development of innovative technologies, personnel training, and collaboration between the public and private sectors. The latter is considered of particular importance for the realization of the adoption of a circular economy. This is because cooperation between both parties provides the resources and knowledge required to develop innovative and sustainable solutions.

In the analysis of the global benefits derived from the implementation of circular economy practices in the Mty WWTP, the internal and external factors that may influence its effectiveness and long-term viability must also be considered. For this reason, the strengths, weaknesses, opportunities, and threats (SWOT) of the circular economy strategies proposed for the Mty WWTP were identified (Table 7). In terms of strengths, this proposal encompasses the integral management of the byproducts of wastewater, sludge, and biogas; each proposal comprises technical, social, economic, environmental and market analysis. The proposals were supported by visits to the WWTP and first-hand information from its staff, although a weakness arises since these are theoretical calculations and hypothetical solutions. Moreover, there is a lack of literature regarding circular economy models in the WWTP sector, especially in Latin America. Regarding opportunities, in Mexico, the recent approval of the General Law of Circular Economy is aimed at facilitating research and the development of new technologies that prioritize reuse, recycling, redesign, and remanufacturing processes involving waste, and promote environmental responsibility in Mexico's population. There is another opportunity in that transitioning to and enforcing a circular economy is essential for countries like Mexico in terms of achieving social, economic, and environmental objectives. Furthermore, implementing the required technologies for each proposal could benefit the public and private sectors. Over time, companies are beginning to focus on green technologies that generate positive environmental impacts.

Table 7. SWOT analysis of the proposals for the Mty WWTP.

Strengths	Weaknesses
Comprehensive waste management in the WWTP sector	Theoretical estimates for calculations
Economic and market evaluation for each proposal	Lack of a circular economy model in the WWTP sector in Latin America
First-hand information was retrieved directly from WWTP Monterrey	
Opportunities	**Threats**
General Law of Circular Economy	Changing Mexican environmental policies
Highlighting the importance of implementing a CE model in the WWTP sector in developing countries	Deficiencies in the WWTP's treatment system
Private investment in the development and implementation of innovative technologies	Fluctuating changes in the national electrical sector

Still, there are threats related to Mexican environmental policies suffering from flexibility, a lack of personnel in the environmental legislation department for evaluating environmental concerns, and the current volatile legislative context which does not allow for the development of a long-term work scheme. Therefore, it is necessary to strengthen the system and make it more rigid to achieve sustainable benefits. A final threat comes from the Mty WWTP itself. As previously outlined, the WWTP lacks updates in its systems and processes, reducing the scope of our project and limiting the implementation of the circular economy approach. These deficiencies could become obstacles down the line in the implementation of circular economy proposals.

This project represents a turning point for future challenges concerning the applicability of circular economy principles in the wastewater treatment sector. In further research, it is recommended that scholars address the limitations that constrained this case study. Additionally, we advise the development of this work in a beta version project, implemented on a small scale, accompanied by a preliminary analysis of the real market.

3. Methodology

This study comprised three phases: (i) the analysis and diagnostics of the case study, (ii) the identification and technical analysis of the WWTP's byproducts, and (iii) the design of sustainable strategies under a circular economy framework. The first phase involved a diagnosis of the current situation and a breakdown of the operation and functioning of the Monterrey Wastewater Treatment Plant (Mty WWTP). The second phase comprised a valorization of the operation to identify the treatment processes and byproducts that could be improved and harnessed with a circular economy approach. For the selection of the byproducts, the following criteria were considered: byproducts with the highest rate of generation at the WWTP, compliance with applicable Mexican environmental regulations, and the technology available for future applications. In the third stage, strategies were formulated and evaluated, considering the three pillars of sustainability: the environment, society, and economy. Regarding the social aspect, the direct and indirect benefits for the stakeholders were considered. In economic terms, we estimated the input costs, selling price, and savings that the sale of each byproduct was expected to provide, and studied potential customers. In environmental terms, we determined the benefit that each strategy would provide with a comparative carbon footprint analysis.

Notably, sand and gravel were not considered for the formulation of sustainable strategies despite their being significant byproducts of the Mty WWTP. Despite the general information regarding these byproducts, information regarding their physicochemical characterization, required to propose an appropriate mitigation strategy under a circular economy and environmental regulation approach, is missing. Moreover, the byproducts of nutrients such as phosphorus and nitrogen were also not considered because currently no WWTP in Mexico possesses the technology needed to extract them. The Mty WWTP merely reduces the amount of these nutrients present during the preliminary treatment to comply with the national regulations.

