

Article

From Conventional to Sustainable: Decadal Evolution of Wastewater Treatment and Its Environmental Impacts in a Fast-Growing City

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Abstract

This study analyzes wastewater treatment plants (WWTPs) in Querétaro, Mexico, over a decade (2013–2022), highlighting the interdependencies between pollutant removal, energy consumption, and greenhouse gas (GHG) emissions. Despite being conventional systems, the WWTPs achieved high pollutant removal efficiencies (92–97% BOD₅, 50–60% TN), preventing 146.1 MtCO₂e over ten years. However, this efficiency came with some drawbacks: a 10% reduction in pollutants increased electricity consumption by 7%. CO₂ emissions from grid-fed operations increased by 130% between 2021 and 2022, emphasizing the carbon intensity of improving water quality. In 2022, the system emitted 0.002 tCO₂e/m³ of treated water, due to indirect N₂O and CH₄ emissions from untreated flows and electricity consumption. With only 70% of wastewater treated and minimal energy recovery, the existing infrastructure offers environmental benefits but operates near its efficiency limits in the face of increasing demand. The transition to energy-neutral models, through biogas cogeneration, solar integration, and advanced nutrient removal, is crucial for achieving urban water systems resilient to climate change. This case study provides valuable insights for cities seeking to balance water security, sustainability, and decarbonization in rapidly developing regions.

Keywords: water treatment; energy-water nexus; greenhouse gas emissions; urban sustainability; global south; decarbonization



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1. Introduction

Urbanization in the Global South is driving unprecedented pressure on water and sanitation infrastructure, with wastewater treatment systems frequently lagging behind population growth and industrial expansion. In this context, mid-sized, fast-growing cities like Querétaro, Mexico—one of Latin America’s most dynamic urban centers—embody a critical challenge: how to deliver effective wastewater treatment while navigating energy constraints, financial limitations, and rising greenhouse gas (GHG) emissions. Despite global commitments under SDG 6 and the Paris Agreement, which aim to guarantee universal and sustainable access to drinking water and sanitation by 2030 in Latin America [1], long-term empirical assessments of wastewater treatment plant (WWTP) performance in

rapidly developing regions remain scarce, particularly those that integrate contaminant removal, energy intensity, operational costs, and net carbon footprint over time [2].

Rapid urban growth in cities of the Global South, particularly in Latin America, has led to significant challenges in wastewater management. Urbanization rates of 80–82% and population growth have placed increasing pressure on wastewater treatment systems [3]. Additionally, deteriorating infrastructure causes resource losses of up to 60% [1], while water stress is exacerbated by a doubling in water demand since 1960 and an expected 43% increase by 2050 [4]. These factors highlight the urgent need for innovative and sustainable solutions to improve wastewater treatment efficiency, reduce environmental impacts (e.g., DBO/NT and greenhouse gas emissions), and support international commitments such as the SDGs.

While high-income countries have advanced toward energy-neutral or even energy-positive treatment facilities through process optimization and resource recovery, many cities in the Global South continue to rely on conventional activated sludge systems, with focus primarily on the removal of DBO and SST, with limited nutrient removal (30–40%) and minimal energy recovery [5]. This technological disparity results in a significant oversight of co-benefits, not only in terms of water reuse potential but also climate mitigation. WWTPs can act as net emitters of GHGs, notably methane (CH_4) and nitrous oxide (N_2O), yet they simultaneously prevent far larger emissions that would occur from discharging untreated wastewater into aquatic ecosystems [6]. Quantifying this dual role, balancing emissions generated during treatment against those avoided by preventing raw discharges, is essential for evidence-based policy and sustainable infrastructure planning [7].

Querétaro provides a compelling case study. Over the past decade, the city has expanded its treatment capacity amid rapid economic development and demographic growth. However, only 70% of generated wastewater is treated, and none of its major plants, except San Pedro Mártir, utilize biogas cogeneration. The interplay between improved effluent quality, rising electricity demand, operational costs, and net carbon footprint has not been systematically analyzed over time. Understanding these dynamics is crucial for identifying leverage points toward decarbonization and resilience [8].

This study addresses a critical gap in research by presenting a ten-year longitudinal analysis (2013–2022) of the wastewater treatment system in Querétaro, offering a detailed dataset that encompasses multiple dimensions of sustainability. By integrating technical and environmental indicators, this work provides insight into the trade-offs involved in sustainable water management. To our knowledge, few studies in Latin America offer such extensive analyses of wastewater treatment systems, making this dataset a valuable contribution to the field. Using IPCC-compliant methodologies, we estimate both the GHG emissions released during treatment and, crucially, those avoided through the prevention of untreated discharges—a net carbon perspective that is rarely applied in practice.

By providing a holistic assessment of a real-world treatment network operating under growing demand, this work contributes to the growing body of knowledge on sustainable urban water management in the Global South. It offers actionable insights for policymakers and engineers seeking to transform conventional WWTPs into climate-resilient, resource-efficient systems. Ultimately, Querétaro's journey reflects a broader imperative: to move beyond basic compliance and embrace wastewater treatment not just as a public health necessity, but as a strategic component of urban sustainability and climate action [9].

2. Materials and Methods

2.1. Water Treatment in Mexico

Mexico ranks among the ten most populous countries globally, with an estimated population of 131.2 million inhabitants [10]. As a signatory to the United Nations 2030

Agenda for Sustainable Development, Mexico has developed a National Strategy for the Implementation of the 2030 Agenda, which provides a long-term framework to guide policy coherence and institutional alignment, including within the water sector [11]. A central component of this strategy is the pursuit of Sustainable Development Goal (SDG) 6: “Ensure availability and sustainable management of water and sanitation for all.” Key national targets aligned with SDG 6 include improving water quality by reducing pollution, eliminating the discharge of hazardous chemicals, halving the proportion of untreated wastewater, and significantly increasing safe water reuse and recycling by 2030 [11].

The average natural water availability in Mexico is 447.26 km³/year, of which 80% corresponds to national surface runoff (354.99 km³/year) and the remaining 20% (92.27 km³/year) contributes to aquifer recharge. In per capita terms, the average national availability is 13,470 m³/person/year, calculated based on the national population and available renewable water resources. This figure reflects adequate availability compared to international standards, but it continues to face regional challenges due to unequal distribution and pressure on water resources [11].

According to data from the 2020 national census, 119.3 million people, 96.1% of the population, have access to drinking water services, and 95.2% are connected to sewage systems [12]. Despite high infrastructure coverage, wastewater treatment remains a critical gap: only 66.7% of generated wastewater is treated nationwide [11]. The country operates a total of 2774 municipal wastewater treatment plants (WWTPs) across its 32 states, with an installed capacity of 195,536.8 L/s (195.5 m³/s) and an average treated flow of 143,756.7 L/s (143.8 m³/s), leaving 33.3% of wastewater discharged without adequate treatment. The predominant treatment technologies include stabilization ponds and activated sludge systems [13].

2.2. 10 Years of Water Treatment in Querétaro

Among Mexico’s federal entities, the state of Querétaro stands out as one of the most economically dynamic regions, ranking sixth nationally in GDP per capita and economic development [14]. With a population of 2,368,467 [12], it comprises 18 municipalities, including Santiago de Querétaro, the focus of this study, hereafter referred to as SQRO [15].

At the state level, Querétaro reports high service coverage: 97.6% for drinking water and 97.1% for sewerage. However, only 50.3% of collected wastewater receives treatment, corresponding to a treated flow of 1612 L/s across its 63 operational WWTPs, which have a combined installed capacity of 2372 L/s [11,16]. These figures indicate that 2.9% of the population lacks sewer connections, and 49.7% of wastewater is discharged untreated, a major contributor to surface and groundwater contamination.

SQRO covers an area of 705.4 km², accounting for 6.04% of the state’s territory, and is home to 1,049,777 residents [12,15]. The city operates six WWTPs, serving approximately 413,509 inhabitants, with 70% of its wastewater receiving treatment based on current technological and financial constraints [16]. These facilities employ conventional activated sludge processes, with design flow rates ranging from 1.07 to 556.5 L/s, as reported by the State Water Commission (CEA Querétaro).

Conventional treatment in these plants primarily targets the removal of solids and organic matter through physical and biological processes. However, they offer limited nutrient removal, meaning that nitrogen-rich effluents, originating from undigested dietary proteins, are commonly discharged into natural water bodies. Under such conditions, nitrogen can undergo microbial transformations leading to the formation of nitrous oxide (N₂O), a potent greenhouse gas (GHG) with a global warming potential 298 times greater than CO₂ over a 100-year horizon [17,18]. In contrast, advanced treatment systems achieve 80–95% nutrient removal through engineered nitrification and denitrification processes,

whereas conventional WWTPs focus on DBO and SST removal, achieving only 30–40% of nutrients removal [18].

It is worth nothing that virtually none of the WWTPs in QRO utilize energy cogeneration. They operate entirely on grid-supplied electricity provided by the Federal Electricity Commission (CFE), contributing to their carbon footprint. Only one plant in the entire state, San Pedro Mártir WWTP, implements biogas recovery from anaerobic digestion, generating 0.3 MW of electrical power [16]. This facility serves as a model for resource recovery, but its benefits remain isolated.

