

Performance evaluation of 388 full-scale waste stabilization pond systems with seven different configurations

Maria Fernanda Espinosa, Marcos von Sperling and Matthew E. Verbyla

ABSTRACT

Waste stabilization ponds (WSPs) and their variants are one of the most widely used wastewater treatment systems in the world. However, the scarcity of systematic performance data from full-scale plants has led to challenges associated with their design. The objective of this research was to assess the performance of 388 full-scale WSP systems located in Brazil, Ecuador, Bolivia and the United States through the statistical analysis of available monitoring data. Descriptive statistics were calculated of the influent and effluent concentrations and the removal efficiencies for 5-day biochemical oxygen demand (BOD₅), total suspended solids (TSS), ammonia nitrogen (N-Ammonia), and either thermotolerant coliforms (TTC) or *Escherichia coli* for each WSP system, leading to a broad characterization of actual treatment performance. Compliance with different water quality and system performance goals was also evaluated. The treatment plants were subdivided into seven different categories, according to their units and flowsheet. The median influent concentrations of BOD₅ and TSS were 431 mg/L and 397 mg/L and the effluent concentrations varied from technology to technology, but median values were 50 mg/L and 47 mg/L, respectively. The median removal efficiencies were 85% for BOD₅ and 75% for TSS. The overall removals of TTC and *E. coli* were 1.74 and 1.63 log₁₀ units, respectively. Future research is needed to better understand the influence of design, operational and environmental factors on WSP system performance.

Key words | anaerobic ponds, compliance, facultative ponds, influent and effluent concentrations, maturation ponds, removal efficiencies, statistical analysis

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INTRODUCTION

Waste stabilization ponds (WSPs) and their variants constitute the simplest form of wastewater treatment, especially for small towns (von Sperling & Chernicharo 2005) because they present favorable characteristics, such as satisfactory performance, low cost, low maintenance, and sustainability (Mara 2008; Muga & Mihelcic 2008). The use of WSPs for sewage treatment in the United States dates back to 1901 in San Antonio, Texas (US EPA 2011). Researchers began publishing papers on ponds in 1950, and from this date the development of these systems began growing in the United States, Australia, New Zealand, Israel, South Africa, India, Canada and Latin America, in Brazil, Mexico, Colombia, Peru, Costa Rica, Cuba and Ecuador (Jordão & Pessôa 2014). In Europe, this type of treatment system is also widely used in France (rural areas with less

than 1,000 inhabitants), Portugal, Spain, Greece, Italy and Germany (Mara & Pearson 1987).

There are different types of WSPs, and the most common are: anaerobic, facultative, maturation, and aerated ponds. A common arrangement includes two or three ponds operating in series, such as an anaerobic pond followed by a facultative pond; depending on the required quality of the effluent, one or more maturation ponds may follow the facultative pond (Mara 2008). Another common configuration is a facultative pond or an aerated pond followed by one or more maturation ponds. The US EPA (2011) also suggests the use of WSPs in combination with other treatment processes.

The scarcity of consolidated performance data from full-scale WSP systems has led to challenges associated with

their design. In most cases, important operational factors that influence the performance are not considered, resulting in systems that may be oversized and too expensive or undersized and incapable of meeting performance standards and complying with water quality and performance goals. The limited availability of effective and consistent performance data for a large set of full-scale systems has created a knowledge gap with regard to the influence of WSP system configuration on the efficiency of treatment. Thus, the creation and maintenance of a database with information of existing systems is considered very important. In this sense, it is expected that this study may assist researchers and practitioners in the interpretation of actual performance of full-scale pond systems with different configurations, regions, climatic conditions and discharge standards.

The objective of this research was to evaluate the performance of full-scale WSP systems, subdivided into different treatment configurations, located in the North and South American continents (Ecuador, Bolivia, Brazil, and the United States), using descriptive statistical analysis of monitoring data for 5-day biochemical oxygen demand (BOD₅), total suspended solids (TSS), ammonia nitrogen (N-Ammonia), thermotolerant coliforms (TTC) and *Escherichia coli*. Compliance with different water quality goals (final effluent concentrations) and targets for system performance (percent removal) was evaluated for each pollutant and for all configurations.