To accomplish the circular economy model in the selected byproducts, the framework proposed by Smol et al. was considered [1]. This emphasized the importance of redesigning the aspects shown in Figure 3 to facilitate the effective utilization of resources in a circular economy model.

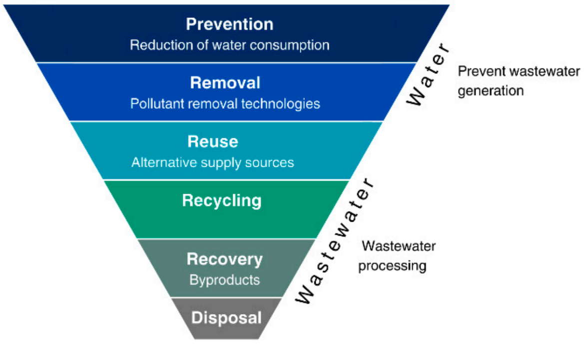

Figure 3. The hierarchy of waste management applied to wastewater treatment with a circular economy [1].

3.1. Current Diagnostic and Operation of the Case Study

The Mty WWTP is the third largest municipal wastewater treatment plant in Mexico and the largest in the state of Nuevo León. Most of the wastewater that arrives at the Mty WWTP comes from domestic use, while less than 10% comes from the diverse industries in the MMA, including food industries and pigment factories. It has an installed capacity of 7500 l/s and treated flow of 7122 l/s [25]. The WWTP involves the following processes (Figure 4): preliminary treatment, primary treatment, secondary treatment, the disinfection process, the anaerobic digestion process, the sale of treated water, and the final disposal of sewage sludge in a landfill.

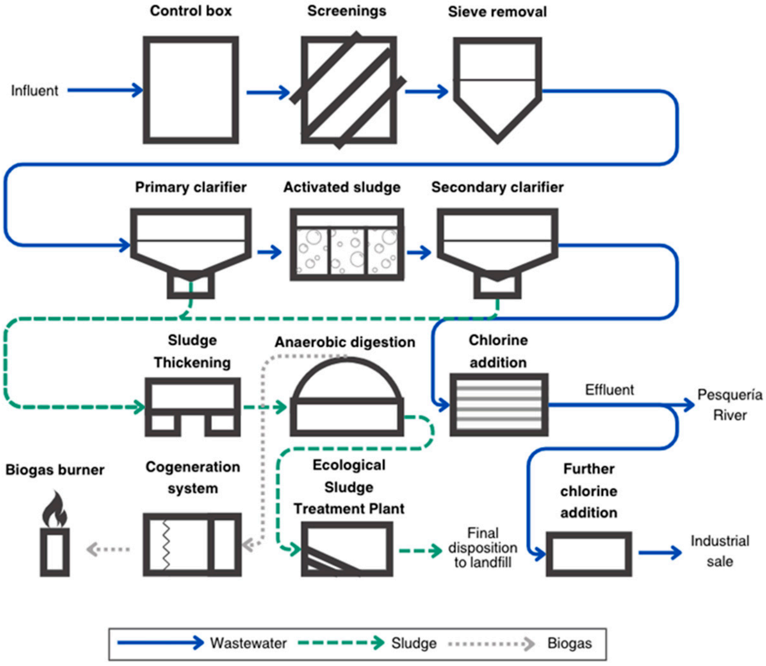

Figure 4. Process flow of Mty WWTP [25].

The preliminary treatment comprises collectors, grates, pumping stations, screenings, and sand removal. The wastewater arrives at the treatment plant via two collectors. This wastewater is pumped to automatic grids that are frequently saturated owing to the arrival of a considerable amount of urban solid waste, which is discarded in a landfill.

Four interconnected clarifiers comprise the primary treatment. They remove 70% of the suspended solids originating from the preliminary treatment flow. The clarifiers have scrapers that move the sedimented sludge to the centers of the clarifiers, wherein the first residual sludge is generated; this is subsequently transported to the anaerobic digesters.

The secondary treatment uses activated sludge technology and secondary clarifiers. It eliminates biodegradable organic matter and other pollutants, thereby generating secondary sewage sludge.

Tertiary treatment involves the disinfection of treated wastewater using chlorine gas. The resulting effluent is discharged into the Pesqueria River or sold to the industrial sector. Moreover, the sewage sludge produced is thickened and stabilized through a high-rate anaerobic digestion process and deposited in landfills within the Mty WWTP facilities. Consequently, the biogas generated is captured and burned in torches as a “Good Practice”. This is because there currently there exists no active cogeneration system owing to the lack of maintenance.