The treatment process in SQRO's activated sludge plants follows a standardized sequence: (1) pretreatment, involving mechanical screening to remove coarse solids that could interfere with downstream operations; (2) extended aeration, where suspended and dissolved organic matter are biologically degraded under aerobic conditions; and (3) secondary settling, in which biomass is separated from treated water via gravity sedimentation [8,19–21]. Sludge handling includes anaerobic digestion followed by dewatering using belt filter presses, after which biosolids are sent for final disposal [13]. All operations are regulated under Mexico's official environmental standards (Normas Oficiales Mexicanas, NOMs), particularly NOM-001-SEMARNAT-2021, which sets limits for wastewater discharges [22], and NOM-003-SEMARNAT-1997, governing the reuse of treated water in public services [23].

The WWTPs to be considered in this case study are listed in Table 1, which details the number of populations served, the flow treated and the type of treatment applied [13].

Table 1. List of SQRO Wastewater Treatment Plants.

Name of the WWTP	Benefited Inhabitants	Treated Flow (L/s)	Type of Treatment
Centro	63,878	104.55	Activated sludge
Santa Rosa Jauregui	13,536	13.88	Activated sludge
Terminal de autobuses	2246	3.67	Activated sludge
San Pedro Mártir	320,544	546.69	Activated sludge with N removal
Hospital del niño y la mujer	979	1.07	Activated sludge
Ciudad del Sol	12,326	23.74	Activated sludge with dynamic sedimentation
Total	413,509	693.6	

SQRO treatment plants have evolved in terms of the number of installations over the years and level of treatment. Water treatment in this area began from 1995 to 2017. Figure 1 shows the evolution of the construction and commissioning of each of the six WWTPs in the study area.

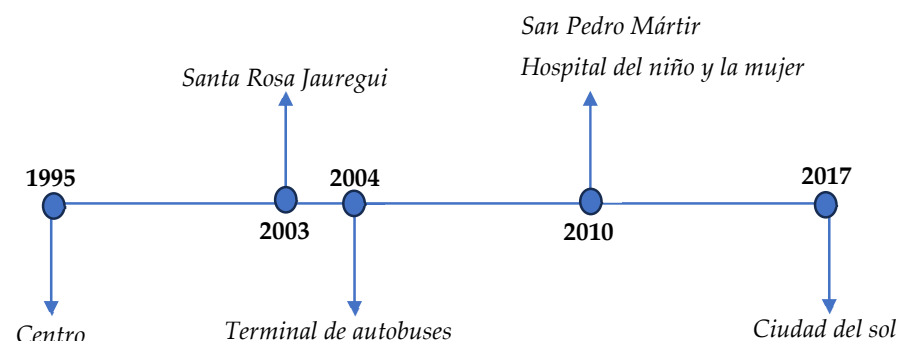


Figure 1. Historical evolution of the commissioning of WWTPs in the study area.

According to the information provided by the CEA, the plants in the study area have a type of activated sludge treatment applied, with the exception of the San Pedro Mártir plant where there is also a reduction in nitrogen and cogenerated energy is used [13,16].

San Pedro Mártir is the only plant designed for advanced nutrient removal, while the other plants, although they do not have tertiary treatment, contribute to nutrient reduction due to the inherent processes of primary and secondary treatment.

The San Pedro Mártir plant is the one that provides the greatest treatment coverage, with a total of 320,544 inhabitants served and a treated flow of 546.7 L/s by 2022. The Hospital del niño y la mujer plant is the one with the lowest installed capacity with 1.1 L/s and 979 inhabitants covered.

This research focuses on the analysis of the functioning and operation of the SQRO WWTPs over the last 10 years. The data to be evaluated are the treated flow and the removal of contaminants (Biochemical Oxygen Demand (BOD₅) and total nitrogen) from 2013 to 2022. Electricity consumption and operating, maintenance, and energy costs are only included for 2021 and 2022.

The available data present some limitations, since some plants do not have a record of the water quality parameters at the entrance and/or exit of the facility. In this research, only the data on electricity consumption and total costs for 2021 and 2022 are available. Consequently, any analysis or conclusion regarding energy consumption, costs, or emissions must be explicitly restricted to the two-year period under study. The administration only provided a single data point on the population served per treatment plant, so it will not be possible to analyze the increase in the population and its relationship with water consumption. These limitations highlight the need for future studies to obtain more comprehensive datasets, including historical records of energy consumption and costs to evaluate long-term trends. The available information is shown below:

Plants that do not record TN data at either the inlet or outlet may be traditional wastewater treatment plants without an advanced nutrient removal stage. The only plant that records this parameter is the San Pedro Mártir plant, which has a nutrient removal treatment stage in its operation. It is important to note that this study analyzes operational data from 2013 to 2022. In 2021, NOM-001-SEMARNAT, which establishes the maximum permissible limits of pollutants in wastewater discharges into receiving bodies in Mexico, was updated. This standard had not been updated for 25 years [22]. Until then, TN was not a mandatory parameter to measure in wastewater discharges. However, starting in 2022, with the implementation of the new standard, all plants began to measure and report this parameter as part of their management.

In 2013, the base year of this research, the WWTPs already had an operating period of between 3 and 18 years for the oldest plant (5 of the 6 total plants in the study area were already operating).

With the data provided by the CEA in Querétaro, an evolution can be observed in the importance of wastewater treatment. Starting from the base year, in 2013 there is only information on the treated flow and the inlet and outlet BOD₅. There are also no records of the operation and maintenance costs, or the energy consumption of the plants. We could consider that for this year there was still no appreciation of the relevance of wastewater treatment, so only the standard for removal of organic matter and solid and bulky waste was met. The treated flow that year was 61,280 m³ per day, with an average BOD₅ input of 460 mg/L and a removal of 439 mg/L, having a removal efficiency of 94.7% (Table 2).

In 2014, the treated flow rate of the 5 WWTPs in the area was 61,915 m³ per day, an average BOD₅ input of 534.8 mg/L, and a removal efficiency of 92.9%. Starting this year, the registration of nitrogen input and output at the San Pedro Mártir plant began, since, according to public information, it is the only plant with N removal as part of the wastewater treatment process. The average N input to the WWTP was 73.7 mg/L of water, with a N removal of 15%. There is no data on electricity consumption or operation, and maintenance and energy costs (Table 3).

Table 2. Operation data of the WWTPs in the study area in 2013.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)
1	San Pedro Mártir	17,717,807	285	30
2	Santa Rosa Jauregui	849,738	591	16.76
3	Centro	3,658,958	277	18.82
4	Terminal de autobuses	115,839	569	15.06
5	Hospital del niño y la mujer	24,804	578	22.04
	Total	22,367,146	460	20.5

Table 3. Operation data of the WWTPs in the study area in 2014.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	18,186,463	560.0	83.0	73.7	62.5
2	Santa Rosa Jauregui	829,629	589.9	44.1	Undefined	Undefined
3	Centro	3,472,750	280.9	21.7	Undefined	Undefined
4	Terminal de autobuses	82,664	568.7	17.9	Undefined	Undefined
5	Hospital del niño y la mujer	27,480	674.7	15.7	Undefined	Undefined
	Total	22,598,986	534.8	36.5	73.7	62.5

In 2015, the WWTPs treated a flow of 53,738 m³ per day, and the average BOD₅ input was 536.2 mg/L, with a removal of organic matter of 96%. The San Pedro Mártir plant had an input of 78.4 mg of nitrogen per liter of water and had a removal efficiency of 28% (Table 4).

Table 4. Operation data of the WWTPs in the study area in 2015.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	15,198,258	557.0	23.0	78.4	56.4
2	Santa Rosa Jauregui	811,732	628.0	17.2	Undefined	Undefined
3	Centro	3,454,790	295.0	22.4	Undefined	Undefined
4	Terminal de autobuses	113,609	592.5	19.6	Undefined	Undefined
5	Hospital del niño y la mujer	36,126	608.5	18.4	Undefined	Undefined
	Total	19,614,515	536.2	20.1	78.4	56.4

In 2016, 60,942 m³ of water were treated per day, with an average input of BOD₅ to the WWTPs of 592.6 mg/L, and a matter removal efficiency of 94.2%. The San Pedro Mártir WWTP had a nitrogen input of 76.7 mg/L and a removal of 12%, which represents that the effluent contained 67.6 mg of N per liter of water (Table 5).

Table 5. Operation data of the WWTPs in the study area in 2016.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	17,776,676	589.0	76.0	76.7	67.6
2	Santa Rosa Jauregui	769,441	749.6	28.4	Undefined	Undefined
3	Centro	3,556,874	308.6	15.0	Undefined	Undefined
4	Terminal de autobuses	108,177	692.5	24.4	Undefined	Undefined
5	Hospital del niño y la mujer	32,803	623.4	24.0	Undefined	Undefined
	Total	22,243,971	592.6	33.5	76.7	67.6

By 2017, the 6 SQRO WWTPs were already operating; the treated flow was 60,322.5 m³ of water per day, and the BOD₅ input to the plants had an average value of 618 mg/L, with

a removal efficiency of 94%. The San Pedro Mártir WWTP presented a total nitrogen input of 57.4% and a removal of 55% of the input nitrogen (Table 6).

Table 6. Operation data of the WWTPs in the study area in 2017.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	16,464,396	352.2	35.4	57.4	25.6
2	Santa Rosa Jauregui	739,084	775.4	10.8	Undefined	Undefined
3	Centro	3,545,580	669.3	15.0	Undefined	Undefined
4	Terminal de autobuses	112,994	878.7	21.8	Undefined	Undefined
5	Ciudad del Sol	1,121,416	589.2	16.9	Undefined	Undefined
6	Hospital del niño y la mujer	34,255	444.0	74.7	Undefined	Undefined
	Total	22,017,725	618.1	29.1	57.4	25.6

In 2018, the plants in the area treated 62,004 m³ of water per day, with a BOD₅ input of 567 mg/L and an organic matter removal efficiency of 97%. In the case of TN, the San Pedro Mártir plant, which is the only one that has a record of this parameter so far, reported a N input of 51 mg/L and a removal efficiency of 60% (Table 7).

