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Constructed wetlands as alternatives for swine sustainability

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ABSTRACT

Objective: To analyze available information about constructed wetlands and to identify the design, substrate, and vegetation advantages that could be an alternative solution to pig production system wastewaters.

Design/methodology/approach: A broad literature review was conducted to identify the main characteristics of constructed wetlands (CWs), as well as the various plant species associated with these systems, and the substrates used as filter beds.

Results: Vertical CWs have provided the best organic matter removal results, estimated indirectly through chemical oxygen demand (COD) and nitrogen derivatives such as total nitrogen (TN), ammonium (NH_3), nitrate $\left(NO_3^-\right)$, and nitrite $\left(NO_2^-\right)$. Several substrates are used as filter beds, but they must be evaluated according to their availability, cost, and feasibility for colonization by nitrifying and denitrifying bacteria to degrade the dissolved pollutants. Combinations of plant species can reduce more than 10% of nitrogen products and organic matter.

Study limitations/implications: The lack of monitoring for the satisfactory application of water care standards by small backyard and transition producers limits the adoption of environmental technologies for livestock sustainability in Mexico.

Findings/conclusions: Constructed wetlands are inexpensive, easy-to-use, adaptive systems that can be feasible alternatives for reducing the pollution caused by the swine wastewater generated by backyard producers.

Keywords: Wastewater, livestock pollution, wetland design, phytodepuration.

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INTRODUCTION

Over the last decades, the nitrogen nutrients concentration in water tables has increased, resulting in a strong eutrophication problem, which limits the use of water for human consumption (Brix, 1997).

Image by Beatrice Hohl at Pixabay

Industrial, anthropogenic, and agricultural activities are the main sources of nitrogen. Agricultural activities include substantial amounts of excreta, urine, and uneaten food from pig farms that are discharged through wastewater (Pacheco and Cabrera, 2003).

Pig farm wastewater provides a 25,205-mg L^{-1} chemical oxygen demand (COD), 15,042-mg L^{-1} total soluble solids (TSS), 2,034-mg L^{-1} total nitrogen (TN), 2,032 mg L^{-1} total Kjeldahl nitrogen (TKN), 0.63-mg L^{-1} nitrous and nitric nitrogen $\left(\text{N-}\left(NO_2^- + NO_3^-\right)\right)$, and 1,760-mg L^{-1} ammonium $\left(\text{N-}NH_4^+\right)$. All of this depends on the number of animals, production process, local climate, among other factors (Garzón-Zúñiga and Buelna, 2014). While livestock activities contribute to rural development, it is necessary to perform them in a sustainable way, preventing pollutants from reaching natural waterbodies (Contreras-Contreras *et al.*, 2018).

Due to its size, backyard pig production is not usually considered as an activity with a significant contribution to nitrogen release; however, the establishment of small backyard farms in Mexican towns has boosted the risk of contamination of natural waterbodies. Small producers do not usually carry out water treatment; they indiscriminately discharge their wastewater —including solid waste— into waterbodies, croplands, or municipal drainage (Solís-Tejeda *et al.*, 2021). This causes soil contamination problems and unpleasant odors in the surrounding area.

In Mexico, the Law of National Waters (DOF, 2020) and the General Law of Ecological Balance and Environmental Protection (DOF, 2021) are implemented in a regulatory way. Those laws establish the following indicators: NOM-001-SEMARNAT-1996 that establishes the permissible pollutant limits for wastewater discharged in national waterbodies and assets; and the NOM-002-SEMARNAT-1996 that establishes the permissible pollutant limits for wastewater discharged in urban or municipal sewerage systems.

The waste released by livestock activities must be quantified in order to regulate it. Conventional wastewater treatment processes have high installation, infrastructure, maintenance, and labor costs; consequently, adopting them in production systems (such as backyard swine) is difficult. Therefore, it is important to provide small producers with affordable solutions that they can adopt and adapt (De la Mora *et al.*, 2014; Solís-Tejeda *et al.*, 2021).

A variety of technologies has been established worldwide to minimize the impact generated by livestock farms —particularly, pig farms. These technologies range from biodigesters or bioreactors (Venegas *et al.*, 2017) to practices of dietary management that minimize nitrogen release (Cervantes *et al.*, 2009).

