Wastewater management from municipal slaughterhouses in Mexico: quantities produced, existing legislation, treatment processes applied and future challenges

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Abstract: Wastewater from municipal slaughterhouses remains a persistent issue in the world, owing to its inherent characteristics it has been categorized as one of the most environmentally detrimental water sources. Mexico has 972 registered facilities dedicated to meat processing, so it is necessary to establish the best treatment options in order to achieve efficient control of the wastewater produced, reduce water consumption and enhance the utilization of natural resources. The objective of this study was to estimate the quantities of municipal slaughterhouse wastewater produced in Mexico and to provide information on the legislation applicable to the disposal and discharge of these effluents. It also presents the nature-based solutions that could be applied and that are technically and economically feasible, as well as future opportunities for the sustainable management of this type of wastewater. The state of Jalisco is the largest generator of wastewater and solid waste in the country, and significant progress has been made in the transition of public policies toward a sustainability model nationwide. These advancements are supported by legal foundations, institutional frameworks, and governmental bodies. The competitive advantages of nature-based solutions such as constructed wetlands over other treatment technologies include low operation and maintenance costs, ease of implementation, low energy consumption, and the fact that they are not harmful to nature and receiving bodies. While significant progress has been made in the management and sanitation of slaughterhouse wastewater, challenges persist with regard to the technologies employed (design and operation parameters, scaling up, biochemical processes involved, etc.) which in turn become excellent areas of opportunity for future research.

Keywords: Wastewater management; slaughterhouses; legislation; nature-based solutions.

Introduction

Municipal slaughterhouses wastewater (SWW) continues to be a latent problem in the world. Due to the unique characteristics of these effluents, they have been deemed among the most environmentally aggressive water sources. (Khalatbari-Limaki *et al.*, 2020). There are efficient technologies available for treating this type of wastewater, including microfilters, green filters, advanced oxidation, membrane treatment, electrocoagulation, and distillation(Musa and Idrus, 2021 ; Brennan *et al.*, 2021 ; Ng *et al.*, 2022), they have not yet become accessible or affordable options for treating municipal SWW in low-income rural communities or those with geographical dispersion, as is the case in Mexico, where 97.7% of the country's total localities are considered rural and classified as having a high marginalization index (Bhunia *et al.*, 2019), this situation is particularly challenging for these places. In Mexico, there are 972 registered facilities dedicated to meat processing, including 117 federal inspection slaughterhouses, 194 private facilities, and 661 municipal ones(SADER, 2023 ; SENASICA, 2023). In developing countries, these wastewaters frequently are discharged to the rivers and lakes without any treatment, causing severe environmental problems. Consequently, it is imperative to establish optimal treatment options to efficiently manage the wastewater produced, minimize water consumption, and enhance overall resource efficiency. To date, there is limited information available on the management of municipal SWW disposal sites, as well as existing legislation regarding discharge and possible appropriate treatments (Philipp *et al.*, 2021 ; Chowdhury *et al.*, 2022) . Based on the information provided above, the objective of the study was to estimate the quantities of trace water residuals occurring in Mexican municipalities and to publicize the legislation applicable to the disposal and discharge of these effluents. Additionally, nature-based solutions that could have been applied and were technically and economically viable were presented, along with future opportunities for the sustainable management of this type of wastewater.

Materials and Methods

This section describes the materials and methods used for the study:

Search for information related with slaughterhouses

This research is qualitative, made up of articles integrated with a database of a large number of publications from the last decade, adding some research from the penultimate and antepenultimate decades to further strengthen the search, especially when it comes to theoretical foundations.

The review was structured by articles, book chapters, books and theses, which have been published in both English (80%) and Spanish (20%). For the search, Google Scholar accounted for 60%, followed by Sciencedirect (15%), Springer (10%), Proquest (5%), 1findr (5%), and EBSCO (5%). The selected articles were reviewed by academic peers, who guaranteed the quality of the data collected. When starting the search, the following keywords were used: nature-based solutions, slaughterhouse wastewater, anaerobic/aerobic treatment, poultry slaughterhouse wastewater, activated sludge, slaughterhouse wastewater characterization, constructed wetlands, biological treatment, conditions of operation, among others.