Table 7. Operation data of the WWTPs in the study area in 2018.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	Bod ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	17,554,264	431.0	12.6	50.9	20.2
2	Santa Rosa Jauregui	741,515	642.3	15.7	Undefined	Undefined
3	Centro	3,502,590	568.6	10.5	Undefined	Undefined
4	Terminal de autobuses	121,629	597.6	26.1	Undefined	Undefined
5	Ciudad del Sol	675,975	557.5	29.2	Undefined	Undefined
6	Hospital del niño y la mujer	35,322	605.4	17.9	Undefined	Undefined
	Total	22,631,295	567.1	18.7	50.9	20.2

In 2019, the treated flow was 65,423 m³ of water per day, the average organic matter content at the entrance to the plants was 556 mg/L, and there was a removal efficiency of 96%. The San Pedro Mártir plant presented a TN input of 77.2 mg per liter and a N removal efficiency of 20% (Table 8).

Table 8. Operation data of the WWTPs in the study area in 2019.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	19,050,803	408.0	19.0	77.2	61.5
2	Santa Rosa Jauregui	727,685	625.2	17.2	Undefined	Undefined
3	Centro	3,335,950	524.2	21.0	Undefined	Undefined
4	Terminal de autobuses	160,664	523.1	26.1	Undefined	Undefined
5	Ciudad del Sol	579,192	606.9	12.0	Undefined	Undefined
6	Hospital del niño y la mujer	24,982	649.6	19.4	Undefined	Undefined
	Total	23,879,276	556.2	19.1	77.2	61.5

In 2020, the WWTPs reported a treated flow of 63,825 m³/day, an input BOD₅ of 570 mg per liter of water, and an organic contaminant removal efficiency of 96%. The San Pedro Mártir WWTP presented a TN input of 82.6 mg/L and a removal efficiency of 60%. For the first time, the Terminal de Autobuses plant reported TN data from the plant's input and output, having an input of 44.5 mg of N per liter and a content removal of 70% (Table 9).

Table 9. Operation data of the WWTPs in the study area in 2020.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)
1	San Pedro Mártir	18,477,895	330.0	28.6	82.6	32.8
2	Santa Rosa Jauregui	541,811	672.8	12.0	Undefined	Undefined
3	Centro	3,609,810	484.1	24.0	Undefined	Undefined
4	Terminal de autobuses	118,944	630.0	25.0	44.5	13.4
5	Ciudad del Sol	508,749	684.0	12.7	Undefined	Undefined
6	Hospital del niño y la mujer	38,804	617.2	15.7	Undefined	Undefined
	Total	23,296,013	569.7	19.7	63.6	23.1

For 2021, the treated flow was 64,063 m³ per day. The average input concentration of organic matter in the wastewater was 508 mg/L, with a removal of 473 mg/L and an efficiency of 92%. This year, the Centro, Ciudad Sol and Hospital del Niño y la Mujer plants did not define the input concentrations of BOD₅, so the value reported this year only considers the information reported from the San Pedro Mártir plants, Santa Rosa Jauregui and Terminal de Autobuses. TN values were only reported by the San Pedro Mártir plant, whose input value was 89.2 mg/L and an elimination percentage of 26%. The Santa Rosa Jauregui, Centro and Bus Terminal plants only recorded the value of nitrogen in the effluent. The Ciudad Sol and Hospital de niño y la mujer plants did not provide any nitrogen records. According to the information provided, this year the energy consumption of electricity was 40,993.484 MWh, which represents 0.0017 MWh per m³ of treated flow. The total cost of treating wastewater was \$77,217,892 Mexican pesos, and therefore the average cost per m³ of treated water was around \$9 Mexican pesos (Table 10). It is important to note that the cost per m³ was calculated based on data provided by the administration regarding the operation and maintenance costs for the years 2021 and 2022, which were used to calculate the average value.

Table 10. Operation data of the WWTPs in the study area in 2021.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)	Annual Consumption of Electrical Energy (MWh/Year)
1	San Pedro Mártir	18,048,874	430.5	11.6	89.2	65.8	28,358.924
2	Santa Rosa Jauregui	762,361	424.0	76.2	Undefined	16.4	3288
3	Centro	3,802,595	Undefined	14.1	Undefined	9.9	5304
4	Terminal de autobuses	114,143	669.0	16.0	Undefined	24.0	825.600
5	Ciudad del Sol	611,548	Undefined	Undefined	Undefined	Undefined	2808.960
6	Hospital del niño y la mujer	43,439	Undefined	Undefined	Undefined	Undefined	408
	Total	23,382,960	507.8	29.5	89.2	29.0	40,993.484

In 2022, a total of 59,928 m³ of water was treated per day, with an organic matter concentration of 511 mg/L, and a BOD₅ removal efficiency of 94%. In terms of nitrogen content in the water entering the plant, the TN removed was 54.1 mg/L with an efficiency of 60%. This removal percentage indicates that 40% of the nitrogen contained in the effluent is discharged into the natural receiving environment, causing serious environmental impacts such as eutrophication and the generation of nitrous oxide (N₂O), a powerful greenhouse gas (GHG). The value of the removed TN does not take into account the Center plant, since the input TN data is not available. For this year, electricity consumption increased by 0.002 MWh per m³ of treated water. Electricity consumption was 90,729.350 MWh/year, which represents 0.0041 MWh per m³ of treated flow. The total cost of treating wastewater was \$161,326,326 Mexican pesos, and the average cost per m³ of treated water was 12 Mexican pesos. There is no information on the electrical consumption of the Hospital del niño y

la mujer plant, since the CEA does not pay for this service, so the electrical consumption per m³ of treated flow may be underestimated (Table 11).

Table 11. Operation data of the WWTPs in the study area in 2022.

#	Name of the WWTP	Treated Flow Rate (m ³ /Year)	BOD ₅ Input (mg/L)	BOD ₅ Output (mg/L)	TN Input (mg/L)	TN Output (mg/L)	Annual Consumption of Electrical Energy (MWh/Year)
1	San Pedro Mártir	17,240,548	327.3	8.0	66.4	31.6	76,788.528
2	Santa Rosa Jauregui	437,677	424.0	6.7	79.9	36.8	741.990
3	Centro	3,297,170	655.9	8.9	Undefined	19.5	11,876
4	Terminal de autobuses	115,839	669.0	16.0	156.5	24.0	186.640
5	Ciudad del Sol	748,713	402.0	86.1	46.5	21.1	1136.192
6	Hospital del niño y la mujer	33,834	588.0	44.4	65.4	30.9	Undefined
	Total	21,873,781	511.0	28.4	83.0	27.3	90,729.350

The only plant that presents nitrogen removal as part of its treatment has an efficiency of between 12 and 60% removal over 9 years. The rest of the WWTPs do not report nutrient removal data and are classified as traditional WWTPs (Table 12).

Table 12. Percentage of N removal from the San Pedro Mártir WWTP in mg/L.

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
San Pedro Mártir	Undefined	11.2	22.0	9.2	31.8	30.7	15.6	49.8	23.4	34.8
%	Undefined	15	28	12	55	60	20	60	26	52

In this analysis it will only be possible to visualize the evolution of the treated flows in the WWTPs and their connection with the performance in the reduction in pollutants contained in the wastewater, the GHG emissions generated, and the emissions avoided by water treatment. In the case of 2021 and 2022, electricity consumption and total costs will be included in the discussion.

The approach taken in this study includes several assumptions that aim to simplify the analysis of the interactions between energy, water, and carbon costs in wastewater treatment systems. These assumptions were necessary due to a lack of specific and representative data.

2.3. Model

2.3.1. Estimation of CO₂ Emission

The CO₂ emission of the WWTPs is estimated from the annual electricity consumption (Equation (1)) of each of the plants in MWh, and the electrical emission factor of the study area for the inventory year in tCO₂e/MWh. The electrical emission factor per inventory year for Mexico is obtained from the National Emissions Registry (RENE) according to the country's electricity mix [24].

$$B_{rp} = E_{rp} * EF_r \quad (1)$$

where B_{rp} is the CO₂ emission from electricity consumption at each WWTP in tCO₂e per year; E_{rp} is the electricity consumption in MWh of each of the analyzed WWTP and EF_r is the annual emission factor in relation to the electricity mix of Mexico obtained from RENE [24].

In this study, energy consumption was considered only for BOD and nitrogen removal processes, which are the most common operations in wastewater treatment plants. This simplification was adopted to provide an initial, manageable model for assessing CO₂ emissions. However, we recognize that this approach does not account for the energy impact of other important processes, such as phosphorus removal, disinfection, or carbon removal, which can vary significantly between plants and affect the results.

2.3.2. Estimation of CH₄ Emission

To estimate the CH₄ emission of the treatment plants analyzed in this study (Equation (2)), a simplified equation from the IPCC methodology [25] was used [26]. Additionally, the correction factors (MCF) proposed by Noyola et al. (2018) [27] were considered.

$$\text{CH}_4 \text{ Emissions} = B_0 * \text{MCF} (TOW - S) \quad (2)$$

where B_0 is the maximum CH₄ production capacity per kg of BOD removed (0.6 kg CH₄/kg BOD_{rem}) from the wastewater or sludge; MCF is the CH₄ correction factor according to the type of treatment (0.06 for a centralized aerobic treatment plant, 0.32 for a centralized aerobic treatment plant with anaerobic sludge digesters, 0.08 for a centralized aerobic anaerobic/anoxic treatment plant and 0.34 for a centralized aerobic anaerobic/anoxic treatment plant with anaerobic sludge digesters) [27]; TOW is the total organic matter in wastewater entering the treatment facility per year (it is obtained from operational data of each plant under study, kg BOD/year) and S is the organic component (sludge) removed from the facility per year (kg BOD/year, value obtained from [28]). The units of the equation are verified as follows: kg CH₄/year = $B_0 \times \text{MCF} \times (TOW - S)$.

