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Decision Strategy Tool for the Design of Natural Treatment Systems for Wastewater (NTSW) from Isolated Livestock Farms

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Abstract: This work proposes a series of strategies and tools for the design and characterization of natural treatment systems of wastewater (NTSW) applied in livestock farms, considering the parameters of flow rate (Q), conductivity (EC) and chemical oxygen demand (COD) of the waste generated, farm location, hydraulic retention time (HRT), and removal/reduction rate targets. The high organic load of the effluent generated in these farms has an important environmental impact, which is amplified in insular or isolated territories. The application of such treatment systems has demonstrated their suitability in these environments, but their design lacks proper characterization and sizing tools for their adequate operation. The proposed tools in this work are based on a collection of experimental data over a ten-year period of application of NTSW in real farms. This work contributes to facilitate the design and implementation of NTSW in farms located in isolated, island, or similar-size environments. Finally, as a practical application, an inventory and implementation of the tool developed for livestock farms on the island of Gran Canaria (Spain) is carried out.

Keywords: effluent characterization; natural systems; wastewater treatment plant design; livestock farms

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1. Introduction

Livestock waste in general, and pig waste in particular, is made up of a dry part, of formed by animal excrement, food remains, bedding, and a liquid part. This mixture is called slurry [1,2]. Pig slurry is a source of multiple mineral constituents: primary and secondary macronutrients and trace elements. The availability of macronutrients in slurry is beneficial for crops, and even comparable to that of mineral fertilizers [3,4].

The new Spanish legal framework establishing basic rules for the management of intensive and extensive pig farms can be found in Royal Decree 306/2020, of 11 February [5]. This Royal Decree (hereinafter referred to as RD306) focuses on environmental issues with respect to the protection of water, soil, and air, and on the fight against climate change. Livestock farm effluent with a high organic load has a strong environmental impact that is amplified in island territories.

Pig slurry may have different properties at any given time due to various factors inherent to production. These include, among others, the number sows, piglets, or fattening pigs, the type of exploitation and management of the farmer, the feed used, farm cleanliness, the season of the year, the frequency of reception pit emptying, and climate conditions [6–8].

For the above reasons, interest has grown in developing a characterization tool based on historical data of the operation of wastewater treatment systems in livestock farms. As indicated in [9,10], an interesting characterization can be carried out based on one or several parameters that are easy to determine in situ, leaving other, more complex parameters for the laboratory. It should also be noted that the excessive or unfavorable application of slurry on land can lead to losses of nitrogen and phosphorus by percolation and runoff into surface and subsurface water bodies [9–11]. Excess phosphorus and nitrogen in the form of ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-), in waters can accelerate the aging of aquatic ecosystems [12–16]. Ammonia (NH_3) is recognized as one of the most important toxic gases present in swine facilities and has profound effects on pig performance [17], with responses to its toxicity found in alterations to the barriers and defense mechanisms of the respiratory tract, facilitating the entry of pathogens and increasing the likelihood of respiratory diseases [18].

Different slurry treatment systems have been proposed with the aim of reducing the pollutant load so that the treated waste can be reused as fertilizer or safely discharged into the sewage system [19,20].

Conventional systems involve treating the effluent by means of concentrated physico-chemical and biological processes in which the hydraulic retention time (HRT) is relatively short, and a stable operation can be ensured within pre-established and carefully controlled parameters. These have been implemented with varying degrees of success, but numerous problems have been reported, associated especially but not exclusively with the modes of operation and the costs of the system [19,21–26].

Many pig farms have very tight profit margins and have few human resources due to direct competition with other more suitable production sectors, making on-farm effluent treatment necessary [20,23,26,27]. Natural treatment systems of wastewater (NTSW) employ effluent storage with a longer HRT which depends on the load applied and the climatic conditions, with the organic matter degraded though the activity of heterotrophic bacteria present in the natural environment. The treatment is carried out by passing the effluent through various types of ponds, artificial wetlands and anaerobic digesters, each of which facilitates a series of natural processes. Such systems have been successfully applied in rural community settings and small settlements with a population equivalent below 1000 [1,2,28].

However, when it comes to sizing such systems, there are no tools available for agricultural and livestock farms in isolated territories, with sizing limited to adaptations based on local farmer experience [29,30].

