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Exploring the Impact of Reclaimed Water on Latin America's Development

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ABSTRACT

This review examines the economic impact of Latin American regulations, strategies, and community involvement in mitigating the detrimental effects of mismanaged municipal domestic wastewater on public health, safety, and the economy. A systematic review and meta-analysis are conducted to assess the economic potential of reclaimed water in the region, utilizing various data sources and methodologies. The findings reveal that Latin America faces challenges in wastewater treatment, regulation, and resource management, affecting the market potential of reclaimed water. However, resource recovery initiatives present economic opportunities, including cost reduction, agricultural growth, energy recovery, and resource reuse.The study also highlights the lack of sanitation and wastewater treatment coverage data in many Latin American countries. By examining the commercial possibilities, regulatory frameworks, and environmental benefits of reclaimed water, this research provides valuable insights for sustainable water management and resource recovery policymakers, practitioners, and researchers. Furthermore, it emphasizes the economic advantages of utilizing reclaimed water and biosolids in Latin America, advocating for the implementation of strong regulations and policies to promote job creation and economic growth.

Keywords: circular economy, biosolids, life cycle assessment, cost-benefit, greenhouse gas emissions, climate change.

INTRODUCTION

The mismanagement of municipal domestic wastewater can lead to serious health, safety, and economic problems. In many parts of the world, untreated wastewater is discharged directly into rivers, lakes, and oceans, contaminating water sources, and threatening human health. Globally, 80% of wastewater enters the ecosystem without treatment or reuse, and therefore 1800 million people use a source contaminated with feces, causing diseases such as hepatitis, cholera, dysentery, typhoid fever, and polio (Goddard et al., 2020; UN Water, 2020). Pathogenic bacteria such as *Campylobacter jejuni* and *Campylobacter coli* are bacteria that are widespread in surface waters and are the main agents of gastroenteritis worldwide (Humaira et al., 2020; Mulder et al., 2020). In addition, untreated wastewater can create foul odors and attract pests such as mosquitoes and rodents, which can spread disease. Consequently, 3% of deaths in any age group occur due to unhygienic water (Mebrahtom et al., 2022; WHO, 2022). Freshwater sources are increasingly contaminated with microplastics, fertilizers, pesticides, heavy metals, and bacteria with antibiotic resistance (Fernández-Luqueño et al., 2010; Scherer et al., 2020; Xu et al., 2020). Water pollution is even predicted to affect pristine places on the planet like Antarctica (Banchón et al., 2019). Besides, more aquatic species will experience extinction, as up to 8% have disappeared since 1970 due to water pollution (UN Water, 2020).

In a circular economy, wastewater is a potential resource, and its use or recovery following appropriate treatment improves public health and generates revenue (Guerra-Rodríguez et al., 2020; Zarei, 2020; Zhang & Liu, 2022). Due to social and environmental concerns, the industry is now aware of the need to remediate its residual discharges (B. Chen et al., 2020). Despite the lack of commitment to protecting natural resources, the pollution resulting from urban and rural human activities, livestock, and agriculture is cause for concern. Given the increasing global water scarcity, it is imperative that society and the government take greater measures to develop technological solutions for the reuse of effluent (Massoud et al., 2009; Bijekar et al., 2022). The utilization of decentralized treatment technologies, like bioreactors and artificial wetlands, is vital for the treatment of wastewater (Fernández del Castillo et al., 2022; Van De Walle et al., 2023).

The mismanagement of domestic wastewater has wide-ranging consequences for health, safety, and the economy. The cholera outbreak in Latin America in 1991 exemplified the public health crisis resulting from inadequate water and sanitation infrastructure (Guthmann, 1995). The ongoing mismanagement of water exacerbates the occurrence of severe health crises, mirroring the magnitude of massive infections like cholera outbreaks. The daily practice of medical advancements plays a pivotal role in mitigating the visibility of current epidemics and endemic diseases, particularly in countries that are still in the process of development. To address these challenges and foster sustainability, it is crucial to implement proper wastewater treatment and management practices. Moreover, shifting towards the reclamation of wastewater as a valuable resource offers economic benefits. It can generate revenue and create sustainable employment opportunities, as highlighted by various studies (Chrispim et al., 2019; Laura et al., 2020; Avellán et al., 2021; Kesari et al., 2021). The utilization of reclaimed water and biosolids in agriculture, industry, and energy production holds significant economic potential (Yadav et al., 2021; Awasthi et al., 2022).

This short review emphasizes the economic benefits of reclaimed water in Latin American countries. It highlights financial constraints, knowledge gaps, and the importance of robust regulatory frameworks and policy support. The goal is to provide insights for developing an enabling environment for wastewater reclamation from municipal treatment plants by summarizing these barriers. A meta-analysis of relevant literature further explores these restrictions, providing a comprehensive understanding.

METHODOLOGY

This review presents a systematic review and meta-analysis of qualitative and quantitative studies exploring the economic potential of reclaimed water in Latin America. The objective was to assess the feasibility and benefits of wastewater treatment and reuse in the region. The study employed a systematic search in peer-reviewed literature using ISI Web of Science Core Collection and Elsevier Scopus databases over the past 20 years.

Studies published within the last 20 years, studies that specifically address the economic potential of reclaimed water in the Latin American region, and local and global perspectives that offer insights into both the local context of Latin America and the broader global implications of wastewater treatment and reuse were the inclusion criteria for this review.

