Natural treatment system for wastewater (NTSW) in a livestock farm, with five years of pilot plant management and monitoring

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ABSTRACT

This paper reports results of a 5-year trial study of a natural treatment system for wastewater (NTSW) on a livestock pig farm on Gran Canaria (Canary Islands, Spain). The pilot plant consist of a rotary screen, a first-generation multi-chamber digester, and two horizontal subsurface flow treatment wetlands (HSFCW) with a pond installed between them. Results show that the removal efficiency of total chemical oxygen demand (CODt), total suspended solids (TSS), volatile solids (VS) and total dissolved solids (TDS) of the treatment were 91.77%, 95.99%, 82.62%, and 55.78%, respectively. Other removal values include 93.79% for total nitrogen (TN) and 93.05% for phosphorus (P_2O_5). The results demonstrate the suitability of NTSW solutions applied to livestock waste in pig farms and their potential application to other farms of similar size.

1. Introduction

The management of waste from livestock farms is necessary due to its environmental impact. While this is true for all types of livestock, it is especially important in the case of pig farming waste due its high concentrations of nitrogen, phosphorus and organic matter (Hou et al., 2017; Oenema et al., 2007; Petersen et al., 2007 and Ramankutty et al., 2018). These residues have caused the contamination of soils and aquifers in many parts of the planet (Steinfeld et al., 2006). Some authors have identified these areas and have made nutrient concentration maps for a wide variety of crops (Lijó et al., 2018; Mallin et al., 2015).

The island of Gran Canaria (Canary Islands, Spain) has a surface area of 1560 km^2 and around 140 pig farms where about 18,000 animals are reared. Of these farms, 90% are small, family-run establishments with just a few animals mainly for self-consumption. Of course, all farms need an adequate waste management system and, on Gran Canaria, most of these farms are located in isolated or hard-to-reach areas which in many instances are close to environmental or landscape protection zones. However, 10% of the farms concentrate 90% of the pig population, with on average 1500 animals per farm which are reared for commercial exploitation. In many areas of the island, there are contamination problems due to inadequate management and the uncontrolled dumping of livestock waste. The impact of nitrate discharge on aquifers and soils

is regulated by Directive 91/676/EEC on the protection of water against pollution by nitrates from agricultural sources (Martinez et al., 2009; Van Grinsven et al., 2012).

Several strategies for waste management have been suggested in the literature which are based on the use of conventional treatments, with variable results according to the type of farm (Burton, 2007; Hou et al., 2018; Loyon et al., 2016). Natural treatment systems for wastewater (NTSW) have been shown to be suitable for application in urban and rural environments. They have a low energy cost, a high capacity for the elimination of contaminants, and allow an adequate reuse of the effluent (Ayaz and Akca, 2000; Belmont et al., 2004; C. M. Chen et al., 2006; Gholipour et al., 2020; Gearheart, 1992; Kim et al., 2006; Pangala et al., 2010 and X. Chen and Fukushi, 2016, 2014). On Gran Canaria island, solutions based on NTSWs have been tested in isolated rural areas (Vera et al, 2010, 2013), with removal efficiency results obtained of over 75% for chemical oxygen demand (COD) and 90% for total suspended solids (TSS).

The management strategy followed in this manuscript consists of the implementation of a NTSW at individual farm scale as an alternative to the conventional treatment systems used in centralized, large-scale facilities (Lopez-Ridaura et al., 2009) and (Flotats et al., 2009), with an emphasis on low cost strategies (management, maintenance, etc.). The local government of the island of Gran Canaria has promoted the

development of this type of facility, and such systems have been designed and tested as an innovation on three pig farms on the island. The systems were evaluated in terms of COD removal efficiency, with values obtained of between 80% and 90%. The pilot plant in this study was the best of those that were tested in terms of total COD (CODt) removal efficiency during the first year of study (Mendieta-Pino et al., 2019).

Residues from pig farms are a valuable resource as fertilizer for soil (Penha et al., 2015 and Villar et al., 2004),. The slurry that is obtained is the combined result of the type of feed, management, slat configuration and water used. As the water content of slurry is high (usually exceeding 90%), it has a liquid consistency (Antezana et al., 2016; Møller et al., 2004; Sánchez and González, 2005 and Theofanous et al., 2014). Given the different variables involved, slurry has a highly variable composition and the effects of its application on land depend on its characteristics, as well as the impact of intensive farming and its management (Astals et al., 2010; Riaño and García-González, 2014 and Widyasari-Mehta et al., 2016). Pig slurry contains a low dry matter content, which is slightly base and saline in character, varying in proportion depending on the livestock management techniques employed (Moral et al., 2005a,b). Part of this organic matter is composed of simple and easily biodegradable compounds, and it contains appreciable amounts of carbohydrates, urea, amino acids, peptides and polypeptides, fatty acids, phenols, and sulfur compounds. It also tends to contain significant amounts of phosphorus, potassium, calcium, magnesium, iron and manganese, as well as, in many instances, copper or zinc used to fatten the animal (Dionisi et al., 2020; Jensen et al., 2016; Jondreville et al., 2003; Nicholson et al., 1999 and Peng et al., 2019), bacterial flora or antibiotics (Argüeso-Mata et al., 2021; Chan et al., 2020).

The objective and scope of this manuscript is to describe the performance of a NTSW pilot plant over 5 years of continuous operation at a pig farm and to evaluate its removal efficiency on the basis of parameters such as CODt, TSS, volatile suspended solids (VSS), total dissolved solids (TDS) and electrical conductivity (EC), among others, while verifying compliance with local discharge regulations. The results of this study can be used to promote NTSW as a waste management alternative in farms of similar sizes. In future works should be studied other variables such as energy consumption, affected-occupied area, bacterial flora, presence of antibiotics, etc.