METHODS

A total of approximately 57,700 data about the performance of 388 WSP systems in Brazil (Federal District, Minas Gerais, São Paulo and Rio Grande do Norte); Bolivia (Yungas region); Ecuador (Cuenca) and the United States (Missouri and Georgia) were analysed. These regions were selected due to their differences in climate and the systems were selected because they included WSPs for at least one unit process and had data available from at least five different sampling events over the course of one or more years. The data were obtained from wastewater or sanitation service provider companies, state environmental agencies and research databases. In the data sets obtained from the various sources there was no clear explanation on the sampling and analytical methods adopted at each plant, and it was assumed that procedures followed the Standard Methods or other accepted protocols. When using secondary data, such as in this study, there is always the chance that incorrect values are used. Those which showed obvious deviations from expected reasonable ranges have been excluded, but the authors tried to preserve the database as close as possible to the original ones, without much interference on them and possible exclusions of data due to indirect inferences from expected behavior.

The data were grouped according to seven different WSP system configurations (Table 1). Concentrations of BOD₅, TSS, N-Ammonia, TTC, and *E. coli* were available at the

Table 1 | WSP system configurations established for this research and the corresponding number of systems for each configuration and location

Configuration	Acronym	Location								Total
		Bolivia BO	Ecuador EC	USA		Brazil				
				GA	MO	MG	RN	SP	FD	
Facultative pond	FP			2	22	1		64		89
Anaerobic pond + facultative pond	ANP + FP ^a			1	1	5		38		45
Facultative pond + maturation pond	FP + MP	1		2	156	1	9	1		170
Aerated pond + facultative/maturation pond	AEP + FP/MP		2	2	13					17
Anaerobic reactor + facultative pond	AR + FP				2	9				11
Anaerobic reactor + other treatment + maturation pond	AR + OT ^b + MP				1	11		4	1	17
Pond + post treatment	P + PT ^c				39					39
	Total	1	2	7	234	27	9	107	1	388

BO, Bolivia; EC, Ecuador; GA, Georgia (USA); MO, Missouri (USA); MG, Minas Gerais (Brazil); RN, Rio Grande do Norte (Brazil); SP, São Paulo (Brazil); FD, Federal District (Brazil).

^aSystems in Missouri and Georgia in this category have anaerobic or aerated ponds (alternating between aerobic and anaerobic conditions to improve the removal of nitrogen), followed by facultative lagoons and maturation ponds.

^bOther treatment refers to anaerobic filters or facultative ponds.

^cRefers to a configuration composed of ponds (anaerobic, facultative, aerated) followed by some other type of post treatment unit process (wetlands, disinfection, etc.).

influent and final effluent of each system, with the exception of WSP systems in the United States, where N-Ammonia, TTC and *E. coli* concentrations were only reported in the final effluent.

The following descriptive statistics of the influent and effluent concentrations and the removal efficiencies of the studied parameters (BOD₅, TSS, N-Ammonia, TTC and *E. coli*) for each WSP system were analysed for each treatment plant: arithmetic and geometric means, medians, maximum and minimum values, percentiles of 5%, 25%, 75% and 95% and standard deviations. Because in most systems data availability was only for the influent (raw sewage) and final effluent, without monitoring at intermediate points of the treatment chain, the statistics presented are for each system, as a whole, and not for the individual units (reactors and ponds) that comprise each system. Similarly, removal efficiencies are for the system, and not for each unit in the series.