Studies that only focus on controlled laboratory experiments or microcosm studies were excluded in order to concentrate on practical and real-world applications. Other exclusion criteria included studies that do not address the economic potential of reclaimed water or wastewater treatment and reuse in Latin America, as well as studies that used non-peer-reviewed sources like conference proceedings, books, or grey literature to ensure the reliability and accuracy of the studies that were included.

Studies published in reputable peer-reviewed journals, the expertise and qualifications of the authors, robust research designs, appropriate sampling methods, and reliable data collection techniques, sample size and representativeness, and studies that include diverse regions within Latin America to capture a comprehensive understanding of the economy were all evaluated to ensure the reliability and validity of the data used in this systematic review and meta-analysis.

The following information was included in the meta-analysis:

1. Statistics related to the production of wastewater, reclaimed water, and biosolids in Latin America, providing a comprehensive overview of the current situation.
2. Analysis of regulatory frameworks and policies from various Latin American countries, highlighting the legal and institutional context surrounding wastewater reclamation.
3. Evaluation of cost-benefit analyses and environmental benefits associated with wastewater

treatment and reuse, assessing the economic viability and ecological advantages.
4. Integration of public investment data from the water sector, specifically considering Gross Domestic Product (GDP) indicators, to understand the financial implications and potential returns on investment.
5. Incorporation of econometric studies to analyze the economic models and factors influencing the economic potential of reclaimed water in Latin America.
6. Expert recommendations regarding the development of wastewater reclamation initiatives from municipal treatment plants, providing insights and guidance for future implementation strategies.

WASTEWATER TREATMENT IN LATIN AMERICA

Latin America exhibits a commendable performance in terms of water accessibility, as 94% of households have access to improved water sources (The World Bank, 2017; Bertoméu-Sánchez & Serebrisky, 2019; ECLAC, 2023). However, approximately 17% of the population still lacks access to improved sanitation facilities (Mahlknecht et al., 2020; Marchetti et al., 2019). Between 1990 and 2015, while some countries in Latin America, including Bolivia, Honduras, and Ecuador, experienced significant progress in increasing access to improved sanitation services with percentage increases ranging from 28 to 85%, others such as Guatemala, Haiti, and Nicaragua still faced worryingly low levels of access in 2015 (Bertoméu-Sánchez & Serebrisky, 2019). While progress has been made in wastewater treatment over the past decade in the Latin American region, the current level of treatment remains below satisfactory levels for a region with high income and urbanization rates. As of 2017, less than 30-40% of wastewater was treated, which falls short of meeting the necessary standards (Benavides et al., 2019; Van Puijenbroek et al., 2019; Jones et al., 2021). Nevertheless, this represents a significant improvement compared to less than a decade ago when only 15% of wastewater received treatment (Noyola et al., 2012), and merely 6% of that met acceptable treatment standards (The World Bank, 2017).

Oxidation ponds are widely employed as the main wastewater treatment method in Latin America (EPA, 2011; UNESCO, 2017). Noyola et al. (2012) analyzed a sample of 2,734 wastewater treatment plants in Latin America, with Mexico having the maximum number (1,653), followed by Brazil (702) and Chile (175). Stabilization ponds (38% of the sample) activated sludge (26% of the sample), and up flow anaerobic sludge blanket reactors (17%) represented 80% of the sample (Noyola et al., 2012). These ponds use natural processes, including sunlight and microorganisms, to decompose organic matter and purify the water (Fig. 1). The reclamation of water from oxidation ponds in Latin America

Figure 1. Oxidation pond for municipal wastewater in Guayaquil, Ecuador, where residents claim the odor inhibits them from sleeping or eating comfortably (Source: https://www.extra.ec/noticia/actualidad/guayaquil-hedor-lagunas-oxidacion-dana-jama-ruca-57025.html)

is limited, despite being favored for their simplicity and low cost (Verbyla et al., 2016).

Although Latin America has made significant improvements in water availability, sanitation service access gaps remain. Because of these inequalities, improved education, funding, and environmentally responsible techniques in wastewater management are urgently needed. Concerns regarding price increases have been prompted by the Latin American wastewater industry's deteriorating performance. The situation is made even more difficult by the fact that many Latin American countries lack precise data on the prevalence of access to sanitation and wastewater treatment facilities.

REGULATORY FRAMEWORKS

The strict rules for wastewater treatment and discharge set forth in the German Wastewater Framework Regulation (Abwasserabgabenverordnung) are well-known (BMUV, 2023). While other nations may have fewer rigorous restrictions than Germany, some may have regulations that are comparable to or even more strict. German regulations, for instance, stipulate that big cities must have BOD values of 15 mg/L and COD values of 75 mg/L in terms of organic matter, which are 40% more severe than EU framework values (Preisner et al., 2020; BMUV, 2023).

Figure 2 illustrates the discharge limits for organic matter in Latin American countries, specifically in surface waters such as rivers. Chile imposes the strictest limit with 35 mg/L for BOD discharge, followed by Panama, Paraguay, Costa Rica, and Argentina at 50 mg/L. Bolivia, Argentina, Peru, and Ecuador have more lenient regulations concerning organic matter contamination in surface waters between 200-300 mg/L regarding