The island of Gran Canaria (Canary Islands, Spain) has a total of 136 pig farms, the majority of which are small and family run. However, 10% of these farms account for more than 90% of the total and are industrial farms, in some cases close to environmental protection zones. For many years, livestock waste has been used as fertilizer in fields or farmland. However, in recent years, the gradual disappearance of small farms, along with the increase in intensive livestock farming, with its high number of animals per farm, and the general abandonment of traditional systems have led to greater fluidity and dilution of the effluent generated and hence an increase in volume, but often without sufficient arable land for its correct disposal [30]. Figure 1 shows the location of the pig farms considered in the present study.

According to the applicable Spanish legislation, which establishes basic rules for the management of intensive pig farms, farms can be classified according to their productive capacity as self-consumption, small or industrial farms, a self-consumption farm is defined as a farm used for breeding animals exclusively for family consumption, with a maximum production per year of 3 fattening pigs and with no breeder. For its part, a small farm is defined as having a maximum number of 5 breeders and no more than 25 fattening animals.

This legislation also establishes standards for the management of livestock waste on the farm and the production of manure (theoretical maximum) by livestock unit (LSU). This unit is established for purposes of comparison between livestock species, classifying farms according to this value. By way of example, the corresponding LSU is 0.30 for boars with a waste production of 6.12 m^3/animal/year, 0.96 for closed cycle sows with a waste production of 17.75 m^3/animal/year, and 0.02 for piglets from 6 to 20 kg with a waste production of 0.41 m^3/animal/year.

Figure 1. Location of the pig farms in Gran Canaria considered in the present study.

The objective and the novelty of this work is the proposal of a series of strategies and tools for the design and characterization of NTSW in livestock farms. As an application, an inventory, characterization, sizing, and design is carried out in 9 pig farms with a high environmental impact located on the island of Gran Canaria.

A basic effluent characterization that would allow the sizing of a pig effluent treatment system requires measurement of the flow rate (Q), the chemical oxygen demand (COD) and electrical conductivity (EC).

2. Materials and Methods

2.1. Locations of the Study

The 9 selected farms on the island of Gran Canaria is shown in Table 1 have from 15 to 217 sows, with a total of 4442 animals, representing 94% of the total census on the island [31]. The farms have between 1180 and 82,065 m^2 of available land [32].

Table 1. Selected livestock farm characteristics.

Farm	X	Y	Z	Available Area (m^2)	No. Sows	Total nº Animals
1	458.08	3091.56	249.26	18,935	217	1034
2	455.82	3084.34	119.28	58,642	134	897
3	446.11	3102.56	705.20	4516	87	800
4	456.59	3086.37	248.09	1180	81	333
5	446.85	3110.52	330.13	6885	50	134
6	440.65	3096.39	1216.72	10,089	43	344
7	457.82	3085.47	97.72	82,065	35	589
8	434.67	3081.32	202.11	5931	30	253
9	445.53	3097.59	1026.85	35,541	15	58

As established in RD360, these farms, given the number of animals and their definition as industrial farms, are obliged to have a waste management system on site. The following table shows the location (X,Y,Z), the available land, the number of sows, and the total number of animals.

2.2. Model

In this article, the methodology was adapted from that shown and applied in [19], in which a study of the water-energy-waste nexus was developed. The model for the evaluation of livestock farms in Gran Canaria considering parameters of water production, waste production, livestock farm, characterization of the waste, and occupied surface area of the farm. The model considering % target removed. As a result of the model, NTSW design and % removed evaluation The model is shown in Figure 2.