2.3.3. Estimation of N₂O Emission

The N₂O emission of the WWTPs that have information on total nitrogen (TN) at the entrance was estimated using the methodology proposed by Snip (2010) [29] and the modification in the emission factor (EF) proposed by Ramírez-Melgarejo et al. (2020) of 0.03 kg N₂O-N/kg N [30] (Equation (3)). This methodology considers as the main parameter the value of TN entering the plant to know the N content in the wastewater. The effluent emission from these WWTPs is estimated using the IPCC methodology (2019) [31] and the modification in the EF range of 0.03 kg N₂O-N/kg N [30] (Equation (4)).

$$\text{N}_2\text{O}_{\text{emission}} = Q * N_{\text{total}} * EF \quad (3)$$

$$\text{N}_2\text{O}_{\text{EFFLUENT,DOM}} = N_{\text{EFFLUENT,DOM}} * EF_{\text{EFFLUENT}} * 44/28 \quad (4)$$

where $\text{N}_2\text{O}_{\text{emission}}$ is the N₂O emission in the inventory year (kg N₂O/year); Q is the inlet flow to each treatment plant (m³/day), to ensure consistency with the annual emissions, the flow is converted as follows: $Q_{\text{annual}} = Q \times 365$ (m³/year); N_{total} is the amount of N input to the plant per day (kg N/day), calculated as: $N_{\text{in}} = \text{TN}_{\text{in}} (\text{mg/L}) \times Q (\text{m}^3/\text{day}) \times 10^{-3} (\text{kg/m}^3)$; EF is the emission factor for N₂O emissions from discharged wastewater (0.03 kg N₂O-N/kg N); $N_{\text{EFFLUENT,DOM}}$ is the amount of N in the effluents discharged to the aquatic environment (kg N/day), calculated similarly: $N_{\text{effluent}} = \text{TN}_{\text{out}} (\text{mg/L}) \times Q (\text{m}^3/\text{day}) \times 10^{-3} (\text{kg/m}^3)$; and 44/28 is the molecular weight conversion factor (g N₂O per g N emitted as N₂O).

The emission of the WWTPs with a lack of TN information at the entrance of the plants was estimated using the methodology proposed by the IPCC (2019) [31], also considering the TN as the determining parameter to know the N content in the wastewater (Equation (5)). This value is obtained from the parameters of per capita protein consumption, the population served and values proposed by default (Equation (7)). The effluent emission from these analyzed WWTPs is estimated using the IPCC methodology (2019) [31] (Equations (4) and (6)), incorporating a modification proposed by Ramírez-Melgarejo et al. (2020) [30] in the EF of 0.03 kg N₂O-N/kg N. Due to the lack of information that exists on the behavior of N₂O in the aquatic environment, indirect emissions continue to be estimated using this IPCC methodology [25,31].

$$\text{N}_2\text{O Plants}_{\text{DOM}} = [\sum (U_i * T_{ij} * EF_j)] * \text{TN}_{\text{DOM}} * 44/28 \quad (5)$$

$$N_{\text{EFFLUENT,DOM}} = \left[\sum (TN_{\text{DOM}} * T_j) * (1 - N_{\text{REM},j}) \right] \quad (6)$$

$$TN_{\text{DOM},j} = (P_{\text{treatment},j} * \text{Protein} * F_{\text{NPR}} * N_{\text{HH}} * F_{\text{NON-CON}} * F_{\text{IND-COM}}) \quad (7)$$

where N_2O Plants_{DOM} are the N_2O emissions from domestic wastewater treatment plants in the inventory (kg N_2O /year); U_i is the fraction of the population in income group in the inventory year (obtained from a table, being 0.56 for Mexico); T_{ij} is the degree of utilization of the treatment/discharge route or system, for each fraction of income group in the inventory year (obtained from a table, being 0.40 for Mexico); EF_j is the emission factor for the treatment/discharge route or system (0.03 kg N_2O -N/kg N); TN_{DOM} is the total nitrogen in domestic wastewater in the inventory year (kg N/year); $P_{\text{treatment}}$ is the population served, or inhabitants; *Protein* is the annual consumption of protein per capita (kg/person/year) (Available in Our World in Data [32]); F_{NPR} is the fraction of N in the protein (0.16 kg N/kg protein); $F_{\text{NON-CON}}$ is the factor for unconsumed protein added to wastewater (1.1 for countries without garbage disposals and 1.4 for countries with garbage disposal); $F_{\text{IND-COM}}$ is the co-depleted industrial and commercial protein fraction (1.25); N_{HH} is the additional N from household products added to wastewater (default = 1.1); EF_{EFFLUENT} is the emission factor for N_2O emission from discharged wastewater (0.03 kg N_2O -N/kg N); 44/28 conversion of kg N_2O -N to kg N_2O ; N_{EFFLUENT} is the N in the effluent discharged to the aquatic environment (kg N/year); and $N_{\text{REM},j}$ is the fraction of total wastewater N removed during wastewater treatment by treatment type (secondary treatment 0.40, tertiary treatment 0.80) [31].

3. Results

With the data available from the SQRO WWTPs from 2013 to 2022, the emissions avoided with the treatment of wastewater, and the emissions released into the atmosphere, produced by the process, were calculated. Avoided emissions consider the N_2O emissions that are avoided by treating the water, and by reducing the N content. The emissions produced by the plants consider CO_2 emissions from electricity consumption, methane (CH_4) emissions due to the degradation of organic matter, and N_2O emissions that occur in the aquatic environment (indirect emission) where raw or partially treated wastewater is discharged.

In the case of the San Pedro Mártir WWTP, the avoided emission of CH_4 is considered from 2016 to 2022, since it is the only plant in the area that has implemented the anaerobic digestion process of waste sludge, with the necessary infrastructure for cleaning and use of biogas in the cogeneration of electrical energy [33]. Therefore, the CH_4 emission from 2013 to 2015 is considered an emission released into the atmosphere (direct emission) in the particular case of this WWTP. To improve the clarity of the analysis, a summary of the emissions considered in this study is presented below, highlighting the categories included and treated as avoided. Table 13 also specifies the periods analyzed for each type of emission.

The total GHG emissions from treating SQRO wastewater throughout the 10 years of study (Figure 2) correspond to 146,395,666 tCO₂e (146.39 MtCO₂e). The avoided emissions represent 99.8% of the total with 146,175,194 tCO₂e (146.1 MtCO₂e), and the released emissions result in 0.2% of the total with 220,473 tCO₂e (0.220 MtCO₂e). In 2022, the avoided emissions were 776,667 tCO₂e (0.776 MtCO₂e) (98.8%), and the released emissions were 9819 tCO₂e (0.0098 MtCO₂e) (1.2%), considering 70% coverage of treated water.

The analysis estimated that GHG emissions avoided due to wastewater treatment represent a difference of almost 98–99% compared to emissions generated by untreated wastewater. This result is linked to the fact that 70% of the wastewater has been treated, which significantly reduces emissions of gases such as N_2O and CH_4 . However, it is

important to clarify that this figure does not imply that 98–99% of the wastewater is treated, but rather reflects the proportion of emissions avoided thanks to treatment. An annual summary of avoided and released emissions is provided below in Table 14.

Table 13. Classification of emissions considered in the analysis, indicating their inclusion, treatment as avoided and the periods analyzed.

Emission Category	Included	Period Analyzed
Avoided		
N ₂ O	Yes	2013–2022
CH ₄ (Cogeneration)	Yes	2016–2022
Released (Direct)		
CH ₄ (Without Cogeneration)	Yes	2013–2022
CO ₂ (Electricity)	Yes	2021–2022
Indirect		
N ₂ O (Aquatic environment)	Yes	2014–2022

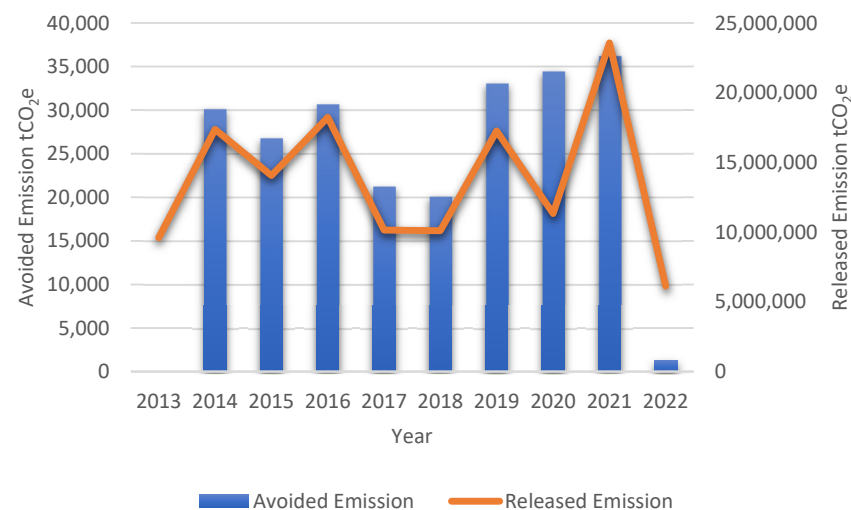


Figure 2. GHG emissions released and avoided by the WWTP analyzed during the inventory period.