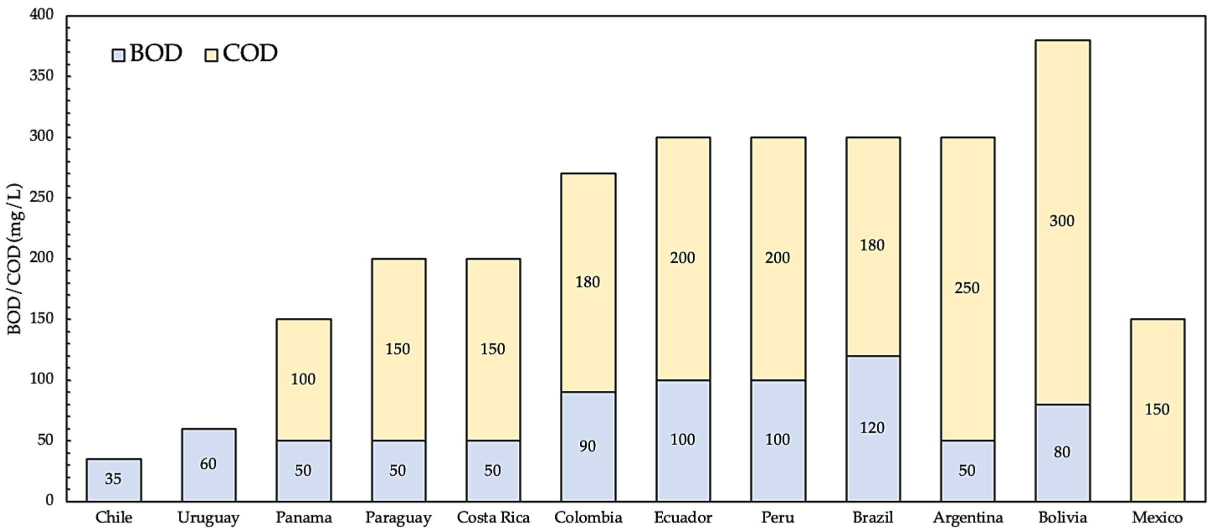

Figure 2. Wastewater discharge standards for BOD and COD in Latin America to surface waters (Source: https://cafscioteca.azurewebsites.net/)

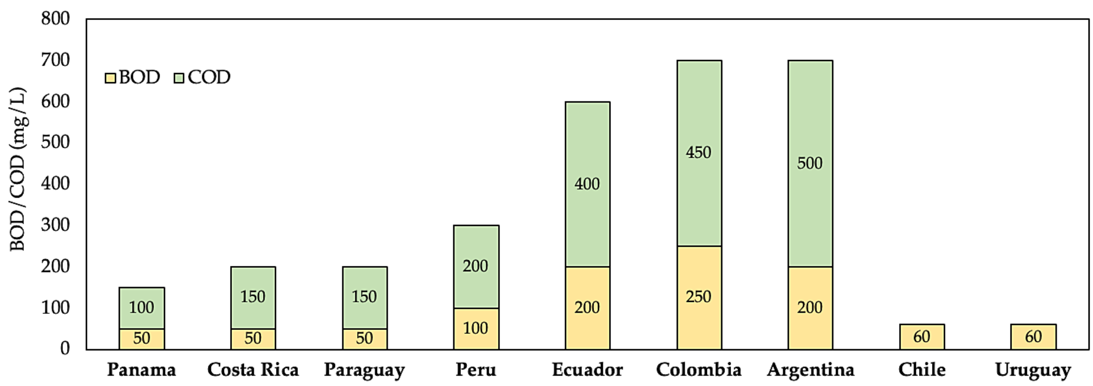

Figure 3. Wastewater discharge standards for BOD and COD in Latin America to marine waters (Source: https://cafscioteca.azurewebsites.net/)

COD. Some countries adopt flexible regulations that consider water body characteristics and the capacity of receiving waters for dilution.

In Figure 3, the discharge limits for organic matter in Latin American countries, particularly in marine waters, are presented. Panama, Costa Rica, and Paraguay have the most stringent restrictions on BOD discharge. Conversely, Argentina, Colombia, and Ecuador demonstrate greater permissiveness in terms of COD, with limits ranging from 400 to 500 mg/L.

To enhance wastewater treatment in Latin America, a comprehensive strategy accompanied by a favorable framework, policies, institutions, and circular economy is necessary (Ulloa-Murillo et al., 2022). However, the adoption of regulations and policies can hinder proper management of municipal domestic wastewater due to enforcement challenges, compliance costs, limited technical expertise, resistance to change, inadequate infrastructure, socioeconomic factors, and lack of awareness. Overcoming these challenges requires capacity-building, stakeholder engagement, and public awareness campaigns to improve wastewater management. The goal is to increase the current wastewater treatment rate of 40.8% and provide quality, sustainable, and inclusive sanitation services, along with the necessary investments and funding (Real et al., 2021).

Community involvement and education play a vital role in attempting the improper management of domestic wastewater. They align with the sustainable development goals (SDGs) that specifically aim to address the sustainable management of water resources, sanitation, and wastewater treatment. These goals underscore the importance of engaging communities and promoting awareness to foster responsible practices and ensure the long-term sustainability of water resources and sanitation systems.

The lack of stringent regulatory frameworks and policies for domestic wastewater management in Latin America can result in significant costs and negative consequences. These include environmental degradation, public health risks, economic losses, water scarcity, and legal compliance expenses. Implementing effective regulations in Latin America is crucial to protect the environment, public health, and economy, while fostering sustainable water resource management.