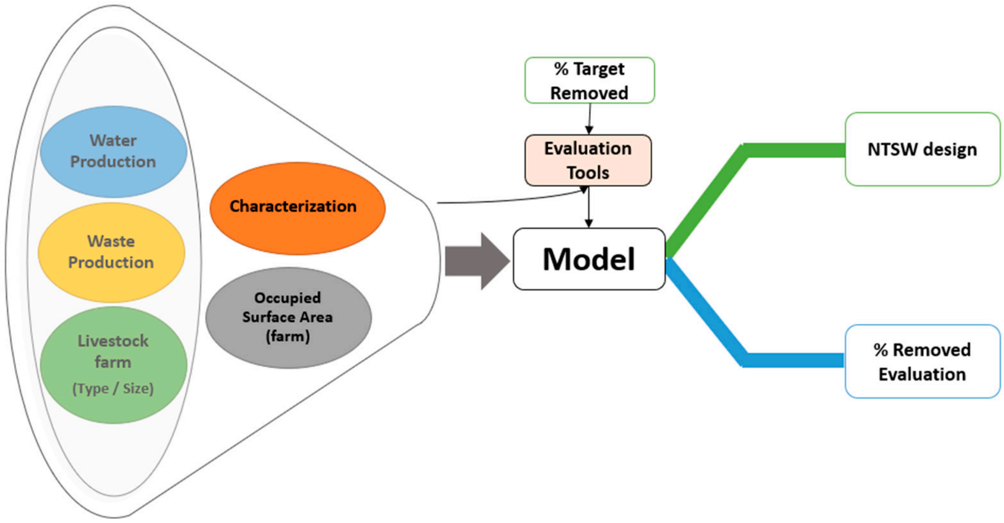

Figure 2. Model for the evaluation of livestock farms.

2.3. Waste Generation and Characterization

Numerous authors have indicated the need to have tools to characterize livestock waste and to monitor parameters that are easy to apply and measure on the farm itself [1,33–37].

For this study, it is necessary to know the Q, COD and EC values of the waste generated from each livestock farm as well as the number of sows. Therefore, simple linear correlations based on already published experimental results were used [2]. The starting parameter to characterize the waste is the number of sows (No.Sow) as this parameter is easy to obtain. The EC value is calculated on the basis of organic matter (OM) content. For this reason, it is necessary to characterize OM, with the correlation being between OM and COD the following Table 2 summarizes the correlations used.

Table 2. Wastewater characterization correlations.

	Correlation	R^2	Reference
Q [m^3/day]	$Q = 4425 + 3029 \times 10^{-7} \cdot (\text{No.Sow})^3$	0.976	[2]
COD [mg/L]	$COD = 7,995,901 + 360,593 \cdot (Q)^2 - 10,134 \cdot (Q)^3$	0.575	[2]
OM [mg/L]	$OM = 162,505 + 0.273 \cdot (COD)$	0.945	[2]
EC [dS/m]	$EC = 0.009 \cdot (OM) - 8.4 \times 10^{-7} \cdot (OM)^2$	0.938	[2]

With respect to the calculation of Q for farms where the number of sows is less than 81, this was carried out in accordance with RD306, which includes manure production (theoretical maximum) by type of livestock, due to the fact that the characterized Q was oversized.

2.4. Decision Strategy Tools for the Design of NTSW

In order to make decisions for the sizing of the NTSW, a flow diagram was designed (Figure 3) based on the research experience of a previous study [2]. The system is potentially composed of three elements: solid-liquid separator, biodigester, and pond + constructed wetlands. The flow diagram has 4 step (circled in Figure 3).