Environmental legislation of municipal slaughterhouses

To establish a correct discharge of SWW into the environment, current international regulations have been consulted, as well as the maximum limits allowed for the discharge of this type of effluent in different jurisdictions around the world, including data provided by the Australian and the Environment and Conservation Council of New Zealand, the Ministry of Environment and Sustainable Development of Colombia, the Council of the European Communities, Environment Canada, the Central Pollution Control Board of India, the Ministry of Environmental Protection Agency of the People's Republic of China, US EPA, World Bank Group, as well as national, regional and local environmental laws and regulations.

Theoretical analysis

This document was organized with all the data collected, highlighting the main characteristics of wastewater from municipal slaughterhouses, as well as the main environmental rules and regulations for the discharge of effluents from municipal slaughterhouses. In addition, relevant information is presented on the anaerobic and aerobic biological treatments used during the last 20-30 years in the handling and management of wastewater from slaughterhouses and the food and meat industry.

Analysis

Descriptive statistics were applied, constructing frequency histograms, tables that describe the main parameters studied and the type of technology used.

Results and Discussion

This section includes a precise description of the experimental results, a discussion of them and their interpretation from the perspective of previous works. Reference is also made to future challenges regarding municipal wastewater treatment.

Characteristics of municipal wastewater

Wastewater from municipal slaughterhouses contains a high level of proteins, fats and carbohydrates that are generated from meat particles, visors, skin and blood residues (Ziara *et al.*, 2018). The sources of phosphorus primarily include residues of blood and meat particles, as well as residues from disinfectants and cleaning products, which may contain both organic and inorganic phosphates. (Baker *et al.*, 2021). The characteristics of this type of effluent are shown in Table 1. The contaminants in this type of effluent are determined in terms of biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (TSS), ammonium (NH_4-H), total phosphorus (TP), pH among others. According to the studies in Table 1, the concentrations of BOD, COD, total suspended solids (TSS), NH_4-H, total nitrogen (TN), total organic carbon (TOC), TP, total sulfide (TS) and pH exceeds the standard limit allowed by the World Bank for wastewater effluent (Mozhiarasi and Natarajan, 2022).

Table 1. Typical parameters of trace wastewater.

Parameter *	Minimum value	Maximum value	Mean ± SE
Alkalinity	12	433	222.30 ± 210.20
VFAs	833	1060	1306.67 ± 473.33
pH	6.5	7.28	6.88±0.15
K	0.04		0.04±0.00
TSS	1462	7267	4530.25 ± 1357.22
TS	4558	27390	16055.33 ± 6591.53
VS	1310	18800	9685.25 ± 3942.86
COD	5577	15385	9718.50 ± 1716.41
FOG	600	666	633.00 ± 33.00
NH_4 - N	30	417.96	223.98 ± 193.98
TN	156	1520	838.00 ± 682.00
TP	26	43	36.10±5.36
TOC	862	5300	3081.00 ± 2219.00
Pb	34.3		34.30 ± 0.00
BOD	2300	10173	5955.38 ± 2033.29
Turbidity	130	275	202.50 ± 72.50
PO_4^{-3}	8	120	64.00 ± 56.00

* All parameters are expressed in mg·L $^{-1}$ except for pH, EE: standard error

Quantities produced

Figure 1 shows the estimated amounts of waste generation from different types of livestock based on the estimated amount of water per slaughtered animal, blood, and solid waste. From this figure, it can be seen that the state of Jalisco is the state that generates the largest amount of residual water and solid waste derived from the slaughter of livestock for human consumption. The state of Veracruz occupies fifth position in the production of wastewater and solid waste derived from the meat industry. The state that produces the smallest amounts of waste and residual effluents is Baja California Sur.