Table 14. Annual summary of GHG emissions: emissions avoided vs. released during the study period.

Year	Avoided Emission (tCO ₂ e)	Released Emission (tCO ₂ e)	Relationships Avoided/Released (%)
2013	9113	15,356	37
2014	18,829,174	27,792	99.85
2015	16,737,052	22,490	99.87
2016	19,166,667	29,159	99.85
2017	13,283,470	16,244	99.88
2018	12,559,689	16,171	99.87
2019	20,655,722	27,611	99.87
2020	21,528,896	18,129	99.92
2021	22,628,744	37,702	99.83
2022	776,667	9819	98.75
Total	146,175,194	220,473	-

CO₂ emissions are obtained from the recorded electricity consumption of each WWTP in 2021 and 2022, using Equation (1). The results show an increase in electricity consumption in 2022 compared to 2021 relative to the treated flow rate, and therefore, an increase in Scope 2 emissions (Figure 3).

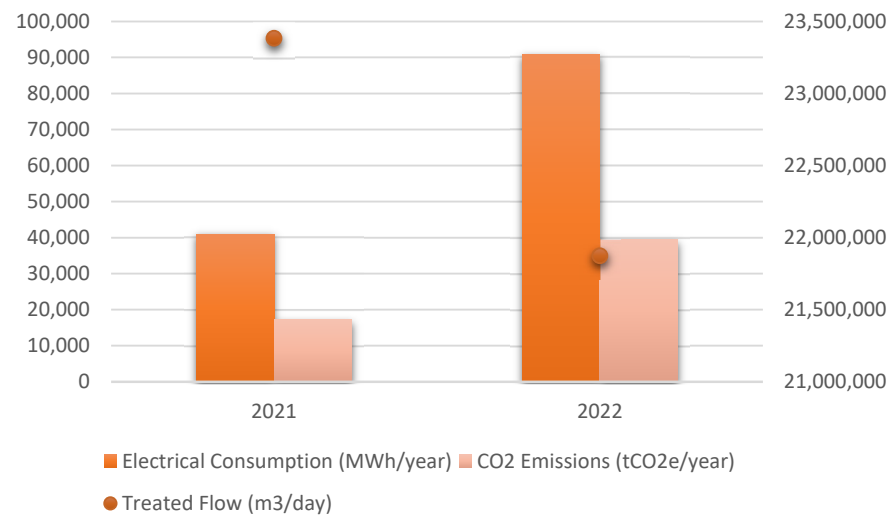


Figure 3. CO₂ emissions resulting from electricity consumption for the operation of the WWTPs in 2021 and 2022.

There is a variation between the electrical consumption and the treated flow of 2021 and 2022, since, although 2021 treated 6% more water (1,509,179 tCO₂e), its electrical consumption is 55% lower than that of 2022 (49,736 tCO₂e). CO₂ emissions from the plants' electricity consumption in 2021 were 17,168 tCO₂e, and 39,467 tCO₂e in 2022, with a difference of 43%.

The San Pedro Mártir plant cogenerates 0.3 MW of energy from biogas, relative to its installed capacity of 750 L/s. In this study, the cogenerated energy of this plant is excluded from the energy balance, as it is considered negligible compared to the plant's total energy consumption. However, it is included in the calculation of avoided CH₄ emissions resulting from biogas combustion/capture.

This approach reflects the system limits defined in the study, where the electrical compensation is not accounted for due to its low energy significance, but the environmental benefits derived from methane capture are considered a significant contribution to the reduction in GHG emissions. Figure 4 shows the percentage contribution of CO₂, CH₄ and N₂O emissions released in two years of the study period. 2021 and 2022 are the only years for which electricity consumption data is available.

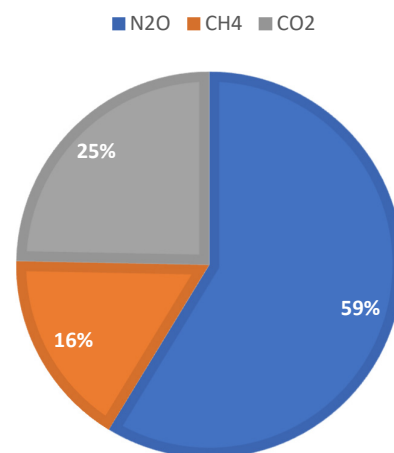


Figure 4. Contribution of emissions of each GHGs during 2021 and 2022.

Only one of the wastewater treatment plants in the study area captures the methane produced during treatment and cogenerates energy for its operation. This plant, which has the largest coverage and treatment capacity (19,050,803 m³/year), stands out from the rest.

The other plants have smaller capacities, ranging from 24,982 m³/year to 3,335,950 m³/year, and are older. Their infrastructure is outdated for biogas recovery, which presents initial investment barriers, technical limitations, and infrastructure challenges for biogas management and utilization. The most recent plant, built in 2017, is medium-sized and serves only 12,326 inhabitants. Due to its design, anaerobic digestion, a fundamental process for biogas production and electricity generation, was not included [34].

CH₄ emissions are produced by the degradation of organic matter contained in wastewater. To estimate the CH₄ emission, Equation (2) and the operation data from 2013 to 2022 were used. The results obtained from the CH₄ emission are expressed in tCO₂e and show a decrease in the emission of methane released into the atmosphere; this is observed to have been starting in 2016 when the San Pedro Mártir WWTP began to cogenerate energy.

There is an evolution of CH₄ emission throughout the 10 years of study. From 2013 to 2016, only five of the six plants that SQRO has were in operation. In 2016, the San Pedro Mártir plant began to capture the methane produced during the treatment of wastewater and cogenerate energy from biogas, thus avoiding the emission of this GHG into the atmosphere and using it as a source of renewable energy. In 2017, the sixth SQRO plant came into operation, which increased the released emission of CH₄, as it is a plant that does not cogenerate energy. In 2021 there is no record of input BOD₅ data in 3 WWTPs, so the emission released into the atmosphere this year is minimized.

The results of the released CH₄ emissions represent 47% (38,065 tCO₂e) of the total emissions of this GHG, and the remaining 53% (43,017 tCO₂e) correspond to the emissions avoided by the use of this gas. Figure 4 shows the percentage contribution of emissions from each of the GHG (CO₂, CH₄ and N₂O) during the study period. CH₄ and N₂O emissions from the produced sludge were not considered in this analysis.

N₂O emissions are produced from the different forms of nitrogen found in wastewater. This nitrogen reaches the water depending on the proteins ingested by the population [35]. The N₂O emission for WWTPs that have TN input data is estimated from Equation (3), this being the emission avoided by water treatment (direct emission); the indirect emission of these same plants is calculated from Equation (4). In the case of WWTPs that do not have TN entry records, the direct emission was calculated from Equation (5) and the indirect emission is obtained with Equation (6); in both cases, per capita protein consumption is used to know the amount of N present in the wastewater.

The results of the emission released to the aquatic environment and the emission avoided by the reduction in nutrients show a decrease in the emission of this powerful GHG due to the percentage of nutrient reduction presented by the WWTPs.

The N₂O emission results show that the emissions released into the atmosphere are insignificant when compared to the emissions avoided with wastewater treatment [36]. The released emissions (indirect emissions) represent 0.08% of the total N₂O emissions; this indicates that the emission in the aquatic environment is drastically reduced due to the high elimination percentage presented by the SQRO WWTPs. Figure 4 shows the percentage of N₂O that was released over the study period.

In 2013, no TN data was reported in any of the treatment plants, so the estimate was made based on the per capita consumption of that year, which is why we can see that there is 52% of the emission released with respect to the avoided emission. In the rest of the years the avoided emission is 99% of the total emission of this GHG. The only WWTP that reduces nutrients as part of its design presented an efficiency of 12–60%, which classifies it as a traditional treatment plant. Advanced treatment plants have a nitrogen reduction of over 80% [18].

According to 2022 data, the wastewater treatment plants had a total nitrogen (TN) removal rate that ranged from 52% to 85%, although this is not explicitly reported as part

of their standard operating procedures. The Bus Terminal plant showed a significantly higher nitrogen reduction efficiency than the San Pedro Mártir plant, with a removal rate of 84.7%, compared to 52.4% for San Pedro Mártir. Table 15 shows the TN removal rates for the wastewater treatment plants analyzed in 2022.

Table 15. Total nitrogen removal percentages in 2022.

#	Name of the WWTP	TN Input (mg/L)	TN Output (mg/L)	% Removal
1	San Pedro Mártir	66.4	31.6	52.40%
2	Santa Rosa Jauregui	79.9	36.8	54.00%
3	Centro	Undefined	19.5	N/A
4	Terminal de Autobuses	156.5	24	84.70%
5	Ciudad del Sol	46.5	21.1	54.60%
6	Hospital del Niño y la Mujer	65.4	30.9	52.80%

A sensitivity analysis was performed on the default-based N_2O estimates from Equations (5)–(7) by varying U_i , T_{ij} , and EF by $\pm 20\%$. The analysis showed that the influence of these parameters is concentrated in 2013, when no TN data were available, whereas from 2014 to 2022 their effect on the annual results is limited because they affect only the fallback N_2O term and plant-level TN data become progressively more available.