2. Materials and methods

2.1. Description of the pilot plant

A medium-sized farm of 1500 pigs was selected for the study, as this is a common size in Gran Canaria for its economic profitability. An initial design flow rate of 8.7 m^3 d^{-1} and COD, based on potassium dichromate oxidation, of 35 g L^{-1} from the livestock farm were considered. The treatment facility consists of an anaerobic digester, two constructed wetlands and a pond.

- Anaerobic digester: rectangular-shaped anaerobic digester of 103.2 m^3, composed of 4 identical chambers (3.8 m length x 1.8 m width x 4 m depth) of 25.80 m^3, and hydraulic residence time (HRT) of 11.86 days. The digester has a rotary screen between the first and second chambers.
- Intermediate tank, placed at the outlet of the digester, which acts as a buffer tank for wetland #1 (4 m $\times$ 1.5 m x 1.5 m).
- Horizontal subsurface flow constructed wetland #1 (HSFCW#1), rectangular-shaped (9 m $\times$ 4.25 m x 1.5 m), with an effective capacity of 22.95 m^3 and HRT of 2.64 days.
- Pond, placed after HSFCW#1 and before HSFCW#2, (10 m $\times$ 6 m x 1.5 m), with an effective capacity of 90 m^3 and HRT of 10 days.
- Horizontal subsurface flow constructed wetland #2 (HSFCW#2), with the same dimensions and capacity as HSFCW#1.

- Final product tank, serving as a buffer for recirculation to the head of the line (4 m $\times$ 1.5 m x 1.5 m).

The digester, tanks, wetlands and pond all had waterproofing systems or geotextile membranes to avoid any liquid material discharge to the ground. Both the HSFCWs and the side slopes of the pond (for strengthening) were filled with gravel of varying size. Figs. 1 and 2 show the ground plan and cross-section of the NTSW pilot plant and photographs of the facility, respectively. With respect to the HSFCW#1 and HSFCW#2 wetlands, native plants were allowed to colonise and grow.

2.2. Operation and sampling points

The NTSW pilot plant was initiated gradually in autumn of 2008 after filling the digester with clean water. No type of external crop was added. An initial study of its operation was conducted in 2009 (Mendieta-Pino et al., 2019), and the plant was in continuous operation until the end of 2018 when it was stopped and subjected to a full clean.

The NTSW initially works in batches to start, and then operates continuously from the digester (Fig. 3). The digester is fed in batches with influent from farm discharges in the first chamber (sampling point #1). After 2–3 days in chamber one, the waste is taken to a rotary screen which consists of a stainless steel sieve located in a horizontal position to remove coarse particles larger than 50 mm. The liquid fraction is separated and discharged into the second chamber (sample point #2). The solid fraction (solid sample point) is stored for reuse. The liquid content in this second chamber moves to the third chamber (overflow). The content of the fourth chamber (overflow) is discharged (sample point #3) into the intermediate tank (capacity of 9 m^3), which acts as a buffer tank, and by gravity to HSFCW#1 (sampling point #4). The liquid flows through the gravel and roots to the 90 m^3 pond (sampling point #5) and then passes to the second wetland (HSFCW#2) with characteristics similar to HSFCW#1. The only energy consumed is by the rotary screen and pump. The installation concludes with a final product tank (sampling point #6). The treated liquid fraction is pumped into irrigation tanks for reuse or recirculation. The total HRT is 28 days.

Data was collected for 28 variables (56 samples in total taken over the course of the 5-year study), distributed between dry and wet periods. Each chamber of the digester (four) has four manhole covers for cleaning and taking samples (at 1 and 3 m depth). The wetlands have venting and sampling tubes located at their ends, with samples taken at a depth of 0.50 m. Sampling in the pond is carried out in three zones (initial, central and end) and at a depth of 0.50 m. Sampling was carried out with horizontal and vertical Van Dorn bottles. Each sample was placed in a container and homogenized. The pH, temperature and conductivity were taken by parametric probe (Hanna Instruments HI 9811-5 N) and the container was then sealed, kept at a low temperature and transferred to the laboratory. The determination of CODcr (CODt in this manuscript based on potassium dichromate oxidation and other forms, soluble and particulate (CODs and CODp)) and Na, K, Cu, Fe, Mg and Zn, among others, were performed by inductively coupled plasma optical emission spectrometry (ICP-OES) (PerkinElmer Optima 8000). Dry matter was measured using a LECO CNS-2000 analyser. All analyses were performed following standard methods (APHA, AWWA, WEF, 2012). The statistical analysis was performed using the IBM SPSS program.

3. Results and discussion

3.1. Characterization

Table 1 shows the distribution of the characteristics of the slurry samples collected from influent and effluent of the pilot plant, the % removal, the corresponding local legal discharge limits and EU fertilising product values.