This article summarizes some targeted policy recommendations for enhanced domestic effluent management in Latin America:

- Enhance regulatory frameworks by setting stricter discharge limits for organic matter in both surface waters (rivers) and marine waters. Consider aligning regulations with international standards to ensure effective water quality protection.
- Improve enforcement mechanisms to ensure compliance with wastewater treatment regulations. This can be achieved through increased monitoring, inspections, and penalties for non-compliance.
- Invest in capacity-building programs to enhance technical expertise in wastewater treatment. Provide training opportunities for professionals involved in wastewater management to improve operational efficiency and knowledge.
- Allocate resources for the development and upgrading of wastewater treatment infrastructure, particularly in areas with limited access to proper sanitation systems.
- Launch public awareness campaigns to educate communities about the importance of proper wastewater management, sanitation practices, and the potential risks associated with inadequate treatment. Foster community engagement and participation in decision-making processes.
- Explore public-private partnerships and innovative financing mechanisms to secure sustainable funding for infrastructure development, operation, and maintenance.
- Promote the adoption of a circular economy approach, encouraging resource recovery and reuse in wastewater treatment processes. Implement measures to facilitate the safe and beneficial use of treated wastewater in agriculture, industry, and other sectors.
- Foster regional cooperation and knowledge sharing among Latin American countries to exchange best practices, lessons learned, and technological advancements in wastewater management. This can contribute to harmonized standards, effective policy implementation, and shared resources.

RECLAIMED WATER

Reclaimed water refers to treated wastewater that undergoes purification to a level suitable for various non-potable applications such as irrigation, industrial processes, groundwater recharge, and environmental restoration. In 2017, the World Bank estimated global municipal wastewater production at around 283 billion cubic meters (UNESCO, 2017). Out of this, approximately 60% was treated, while 40% was planned for indirect reuse, involving activities like crop irrigation and aquifer recharge with treated effluent (Mizyed & Mays, 2020). Direct reuse, on the other hand, accounted for about 5% and involved utilizing treated effluent directly for drinking water or industrial purposes.

Agriculture is the largest user of reclaimed water in terms of volume when compared to other water applications due to its high-water demand (Gil-Meseguer et al., 2019). China, Mexico, and the United States stand out as the nations with the highest volume of reclaimed water when considering the total amount (Jimenez & Asano, 2015). Nevertheless, Israel's position as a global leader in agricultural wastewater reuse stems from its longstanding legislation and institutions that have cultivated trust among users of reclaimed wastewater (Duong & Saphores, 2015). In water-scarce countries and regions, the practice of wastewater recycling offers a promising solution to alleviate the strain on limited freshwater resources by substituting them with reclaimed water for non-drinking purposes (Helmecke et al., 2020).

There are several opportunities and challenges related to the economic potential of reclaimed water in Latin America. However, it is crucial to address the issue of insufficient and suboptimal wastewater treatment, as it poses potential risks to human health (Deng et al., 2019). Inadequate treatment may allow the presence of pathogens such as bacteria, viruses, parasites, as well as organic chemicals including antibiotics, food additives, preservatives, corrosion inhibitors, textile chemicals, and biocides (Peña-Guzmán et al., 2019). Therefore, the reclamation of wastewater should be approached with caution, emphasizing the proper application of effective treatment technologies to ensure the safety and quality of reclaimed water.

In Latin America, many countries still lack regulations defining minimum budgets applicable in all jurisdictions for wastewater destinations, including agricultural reuse (UNESCO, 2015). Therefore, there is a limited knowledge and understanding of the benefits and potential uses of reclaimed water and biosolids, which can limit their market potential. Besides, limited financial resources for investment in wastewater treatment infrastructure and marketing efforts to promote the use of reclaimed water and biosolids.

In Latin America, a significant challenge persists as many countries lack comprehensive regulations that establish minimum budgets applicable across all jurisdictions for the proper management of wastewater, including its potential use in agriculture (UNESCO, 2015). For instance, in terms of reuse, in Brazil there was no legal framework for specifying the required water quality as a function of the use of the treated effluent (agricultural, urban, industrial, etc.) (Von Sperling, 2007). This lack of regulatory frameworks leads to limited awareness and understanding of the advantages and potential applications of reclaimed water and biosolids, thereby hindering their full market potential. Furthermore, the constrained financial resources allocated for investment in wastewater treatment infrastructure and marketing initiatives further impede the promotion and adoption of reclaimed water and biosolid utilization.

Latin American countries have the potential to benefit economically from reclaimed water and biosolids. This could be accomplished through resource recovery projects which would produce income and create jobs (Chrispim et al., 2019; Laura et al., 2020; Avellán et al., 2021; Kesari et al., 2021).

Table 1. Demands, Opportunities, and Challenges in Reclaimed Water and Biosolids Management

Demands	Opportunities	Challenges
Increasing demand for water resources and agriculture amendment	Market for reclaimed water and demand for biosolids as a soil amendment	Lack of infrastructure for the collection, treatment, and distribution of reclaimed water and biosolids
		Perceptions of reclaimed water and biosolids as low-quality or unsafe
Growing demand for organic fertilizers	Revenue generation through the sale of reclaimed water, biogas and biosolids	Awareness of the need to manage water resources sustainably
		Cultural or social barriers to accepting recycled water
Policies promoting sustainable resource management	Government incentives Economic incentive to use reclaimed water	Outreach campaigns to increase public awareness and acceptance of reclaimed water

Table 2. Economic benefits from water reclamation and biosolids production

Economic benefits	Effects of reclaimed water production
Reduction of health costs	Proper treatment of wastewater reduces the risk of waterborne diseases
Increase of agricultural production	Reclaimed water for irrigation reduces the consumption of freshwater Savings on fertilizers and other agriculture inputs
Energy recovery	Production of biogas Revenue from electricity generation
Resource recovery	Reuse of nitrogen, phosphorus, and organic matter for agriculture Composting of wastewater sludge to produce biosolids

The cost of producing 1 ton of reclaimed water varies based on factors like location, treatment process, quality standards, infrastructure, and operational expenses. It includes capital and operational costs, treatment technology, water source, pretreatment, and facility scale. For example, the cost of producing 1 ton of reclaimed water in Beijing using coagulation-sedimentation-filtration is covered at 0.14 USD, while with advanced treatment, it stays below 0.35 USD (W. Chen et al., 2013). These costs are significantly lower than seawater desalination for water production. In Latin America, the wastewater treatment pricing system does not include capital investments and ongoing operational costs. Thus, wastewater treatment facility construction and maintenance costs are not fully recovered by user fees.