Focusing on 2022, the year in which we have more data on the operation and functioning of the SQRO WWTPs, we obtained that the avoided emissions corresponded to 776,667 tCO₂e (98.8%) and the emissions released were 9819 tCO₂e (1.2%) for only 70% of the treated wastewater; 30% of the produced and untreated wastewater that was discharged into the natural aquatic environment produced 8602 tCO₂e, which is equivalent to a total of 18,421 tCO₂e emissions released this year, considering indirect CH₄ and N₂O emissions.

According to these results obtained from emissions released from SQRO wastewater, there is a variation of 0.007 tCO₂e per m³ of treated water over the study period (Figure 5). The total per capita emission was 18,421 tCO₂e, with a variation of 0.39 tCO₂e over the 10 years analyzed (Figure 6).

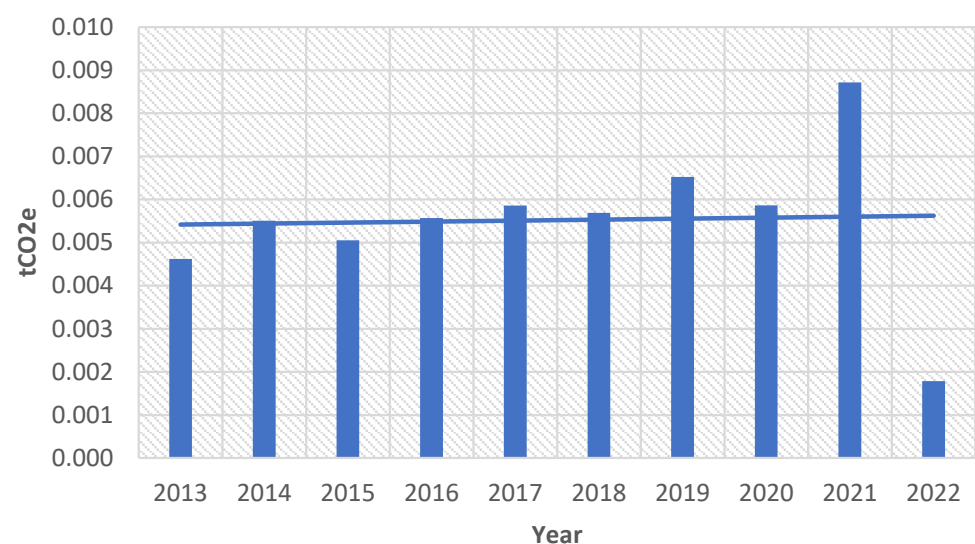


Figure 5. Temporal variation in emissions in tCO₂e per m³ of treated water during the study period.

The results in Figure 5 show an increase in the emission per treated flow, this being due to greater water consumption by the population, with a higher concentration of contaminants present in the wastewater. The emission generated per m³ of treated flow ranges between 0.002 and 0.009 tCO₂e, with the average being 0.006 tCO₂e/m³. In 2021,

the highest emission per treated flow occurs, since there is no record of the water quality at the entrance to three WWTPs, so the total estimated emissions were distributed among the total flow generated. This could cause an overestimation of the value obtained, since we do not know the efficiency of three WWTPs. The lowest emission per treated flow was generated in 2022. This result may be influenced by the large amount of data available this year, such as the BOD₅ of entry and exit of all WWTPs, the TN of entry and exit, and energy consumption. Additionally, nutrient removal in all treatment plants exceeded 50% reduction.

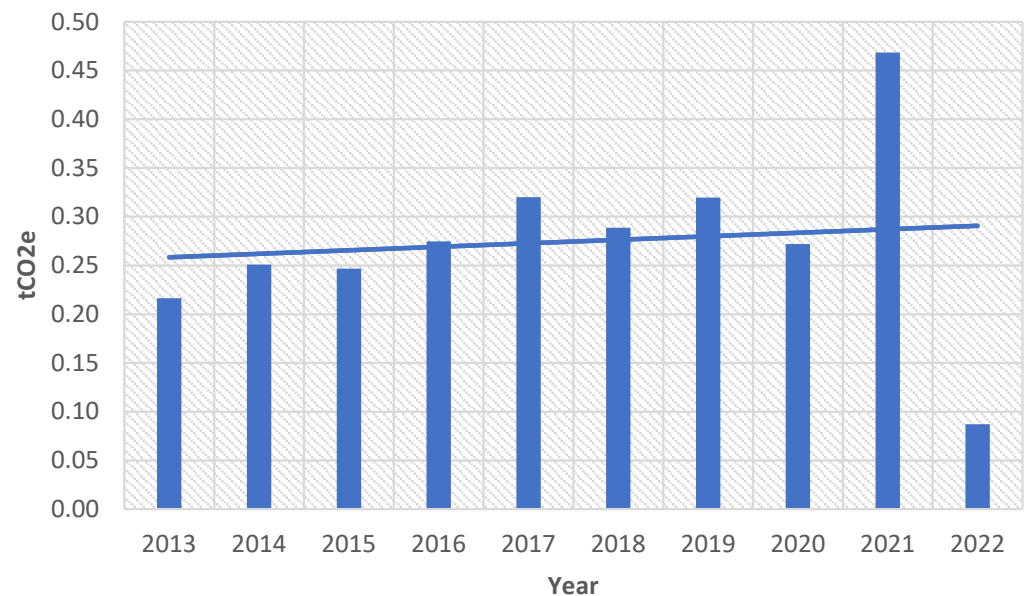


Figure 6. Temporal variation in emissions in tCO₂e per inhabitant served during the study period.

Figure 6 shows an upward trend in the emission generated per inhabitant. The emission per inhabitant over the years is in a range of 0.08 and 0.47 tCO₂e, with the average value being 0.3 tCO₂e/inhabitant. It is important to note that the number of inhabitants used in this analysis remained constant over the years, as no updated population data were available from the administration. As a result, the per capita emissions values are overestimated and do not reflect actual population dynamics over the 10-year period.

The main findings of this research show that the SQRO WWTPs carry out wastewater treatment very efficiently throughout the 10 years of study, even when they are traditional type plants. In traditional plants, the percentage reduction in contaminants is 20–30%, while the study plants present minimum reductions of 50–70% of contaminants in the water. These plants have increased the treated flow and the percentage of elimination of contaminants contained in wastewater, and therefore have improved their environmental, social and economic efficiency. The results show that the emissions avoided by treating wastewater exceed the emissions released into the environment by 90%. This is closely related to the increase in the cost of m³ of water that is treated, which goes from \$8.5 Mexican pesos in 2021 to \$12 Mexican pesos in 2022.

It should be remembered that, according to the information shared by the CEA, only 70% of SQRO's wastewater is treated. This tells us that there is 30% of wastewater that is not treated and is discharged into a natural aquatic environment, where serious impacts are generated on the environment. 776,667 tCO₂e emissions are avoided, while 18,421 tCO₂e are indirectly released, contributing to climate change, water contamination and the serious water crisis facing the state of Querétaro (Figure 7).

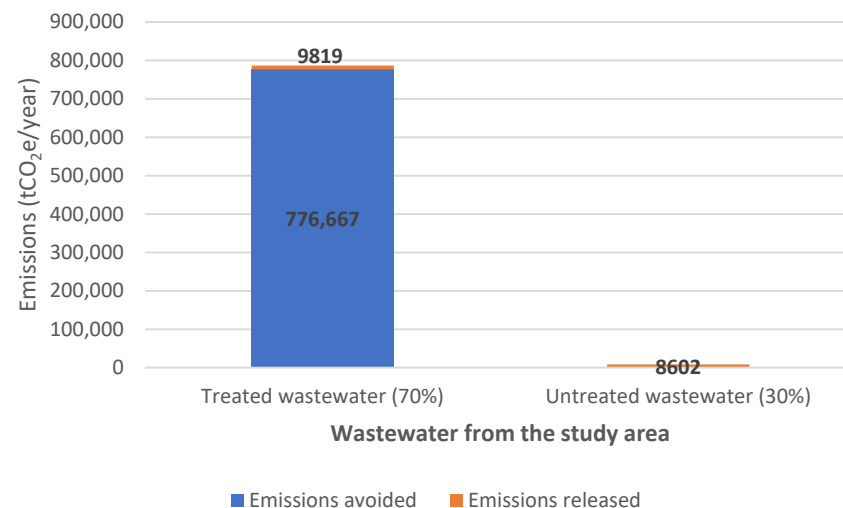


Figure 7. GHG emissions avoided and released from 100% of the wastewater produced in the study area in 2022.

4. Discussion

In recent years, the state of Querétaro has experienced high levels of drought during the dry season, presenting problems with water supply and contamination of its aquifers, rivers and dams, making the water unfit for human consumption [37]. The information presented in this study is relevant to show the importance of treating 100% of the wastewater in the study area, in this way not only contributing to mitigating climate change, but also helping to preserve and decontaminate this vital resource, contributing to achieving SDG 6 and the environmental goals established by the country, reducing the amount of untreated wastewater, water and natural body pollution, and promoting sustainable management, water availability and sanitation of the resource [38].