Existing legislation

Municipal SWW has been considered by the United States Environmental Protection Agency (US EPA) as the most dangerous wastewater for nature and living beings (Yetilmezsoy *et al.*, 2022) . The discharge of this type of effluent can cause deoxygenation of rivers, lakes, streams and contamination of other natural receiving bodies (Wizor and Nwankwoala, 2019) . Anaerobic treatment is the most used due to the large amount of organic matter contained in this type of effluent (Khawer *et al.*, 2022) . However, normally, anaerobic treatment is not sufficient for a complete elimination of the organic load contained in the effluent, so post-treatment based on aerobic systems is necessary (Aziz *et al.*, 2022) . The physicochemical properties of this type of effluent make it advisable not to rely solely on anaerobic or aerobic processes. This is because the effluent discharge must adhere to the limits and standards set by various international organizations concerning wastewater disposal (Musa and Idrus , 2021).

Standards and guidelines are an essential part of addressing the ecological effect of municipal SWW in the industrial and commercial framework (Preisner *et al.*, 2020) . Figure 2 presents the standard allowable limits for wastewater effluent discharge from municipal abattoirs set by the World Bank, Environment Organization of Canada (2001-2012), Australian Environment Council (ANZECC, 2000), Environmental Quality Malaysia (2009) and the European Communities (CCA, 1999), in addition to other instances.

The limits of permitted contaminants in wastewater and the corresponding legislation change depending on the type of wastewater (food, agricultural, industrial, etc.) (Parida *et al.*, 2021) .

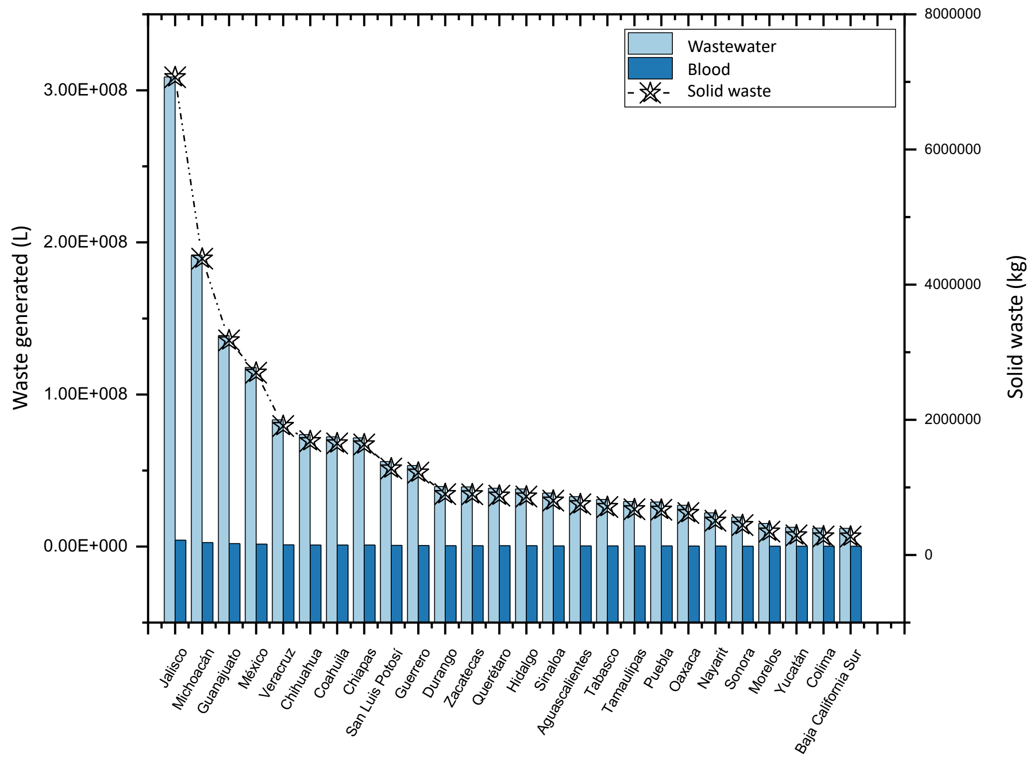

Figure 1. Waste generated by livestock slaughter in 2022.