Using the raw data of each of the WSPs (within each configuration), the descriptive statistics of the concentrations (mean, median, geometric mean, maximum, minimum, standard deviation, percentiles 5% and 95%, etc.) of each parameter were calculated. The medians (for BOD₅, TSS and N-Ammonia) and geometric mean (for TTC and *E. coli*) of each system were used in the descriptive statistics of each configuration (removal efficiencies and concentrations). This was done in order to give the same weight to each treatment plant, regardless of their number of data. Finally, the value of total removal efficiency of each configuration corresponds to the median of the median removal efficiencies from each system. The Kruskal–Wallis one-way

analysis of variance (ANOVA) with post hoc multiple comparison test was used to compare the removal efficiencies between the seven configurations ($\alpha = 0.05$). The Portal Action software (São Carlos, SP, Brazil) add-on for Microsoft Excel was used for all statistical tests.

In order to assess the capacity of the treatment systems to comply with discharge regulations, typical quality and performance goals were established for the final effluent concentrations and removal efficiencies for BOD₅, TSS, N-Ammonia, TTC and *E. coli*, according to common limits presented in the literature (EC 1991; Oliveira 2006; Noyola et al. 2012; US EPA 2013) and required by law (Bolivia 1992, 33 U.S.C. 1251 et seq. 1992; Tulas 2003; COPAM-MG 2008; CONAMA 2011) in the countries or regions where the systems under study are located. Table 2 shows the quality goals established in this study, expressed in terms of values and also a qualitative interpretation expressed in terms of the least to the most stringent standard. The percentages of compliance to these goals were calculated according to Equations (1) and (2):

% in compliance in terms of effluent concentration

$$= \frac{(N_{ec})}{(N_{tec})} \quad (1)$$

$$\% \text{ in compliance in terms of removal efficiency} = \frac{(N_{re})}{(N_{tre})} \quad (2)$$

where N_{ec} is the number of measurements with effluent concentrations below the target effluent concentration, N_{tec} is

Table 2 | Quality and performance goals established for effluent concentrations and removal efficiencies

Effluent concentrations

Level of goal	BOD ₅ mg/L	TSS mg/L	N-Ammonia mg/L	TTC MPN/100 mL	<i>E. coli</i> MPN/100 mL
Most stringent	20	20	5	1.00E + 02	1.00E + 02
More stringent	60	60	10	1.00E + 03	1.00E + 03
Less stringent	100	100	15	1.00E + 04	1.00E + 04
Least stringent	140	140	20	1.00E + 05	1.00E + 05

Removal efficiencies

Level of goal	BOD ₅ %	TSS %	N-Ammonia %	TTC Log ₁₀ units	<i>E. coli</i> Log ₁₀ units
Most stringent	90	90	80	5	5
More stringent	80	80	70	4	4
Less stringent	70	70	60	3	3
Least stringent	60	60	50	2	2

the total number of measured effluent concentrations, N_{re} is the number of removal efficiencies above the target removal efficiency, and N_{tre} is the total number of measured removal efficiencies.

Following a methodology similar to that used by Oliveira (2006), for the purpose of comparison and examination of compliance with the quality and performance goals, three criteria were established. *High* stipulates that the system has high compliance, with 90% or more of the samples complying with the established goal; *Medium* states that the system has medium (intermediate) compliance, with 50% to 90% of samples meeting the goals; *Low* indicates that the configuration has low compliance, with less than or equal to 50% of sampling occasions satisfying the goals. These criteria were used for both the effluent concentration and the removal efficiencies goals for the five parameters: BOD₅, TSS, N-Ammonia, TTC and *E. coli*. The evaluation was made for each WSP system within each configuration and for each parameter separately.

RESULTS AND DISCUSSION

Concentrations and removal efficiencies

Figures 1 and 2 show the influent and effluent concentrations of BOD₅ and TTC for each of the seven configurations and the removal efficiencies of BOD₅ and TTC (log₁₀ units). Due to the space limitation, it is not possible to show all graphs from the other constituents. TSS were similar to BOD₅ graphs and *E. coli* was similar to TTC graphs. N-Ammonia had insufficient data to lead to conclusive graphs. Median values of concentrations and removal efficiencies are presented in Table 3. Detailed descriptive statistics for each parameter and configuration are provided as annexes in the Supplementary Material (available with the online version of this paper).