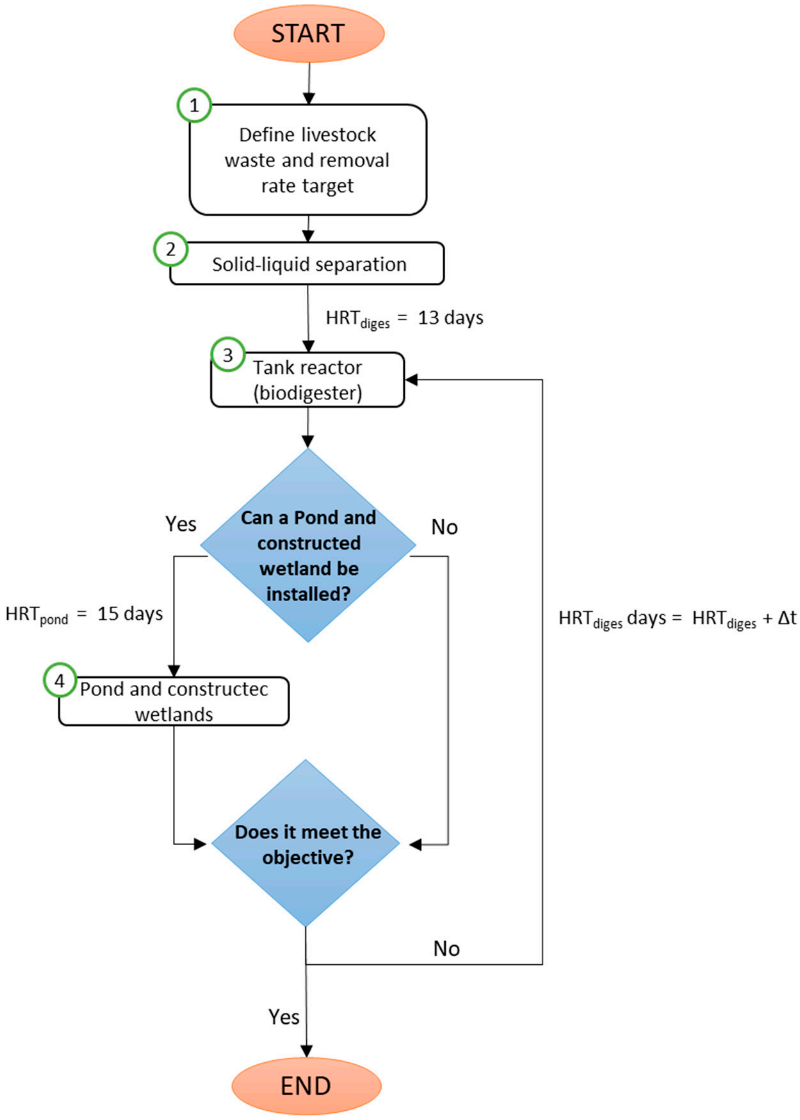

Figure 3. Flow diagram tool for NTSW design.

The first step (circled 1 in Figure 3) is to define the livestock waste and removal/reduction rate targets (Table 3). The second step (circled 2 in Figure 3) is to pre-sizing of solid-liquid separation, the third step (circled 3 in Figure 3) is to pre-sizing of to tank reactor (biodigester) and the fourth step (circled 4 in Figure 3) is to pre-sizing of the pond + constructed wetlands. The following is a detailed description of the steps to follow.

Table 3. COD % removal and EC% reduction of solid-liquid separator, biodigester and pond + constructed wetlands.

	Solid-Liquid Separator (%)	Biodigester (%/Day)	Pond + Constructed Wetlands (%/Day)
COD % removal	45	2.3	1.34
EC % reduction	7.5	0.2	1.51

Input data and pre-sizing:

The first step (circled 1 in Figure 3) is to define or characterization of the waste generated from each livestock farm, Section 2.3 Table 2, and the removal/reduction rate of targets.

The next step (circled 2 in Figure 3) consists of applying to the wastewater a solid–liquid separation pre-treatment, with the objective of reducing the COD and EC values in accordance with the values shown in Table 3. Subsequently, the biodigester is pre-sized, complying again with the reduction parameters shown in Table 3. An HRT of 13 days is assigned as an initial criterion.

Decision making:

If the removal/reduction rate targets are not met, we return to step (3) and resize of the digester, assigning a new HRT. If the objective is now met, we continue to step (4), which involves sizing of the pond + constructed wetlands. In this case, an HRT of 15 days is assigned as an initial criterion for the reduction of COD and EC parameters as indicated in Table 2. Note that the possibility of installing a pond + constructed wetland is based on location criteria, including, for example, nearby population, humid climatic conditions, etc.

Equipment sizing:

On the basis of the results obtained (Q, HRT, EC, and COD), calculation was made of the volume and surface area required for the biodigester and pond + constructed wetlands.

3. Results and Discussions

3.1. Types of Farms and Waste Characterization

This study focused on 9 farms which, due to their characteristics, type and number of sows, require a treatment system. The waste of the studied farms was characterized, obtaining COD values between 24,078 and 8049 mg/L and EC values between 23 and 16 dS/m (Table 4).

Table 4. Characterization of farms and livestock waste.