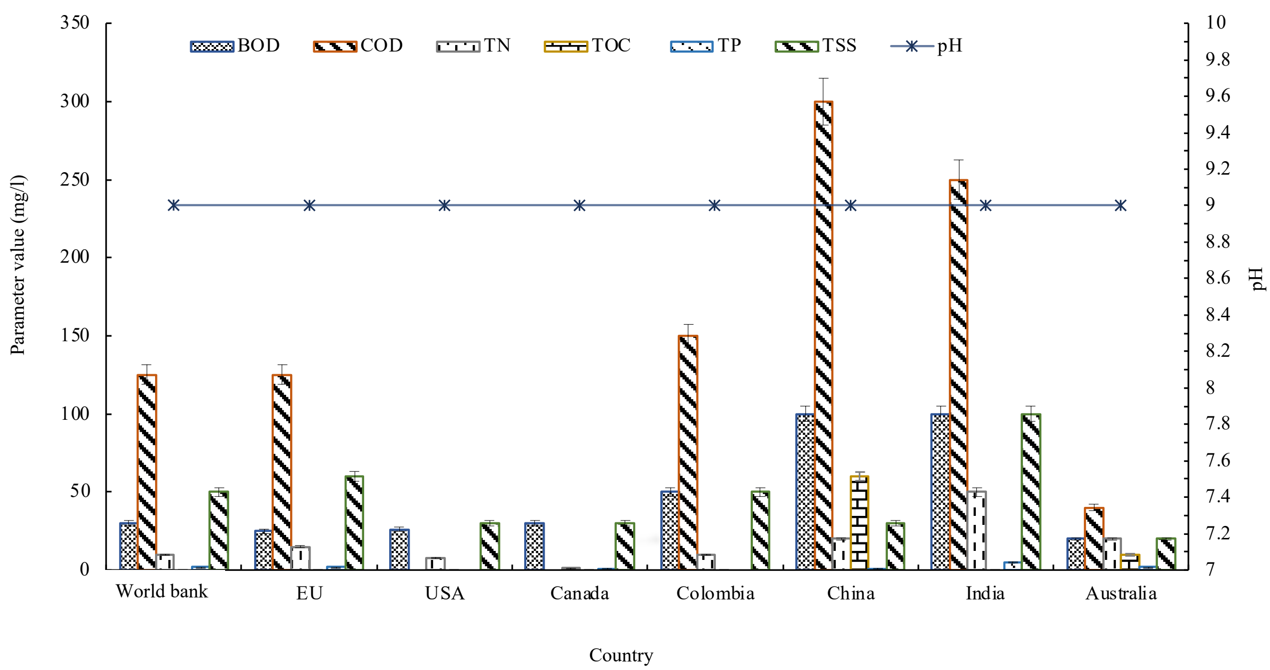

Figure 2. Comparison between various countries' standard limits for wastewater discharge from slaughterhouses.

Table 2. Environmental regulation applicable to slaughterhouse waste.

Environmental regulation	Instrument	Aim
National	Mexican Political Constitution	Establishes the right to a healthy environment for development and well-being
	General Law of Ecological Balance and Environmental Protection (LGEEPA)	Promotes sustainable development and establishes the foundations for environmental care
	General Law for the Prevention and Comprehensive Management of Waste (LGPGIR)	Waste regulation
	NOM-194-SSA1-2004	Technical specifications that must be considered in a slaughterhouse, for supply, storage, transportation, sale; and the health specifications of the products
	NOM-161-SEMARNAT-2011	Criteria for Waste to classify them and determine which ones are subject to a Management Plan
	NOM-052-SEMARNAT-2005	Identification, classification and listings of hazardous waste
	NOM-002-ECOL-1996	Establishes the maximum permissible limits of contaminants in wastewater discharges to urban or municipal sewage systems.
	NOM-001-SEMARNAT-2021	Establishes the permissible limits of contaminants in wastewater discharges in receiving bodies owned by the nation.
Regional	Municipal Organic Laws	They point to the public trace service as a responsibility of the municipality
	Public Health Law of the States	Establishes that it is up to the state in matters of local health, the regulation, control and health promotion of slaughterhouses.
Local	Regulation of the Municipal Trail	Regulates everything related to the operation of this public service