In contrast, constructed wetlands (CWs) are a low cost, efficient, and easy-to-use sustainable technology that can be used to treat wastewater (from pig farms and other sources) with a high content of nitrogen derivatives (Sandoval-Herazo *et al.*, 2020). Consequently, the purpose of this literature review is to analyze the information generated about constructed wetlands and to identify the advantages of the designs, substrates, and vegetation that can be used as an alternative solution to swine production system wastewater.

Constructed Wetlands

The first constructed wetlands (CWs) —formerly known as "root zone method"— were developed by Seidel and Kickut in the 1970s (Brix, 1997). CWs are man-made engineering systems that —with the help of soils, vegetation, and microorganisms— are meant to mimic the processes of natural wetlands and are used to treat wastewater. The first CWs were used in the petrochemical industry, slaughterhouses, meat and dairy processing plants, and paper producing companies (Vymazal, 2014). These wetlands have efficiently reduced nitrogen and other environmental pollutants.

CWs reproduce natural processes and their effectiveness depends on the technical design specifications, type of substrate, hydraulic loading rates, plant species, flow type, hydraulic retention time, load of applied pollutants, among others (Jun *et al.*, 2017).

The substrate is the filter material to which bacteria that will degrade the compounds adhere; therefore, it must promote the development of microorganisms. The substrate adsorbs up to 90% of the pollutants (Luna and Ramírez, 2004).

The processes for the elimination or retention of nitrogen derivatives from the water in the CWs include: volatilization, nitrification, denitrification, nitrogen fixation by plants, microbial adsorption, mineralization (ammonification), nitrate reduction to ammonium (nitrate-ammonification), anaerobic ammonium oxidation (anammox), fragmentation, sorption, desorption, burial, and leaching. Microbial nitrification and denitrification are the most important of such processes (Jun *et al.*, 2017).

One or more methods for reduction of nitrogen derivatives can be managed according to the CW design. Nitrification is the use of nitrifying bacteria to oxidize ammonia (Jetten *et al.*, 1997). This process is achieved through the aeration of the problem water and by nitrifying bacteria. This usually takes places in the vertical flow CWs, where water cascades down through the substrate and dissolved oxygen is obtained (Sandoval-Herazo *et al.*, 2020). Denitrification (Figure 1) takes place under anaerobic conditions and is a process in which NO_3^- transforms into dinitrogen gas N_2 (Jetten *et al.*, 1997). This process takes place at the bottom of the wetlands where an anoxic environment is generated (Sandoval-Herazo *et al.*, 2020).

This establishes the theoretical basis for CWs as an alternative solution to high nitrogen wastewater discharges, in compliance with NOM-001-SEMARNAT-1996 and NOM-002-SEMARNAT-1996. In both cases, wastewater discharges must contain $<$40 mg L^{-1} (monthly sampling average) and 60 mg L^{-1} (daily average) of nitrogen.

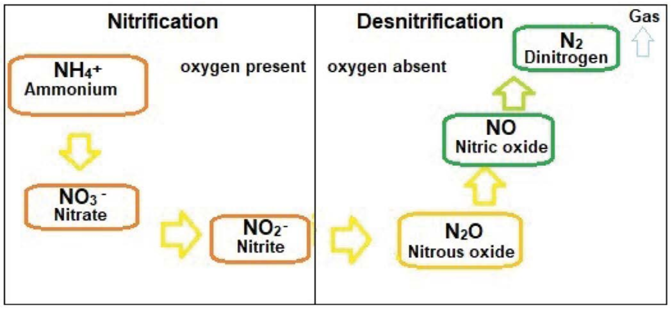


Figure 1. Nitrification and denitrification processes in constructed wetlands.