Biosolids, a nutrient-rich soil amendment derived from wastewater sludge, enhance soil fertility, foster healthy plant growth, and result in increased crop yields while reducing fertilizer expenses for farmers. Composting biosolids emerges as a cost-effective treatment option, with prices ranging from $20 to $50 per ton, depending on facility conditions and market demand. According to the United States Environmental Protection Agency, composting costs range from $20 to $60 per ton, making it an economically viable alternative to other treatment methods (EPA, 2011). For a summary of the economic benefits due to the production of biosolids from municipal residual sludge and water reclamation techniques, see Table 2.

Socio-cultural factors play a significant role in the use and acceptance of reclaimed water in Latin America. These factors influence public perception, attitudes, and behaviors towards reclaimed water, ultimately shaping its acceptance and adoption. Here are some key socio-cultural factors to consider:

- The perception of water quality is crucial in determining the acceptance of reclaimed water. Public concerns regarding the safety and purity of reclaimed water can influence its acceptance. Effective communication and education campaigns are essential to address misconceptions and enhance public understanding of the treatment processes that ensure reclaimed water's safety.
- Cultural beliefs and practices surrounding water use can impact the acceptance of reclaimed water. Attitudes towards water reuse, such as the notion of water purity and cleanliness, cultural taboos, and traditional water sources, can influence the willingness to embrace reclaimed water as a viable resource.
- Building trust and confidence in reclaimed water systems is essential. Transparent governance, effective regulation, and robust monitoring of reclaimed water quality are crucial to instill confidence in the public. Engaging communities, stakeholders, and local leaders in the decision-making process can help address concerns and build trust.
- Engaging local communities in the planning, implementation, and management of reclaimed water projects is vital for acceptance. By involving communities, their concerns can be addressed, and their input can shape the design and operation of systems, ensuring that they align with cultural values and practices.
- Increasing public awareness and understanding of the benefits and safety of reclaimed water is essential. Educational campaigns targeting schools, community centers, and public forums can provide accurate information about the treatment processes, quality standards, and successful examples of reclaimed water use, helping to overcome resistance and foster acceptance.

By understanding and addressing these socio-cultural factors, policymakers, practitioners, and stakeholders can foster greater acceptance of reclaimed water in Latin America. Public engagement, education, trust-building, and culturally sensitive approaches are vital to promote the sustainable use of reclaimed water and secure its long-term benefits for the region.

Quality standards

For reclaimed water used in agriculture, the quality standards listed below are essential. These restrictions protect crops, soil, and groundwater from hazardous concentrations. To ensure the safety and sustainability of agricultural techniques using reclaimed water, compliance with these requirements is crucial.

- Pathogens: Water should be treated with advanced technologies such as disinfection, oxidation, or filtration to reduce or eliminate pathogens such as bacteria, viruses, and parasites to low or undetectable levels (Fernandez-Cassi et al., 2016). At the local level, a substantial proportion of gastrointestinal illness is caused by protozoa (such as amoebas, Giardia, etc.) found in untreated water intended for consumption.
- Chemical pollutants and nutrient content: To ensure effective management of chemical pollutants, it is important to establish guidelines for substances like heavy metals, pesticides, pharmaceuticals, and organic compounds. Furthermore, proper monitoring and management of nutrients such as nitrogen and phosphorus are essential to prevent overfertilization, which can lead to water pollution and ecological imbalances.
- Salinity: High salinity more than 2000 mg/L can adversely affect plant growth and soil quality.
- pH and Turbidity: Reclaimed water should have a pH level within a range of 6 to 9 for agricultural use. Turbidity, which refers to the clarity of water, should also be controlled to less than 5 turbidity units to prevent clogging of irrigation systems and to ensure proper water distribution.

Depending on factors including local restrictions, crop types, irrigation methods, and environmental factors, the precise quality standards for reclaimed water utilized in agriculture may vary. Safe and successful use of reclaimed water in agriculture requires constant monitoring and adherence to set guidelines.

ECONOMIC IMPLICATIONS

Public investment in the water sector

In Latin America, the provision of water and sanitation services faces challenges such as limited availability and inadequate service standards, which have detrimental effects on public health. Compared to other developing regions, Latin America's investment in water and sanitation is relatively low, accounting for less than 3 percent of its GDP, while other countries allocate a higher percentage, ranging from 4 to 8 percent (The World Bank, 2017; Brichetti et al., 2021). Consequently, securing adequate funding for water and sanitation continues to be a major obstacle in the region.