In relation to total CODt, similar values have been reported of 21.63 g L^{-1} in Modena (Italy), 17.53 g L^{-1} in Murcia (Spain), 21.28 g L^{-1} in
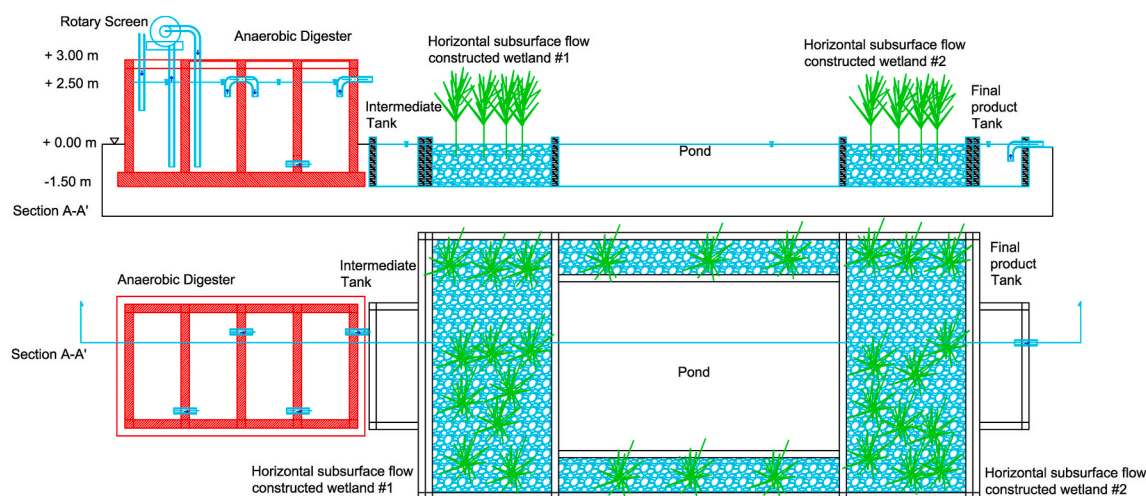
Fig. 1. NTWS Pilot plant - ground plan and section.

Fig. 2. From left to right: digester and rotary screen and solid, pond, constructed wetlands, final tank and (below) panoramic view.

Goshen (USA) (Sánchez and González, 2005) and 21.20 g L^{-1} (Villamar, 2015). In relation to pH, similar values have been reported of 7.4 (Moral et al., 2005a,b), 7.6 (Gómez et al., 2009), and 7.2 in liquid pig feed and 7.1 in conventional feed (Cano et al., 2005). In relation to the EC range, similar values of 17.9 dS m^{-1} (Moral et al., 2005), 23.2 dS m^{-1} (Moral et al., 2008) and 22 dS m^{-1} have been reported in liquid pig feed (Suresh et al., 2009). Finally, similar values have also been reported of TSS: 17.30 g L^{-1} (Otero, 2010) and 16.86 g L^{-1} (Suresh and Choi, 2011). It should be noted that there is a discrepancy in the influent TOC values, which were not related with the CODt findings due to an error in the analysis. Other influent values, including those for sodium, potassium, calcium and magnesium, are similar to values found in other studies (Cano et al., 2005; Sánchez and González, 2005; Wong and Selvam, 2009), indicating the similarity of this wastewater (and hence the operation of the farm) to that generated in other regions.

Today, efforts are being made to move the pig-farming sector towards closed-cycle systems. In such cases, the applicability of NTSW products (Table 1) can be compared with alternatives (Montemayor et al., 2019). Macronutrients and micronutrients, pH, dry matter and organic matter influence the suitability of the use of the treated slurry as soil fertilizer (Sánchez and González, 2005). Nitrogen is an essential macronutrient for the development and growth of plants. It is highly

abundant in the soil and is dependent on the organic matter content. Phosphorus is also vital for the growth and health of plants. It works as one of the main actors of photosynthesis, as a nutrient transporter and energy transmitter. Potassium is another essential macronutrient for plants, controlling stomata opening and closure. The other elements also have a series of functions that ensure the correct development of the plant, intervening in cellular processes and the use of energy. Both the liquid and solid fractions produced by this NTSW show interesting values for reuse. In this regard, the liquid and solid values of the effluent (Table 1) were found to be suitable for discharge (according to the Canary Government discharge limit values) and were similar to other reported values (Cavanagh et al., 2011). Values required for EU fertilising products ((EU) 1069/2009) are, as solid part (at least 2% by mass of total nitrogen (TN), 2% by mass of total phosphorus pentoxide (P$_2$O$_5$), and 2% by mass of total potassium oxide (K$_2$O). The sum of those solid nutrient contents shall be at least 4% (6.58% in this case) and as liquid part (at least 1% by mass of TN, 1% by mass of total phosphorus pentoxide (P$_2$O$_5$), and 1% by mass of total potassium oxide (K$_2$O), the sum contents shall be at least 3% (3.29% in this case). By measuring these values, it is possible to ensure a more efficient reuse in agriculture and to reduce potential risks to the environment (Scotford et al., 1998; Díez López et al., 2004; Thygesen et al., 2012).
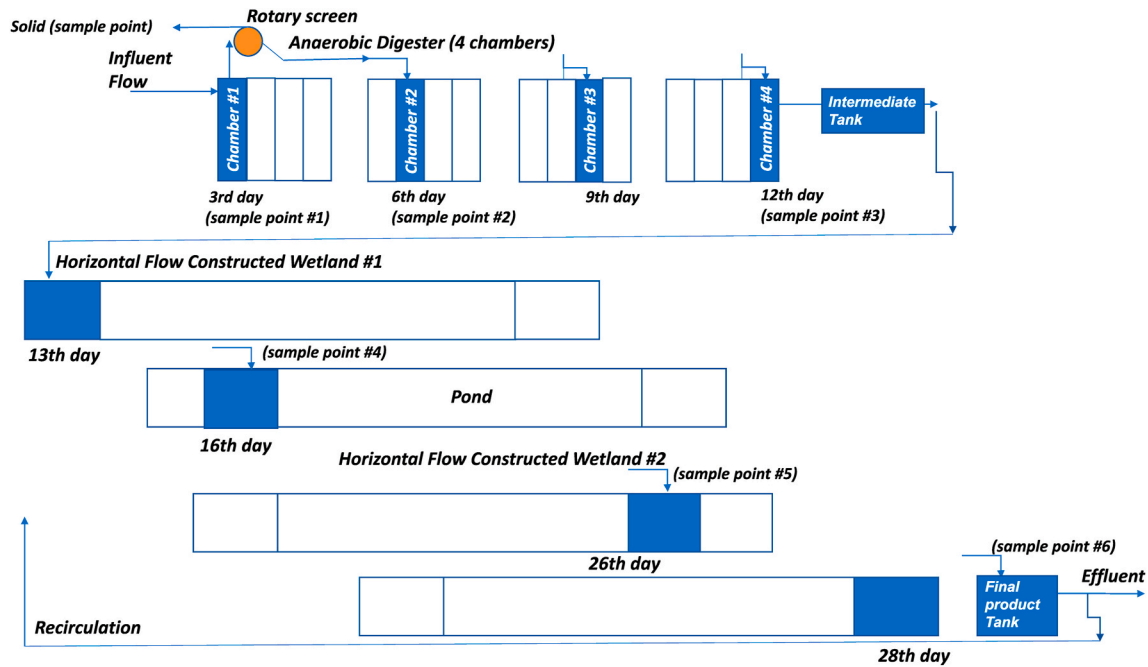
Fig. 3. Plant operation.