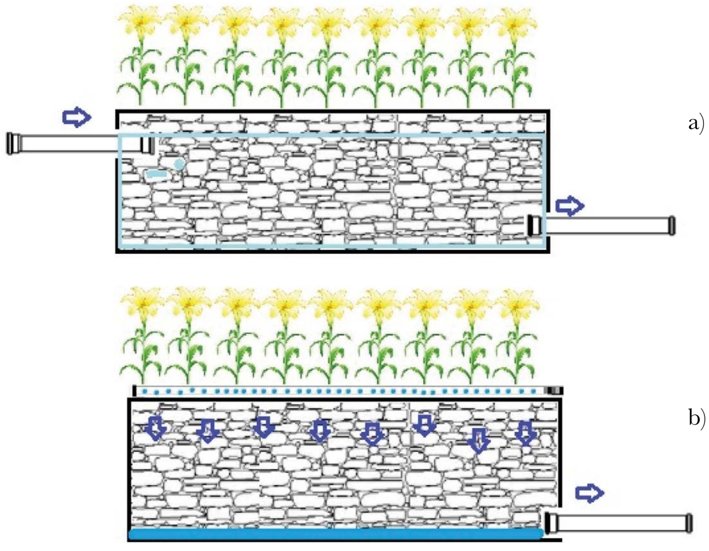
Constructed Wetland Design

Traditional CWs can be divided into two types: the surface CW (in which water flows over the substrate) and the subsurface CW (in which the water flows through the substrate). The latter can be categorized into two types: horizontal or vertical, according to the direction in which the water flows (Figure 2). There are hybrid systems made up of the union of two of these three designs. CWs with more than two stages —with the addition of mechanical or artificial aeration— have also been designed and lately circular flow designs are being evaluated (Rahman *et al.*, 2020).

Horizontal surface flow CWs have been assessed for swine wastewater treatment. To achieve an acceptable reduction of N and COD (>70%), a division into two blocks of treatment must be carried out, as a consequence of the high amount of nitrogen products (De la Mora *et al.*, 2014). Horizontal CWs are efficient secondary treatment systems which contributes to the elimination of the finest particles in the effluents and their installation requires a larger area (Jaramillo-Gallego *et al.*, 2016).

Vertical CWs have been used to treat wastewater with high N content, such as urban sewage. Treatment plants based on these systems have eliminated a high level of nitrogen pollutants (>90%) (Paing and Voisin, 2005). There are several ways to transform nitrogen through CW systems; however, only few processes can remove TN from wastewater. The removal of TN in both CWs varies between 40 and 55%, depending on the design and the input load. Nevertheless, the magnitude of the processes responsible for the removal of compounds differ between both systems. Vertical flow CWs successfully remove ammonia, but a poor denitrification takes place. Meanwhile, horizontal CWs provide good denitrification conditions; however, their capacity to nitrify ammonia is limited (Vymazal, 2007).

Vertical partially saturated CWs (VPS-CWs) combine nitrification with denitrification in a single system, maintaining an area with oxygen for nitrifying bacteria, as well as an



a) Horizontal constructed wetlands.

b) Vertical constructed wetlands.

Figure 2. Main constructed wetland designs.

anoxic area for the production of denitrifying bacteria. Compared with the treatment of pig wastewater with traditional vertical CWs, a higher reduction of pollutants —such as COD (5%), TSS (20%), N-NH4 (25%), TKN (32%), and CF (20%)— was found (Sandoval-Herazo *et al.*, 2020).

Substrates Used in Constructed Wetlands

Substrates are the main element of the CWs. They play an active role in water purification. Substrate porosity is a requisite for the facilitation of the pollutant adsorption process and it is a medium for the fixation of the bacterial biofilms that will transform the contaminants adsorbed by the material (Gao *et al.*, 2018). Substrate efficiency is affected by the hydraulic retention rate (HRT) which is the time that a volume of problem water remains in contact with the substrate (Jun *et al.*, 2017).

Based on these qualities, several types of substrates have been studied for the treatment of effluents from various activities (Table 1). It is important to consider the use of recycled, inexpensive, and readily-available materials to supply replacements (Zamora *et al.*, 2019).

Effect of Vegetation

The relationship between CWs and macrophytes has been studied since 1950 —particularly, emergent and submerged vegetation with floating leaves. All CWs efficiently remove organic matter and suspended solids; however, nitrogen removal may be lower, although this can be improved by vegetation (Vymazal, 2010). Plants must have certain characteristics to perform their function in CWs: 1) tolerance to high organic

Table 1. Main advantages and disadvantages of constructed wetlands.

Substrate	Advantages	Disadvantages	Author
Oyster shell	High reduction of total nitrogen (44.3%) and 73.1% of nitrite. Economic.	Requires very low HRR.	1
Zeolite	High reduction of total nitrogen (43%) and 22% of ammonia. Porous laminar structure. Facilitates chemical absorption and bacterial adhesion.	Costly.	1
Gypsum	Economic and easy to supply.	Low reduction of total nitrogen. Lower HRR compared to zeolite.	1
Ceramic	Reduces 45.8% of total nitrogen and 23.5% of ammonia. High microbial area.	Costly and difficult to supply.	1
Tezontle (coarse pumice)	Reduces 70% of COD and 49.2% of ammonia. Porosity 0.53. Large contact surface. Inexpensive and easy to supply.		2, 3
Sand (25%), peat (12.5%), pebbles (50%) and rock fragments (12.5%)	Reduces COD by 68% and ammonia by 66-83%. Inexpensive and easy to supply.	Low HRR to avoid clogging.	4
Porous construction stone (50%), 49% fine pumice (tepezil) and 1% soil	Reduces TSS by 34-35% and COD by 76-78%. Inexpensive and easy to supply.		5
Polyethylene terephthalate (50%), 49% fine pumice (tepezil) and 1% soil	Reduces TSS by 34-35% and COD by 76-78%. Very inexpensive, easy to supply, and ecological.		5