In terms of GDP, the bulk of infrastructure investment is driven by the region's three largest economies: Argentina, Brazil, and Mexico (The World Bank, 2017; Brichetti et al., 2021). However, there are also some countries like Belize, Bolivia, Costa Rica, Honduras, Nicaragua that invest more than 3% of their GDP annually in infrastructure (Figure 4). In order to maintain current access rates in urban areas and improve access rates in rural areas by closing coverage and quality gaps, it is necessary for Latin America and the Caribbean to allocate 0.30 percent of GDP

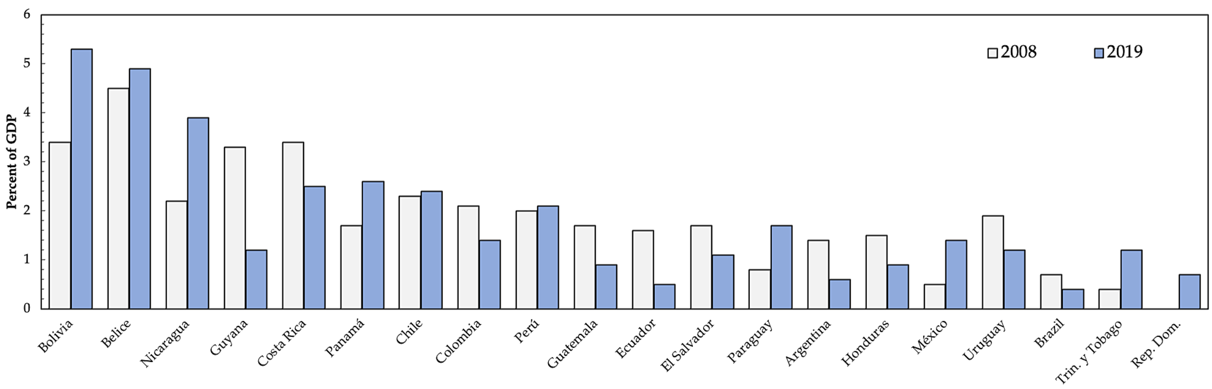

Figure 4. Public Investment on water sector – Percent of GDP (Source: http://infralatam.info downloaded on May 06, 2023)

annually until 2030 to meet water and sanitation needs (Brichetti et al., 2021).

Many public utilities in Latin America's water sector have poor creditworthiness, making it difficult for them to borrow money from commercial sources. Only 20 percent of water utilities in Latin America have generated enough revenue to mobilize commercial borrowing, meaning 80 percent would struggle to do so without significant reforms. This suggests that greater efficiency could bring in more financing, as utilities would be able to generate more revenue and reduce their reliance on government-guaranteed financing (The World Bank, 2017).

Economic viability is crucial, especially with private investor interest. Ownership and regulation of water utilities differ among countries, with England having privately owned facilities regulated by the Office of Water Services (OFWAT). In France, many communities opt for private operation, while Greece mainly has municipally owned facilities. Sweden predominantly operates water facilities through regional municipalities, with few privately owned ones (Malmsten & Lekkas, 2010).

In Latin America, wastewater treatment plants are primarily publicly owned, with varying degrees of centralized regulatory oversight. The limited private investor interest in the sector can be attributed to unfavorable economic conditions, inadequate government policies, and low potential for financial returns. Economic indicators would play a crucial role in guiding resource allocation, pricing, investment planning, market efficiency, and sustainable development on the Latin American water market. They promote environmental conservation while facilitating informed decision-making, efficient resource allocation, cost recovery, and the long-term viability of water services.

This review highlights the lack of sanitation and wastewater treatment data in Latin America. By utilizing existing data and discussing limitations, it provides clarity and context. The study advocates for enhanced data collection and reporting systems, emphasizing standardized frameworks and capacity-building initiatives to address data limitations.

Cost-effectiveness of wastewater treatment

The cost-effectiveness of municipal wastewater treatment options is influenced by several factors, including community size, treatment level, and local environmental conditions. It is important to assess the specific circumstances and treatment requirements of each community to determine the cost-effectiveness of a wastewater treatment option. Evaluating different options should not solely focus on cost but also consider factors like environmental impact, energy consumption, and public health considerations. Taking a comprehensive approach when evaluating wastewater treatment options ensures that all relevant factors are considered to make informed decisions.

Specific economic indicators play a crucial role in assessing the impact of reclaimed water initiatives in Latin America. They include cost reduction, agricultural productivity, energy recovery, job creation, revenue generation, and overall economic growth. Employing relevant data and metrics like cost-benefit analysis and financial modeling, the economic potential and impact of reclaimed water can be quantified. This information guides decision-making, policy formulation, and resource allocation to maximize economic benefits and drive sustainable economic growth in the region.

Innovative business models have the potential to enhance the financial sustainability of wastewater treatment plants by exploring new revenue streams and cost-saving opportunities. One such model is the generation of electricity through the utilization of biogas produced during the treatment process. Wastewater treatment plants can employ anaerobic digestion technology to convert organic matter in sludge into biogas, which can then be used to generate electricity. This not only reduces energy costs but also provides an additional source of revenue through the sale of excess electricity to the grid.

Another innovative business model involves the commercialization of sanitized sludge. After undergoing advanced treatment processes, the sludge can be transformed into a valuable resource with various applications. It can be used as a soil conditioner or fertilizer in agriculture, or as a raw material in the production of biogas or other bio-based products. By selling sanitized sludge, wastewater treatment plants can generate revenue while reducing disposal costs and promoting resource recovery.

Implementing innovative business models in wastewater treatment plants not only improves their financial viability but also fosters sustainability and resilience. By diversifying revenue streams and reducing operational costs, these models contribute to the long-term viability of treatment facilities, enabling them to maintain high-quality services while minimizing the financial burden on local governments and communities. Moreover, they promote the transition towards a circular economy by maximizing resource recovery and minimizing waste generation.