3.2. Correlations

Studies have been published characterizing the physicochemical composition of slurries from livestock farms (Suresh and Choi, 2011 and Suresh et al., 2009), in which high linear correlations were found. As reported by (Moral et al., 2005a,b and Van Kessel et al., 1999), chemical analyses using standard laboratory methods are accurate, but they also take time and entail a certain cost to the farmer (Antezana et al., 2016; Moral et al., 2008; Ngwabie et al., 2018). In this study, strong correlations were found between effluent flow rate (Q_{eff}) in [m^3 d^{-1}] and number of sows (No.Sow), (p < 0.01 and r = 0.976; Q_{eff} = 4.425 + 3.029·10^{-7}·(No.Sow)^3), between number of sows (No.Sow) and CODt [g L^{-1}], (p < 0.01 and r = 0.829; CODt = 3.247 + 0.155·(No.Sow)) and SV [g L^{-1}] and CODt [g L^{-1}], (p < 0.01 and r = 0.894; SV = 0.357 + 0.070·CODt. With conductivity (CE), significant correlations were found between FS [g L^{-1}] and EC [dS m^{-1}], (p < 0.01 and r = 0.970; FS = −12.467 + 1.833·EC-0.32·(EC)^2, TS [g L^{-1}] and EC [dS m^{-1}] (p < 0.01 and r = 0.851; TS = 62.403–4.726·EC+0.155·(EC)^2 and TDS [g L^{-1}] and EC [dS m^{-1}] (p < 0.01 and r = 1; TDS = −0.250 + 0.655·EC, better than the r = 0.52 of Suresh and Choi (2011). Other statistically significant correlations were found in this work between CODt [g L^{-1}] and organic matter (OM) [g L^{-1}] (p < 0.01 and r = 0.910; CODt = −0.707 + 1.209·OM, between CODs [g L^{-1}] and CODt [g L^{-1}], (p < 0.01 and r = 0.963; CODs = −0.192 + 0.08·CODt) and between CODp [g L^{-1}] and CODt [g L^{-1}], (p < 0.01 and r = 0.981; CODp = 0.163 + 0.821·CODt.

3.3. Flow and fouling

When designing the pilot plant, it was important to know how the variable flow rate and load of the influent and system fouling might affect the envisaged HRT of each of the stages of the NTSW. Variations in the composition of pig farm influent can be due to a number of factors, including total number of animals, number of mothers and their condition (breeding, rearing, fattening, gestation, maternity), type of farm and management strategy, type of food, quality and quantity of water consumed, and climate. The actual flow was compared with base values provided by the Spanish Ministry of Agriculture and the work of (Gómez et al., 2009), and with estimation of purine production based on the annual consumption of dry matter by breeding sows and their offspring,

along with an estimation of the amount of farm food waste. In the study years, the flow varied between 5.2 and 8.7 m^3 d^{-1}. Given that experimental flow values were not known and given the impossibility of estimations through correlations (as seen in the previous section), it was decided that the most appropriate method for flow estimation was to use the parameter based on annual dry matter consumption (Eq. (1)).

$$SP = \frac{0.24 \cdot CDM}{sdm/100} + \frac{WDM}{sdm/100} \qquad (1)$$

SP = slurry production[kg]; CDM = consumed dry matter[kg]; WDM = waste dry matter[kg]

sdm = slurry dry matter (5 − 9%)

With respect to fouling, it was considered appropriate to consider an annual storage capacity reduction of 10% (Lopez-Ridaura et al., 2009). Likewise, use of a rotary screen was considered appropriate to avoid early silting of the digester (Hjorth et al., 2010). The results obtained show that the global HRT ranged between 28 and 36 days over the five years of steady state operation.