According to Figure 2, the most stringent level of standard allowable contaminant limits among the standards addressed are the guidelines of Canadian regulations and those established by the United States, while the lowest requirements are established by the Ministry of Environment of the People's Republic of China, Protection and the Central Pollution Control Board of India. The limits that have a greater tolerance range are those established by Canada. The margin allowed by environmental standards provides an area of opportunity for the use of nature-based technologies (aerobic and/or anaerobic) with the purpose of minimizing the characteristic pollutants of this type of effluent and at the same time obtaining secondary products such as biogas (Baker *et al.*, 2021).

Table 2 presents the main regulatory bodies for waste from municipal waste disposal sites and the objective of their application in Mexico. As seen in Table 2, there has been progress in the transition of the country's public policies towards the sustainability model, and these advances are supported by legal bases, institutional frameworks and government bodies. From its beginnings until the 1980s, the dynamism of the legal framework contributed to the consolidation of laws in Mexico. At this time, in 1988, the General Law of Ecological Balance and Environmental Protection was promulgated, which has served as the foundation for the implementation of environmental policy since then. The instruments created finally established the foundational legal framework for waste regulation at the federal level in our nation. This framework is based on the Political Constitution of the United Mexican States, the General Law of Ecological Balance and Environmental Protection, the General Law for the Prevention and Comprehensive Management of Waste, along with their respective regulations and the relevant Official Mexican Standards that are applicable across all government levels.

Treatment processes

Table 3 addresses information on different nature-based aerobic and anaerobic technologies used in the last 20 years in the treatment and management of municipal SWW in Mexico, involving the study area, type of treatment, removal efficiencies of contaminants, etc. The Table shows some of the treatments that have been developed in order to solve this environmental problem. Many of the technologies listed in the table are still not financially accessible for municipal slaughterhouses located in low-income rural communities or those with geographic dispersion. This is particularly relevant for numerous cities in developing countries like Mexico, where 97.7% of all localities are considered rural and are characterized by a high marginalization index. Due to the numerous benefits and outstanding results achieved through the utilization of nature-based solutions, such as treatment wetlands, they have become an increasingly suitable option for treating various types of wastewater, including domestic and industrial sources. The adoption of this technology has recently witnessed significant growth. Treatment wetlands have found applications in treating a wide range of wastewater types, including stormwater runoff, agricultural effluents, hospital wastewater, landfill leachate, as well as industrial wastewater stemming from sectors like the sugar industry, pig farming, and meat processing (Vymazal *et al.*, 2021).

These types of wastewater exhibit contaminant concentrations similar to those found in municipal wastewater. Consequently, recent studies have positioned nature-based solutions as a viable alternative for exploring wastewater treatment methods (Sharma et al . , 2023). Given the success of these solutions in purifying contaminants present in such effluents, they can be implemented in various stages. This approach not only reduces construction, implementation, operation, and maintenance costs but also aligns with the socioeconomic and cultural conditions prevalent in municipal slaughterhouses. These facilities are typically situated in remote areas with limited access to basic electrical services, making nature-based solutions a practical choice (Hale *et al.*, 2023).

In this sense, it is important and attractive to explore these alternatives in order to achieve an optimization of environmental and operational parameters for subsequent scaling and application on a real scale.