HRR=Hydraulic Retention Rate. COD=Chemical Oxygen Demand. TSS=Total Soluble Solids. 1= Jun *et al.*, 2017. 2=Mateo *et al.*, 2019. 3=Sandoval-Herazo *et al.*, 2020. 4=Rodríguez-González *et al.*, 2013. 5=Zamora *et al.*, 2019.

loads (5-day biochemical oxygen demand: BOD_5), between 3 and 25 g BOD_5 m^{-2} d; 2) abundant roots and rhizomes; and 3) above ground biomass to assimilate nutrients (Vymazal, 2011).

Plants degrade, absorb, and assimilate organic matter and nutrients (*e.g.*, nitrogen) in their tissues; furthermore, their roots provide a medium that favors bacterial growth and retain suspended solids, acting as a filter medium (Upadhyay *et al.*, 2016). Common plants —such as reeds (*Phragmites australis*), bulrushes (*Typha domingensis* Pers.) or tule (*Schoenoplectus* spp.)— have proved to be efficient and have therefore been studied. Recently, ornamental plants —such as gannet (*Zantedeschia aethiopica*) and lilies (*Canna* spp.)— have been researched. The performance of lilies in the absorption of pollutants improves the landscape; additionally, these plants can also be commercialized (Morales *et al.*, 2013).

The plant species that are intended to be used in the CWs must be previously studied: sometimes they do not have favorable effects and the organic matter of the roots of some of them may even increase values such as BOD_5 and COD (Jaramillo-Gallego *et al.*, 2016). When the system does not obtain the expected results, HRT can sometimes be adjusted, increasing the contact time with nitrifying and denitrifying bacteria.

Rodríguez-González *et al.* (2013) recommend yellow lily in vertical flow CWs to improve the removal of organic matter. Yellow lily improves the treatment for DOC elimination by 13%. In addition, it reduces 10% more ammoniacal nitrogen. De la Mora *et al.* (2014) tested surface flow CW related to bulrushes and species of the genus *Sirpus* to treat swine waters. Acceptable removal percentages attributed to the plants were achieved: 75% and 70% for COD and TN, respectively.

Yellow lily (*Iris pseudacorus*) improves the elimination of organic matter and nitrogen in CWs through plant adsorption by 13% (Rodríguez-González *et al.*, 2013). Sandoval-Herazo *et al.* (2020) compared the effect —reducing pollutants in dilute swine wastewater— of blue lilies (*Iris germanica*) as VPS-CW vegetation with lilies (*Canna hybrids*), removing >90% TN. No significant differences were observed between them. The adsorption effect of *Canna hybrids* was quantified by Mateo *et al.* (2019) who found an 18% reduction in $N\text{-}NO_4$.

CONCLUSIONS

The literature shows that constructed wetlands are efficient and low-cost systems for the treatment of wastewater with high loads of nitrogen products; therefore, they can be ideal for the treatment of swine wastewater. The horizontal constructed wetlands provide a considerable crop area for the exploitation of plants and reduce nitrogen; however, studies show that they have less impact than VPS-CWs or hybrid systems that combine nitrification and denitrification processes.

Further research supports that plants of the genus *Canna* absorb a large amount of nitrogen; these plants have suitable characteristics for the treatment of swine wastewater and they can also generate an additional income to production. Tests performed on substrates such as tezontle, tepezil, and recycled materials have efficiently eliminated nitrogen products and organic matter; they are also considered inexpensive and easy to acquire. In order to maximize its effectiveness, the size of the substrate particles and the hydraulic retention rate must be taken into account.

Government incentives focused on increasing livestock infrastructure must be directed towards the installation of swine production systems which consider constructed wetlands as an essential element in the reduction of environmental impacts.

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