3.4. Removal efficiency and performance

As indicated in (Mendieta-Pino et al., 2019), the NTSW considered in this study is one of three installed on the island, and the one that gave the best results in the first year of operation. The performance of a pilot plant and its different components can be evaluated through the variation in a number of parameters, including COD, TSS, etc. Such variations can be influenced by different factors, including flow rate, atmospheric parameters, etc. For example, the CODt removal rate (%) can be defined by re_{CODt}, Eq. (2), which allows evaluation of the variation in removal between two sampling points (Mendieta-Pino et al., 2019):

$$re_{CODt(i-j)} = \frac{\overline{COD_i} - \overline{COD_j}}{\overline{COD_i}} \ (\%) \qquad (2)$$

As can be seen in Table 1, over the five years of the study period the NTSW plant showed a stable performance, with notable reductions in CODt, TSS and VS (91.77%, 95.99% and 82.62%, respectively) and important removal rates of TN and P$_2$O$_5$ (93.79% and 93.05%,

Table 1
Characterization and % removal NTSW.

Liquid part (n = 56) Parameters-Abbrev.	Influent Min (ymin)	Max (ymax)	Mean – SD ($\hat{y}$ ± SN-1)	Discharge limit value Canary Gov.	Effluent Min (ymin)	Max (ymax)	Mean – SD ($\hat{y}$ ± SN-1)	EU fertilising products (EC) 1069/09	re (% removal) (2010–2015) Min (remin)	Max (remax)	Mean – SD ($\bar{r}$e ± SN-1)
Effluent Flow Rate (m3 d-1)-Qeff	5.2	8.7	6.42 ± 1.25	–	–	–	–	–	–	–	–
Total Chemical Oxygen Demand (g L-1)-CODt	13.2	28.0	20.41 ± 5.73	1.6	0.8	2.4	1.52 ± 0.52	–	85.09	96.43	91.77 ± 4.02
Particulate Chemical Oxygen Demand (g L-1)-CODp	11.01	23.3	16.91 ± 4.71	–	0.1	1.1	0.59 ± 0.39	–	90.1	99.57	96.11 ± 3.08
Soluble Chemical Oxygen Demand (g L-1)-CODs	1.0	2.6	1.59 ± 0.52	–	0.1	0.3	0.17 ± 0.06	–	70.0	95.24	87.72 ± 7.76
Inert Chemical Oxygen Demand (g L-1)-CODi	1.0	2.6	1.80 ± 0.62	–	0.5	1.2	0.72 ± 0.21	–	14.29	76.00	56.00 ± 19.09
Total Organic Carbon (g L-1)-TOC	3.0	6.2	4.53 ± 1.29	–	0.4	1.6	0.99 ± 0.39	–	52.94	90.83	75.96 ± 12.68
Total Suspended Solids (g L-1)-TSS	15.0	21.0	17.17 ± 2.07	1.0	0.4	1.0	0.68 ± 0.21	–	93.42	97.63	95.99 ± 1.37
Volatile Suspended Solids (g L-1)-VSS	3.2	5.0	3.84 ± 0.57	–	0.1	0.7	0.30 ± 0.17	–	15.0	83.3	51.76 ± 26.64
Total Dissolved Solids (g L-1)-TDS	9.1	15.0	11.07 ± 1.87	–	1.85	9.45	5.65 ± 2.73	–	14.71	88.58	55.78 ± 26.55
Fixed Suspended Solids (g L-1)-FSS	10.2	16.5	13.33 ± 1.95	–	2.1	9.5	6.09 ± 2.83	–	81.25	94.0	89.84 ± 3.54
Fixed Solids (g L-1)-FS	6.9	12.6	9.29 ± 1.86	–	1.7	9.2	5.59 ± 2.69	–	1.22	76.74	39.04 ± 30.12
Volatile Solids (g L-1)-VS	1.2	2.4	1.78 ± 0.45	–	0.1	0.5	0.30 ± 0.12	–	64.29	93.75	82.62 ± 10.38
Total Solids (g L-1)-TS	24.7	36.0	28.24 ± 3.41	–	2.7	10.3	6.77 ± 2.91	–	61.72	90.72	75.65 ± 11.14
Concentration of Protons in a Solution - pH	7.0	7.7	7.39 ± 0.22	–	7.7	8.5	8.12 ± 0.24	–	–	–	–
Conductivity (dS m-1)-EC	14.2	23.2	17.27 ± 2.85	2.5	3.2	14.8	9.44 ± 4.43	–	9.27	77.46	44.70 ± 27.26
Boron (mg L-1)- B	1.1	4.0	2.71 ± 1.12	3.0	0.5	2.0	1.14 ± 0.57	–	33.33	83.33	55.95 ± 14.96
Copper (mg L-1)-Cu	2.0	4.0	3.30 ± 0.84	3.0	0.2	1.0	0.57 ± 0.37	–	50.0	95.0	82.00 ± 13.73
Density(kg m-3)-ρ	850	1100	951 ± 83.19	–	–	–	–	–	–	–	–
Iron (mg L-1)-Fe	13.0	25.0	19.22 ± 4.68	10.0	1.0	5.0	2.90 ± 1.52	–	0.00	98.0	58.17 ± 23.38
Manganese (mg L-1)-Mn	3.0	6.0	4.50 ± 0.85	10.0	0.1	1.0	0.59 ± 0.45	–	66.67	98.0	85.48 ± 12.32
Zinc (mg L-1)-Zn	8.0	23.0	15.30 ± 5.16	15.0	0.2	4.0	1.89 ± 1.49	–	68.0	96.16	86.26 ± 11.68
Total Nitrogen (g 100 mL-1)-TN	0.08	0.24	0.18 ± 0.05	–	0.01	0.01	0.01 ± 0 limit	>1%	87.5	87.5	93.79 ± 2.46
P_2O_5(g 100 mL-1 P O)-P	2.0	3.0	2.51 ± 0.29	–	0.01	0.03	0.01 ± 0.01	>1%	90.0	94.74	93.05 ± 1.47
K_2O_2 (g 100 mL-1 K O)–K	0.12	0.2	0.17 ± 0.02	–	0.07	0.11	0.09 ± 0.015	>1%	37.5	65.0	47.52 ± 9.41
CaO (g 100 mL-1 CaO)–Ca	0.05	0.09	0.06 ± 0.01	–	0.01	0.02	0.02 ± 0.02	–	60.0	87.5	73.67 ± 10.06 M
MgO (g 100 mL-1 MgO)–Mg	0.01	0.01	Limit	–	0.01	0.01	Limit	–	–	–	–
Sulfur (g 100 mL-1 S)–S	0.01	0.01	Limit	0.035	0.01	0.01	Limit	–	–	–	–
Sodium (g 100 mL-1 Na)–Na	0.05	0.08	0.06 ± 0.01	0.06	0.01	0.05	0.03 ± 0.01	–	33.33	83.33	56.18 ± 14.61
Solid part (n = 56)											
Parameters	Min (ymin)	Max (ymax)	Mean – SD ($\hat{y}$ ± SN-1)		Min (ymin)	Max (ymax)	Mean – SD ($\hat{y}$ ± SN-1)		Min (ymin)	Max (ymax)	Mean – SD ($\hat{y}$ ± SN-1)
Humidity(%)	25.4	31.5	29.03 ± 2.58	**CaO(%)**	4.39	7.7	6.45 ± 1.45	**B(mg kg-1)**	26.0	39.0	32.25 ± 5.38
Dry Part(%)	68.5	74.6		**MgO(%)**	0.52	0.78		**Cu(mg kg-1)**	79.0	99.0	