This study presents one of the few longitudinal assessments of wastewater treatment performance in a rapidly growing city in the Global South, offering critical insights into the water–carbon nexus over a decade (2013–2022) in Santiago de Querétaro (SQRO), Mexico. Our analysis reveals that despite operating primarily with conventional activated sludge systems, SQRO's wastewater treatment plants (WWTPs) achieve high contaminant removal efficiencies, particularly for BOD₅ (92–97%), and prevent an estimated 146.1 MtCO₂e of greenhouse gas (GHG) emissions over ten years by avoiding methane (CH₄) and nitrous oxide (N₂O) releases from untreated discharges. However, this environmental benefit comes at a steep operational cost; a 10% reduction in BOD₅ corresponds to a 7% increase in electricity consumption, reflecting the inherent trade-offs between water quality improvement and energy intensity. This finding is based on a linear regression analysis performed on a sample of operational data obtained from six wastewater treatment plants (WWTPs) over a 10-year period (2013–2022), encompassing a total of 12 months of measurements for each plant. The uncertainty associated with this relationship was estimated at $\pm 10\%$ of the slope value, which is considered acceptable for this type of analysis, based on the typical variability reported in the literature for relationships between energy consumption and pollutant reduction in wastewater treatment systems.

In this study, it was assumed that 30% of untreated wastewater generates N₂O and CH₄ emissions, while 70% of partially treated wastewater does not significantly contribute to the generation of these greenhouse gases. These assumptions were adopted as an initial approximation for modeling emissions under different treatment scenarios. However, we acknowledge that these estimates lack a solid experimental basis and may not accurately reflect the actual dynamics of gas generation in these systems. Therefore, we recommend that future studies focus on conducting experimental research or developing more robust

models to validate these assumptions and provide more reliable estimates of the impact of wastewater on N_2O and CH_4 emissions.

A key finding is that traditional WWTPs in SQRO exhibit far higher organic matter removal than typically expected. In many developing regions, conventional systems are reported to achieve only 60–80% BOD_5 removal [28], yet our data show consistent performance above 92%. This suggests either superior process control, favorable influent characteristics, or underreported technological upgrades. The average BOD_5 removal efficiency across the decade was 94.5%.

This performance may be attributed to extended aeration processes used in most SQRO plants, which enhance biological degradation at the expense of higher energy demand, a phenomenon documented in energy-intensive small-scale systems [39]. However, such high efficiency without concurrent nutrient removal raises concerns about nitrogen loading into receiving waters, especially given that only 70% of wastewater is treated and N_2O emissions from aquatic environments remain significant.

Every 10% decrease in BOD_5 load increases energy consumption by 7%, thus it is important to note that this relationship is correlative and not necessarily causal. This aligns with the concept of “energy rebound” in water treatment, where marginal gains in effluent quality require disproportionately higher energy inputs [40]. For instance, achieving lower BOD_5 thresholds often requires longer hydraulic retention times, increased aeration, and more frequent sludge recirculation and all energy-intensive operations.

Notably, electricity-related CO_2 emissions rose by 130% from 2021 to 2022, despite a 6% drop in treated volume. In 2022, the carbon footprint reached $0.002 \text{ tCO}_2\text{e}/\text{m}^3$, comparable to Latin American averages but significantly higher than best-practice benchmarks in energy-neutral plants [2].

This increase in electricity consumption in 2022 could reflect several factors, including operational issues, maintenance shutdowns due to equipment aging, and longer retention times due to facility breakdowns.

A closer look at these potential causes reveals that equipment aging is generating operational inefficiencies, as equipment performance tends to decrease with wear, resulting in higher energy consumption to maintain the same treatment levels. Frequent maintenance shutdowns could have contributed to longer retention times, further increasing energy consumption.

In addition, facility breakdowns may have required the operation of backup or alternative equipment that is not as energy efficient, which would explain the increase in electricity consumption. Finally, another factor to consider is the carbon intensity of the electricity mix, which increased by 3% in 2022 compared to 2021, which could partially explain the increase in CO_2 emissions [24].

To address these issues, a detailed analysis of the operation of the treatment plants and the condition of the equipment is recommended, including energy audits and maintenance assessments to identify areas where improvements can be implemented. Operational optimization, such as upgrading older equipment to more efficient models and implementing preventive maintenance programs, could significantly reduce energy consumption and associated CO_2 emissions.

CO_2 emissions resulting from electrical consumption can be reduced if SQRO plants use renewable and low-carbon energy for their daily operation, lessening their reliance on high-carbon energy sources. The biogas obtained from methane could be used for the cogeneration of energy in the plants, and in this way, reduce the carbon footprint of the facilities.

It is important to note that this analysis focused on the energy consumption associated with BOD and nitrogen removal as representative processes in wastewater treatment plants.

However, we recognize that the operational characteristics of these plants can vary significantly depending on the additional systems implemented, such as phosphorus removal, disinfection, or carbon removal. These additional operations entail energy consumption that could influence CO₂ emissions and, consequently, the results obtained. While this simplification allows for an initial approach to assessing the energy impact and CO₂ emissions, future research should consider a more comprehensive analysis that incorporates these additional processes to more accurately reflect the variations in CO₂ emissions based on the specific characteristics of each plant.

This underscores a central challenge for cities like Querétaro: how to maintain high water quality standards while decoupling treatment from fossil-fuel-dependent energy sources. According to Lundie et al., (2004) [41], energy can constitute up to 30–40% of total lifecycle emissions in conventional WWTPs. Although no lifecycle assessment was conducted in this study, this bibliographic context emphasizes the importance of transitioning to renewable energy as a necessity for climate-resilient sanitation.

One of the most impactful findings was the role of biogas cogeneration at San Pedro Mártir WWTP in mitigating CH₄ emissions. From 2016 onward, this facility has avoided 43,017 tCO₂e of CH₄ through anaerobic digestion and energy recovery—nearly matching the 38,065 tCO₂e still emitted annually from non-cogenerating plants. This result reinforced the conclusions of Paredes et al. (2019) [26], who demonstrated that Mexican WWTPs could reduce their GHG footprint by 40–60% if all digesters captured biogas. Globally, only ~20% of large WWTPs utilize energy recovery [42], leaving vast untapped potential in the Global South. If all six SQRO plants implemented cogeneration, we estimate that up to 81,081 tCO₂e of additional CH₄ emissions could have been avoided during the study period, equivalent to removing over 17,000 passenger vehicles from the road annually [43]. Moreover, self-generated power would reduce reliance on Mexico's carbon-intensive grid (which relies heavily on natural gas and oil).

Implementing cogeneration systems at all wastewater treatment plants in the area requires a high initial investment for the installation of biogas engines, biodigesters, scrubbing tanks, and safety systems, in addition to operating and maintenance costs, which impacts the short-term return on investment. This is compounded by regulatory and technical challenges related to grid connection, the country's electricity market regulations, and the quality of the energy produced. The study area has a deficient public electricity infrastructure, which must be improved to incorporate new generation sources [44,45].

To facilitate the implementation of biogas cogeneration at other plants, financial, infrastructure, and public policy barriers must be addressed. Although the initial investment for biogas cogeneration infrastructure is high, the long-term benefits include reduced operating costs due to self-generation of energy, decreased greenhouse gas emissions, and the possibility of selling excess energy to the grid.

The emission of methane could be avoided if the plants in the study area captured this GHG and used it for energy cogeneration and the operation of the plants themselves. By cogenerating energy, CO₂ emissions due to electricity consumption and CH₄ emissions would be reduced.

N₂O emission could be avoided from the SQRO WWTPs if their type of treatment was modified to an advanced treatment, with a reduction of 80–95% of the nitrogen content. In this way, the impact on the natural receiving environment would be avoided and it would contribute to combating climate change through a mitigation measure.

While direct N₂O emissions from SQRO's WWTPs are low (<0.1% of total GHGs), indirect emissions from untreated flows represent a major blind spot. With only 70% treatment coverage, 30% of nitrogen-rich wastewater enters rivers and aquifers, where it undergoes nitrification/denitrification, producing N₂O, a GHG with 298× the global warming potential

of CO₂ [31]. In 2022 alone, indirect N₂O emissions amounted to 8602 tCO₂e, contributing significantly to the net carbon burden. This mirrors findings by [6] that untreated wastewater is often a larger source of N₂O than the treatment process itself. Furthermore, although San Pedro Mártir claims nitrogen removal capability, its efficiency fluctuates between 12% and 60%, classifying it as sub-advanced. Advanced systems should achieve >80% TN removal via full nitrification–denitrification [18]. The fact that other plants—without formal nitrogen removal design—achieved similar or better removal (e.g., Terminal de Autobuses: 70%) suggests that uncontrolled biological processes may be occurring, possibly increasing N₂O production risk during incomplete denitrification [46]. These findings support calls for a paradigm shift: treating nitrogen not just as a water quality parameter, but as a climate mitigation target. As argued by [7], integrating nutrient recovery (e.g., struvite precipitation) and advanced nitrogen removal (e.g., anammox, bioelectrochemical systems) can transform WWTPs from pollution sources into resource recovery hubs.

It is important to note that the TN monitoring data prior to the implementation of the regulatory change have limitations due to potential differences in the frequency, quality, and scope of monitoring conducted during that period. This may have influenced the representativeness and completeness of the data available for analysis. Additionally, the regulatory changes introduced during the study period may have incentivized improvements in monitoring procedures and reporting quality, which could have biased the observed trends. For this reason, a careful analysis was conducted to distinguish between trends derived from measured data and those that may have been driven by the regulatory changes. These considerations are fundamental for interpreting the results appropriately, recognizing the limitations of historical data and avoiding generalizations that are not fully supported by the available measurements.