Table 8 lists the wastewater quality parameters of the Mty WWTP, obtained directly from the management of the WWTP.

Table 8. Annual water quality parameters of Mty WWTP.

Parameters	Influent	Effluent
Biological Oxygen Demand (BOD) (mg/L)	298 ± 34.04	9.5 ± 3.43
Chemical Oxygen Demand (COD) (mg/L)	1030 ± 124.45	82 ± 27.64
Total Suspended Solids (TSSs) (mg/L)	459 ± 45.76	32 ± 16.21
N-NH3 (mg/L)	35.7 ± 4.47	8.2 ± 5.73
ORG-N (mg/L)	28.0 ± 2.48	3.4 ± 1.47
pH	7.2 ± 0.2	7.2 ± 0.2

3.2. Identification and Technical Analysis of the Byproducts of Mty WWTP with a Circular Economy Potential

The data used for the identification and technical analysis of the byproducts were obtained through visits to the Mty WWTP. Consequently, areas of opportunity and byproducts with high potential for the implementation of a circular economy approach were identified.

3.2.1. Treated Wastewater

Despite water being the primary byproduct of Mty WWTP, only 10% of it is destined for industrial use. As Nuevo León is a hub of industrial activity due to its proximity to North America, the sale of treated wastewater can potentially be increased. Companies could employ treated water instead of potable water in their processes and thus reduce water stress in the region. Moreover, treated wastewater could also be used in agriculture, irrigation, toilets, and the refilling of subterranean water [29].

According to the technical operative reports of Mty WWTP, the volume of treated water currently obtained per year is 242,605,722 m^3. Table 9 presents a comparison of the quality of the treated wastewater of Mty WWTP with the maximum permissible limits (MPLs) established by Mexican regulations for the wastewater treatment sector. The NOM-001-SEMARNAT-2021 [54] regulates the quality of water disposed of in national waters, whereas the NOM-003-ECOL-1997 [26] regulates the quality of water designated for reuse in public services. As evident, the quality of the wastewater treated by the Mty WWTP is acceptable as per their corresponding MPLs. This indicates the significant potential of the incorporation of this byproduct under a circular economy approach.

Table 9. Evaluation of the wastewater quality of Mty WWTP as per the MPLs established by Mexican normativity (2021) [26,54].

Residual Wastewater Parameters	NOM-001-SEMARNAT-2021	Treated Water Disposed of into the Pesquería River by the WWTP	NOM-003-ECOL-1997	Treated Water Sold by the WWTP
TSSs (mg/L)	60	32	20	6.1
COD (mg/L)	150	82	N/A *	N/A
BOD5 (mg/L)	38	9.5	20	6.7
ORG-N (mg/L)	25	3.4	N/A	N/A
Fecal Coliforms (NMP/100 mL)	250	196	240	154

* N/A: Not available.

3.2.2. Sewage Sludge and Anaerobic Digestion Process

The Mty WWTP produces on average 158,900 cubic meters of sludge every month. Most of this sludge is dumped in a landfill and thus remains unused for any other purpose. Operational data of the sewage sludge characterization and anaerobic digestion process for the Mty WWTP were determined based on data reported in the operating logbook of the facility (Table 10). Notably, the anaerobic digestion process of Mty WWTP exhibits a low efficiency rate (32% of volatile solids removal) owing to inadequate operation conditions, such as issues with temperature, agitation, unbalanced feed, unbalanced microflora, among others [55].

Table 10. Operational data of the sewage sludge characterization and anaerobic digestion process for the Mty WWTP.

Operational Data	Units	Mty WWTP
Sewage sludge characteristics		
Influent sludge	m^3/d	2240 ± 341
Total solids content (TS)	%	3.7
Total solids (TS)	g/L	38 ± 3.3
Volatile solids (VS)	g/L	21 ± 2.1
Volatile fraction	%	55%
Anaerobic digestion process		
Total digestion volume (use)	m^3	61,365
Number of digesters	unit	5
Solid retention time (SRT)	days (d)	22
Operational temperature	°C	32 ± 3
% vs. removal	%	32 ± 6