Table 1 (*continued*)

			71.23 ± 2.54				0.66 ± 0.13				90.50 ± 9.29
Total Nitrogen(%)	1.68	2.26	1.92 ± 0.25	**S(%)**	0.49	0.53	0.51 ± 0.02	**Fe(mg kg-1)**	1248	1591	1414.50 ± 165.80
P2O5(%)	2.54	6.41	4.12 ± 1.64	**K2O(%)**	0.46	0.66	0.54 ± 0.09	**Zn(mg kg-1)**	300.0	364.0	332.50 ± 27.15
Organic Material(%)	59	71.6	64.70 ± 6.09	**Na(%)**	0.13	0.28	0.20 ± 0.07	**Mn(mg kg-1)**	382.0	740.0	554.75 ± 148.17

respectively).

Fig. 4 shows the mean CODt and TSS effluent values over the course of the study with the legal limit discharge values. As can be observed, in the summer CODt values exceed the limit (mean = 1.5 g L^{-1}, legal limit = 1.6 g L^{-1}), but the TSS values do not (mean = 0.68 g L^{-1}, legal limit = 1.2 g L^{-1}). Note the constancy in CODt and TSS % removal. It was also found that EC, CODt and TDS (mean removal rate of 55.38%) were highly sensitive to the annual rainy period, as this is an open system with the presence of a pond and wetlands.

The individual analysis of the components of the system shows how each contributes to the overall removal capacity of the system (Fig. 5-A). Notably, the capacity of the HSFCW#1-Pond-HSFCW#2 combination to reduce EC (40.85%) and TDS (39.26%) considerably exceeds that of the digester (5.56% and 4.49%, respectively) (Fig. 5-A). Likewise, it was found that the digester has a higher overall CODt and TSS removal capacity (57.27% and 89.05%, respectively) than the pond (36.12% and 6.94%, respectively) (Fig. 5-A). Again, the VSS removal capacity is higher with the digester (56.66%) than the pond (32.85%) (Fig. 5-A). The above confirms the conclusion of (Mendieta-Pino et al., 2019) that a combination of equipment improves the adaptation and performance of the facility and its overall removal efficiency. To consider in greater depth the removal performance of each component of the pilot plant and compare it with that of other technologies, and given that components with better removal rates need less HRT, we can use Eq. (3) and Eq. (4):

$$\Phi_{Parameter_{component}} = \frac{re_{Parameter\ (component)}}{capacity_{component}} \quad \left[\% \ m^{-3}\right] \tag{3}$$

$$\theta_{Parameter_{component}} = \frac{re_{Parameter\ (component)}}{HRT_{component}} \quad \left[\% d^{-1}\right] \tag{4}$$

By defining these ratios ϕ and θ, we can compare the performance of different equipment of varying size and operation. With these specific parameters, it can be seen how the HSFCW#1-Pond-HSFCW#2 combination, with respect to EC and TDS, shows a similar removal capacity in terms of % m^{-3} and % d^{-1} (Fig. 5-B, 5-C).

With respect to CODt, a better performance of the wetlands (particularly HSFCW#2) is observed compared to that of the digester, confirming the utility of wetlands for CODt removal (Vera et al., 2013; Ayaz and Akca, 2000). ϕCODt removal will evidently be enhanced when HSFCWs are accompanied and complemented by a digester (0.55% m^{-3}), and even more so when combined with a pool with a specific ϕCODt removal capacity of 0.65% m^{-3} and 0.80% m^{-3} (HSFCW#1 and HSFCW#2) (Fig. 5-B).