The selection of the appropriate cost-effectiveness measurement method depends on the specific context, objectives, and priorities of the wastewater treatment project. The cost-effectiveness of municipal wastewater treatment can be measured through various approaches and indicators. Here are some commonly used methods:

Benefit Cost- Analysis (CBA)

CBA involves comparing the costs incurred in implementing and operating wastewater treatment systems with the benefits derived from improved water quality, reduced health risks, and other environmental and socioeconomic gains (Arena et al., 2020; Ćetković et al., 2022). CBA assesses the profitability of a public investment project by comparing the monetary value of social benefits with the monetary value of social costs (Tudela-Mamani, 2017). It is employed when the social benefits of the project can be quantified and expressed in monetary terms.

CBA quantifies net benefits in monetary terms to assess treatment process cost-effectiveness, but faces challenges in valuing intangibles, predicting long-term impacts, and decision biases. CBA employs Net Present Value (NPV) and Internal Rate of Return (IRR) as key indicators, considering societal impacts, shadow prices, conversion factors, and stakeholder willingness to pay.

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{1}$$

$$0 = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{2}$$

where: B_t – revenues directly paid by users in year t for the services provided by the operation;
C_t – investment, operation, and replacement costs to run the project in year t;
i – social discount rate

In Latin America, the willingness to pay is greatly influenced by socioeconomic variables, including the social discount rate, household budget, educational level, and geographic location of the residence (Gil et al., 2013; Tudela-Mamani, 2017). Nevertheless, financial analysis should not be the only factor considered when selecting whether to construct a project because socioeconomic benefits hold a bigger specific weight than financial benefits in such water reclamation projects.

Cost-Effectiveness Analysis (CEA)

CEA focuses on comparing the costs of different wastewater treatment options in relation to their effectiveness in achieving desired outcomes. It helps identify the most cost-effective option by evaluating the ratio of costs to specific outcome measures, such as pollutant removal efficiency or health risk reduction (van Soesbergen et al., 2008; Wood et al., 2015). While CBA evaluates the monetary value of benefits and costs to evaluate the overall desirability and profitability of an intervention, CEA focuses on comparing costs and effectiveness to identify the most cost-effective solution. CBA assists in assessing the investment-worthiness of an investment.

A project with a high cost-effectiveness analysis successfully achieves its goals while keeping costs low (Belfield & Levin, 2010). It demonstrates a favorable balance between cost and effectiveness, highlighting resource efficiency and excellent value. A high cost-effectiveness analysis highlights the project's ability to deliver optimal outcomes at a minimal expense.

In Beijing, China, the implementation of a wastewater reclamation and reuse program has yielded significant positive outcomes (Yi et al., 2011). The program has generated a net benefit of 100 million USD per year, indicating the value derived from the project's outcomes exceeds the total costs incurred (Fan et al., 2013). Specifically, the total benefit derived was 1.7 times higher than the total cost invested, highlighting the economic viability and success of the wastewater reclamation and reuse initiative in Beijing (Fan et al., 2013). Besides, the cost of removing a specific quantity of pollutants (e.g., cost per kilogram or ton of pollutant removed) is used to assess the efficiency and cost-effectiveness of various treatment technologies or processes in terms of pollutant removal. A study found that the cost per unit of phosphorus removal varies across different treatment options, ranging from \$42.22 to \$60.88 per pound of phosphorus removed (Bashar et al., 2018).

New wastewater treatment plants may not be cost-effective in terms of reducing public health risks, especially when considering the costs of sewer systems and house connections (Costa et al., 2009; Drechsel & Seidu, 2011). However, if their broader environmental benefits are considered, the assessment may change.

Thus, there is a need for more comprehensive CEA in urban and peri-urban areas, where informal wastewater use is common. Additionally, the combination of low-energy wastewater treatment plants, such as oxidation ponds commonly used in Latin America, with centralized facilities, decreases the cost-effectiveness of public health risks.

Life Cycle Cost Analysis (LCCA)

In the field of economics, applying an econometric approach to the management of municipal wastewater offers a valuable tool for evaluating the cost-effectiveness of different treatment options (Hecker et al., 2020). Econometric analysis in wastewater management involves studying the relationship between treatment costs, treatment levels achieved, and environmental benefits. By considering population density and income levels of affected communities, this approach provides insights for resource allocation optimization (Rebitzer et al., 2003; Rodríguez Miranda et al., 2015).

When assessing the costs of a water reuse program, be it for non-potable or potable uses, various factors come into play. These factors include the location of the reclaimed water source, the infrastructure required for treatment, the influent water quality, customer demands, transmission and pumping requirements, storage needs, energy consumption, concentrate disposal, permitting, and financing costs (Voulvoulis, 2018). By examining these elements, economists can identify cost drivers and develop strategies to optimize resource allocation and minimize financial burdens associated with water reuse projects.

In addition to econometric analysis, system value assessment methods such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are valuable tools for evaluating the overall value and benefits of wastewater technologies (Rebitzer et al., 2003). LCA focuses on assessing the environmental impacts of a system, while LCC specifically analyzes costs. By utilizing LCA and LCC in tandem, researchers can gain a comprehensive understanding of the sustainability and economic viability of wastewater reclamation projects (Lorenzo-Ginori et al., 2009; Suryawan et al., 2021). These methods facilitate comparisons between treatment options, evaluate environmental impacts, and provide crucial information for making informed and sustainable decisions.