As can be seen, the anaerobic digestion process operates at the lower end of the mesophilic temperature interval (32 to 36 °C), hindering organic degradation and the corresponding methane production [34]. Furthermore, the solids retention time (SRT) is a critical operating parameter in anaerobic processes. In this case, the anaerobic digesters operate at higher values than those typically used in practical applications for these processes (10 to 20 days) [34]. The typical TS in the sludge for this type of process ranges from 4.0 to 5.8% [34]. Lower values could cause negative impacts on digester operation, including limited vs. removal, reduced CH_4 production, and increased heating requirements [56]. Lower values could cause negative impacts on digester operation, including limited vs. removal, reduced CH_4 production and increased heating requirements [56]. Additionally, the low vs. removal efficiency is attributed to the low operating temperature of anaerobic digesters, resulting in partial sludge stabilization. The characteristic range in a mesophilic anaerobic digestion process is between 40 and 60% of vs. removal, depending on the operating temperature range, its retention time, and the type of digester [34].

This study conducted an analysis of the primary parameters related to sewage sludge quality (heavy metals, pathogens, parasites, and vector attraction) to determine whether the sludge treated with the Mty WWTP complied with the NOM-004-SEMARNAT-2002 [14], which establishes the specifications and MPLs of contaminants for the use and final disposal of sewage sludge and biosolids.

The sludge was observed to comply with the standards for the presence of heavy metals (Table 11); however, it did not comply with the parameters regarding the MPLs for pathogens and parasites (Table 12). Although it exhibited acceptable levels of helminth eggs on a dry basis, it did not satisfy the standards for fecal coliforms. Thus, the digested sludge of this case study cannot be classified under any of the categories in relation to normativity. Moreover, the results of the vector attraction analysis indicated that the residual sludge yielded a 30% removal rate of volatile solids, which was 8% below the limit established by the normativity standards (>38%).

Table 11. Comparison of the Mty WWTP sewage sludge with the MPLs for heavy metals in sludge (NOM-004-SEMARNAT-2002) [14].

	NOM-004-SEMARNAT-2002		**Mty WWTP (2021)**	
Contaminants	**Excellent (mg/kg on a Dry Basis)**	**Good (mg/kg on a Dry Basis)**	**Digested Sludge (mg/kg on a Dry Basis)**	**Classification**
Arsenic	41	75	2	Excellent
Cadmium	39	85	43.6	Good
Chromium	1200	3000	136	Excellent
Copper	1500	4300	121	Excellent
Lead	300	840	1032	Good
Mercury	17	57	58	Good
Nickel	420	420	395	Good
Zinc	2800	7500	2208	Excellent
Overall Classification				Excellent/Good

Table 12. Comparison of the Mty WWTP sewage sludge with the MPLs for pathogens and parasites in sludge (NOM-004-SEMARNAT-2002) [14].

NOM-004-SEMARNAT-2002			**Mty WWTP**		
Classification	**Fecal Coliforms/g on a Dry Basis**	**Helminth Eggs/g on a Dry Basis**	**Fecal Coliforms/g on a Dry Basis**	**Helminth Eggs/g on a Dry Basis**	**Classification**
A	<1000	<1	43,000,000	<1	Out of Level C
B	<1000	<10			
C	<2,000,000	<35			

To improve the treatment and management of the sludge in the Mty WWTP, the issues that cause the poor quality of the sludge must be identified and fixed. The solutions to render the sludge feasible for use in circular economy strategies include increasing the solid retention time, which entails reaching mesophilic or thermophilic temperatures during the anaerobic digestion process, and repairing leaks in the digesters. Moreover, the Ecological Sludge Treatment Plant (ESTP), which has been out of operation since 2019 due to a lack of maintenance and the high costs incurred by its demand for natural gas, can be reactivated.

The ESTP is a thermal sludge-drying plant equipped with technology for biofuel conversion which has the capacity to transform 400 tons of sewage sludge for industrial use daily. In this plant, natural gas was used as the fuel for combustion. The flue gas generated from burning natural gas was then utilized as the drying medium. The heat carried by the flue gas, along with the gases produced during combustion (e.g., CO_2, water vapor), helped to dry the material.

The plant utilized thermal drying technology to treat residual sludge, reducing the sludge volume by up to 70%, which facilitated its transportation and storage. The sludge-drying process comprised the following four phases:

- Reception and extrusion: the sludge is deposited in a hopper and then transferred onto belts, where air flows through the sludge.
- Belts: the sludge-loaded belts move through a tunnel. In this phase, the sludge must remain stationary to prevent dust generation and potential clogs.
- Drying: the drying process is conducted using fans that generate hot and dry air between 85 and 90 °C in a closed circuit.
- Final product: the dry sludge is stored in 200 L containers for commercialization.