Constructed wetlands

Constructed wetlands have been widely used for wastewater treatment and management. This type of bioremediation technology is typically used after primary and secondary treatment, as a tertiary treatment. In this nature-based technology, vegetation, bacterial consortia, soil, porous material, and other natural processes are used to remove contaminants from the effluents to be treated (Vymazal *et al.*, 2021). The competitive advantages of these over other treatment technologies are: low operation and maintenance cost, easy implementation, low energy consumption, and they are harmless to nature and receiving bodies (Moreira and Dias, 2020). There are two types of constructed wetlands, and they are classified as surface flow and subsurface flow constructed wetlands. Taking into account the direction of flow, they are divided into two groups: horizontal flow wetlands and vertical flow wetlands. Filter media used in wetlands, such as tezontle, river gravel, stone, among others; Contaminant removal in subsurface flow wetlands is much better compared to removals achieved with surface flow wetlands (Parde *et al.*, 2021). To prevent effluent seepage through the bottom, wetlands are covered with polyethylene plastic. In the late 1960s, the first large-scale implementation of constructed wetlands took place. In the first instance, domestic and municipal wastewater was treated, however, over the years it has been possible to treat industrial, agricultural, hospital, food, leachate and slaughterhouse wastewater (Kataki *et al.*, 2021).

Table 4 summarizes some of the main applications of SWW treatment over time. One of the studies listed in the Table evaluated the effectiveness of a large-scale constructed wetland system in Mexico for the treatment of wastewater from slaughterhouses (Gutiérrez-Sarabia *et al.*, 2004). In the treatment unit, a series system was established consisting of a sedimentation tank, anaerobic lagoon and artificial wetland. The total removal efficiencies were 91% for BOD $_5$, 89% for COD and 85% for TSS. However, the wetland system, which used 12 mm gravel in size, only managed to reduce organic matter by 30%. However, the presence of *Typha latifolia* and *Phragmites plants australis* also helped eradicate some bacteria, including coliforms. The authors place special emphasis on the implementation of constructed wetlands as a tertiary treatment unit for municipal wastewater effluents.

Table 3. Main treatments studied.

Type of treatment	Mexico zone	Size	Removal of contaminants	Observation	Reference
Batch and Upflow Anaerobic Sludge Blanket Reactors (UASB)	Saltillo Coahuila	Laboratory Scale	The coefficient of performance, Y_p, was 343 and 349 ml of CH_4 /g of COD, for batch reactors and UASB reactor, respectively.	The rate of methane formation can be influenced by different COD concentrations.	Rodríguez-Martínez *et al.* (2002)
Primary sedimentation tank, anaerobic lagoon and a subterranean flow constructed wetland, in series	Estad Hidalgo.	Big scale	$_5$ removal efficiency: 91%, COD: 89% and TSS: 85%. NTK: 80%, Coliforms: 5 logs	The final effluent failed to meet Mexican environmental regulations for fecal coliform counts, five-day biochemical oxygen demand (BOD5), and total suspended solids (TSS).	Gutiérrez-Sarabia *et al.* (2004)
Anaerobic filter (AF) coupled to an aerobic sequential batch reactor (SBR)	Celaya, Guanajuato	laboratory scale	COD removal efficiency: 50 - 81%	The quality of the treated effluent met the limits required by Mexican regulations for the discharge of wastewater into federal waters and lands.	López-López *et al.* (2010)
Chemical adsorption	Toluca, Mexico	laboratory scale	COD removal efficiency: 73%; TOC: 63% Color: 84%	Chemical adsorption is the main mechanism for TOC adsorption by zeolitic materials and physical adsorption for COD removal.	Torres-Perez *et al.* (2014)
Anaerobic bioreactors	Saltillo Coahuila.	laboratory scale	COD removal efficiency: 90%	The electricity generation potential from slaughterhouse wastewater is sufficient to manage a reasonable fraction of the slaughterhouse operation.	Hernandez *et al.* (2018)
Sequential Batch Reactors (SBR)	Mexico City	Laboratory Scale	COD removal efficiency: 54%, NT: 60%	Prefermentation failed to improve biodegradability; however, treatment with raw water under acidic conditions produced an effluent with quality to be discharged according to Mexican Regulations.	Hernandez-Fydrych *et al.* (2018)
Anaerobic digestion	León, Guanajuato	Environmental and laboratory conditions	Ammonia removal efficiency: 80.4%	Light mitigation strategies, such as the use of granular sludge, will be effective when applying the consortium process under ambient conditions.	Akizuki *et al.* (2019)
Photolysis (PHO) and Photo-Fenton	Toluca, Mexico	laboratory scale	PHO-HSPF achieved efficiencies of 84.5–91.6% and 95.8–99.9% for COD and color respectively.	Direct photolysis proved to be the best treatment at the pH of the sample (6.4).	Garduño-Pineda *et al.* (2022)