Also shown in Fig. 5, is the performance of the equipment with respect to the degradation capacity of OM, measured by means of the particulate and soluble COD fractions (CODp and CODs), and TN (Fig. 5). In the digester, 54.12% and 69.05% of reCODp and reCODs are eliminated, respectively. However, in the analysis according to cubic meters and days (Fig. 5-C), a better performance of the HSFCW#1 (θCODp = 5.69% d^{-1}), and HSFCW#2 (θCODp = 6.39% d^{-1}) is observed
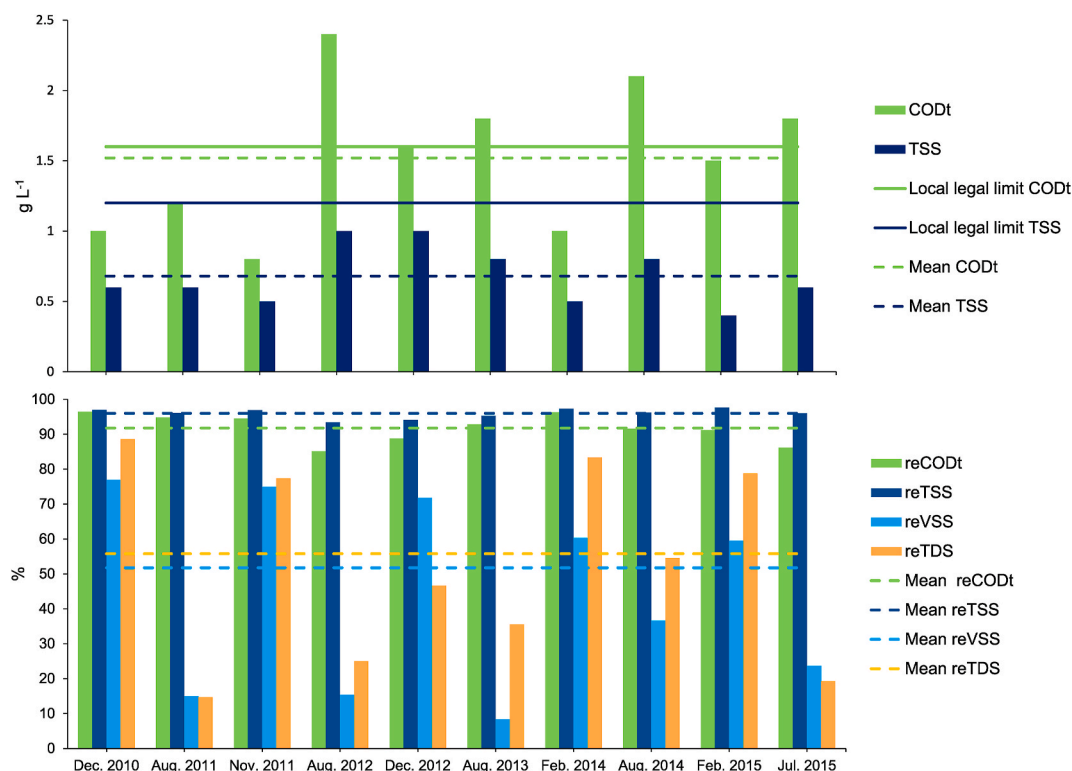

Fig. 4. Mean COD and TSS effluent values and legal discharge limits (up). % removal of total COD, TSS VSS and TDS (down).

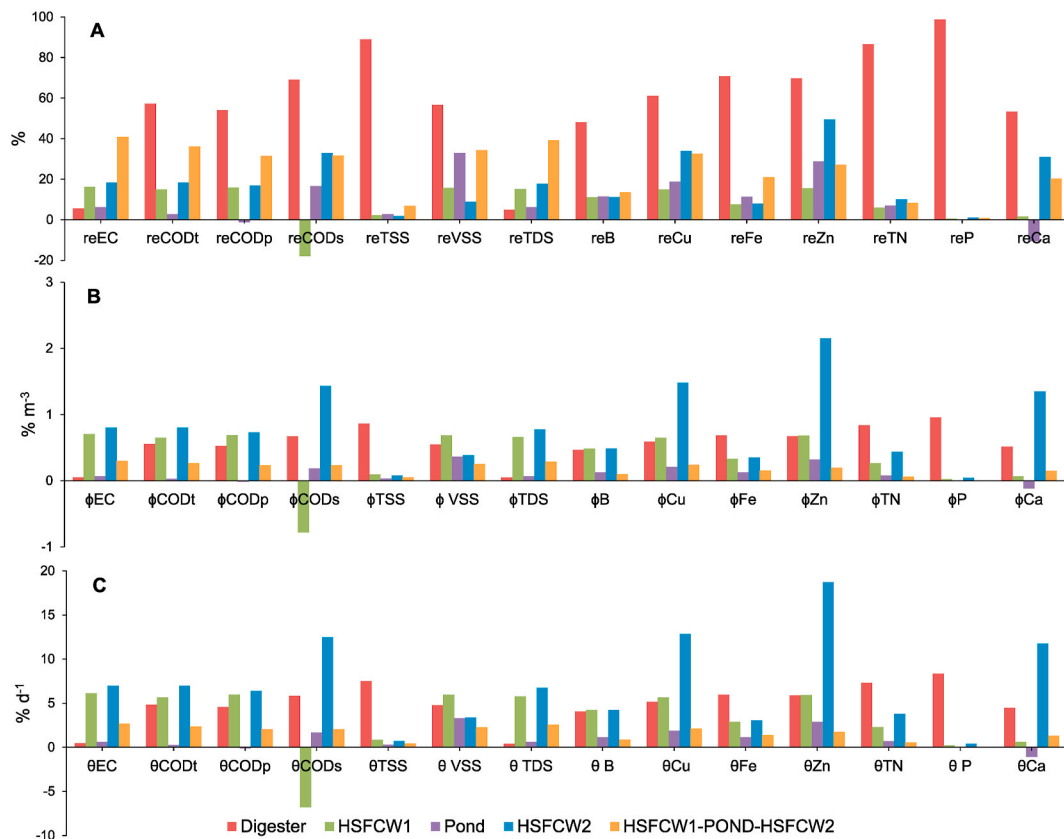**Fig. 5.** Removal and ϕ and θ specific removal by each NTSW component.