If the ESTP were to be reactivated, the sewage sludge could reach the "A" classification level, facilitating its commercialization as a biofertilizer without any restrictions.

3.2.3. Biogas Production

The amount of biogas produced in the Mty WWTP, which comprises 65% methane on average [57], has declined by nearly half in recent years (Table 13). This can be attributed to the strong correlation between biogas production and sludge production. The poor quality of the sludge, as well as the lack of maintenance for the equipment in the WWTP, has led to the anaerobic digestion process occurring in non-optimal conditions. The biogas currently produced is burned in torches because the cogeneration system of the WWTP is not in an operative state. This is undertaken as a "Good Practice" because it converts methane (CH_4) into carbon dioxide (CO_2), thereby reducing its impact as a GEI. However, improving sludge management could significantly increase methane production. This would make the biogas recovery process more viable, enabling the generation of electric or thermal energy for internal use and potentially even for external distribution.

Table 13. Average daily biogas and methane production in the Mty WWTP (2016–2021).

	2016	2017	2018	2019	2020	2021	Annual Average
Average amount of biogas (m^3)	40,153	33,594	44,215	31,313	24,118	17,412	31,801
Average amount of methane (m^3)	26,100	21,836	28,740	20,354	15,677	11,318	20,671

4. Conclusions

This study aimed to design proposals for the incorporation of a circular economy scheme into the wastewater treatment sector so that it can be replicated around Mexico. The three pillars of sustainability were considered. Consequently, three proposals were developed: the production of organic fertilizer from biosolids, cogeneration from biogas, and the treatment of water for the industrial sector.

A potential opportunity was detected regarding the use of water in more industries that are yet to employ treated water in their processes. This would reduce the use of drinking water and further enhance the availability of water for the community. In the sewage sludge proposal, the reactivation of the ESTP can improve the quality of the sludge to a classification "A" so that it can be used in direct contact with the public. The economic analysis considered the transportation, packaging, and maintenance costs of the ESTP. Consequently, a selling price for the biosolids below the average of the current market was obtained because this byproduct was not pure. Improvements and theoretical changes were implemented for the development of the biogas proposal with the aim of obtaining a feasible proposal. Starting from an ideal scenario, the proposal used the methane originating from the biogas as fuel for a cogeneration plant to facilitate the production of electrical and thermal energy. This rendered the Mty WWTP energetically self-sufficient. Private investment is crucial to integrating circular economy models in the wastewater treatment industry. In our case study, a public–private alliance was vital for the commercialization of biogas.

Considering a world that has begun to experience water stress events, Nuevo León, Mexico, is no exception owing to its dry climate. The region has been impacted by the exponential growth of the population and industry because of nearshoring. This has rendered the strengthening and maintenance of the water and drainage system and with it, the water cycle, essential. The current system suffers from deficiencies owing to the connection of its distribution network to its water treatment system, lacking the economic support from the state government required to sustain the different plants. Through the incorporation of circular economy strategies in the Mty WWTP, the water stress of the city can be mitigated and thus set an example for other wastewater treatment plants in the country.

For a circular economy model to be successful, all actors involved must be committed to meeting the requirements expected of them. Some key factors to consider include sanitation plans and innovative agreements for the reuse of different byproducts with industrial sectors, generating economic, environmental, and social benefits for the community. Encouraging participation in pilot projects that demonstrate the feasibility and benefits of reusing treated water, generating bioenergy, and selling biofertilizers is essential. At the government level, public policies must be generated, including legal, technical, and environmental recommendations, to promote the use of treated wastewater. It is also necessary to establish fixed and affordable water tariffs, and to facilitate public–private partnerships for the operation and transfer of the technology required to ensure the circularity of byproducts, fostering continuous improvement and good practices. Finally, in some cases, modernizing existing WWTPs with innovative technology may be enough to advance towards the sustainable management of the wastewater treatment sector.

Author Contributions: J.A.O.G. Conceptualization, methodology, software, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration. M.G.U. Methodology, formal analysis, investigation, data curation, writing—original draft preparation, visualization. M.G.P.F. Conceptualization, validation, resources, writing—review and editing, supervision, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Research Projects 2024 of the Research Directory of the UDEM.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors are grateful to the Mty WWTP staff for providing the data used in this study obtained during the Final Evaluation Project.

Conflicts of Interest: The authors declare no conflicts of interest.

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