Farm	Q (m^3/Day)	COD (mg/L)	OM (mg/L)	EC (dS/m)
1	7.52	24,078.48	6699.93	22.59
2	5.15	16,186.60	4545.45	23.55
3	4.62	14,705.19	4141.02	22.86
4	1.76	9056.79	2599.01	17.72
5	1.00	8346.36	2405.06	16.79
6	1.67	8953.96	2570.94	17.59
7	2.60	10,262.17	2928.08	19.15
8	0.81	8228.20	2372.80	16.63
9	0.39	8049.96	2324.14	16.38

As mentioned above, in order to propose a natural purification treatment system, it is necessary to know the parameters of Q, COD and EC generated in each farm.

The slurry flow rate was characterized on the basis of either the correlations shown in Table 1 and/or in accordance with RD306. The choice or one method or the other was based on the number of sows. This was required because, in the case of industrial farms with fewer than 81 sows, an error was found in the calculations of 62–92% and, consequently, the capacity of the NTSW of the farms was being overestimated.

The COD values obtained ranged between 8049.96 and 24,078 mg/L. The mean value is within the range of the observed values of 5000 and 25,000 mg/L [36], 13,200 and 28,000 mg/L [1], 9400 and 14,200 mg/L [34].

The EC values ranged between 16.4 and 23.5 dS/m. Previous studies have reported values ranging from 13.2 to 33.2 dS/m [33] and from 9.9 to 25 dS/m [34]. Hence, it can be concluded that these results are valid.

3.2. Natural Wastewater Treatment System

As input data we have on the one hand the Q, COD, and EC parameters of the waste generated from the livestock farms (Table 4), and on the other hand the treatment objectives set out in RD306, establishes sets a maximum discharge objective of 1600 mg/L for COD and 2500 µs/cm for EC. Comparing these parameters with the values obtained from each study farm, Table 4. It is observed that they do not meet the treatment objective and, therefore, these wastes should be treated.

For Farm 1, the biodigester was pre-sized to an HRT of 13 days and it was not possible to install a pond + constructed wetland. For this reason, the HRT was increased to 39 days, Tables 5 and 6, increasing COD removal to 89% and EC reduction to 7.8%. The NTSW therefore comprised a solid-liquid separation process and a biodigester with a required volume of 96.8 m^3, with 10 chambers, a chamber volume of 22 m^3 and a surface area of 83.61 m^2.

Table 5. Proposed NTSW design.

Effluent				Solid-Liquid Separation				Biodigester							
Farm	Q (m^3/Day)	COD (mg/L)	EC (dS/m)	% Removal COD (%)	% Reduction EC (%)	COD (mg/L)	EC (dS/m)	% Removal COD (%/Day)	% Reduction EC (%/Day)	HRT_{dig} (Day)	$V_{chamber}$ (m^3)	V (m^3)	Chambers (Units)	COD (mg/L)	EC (dS/m)
1	7.520	24,078.48	22.59	45	7.45	13,243.16	20.91	2.3	0.2	39	22	293.2	13	1364.05	19.28
2	5.154	16,186.60	23.55	45	7.45	8902.63	21.80	2.3	0.2	36	22	185.5	8	1531.25	20.23
3	4.624	14,705.19	22.86	45	7.45	8087.85	21.16	2.3	0.2	33	22	152.5	7	1949.17	19.76
4	1.759	9056.79	17.72	45	7.45	4981.23	16.40	2.3	0.2	30	22	52.7	2	1544.18	15.42
5	1.000	8346.36	16.79	45	7.45	4590.50	15.54	2.3	0.2	26	22	26.0	1	1845.38	14.73
6	1.670	8953.96	17.59	45	7.45	4924.68	16.28	2.3	0.2	26	22	43.4	2	1979.72	15.43
7	2.604	10,262.17	19.15	45	7.45	5644.19	17.72	2.3	0.2	29	22	75.5	3	1879.52	16.69
8	0.812	8228.20	16.63	45	7.45	4525.51	15.39	2.3	0.2	28	10	22.7	2	1611.08	14.53
9	0.389	8049.96	16.38	45	7.45	4427.48	15.16	2.3	0.2	23	5	8.9	2	2085.34	14.46

Table 6. Proposed NTSW design.