Financially, the average cost of treatment rose from 8.5 MXN/m³ in 2021 to 12 MXN/m³ in 2022, driven largely by rising electricity prices and maintenance costs. This trend threatens long-term sustainability, particularly as expansion is needed to reach the remaining 30% of untreated flows. According to [47], economic efficiency in WWTPs depends critically on scale, technology choice, and energy strategy. Our results suggest that SQRO's current model, relying on centralized, energy-intensive plants, is approaching diminishing returns. Decentralized systems, solar-powered pumps, and modular treatment units could offer more resilient and cost-effective alternatives, especially for peri-urban areas [48]. Decarbonization strategies in wastewater treatment systems must be addressed from an integrated perspective that considers technical, environmental, and economic dimensions. This approach is fundamental for identifying and managing the inherent trade-offs between improved treatment performance, reduced carbon emissions, and lower energy and operating costs. In this regard, assessments based solely on single indicators may be insufficient to capture the complexity of these trade-offs. Studies such as that by Castagnoli et al. (2025) have demonstrated how integrating process modeling, lifecycle assessment, and life cycle cost analysis reveals sustainability trade-offs that would otherwise go unnoticed [49]. Although this study focuses on operational carbon accounting, the results presented here could be complemented in future work with more integrated approaches that include expanded boundaries and detailed economic analyses to strengthen sustainability strategies in wastewater treatment systems.

Moreover, the lack of revenue from water reuse or energy sales exacerbates financial strain. In contrast, cities like Singapore and Windhoek have closed loops through potable reuse and energy-positive operations, demonstrating that economic viability and environmental sustainability are mutually reinforcing [50].

Estimates indicate that GHG emissions avoided due to wastewater treatment represent a difference of almost 98–99% compared to emissions generated by untreated wastewater.

This result reflects the high proportion of treated wastewater (70%), which significantly contributes to the reduction in the emissions of gases such as N_2O and CH_4 . The extreme relationship between avoided and released emissions is primarily due to the following factors: (1) Treatment coverage: The calculation of avoided emissions assumes 70% treated water coverage, which amplifies the positive impact of treatment; (2) Emission factors: Avoided emissions are calculated using emission factors that reflect the significant reduction in greenhouse gases (GHGs) due to the capture and treatment of organic matter; and (3) IPCC methodology: The methodology used assumes that wastewater treatment has a considerable impact on emissions reduction, especially in systems with anaerobic digesters.

Querétaro's experience reflects a broader dilemma faced by mid-sized cities in the Global South; rapid growth outpaces infrastructure planning, creating path dependencies on carbon-intensive technologies. Yet, our findings also reveal opportunities such as (i) Expand Treatment Coverage to 100%: eliminating open discharges would avoid ~18,421 tCO₂e/year in indirect emissions; (ii) Scale Biogas Cogeneration: replicating San Pedro Mártir's model across all plants could cut direct emissions and generate ~15 GWh/year of renewable electricity; (iii) Integrate Solar PV: given Querétaro's high solar irradiance (~5.5 kWh/m²/day), rooftop photovoltaics could offset 30–50% of electrical demand [49]; (iv) Adopt Nutrient Recovery Technologies: recovering phosphorus and nitrogen as fertilizers adds value while reducing eutrophication risks; and (v) Implement Real-Time Monitoring and AI-Based Control: smart sensors and predictive models can optimize aeration and chemical dosing, reducing energy use by 15–30% [51]. These strategies align with the “net-zero water” vision gaining traction globally [2,52]. They move beyond compliance-driven regulation toward circular economy principles, where wastewater is no longer waste but a source of energy, nutrients, and reclaimed water.

Our study is constrained by data gaps, inconsistent reporting of BOD₅/TN, missing population dynamics, and limited energy records prior to 2021. These reflect systemic challenges in public utilities in the Global South, where monitoring capacity lags behind infrastructure development. Therefore, these results should only be considered indicative, and any trend observed in per capita emissions cannot be interpreted as representative of actual changes over time. For future analyses, obtaining annual population estimates or using indirect indicators, such as the number of connections or the volume of water treated, would provide a more accurate representation of the emissions per capita.

The lack of precision in this data can significantly affect the overall results and the accuracy of emissions estimates. For example, we might be underestimating per capita emissions by considering a higher number of inhabitants served per treatment plant, since the population data used corresponds to the most recent years of 2021 and 2022. The absence of complete BOD₅ and TN records limits the calculation of emissions, as not all emissions released are included in the reported total. This type of omission can lead to erroneous conclusions about the effectiveness of the treatment and the actual amount of pollutants being emitted into the environment.

The identified data gaps, particularly the outdated population estimates and inconsistent reporting of TN, highlight critical vulnerabilities in current emission inventories. These omissions can bias emission factors and reduce model transferability across regions. To address this, future studies should prioritize systematic, high-frequency monitoring of key operational parameters using automated sensors and centralized digital platforms. Building on our previous work [53], which demonstrated the value of probabilistic imputation under severe missingness, subsequent research could integrate real-time data assimilation with ML-based gap-filling techniques. This hybrid approach would not only improve accuracy but also enable dynamic carbon accounting in near-real time, an essential step toward climate-resilient urban water management.

Furthermore, the total annual emissions should include emissions from electricity consumption, which are currently not accounted for due to the lack of this data. The lack of information on energy consumption and its corresponding emissions could underestimate the total carbon footprint of the wastewater treatment system.

To address these limitations, it is essential to improve the accuracy and updating of population data through regular censuses and the use of real-time data collection technologies. Furthermore, standardized protocols for the collection and reporting of BOD₅ and TN data must be established at all treatment plants.

The use of more advanced monitoring technologies, such as online sensors for continuous measurement of water quality parameters and integrated data management systems, is also crucial. These technologies would not only improve the accuracy of the collected data but also facilitate real-time monitoring and analysis of emissions.

This work sought to explore the interactions between energy, water, and carbon costs in wastewater treatment systems, adopting a preliminary conceptual approach due to the limited availability of specific data. We acknowledge that this lack of data represents a significant limitation in the analysis and restricts the ability to draw definitive conclusions. These data must be reviewed with the administration and their veracity verified for future studies. It is important to emphasize that this study does not include electricity consumption data prior to 2021, and therefore, any reference to long-term trends or “decadal compensations” between energy consumption and water quality must be interpreted as speculative. Future research should aim to collect historical datasets to validate these trends and provide a more robust basis for long-term conclusions.

Future research should prioritize: high-frequency sensor deployment for real-time emission tracking; per capita emission accounting using updated demographic data; life-cycle assessment (LCA) of retrofitting scenarios (e.g., solar integration vs. membrane bioreactors); and social acceptance studies on water reuse and decentralized systems. In addition, comparative analyses across Mexican metropolitan areas (e.g., Guadalajara, Monterrey) would help generalize findings and inform national policy. The development of more robust data collection strategies and automated monitoring systems would enable more accurate and consistent evaluation of wastewater treatment plant performance. This includes implementing training programs for operations and maintenance personnel, as well as producing detailed and consistent operations and management reports.

Internationally, various mechanisms can support the transition of wastewater treatment plants (WWTPs) in developing economies towards energy-positive systems. For instance, the Green Climate Fund and UN technology transfer programs provide opportunities for financing and capacity building [54]. However, to ensure relevance at the local level, it is essential to explore mechanisms tailored to Mexico, such as partnerships with the CEA and alignment with national climate goals. Future studies should analyze how these international frameworks can be effectively integrated into regional strategies.

These results show the importance of wastewater treatment to reduce the GHG emissions contributed by these facilities. The study carried out proves that the state of Querétaro is not only growing economically but also seeks to be an example and reference in environmental performance issues in Mexico. The study area still has areas for environmental improvement, such as treating 100% of its wastewater, cogenerating energy from the CH₄ produced or applying other low-carbon energy sources and modifying its treatment systems to advanced processes.

5. Conclusions

This decade-long analysis of wastewater treatment in Santiago de Querétaro (SQRO) reveals a critical duality: while conventional infrastructure achieves remarkable efficiencies

in pollutant removal, consistently exceeding 92% for BOD₅ and reaching up to 60% for total nitrogen in its operation generates significant challenges in terms of energy consumption, carbon emissions, and financial costs. The data show that every 10% reduction in organic load correlates with a 7% increase in electricity consumption, highlighting the system's energy intensity. In terms of carbon emissions, a 130% increase in CO₂ emissions related to grid-dependent operations was observed between 2021 and 2022, despite a decrease in treated volume. This underscores the system's vulnerability to carbon-intensive energy sources. However, during the period analyzed, wastewater treatment prevented approximately 146.1 MtCO₂e, mitigating 99.8% of the potential emissions from untreated effluent discharge. In 2022, direct process emissions were estimated at 0.002 tCO₂e per cubic meter, treated with a significant proportion attributed to untreated flows that generate indirect emissions of methane and nitrous oxide. Although treatment plants have proven to be key tools in mitigating climate change, there are still critical areas for improvement. For example, biogas cogeneration in San Pedro Mártir has prevented more than 43,000 tCO₂e of methane since 2016, demonstrating the potential of these technologies to transform the system into a net energy producer. However, nitrogen removal remains inconsistent, fluctuating between 12% and 60%, highlighting the need to optimize processes and monitor indirect emissions. To ensure long-term sustainability, SQRO must move toward a circular and integrated model. This includes achieving 100% treatment coverage, incorporating renewable energy sources such as solar photovoltaics to reduce dependence on the electrical grid, digitizing operating systems to optimize aeration and chemical dosing processes, and promoting nutrient recovery and the reuse of treated water. Furthermore, it is crucial to implement policies that incentivize the adoption of clean technologies, such as tax credits, direct subsidies, and sustainability certifications. Querétaro's experience reflects the challenges and opportunities facing rapidly urbanizing cities in the Global South. To lead the transition to climate-resilient and carbon-neutral systems, it is essential to combine technological innovation with institutional capacity and political vision.

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