Environmental Life Cycle Costing (ELCC) is a vital cost management approach within the sustainability framework that estimates costs associated with the entire lifecycle of reclaimed water, surpassing traditional financial or managerial accounting methods (Ankley, 2008; Kamble et al., 2019). By employing tools such as LCA and ELCC, economists and environmental managers can ensure comprehensive evaluation of the costs and environmental consequences of wastewater management initiatives, enabling informed decision-making (Ankley, 2008).

The integration of economic principles, environmental considerations, and management techniques, including econometric analysis, cost assessments, and system value assessment methods such as LCA and LCC, enables policymakers and stakeholders to make informed decisions, promote sustainability, and mitigate environmental harm in wastewater management strategies.

SAFETY IMPLICATIONS

Public health can be significantly compromised by inadequate wastewater management practices. For instance, the discharge of untreated wastewater into rivers or oceans poses a risk to individuals involved in recreational activities like swimming, fishing, or boating (The World Bank, 2017). Wastewater often contains hazardous substances, including heavy metals, microplastics, and pesticides, which can contaminate soil and groundwater (Hamidian et al., 2021; Saravanan et al., 2021). Such contamination can have severe and long-lasting health implications for both humans and the environment. It is crucial to address these risks associated with wastewater management to ensure the successful reclamation of water resources.

- *Waterborne Diseases*: Untreated wastewater can contain pathogens such as bacteria, viruses, and parasites, which can cause waterborne diseases (Helmecke et al., 2020). These diseases can cause diarrhea, vomiting, and other serious health problems. On the other hand, US EPA includes adenovirus, calicivirus, enterovirus, and hepatitis A virus on the list of common candidates in water (Rachmadi et al., 2020). It has been detected that some adenoviruses are resistant to disinfection by ultraviolet rays (Humaira et al., 2020). Viruses such as hepatitis A are stable in water and survive for long periods; its 99% inactivation takes about 56 days (Salvador et al., 2020; Wang et al., 2020). As a consequence of the excessive use of antibiotics, the fecal bacterium E. coli has genes involved in antibiotic resistance (Camiade et al., 2020; Ortega-Paredes et al., 2020). In Ecuador, 26.6% of the population is supplied with water with the presence of E. coli (Mills et al., 2018; Borja-Serrano et al., 2020; Moreno et al., 2020). It is estimated that 2.9 billion people consume seafood, in which the presence of fecal bacteria has been reported (Gyawali & Hewitt, 2020). The lack of understanding regarding responsible water management leads humans to become unwitting contributors to superinfections and genetic mutations, thereby amplifying the pathogenic load through their everyday and occupational activities.

- *Bioaerosols*, which consist of airborne biological particles like bacteria and fungi, are emitted during the wastewater treatment process and can pose health risks to workers and nearby communities, resulting in respiratory illnesses and other diseases. These bioaerosols can also cause unpleasant odors, reducing property values and negatively impacting tourism. Wastewater bioaerosols have been found to contain opportunistic pathogenic bacteria, such as *Staphylococcus aureus*, *Aeromonas hydrophila*, *Comamonas testosterone*, *Moraxella osloensis*, *Pseudomonas stutzeri*, and *Pseudomonas aeruginosa* (Banchón, 2021). Consequently, bioaerosols have both health and economic implications, including decreased productivity and increased healthcare expenses.
- *Food Safety*: The utilization of untreated and treated wastewater for irrigation in arid and semi-arid regions is widespread, with a total area of approximately 8.42 million hectares being irrigated. Approximately 49% of this area, accounting for 4.14 million hectares, is irrigated with untreated wastewater, while the remaining 4.28 million hectares use treated wastewater (Helmecke et al., 2020; Othman et al., 2021). However, analysis of metadata reveals that untreated wastewater contains higher concentrations of heavy metals and microbial pathogens than the world standard limits (Othman et al., 2021; Peña-Guzmán et al., 2019). Although the heavy metals in treated wastewater fall within safe limits, long-term reuse of treated wastewater can result in an accumulation of these toxic metals in soil and crops (Natasha et al., 2021).
- *Climate Change*: Wastewater management can also have implications for climate change. Untreated wastewater can contribute to greenhouse gas emissions, which can exacerbate climate change (Zarei, 2020). However, if treated properly, wastewater can also be a source of renewable energy, reducing the carbon footprint of wastewater management. By 2025, two-thirds of the global population is expected to face water scarcity due to climate change (du Plessis, 2019). In order to meet the increasing demands of a projected global population of 9 billion people by 2050, food production needs to be scaled up by at least 50%, while concurrently addressing water scarcity through the utilization of approximately 15 million cubic meters of untreated wastewater for crop irrigation on a daily basis (Ungureanu et al., 2020).

CONCLUSIONS

The progress made in improving water accessibility in Latin America is worthy, but challenges remain in sanitation and wastewater treatment. The region requires increased awareness, investment, and sustainable practices in wastewater management to address the existing deficiencies. Economic indicators play a crucial role in guiding resource allocation, pricing, and investment planning, promoting market efficiency and the long-term viability of water services. Integrating economic principles, environmental considerations, and management techniques can enable informed decision-making and mitigate environmental harm. Investing in the water sector is crucial as it addresses challenges related to water access, sanitation, and quality, which impact public health, economic growth, and environmental sustainability. Improving water infrastructure offers multiple benefits, including better health outcomes, economic stimulation, and environmental conservation. Innovative business models, such as generating electricity and selling sanitized sludge, can enhance the financial sustainability of wastewater treatment plants. Proper wastewater treatment is essential to mitigate environmental and health risks, and it also presents renewable energy opportunities. Addressing these issues will contribute to achieving the United Nations' Sustainable Development Goals and promoting a prosperous and sustainable future for Latin America.

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