	Pond + Constructed Wetlands							NTSW		
Farm	HRT (Day)	% Removal COD (%/Day)	COD (mg/L)	% Reduction EC (%/Day)	EC (dS/m)	V (m^3)	Surface (m^2)	V (m^3)	Surface (m^2)	HRT (Day)
1	-	-	-	-	-	-	-	293.2	97.7	39
2	-	-	-	-	-	-	-	185.5	61.8	36
3	15	1.34	1557.39	1.51	15.29	69.37	46.24	221.9	97.1	48
4	-	-	-	-	-	-	-	52.7	17.6	30
5	15	1.34	1474.46	1.51	11.40	15	10	41.0	18.7	41
6	15	1.34	1581.80	1.51	11.94	25.04	16.7	68.4	31.2	41
7	-	-	-	-	-	-	-	75.5	25.2	29
8	-	-	-	-	-	-	-	22.7	7.6	28
9	15	1.34	1566.19	1.51	11.19	5.84	3.89	14.7	6.8	23

In the case of Farm 2, the same criteria were followed and the biodigester HRT was increased to 36 days, Tables 5 and 6, with a COD removal of 82.8% and EC reduction of 7.2%. The reason for not installing the pond and constructed wetland is because the area where Farms 1 and 2 are located has low rainfall and therefore does not favor the degradation of organic matter in the pond.

As for Farm 3, the biodigester was again pre-sized to an HRT of 13 days and the pond + constructed wetlands were also sized since in this case installation was possible because the farm is located in an area with high rainfall and no nearby population. However, on the basis of these initial criteria, the RD306 treatment objectives were not met, and therefore the biodigester HRT was increased to 33 days.

For Farms 4, 5, 6, 7, 8 and 9 an NTSW was also designed, consisting of a solid-liquid separator and biodigester. In these cases, the biodigester will vary in terms of HRT, COD % removal, EC % reduction, volume, etc., depending on effluent conditions. Due to their location, Farms 5, 6 and 9 could also be equipped with a pond + constructed wetland, which would be recommended even if the farms met the RD306 treatment objectives, since this will further improve the conditions of the final discharge. Tables 5 and 6 shows the results obtained in this study in the different farms.

As can be seen, certain designs have been used for Farms 1, 2, 4, 7 and 8. They consist of solid-liquid separation and biodigesters, Tables 5 and 6. As a result, the proposed purification objective is achieved. All of these farms are located in a low rainfall area of the island.

On the other hand, alternative designs have been used for Farms 3, 5, 6, and 9. They consist of solid-liquid separation, biodigesters, and the creation of a pond + constructed wetland, Tables 5 and 6. As a result, the proposed purification objective is achieved. These farms are located in a high rainfall area of the island.

On farms located in areas with lower rainfall, the choice was made to amplify the system by means of digesters only, in order to minimize evaporation losses and thus avoid less dilution. This is why Farms 5 and 6 have larger digesters than Farms 7 and 8, where a pond and constructed wetland can be installed to meet the purification objective.

4. Conclusions

The high organic load of the effluents generated in these farms has a significant environmental impact, which is amplified in island or isolated territories. The application of these treatment systems has demonstrated their suitability in these environments, but their design lacks adequate characterization and sizing tools for their proper operation. This work proposes a series of strategies and tools for the design and characterization of NTSW applied in livestock farms, considering the Q, EC and COD parameters of the waste generated, location of the farm, HRT, and elimination/reduction rate objectives. This tool is developed and implemented in nine livestock farms on the island of Gran Canaria (Canary Islands, Spain), which represents 94% of the total census of the island.

After the study carried out and the application of this tool, the following statements are reached:

The characterization of the COD, Q and EC parameters of the nine study farms indicates the importance of adequate treatment on the farm itself to minimize the environmental impact that this activity has on the environment.

The NTSWs are adequate systems and constitute a viable alternative treatment for pig waste in insular or isolated territories. This tool has shown that there is no single model for these systems for all pig farms, since the size, flow, organic load and location of each one of them will dictate the conditions for their design.

The proposed decision strategy tools for NTSW design have proven to be a useful tool for the sizing of the farms considered in the study.

As a final conclusion, the characterization of the waste generated in the farms together with the proposed decision strategy tool for the design of NTSWs applied in livestock farms located in isolated, island or similar-sized environments contributes to facilitate the pre-dimensioning of these systems and have proven to be a useful tool for the sizing of the farms considered in the study.

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