compared to the digester (r CODp = 4.56% d^{-1}). It was also found that the soluble fraction increases in HSFCW#1 (θCODs = − 6.79% d^{-1}) and is subsequently degraded in HSFCW#2 (θCODs = 12.47% d^{-1}). The better performance of HSFCW#2 compared to HSFCW#1 is due to the intermediate pond and its particulate COD removal (θCODp = − 0.12% d^{-1}) and overall HSFCW#1 (θCODt = 5.66% d^{-1}) and HSFCW#2 (θCODt = 6.98% d^{-1}). For its part, the nitrogen is mostly eliminated in the digester (θTN = 7.30% d^{-1}). The performance of the other elements can also be seen in Fig. 5. Of particular note is the removal by HSFCW#2 of copper, zinc, potassium and calcium, performing better than the other components in all those parameters, and the increased presence of calcium in the pond. For its part, phosphorus was mostly removed in the digester (θP = 8.33% d^{-1}). The presence of boron (θB) is the result of the use of cleaning water from wells with seawater infiltration (removed in digester, HSFCW#1 and HSFCW #2, 4.05% d^{-1}, 4.23% d^{-1} and 4.25% d^{-1}, respectively), while the presence of copper (θCu) is due to the

animal feed (majority removed in pond 12.85% d^{-1}).

Finally, although the NTSW, a low-cost system, has been shown to have overall CODt, TSS or TN removal rates comparable with other conventional technologies (Table 2), including anoxic-aerobic systems described by (Alvarez, 2006) or anaerobic-aerobic systems (90.10% CODt and 77.60% TSS) described by (Font et al., 1997), if a comparison is made using the ratio given in Eq. (4) with technologies like the membrane bioreactor (MBR) (Fugère et al., 2005) or the sequencing batch reactor-membrane bioreactor (SBR-MBR) (Su et al., 2020), the latter present higher values as the required energy consumption is not considered with this parameter and so these technologies give more optimal results in the removal of the parameters studied.

4. Practical applications

Pig farms in insular or isolated areas lack of adequate systems to treat

Table 2
NTSW system and other technologies with respect to various parameters.

Treatment	HRT (d)	reCODt (%)	reTSS (%)	reTN (%)	θCODt (% d-1)	θTSS (% d-1)	θTN (% d-1)	References
Anaerobic + biofilters	6.0	98.0	–	55.0	16.3	–	9.2	Kalyuzhnyi et al. (2003)
Anaerobic + SBR	4.5	96.7	98.0	96.8	21.5	21.8	21.5	Deng et al. (2007)
Anoxic + aerobic	54.0	95.9	–	98.0	1.8	–	1.8	Choi et al. (2005)
Anaerobic + anoxic + aerobic	48.0	95.0	–	99.5	2.0	–	2.07	Choi et al. (2005)
Anoxic + aerobic	13.0	93.6	96.0	96.1	7.2	7.4	7.4	Alvarez (2006)
NTSW	28.0	91.8	96.0	93.8	3.3	3.4	3.3	This study
Anaerobic-aerobic	3.0	90.1	77.6	–	30.0	25.9	–	Font et al. (1997)
SBR + MBR	1.0	87.0	96.0	–	87.0	96.0	–	Su et al. (2020)
Anoxic + aerobic	13.0	86.9	93.7	95.7	6.7	7.2	7.4	Alvarez (2006)
SBR	6.0	70.4	–	83.0	11.7	–	13.8	Choi et al. (2005)
Co-digestion anaerobic	15.5	69.2	–	–	4.5	–	–	Ferreira (2006)
Aerobic thermophilic	3.0	62.0	–	80.0	20.7	–	26.7	Yi et al. (2003)
MBR	1.0	51.2	–	50.0	51.2	–	50.0	Fugère et al. (2005)

their waste. NTSW is suitable to be used in this type of farms, which are also normally working on a self-consumption way and are considered small (having less than 120 sows). NTSW allows an economic management of waste in situ and promote the circular economy due to the reutilization of the effluent and solids coming from the system as liquid and solid soil fertilizers. Anaerobic digesters (built with at least 4 chambers) are the best solution for the first treatment stage, combined with a rotary screen, while constructed wetlands combined with a pond are the best to use regarding a second stage (better stabilization results). The main parameters to be monitored as input for plant design, are: the flow, COD, pH and conductivity. Regarding future research prospect, this experience will provide characterization, correlations and parameters applicable to future designs and applications in other farms having similar sizes and conditions.

5. Conclusions

The use of NTSW raises the awareness of livestock farmers with respect to the value of their waste as a potentially profitable resource, which in turn encourages them to become more involved in waste management. Livestock farms with NTSW have the possibility of reusing or discharging the waste under better conditions than previously. High removal rates of CODt were obtained with the NTSW, as well as numerous statistically significant correlations between different relevant variables. The NTSW system that was studied displayed a stable performance throughout the study period. HRT of 30 days is an adequate period for stabilization from this type farm effluent. The integration and combination of different equipment allowed the NTSW to obtain good elimination performances and stability in the face of load and flow variations, and it can be considered a viable alternative solution to wastewater management in livestock farms of similar size.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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