Table 4. Different applications of constructed wetlands in the treatment of wastewater from slaughterhouses

Wetland Type	Treatment	Wastewater type _	Size	HRT (days)	Pollutants removed	Vegetation	Reference
Surface flow Flow Underground	Primary Primary	meat processing dairy farm	Large scale Large scale	8.7 3	Nitrogen Nitrogen	*Maximum glyceria.* *Schoenoplectus validus*	Russell *et al.* (1994)
Surface flow	Four wetlands in series	meat processing	Large scale	7	N: 87%	*Maximum glyceria*	Van Oostrom (1995)
Primary sedimentation tank, an anaerobic lagoon and an artificial underground flow wetland, in series	Tertiary	Slaughterhouse wastewater _ _	Large scale	10.6	BOD_5: 91%; COD: 89%; TSS: 85%; Coliforms: 2 to 3.5 logs	*Phragmites australis (junco) and Typha latifolia (cattail)*	Gutiérrez-Sarabia *et al.* (2004)
Horizontal flow	Secondary	Slaughterhouse wastewater	NR	NR	Wastewater meets environmental protection requirements according to organic (BOD_5) and biogenic ($_{total}$ N and $_{total}$ P) contaminants.	*NR*	Struseviciene and Strusevicius (2006)
Vertical flow	Secondary	Animal processing	Microcosm	NR	COD: 167 mg/l; Ammonia: 63 mg/l; TSS: 15 mg/l, in the effluent	*Typha latifolia*	Scholz (2006)
Vertical and horizontal flow	Serial and combined system	Slaughterhouse wastewater	Microcosm	NR	BOD_5: 99.9%; COD: 97.4%; TSS: 94.9; NH_4-N: 99.3%; NT: 78.2%	*Phragmites australis*	Soroko (2007)
Horizontal underground flow	Secondary	Wastewater of different chemical composition.	NR	NR	N: 37 - 44%	*Phragmites australis*	Gasiunas *et al.* (2005)
Constructed overland flow	Secondary	Slaughterhouse wastewater	Big scale	111	BOD_5: 95%; SST: 72%; TDS: 81%; PT: 88%; SRP: 97%; TKN: 87%; SO: 87%	*Typha latifolia*	Carreau *et al.* (2012)
Vertical flow	Secondary	Pig slaughterhouse wastewater	Big scale	5	COD: 36%: BOD: 66%; bacteria coliforms: 97%; bacteria fecal matter: 99%	*Typha*	Pitaktunsakul *et al.* (2015)
Horizontal underground flow	Tertiary	Slaughterhouse wastewater	Big scale	1.16	NH_4-N: 76%; NT: 48%; o-PO_4-P: 46%; PT: 74%; COD: 63%; Fecal coliforms: 100%	*Cyperus papyrus*	Odong *et al.* (2015)
Vertical subsurface flow	Primary	Slaughterhouse wastewater	Mesocosms	5	BOD_5: 50%; COD: 55%; SST: 82%; NH_4–N: 26.5%	*NR*	Mburu *et al.* (2019)

NR: Not Reported

Future challenges

Although good results have been obtained in the management and sanitation of wastewater from slaughterhouses, there are still some challenges associated with the technologies used. Therefore, an evaluation of these treatments is presented below, followed by recommendations that can become excellent areas of opportunity for future research, as reported by Musa and Idrus (2021) (Table 5):

Table 5. Main limitations of aerobic and anaerobic treatments.

Type of treatment		**Limitations**
Biological Treatment	Aerobic	- High start-up costs due to aeration devices - Consumes a large amount of electricity - Generates a large volume of sludge, which requires additional processes to treat - Sludge can only be removed by soil application or burning means. - Prone to toxin inhibition. - An unbalanced nutrient ratio (COD:N:P) can prevent viability
	Anaerobic	- Highly dependent on climate, geography and accessibility to large spaces - Long hydraulic retention time (HRT) - Long start-up period - Low efficiency - The effluent does not satisfy the discharge limit (N and P) and may require further treatment - Odor problems - Prone to toxin inhibition.
Physiochemical	Dissolved air flotation	- Consumes a large amount of electricity - The use of chemicals renders the sludge useless - Frequent breakdowns - Freezing problems
	Coagulation-Flocculation	- Uses a large amount of coagulant or flocculant chemicals - Generates a large volume of sludge, which requires additional processes to treat - Sludge can only be removed by soil application or burning means.
	Electrocoagulation	- Consumes a large amount of electricity - Low profitability

- Numerous studies have been reported on the treatment of SWW by applying nature-based solutions. Although excellent contaminant removal has been achieved with anaerobic digestion and at the same time biogas can be generated as a high value-added product, a disadvantage of this process is that high amounts of organic load are generated, which results in the inhibition of biogas production. and lower COD removals. It is recommended to investigate anaerobic co-digestion in which slaughterhouse wastewater is combined with another organic substrate (fat and oil) to achieve higher biogas production, compared to anaerobic digestion alone.
- The use of constructed wetlands has been used for the treatment of wastewater from slaughterhouses, the effluents obtained after the use of this technology, in general, the treated water does not comply with the regulations to be discharged into the environment. Therefore, it is suggested to combine these methods with some other nature-based techniques to comply with the applicable regulations before discharge.

- One of the most promising nature-based solutions for bioremediation of slaughterhouse water is the combination of aerobic/anaerobic techniques. These joint techniques are more effective in eliminating high concentrations of contaminants present in effluents such as wastewater from slaughterhouses. If these combined technologies are complemented with some disinfection technique, the effluents generated can comply with the standards and regulations for wastewater discharge.
- An important area of opportunity regarding nature-based solutions in the bioremediation of slaughterhouse wastewater is the optimization of the techniques that have been reported so far, as there is limited literature on the topic so far. In addition, it is important to explore the elimination of other types of organic components, such as pharmaceutical compounds and pathogenic microorganisms present. It is necessary to carry out more *in situ studies*, and the application of existing technologies on a large scale.
- It is very necessary to know the environmental factors that influence the removal of contaminants; more detailed studies are required to identify the mechanism of action of each environmental, physical-chemical or biological factor in this process and its contribution to the efficiency of the treatment, for its subsequent escalation.
- The drawbacks of anaerobic (temperature control, long HRT, sludge washing, among others) and aerobic technologies (energy cost, construction areas, inefficient scaling, sludge production, among others) make more research on waste necessary. organic, inorganic or cellulosic materials to make the nature-based technologies studied more sustainable.

Conclusions

The objective of this study was to estimate the quantities of municipal wastewater produced in Mexico and to publicize the legislation applicable to the disposal and discharge of these effluents, as well as the treatments that could be applied and that are affordable from the technical and economic point of view, and future opportunities for the sustainable management of this type of wastewater. Constructed wetlands have become an appropriate solution to treat aggressive wastewater such as effluents from municipal wastewater disposal sites. When this technology is used in conjunction with others such as anaerobic digestion, it has been shown that the quality of the treated effluent meets the limits required by Mexican regulations for the discharge of wastewater into federal waters and lands. However, there are still some challenges related to these technologies used (design and operation parameters, scaling, biochemical processes involved, etc.) which in turn become excellent areas of opportunity for future research. Further exploration of integrated nature-based techniques, such as combining constructed wetlands with complementary methods, is necessary for regulatory compliance in treated water discharge. Additionally, extensive studies are required to optimize existing nature-based solutions, with a specific focus on removing various organic components, including pharmaceutical compounds and pathogens.

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