BOD₅

All configurations, except for AEP + FP/MP, showed similar BOD₅ influent concentrations, with median values that

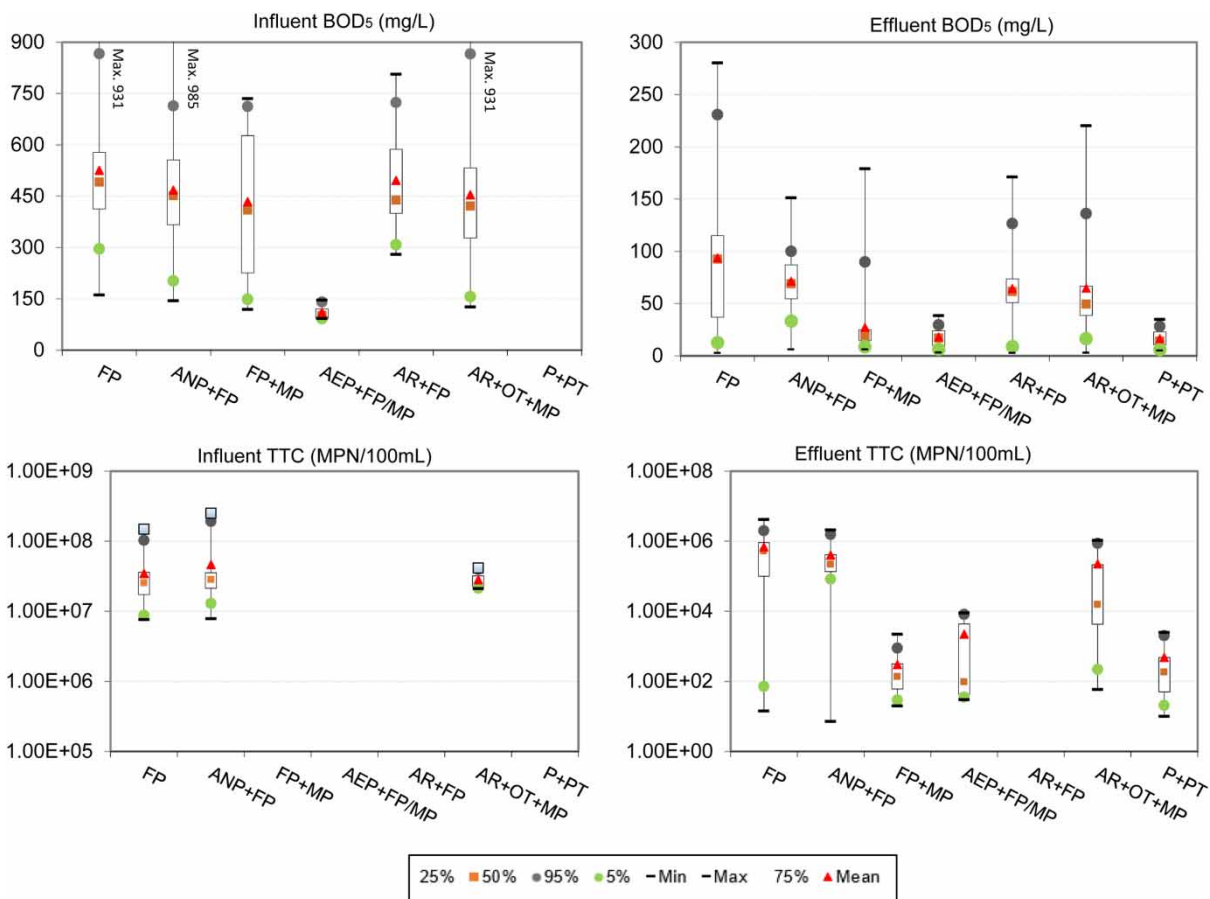


Figure 1 | Box-plot of influent and effluent concentrations of BOD₅ and TTC of seven configurations.

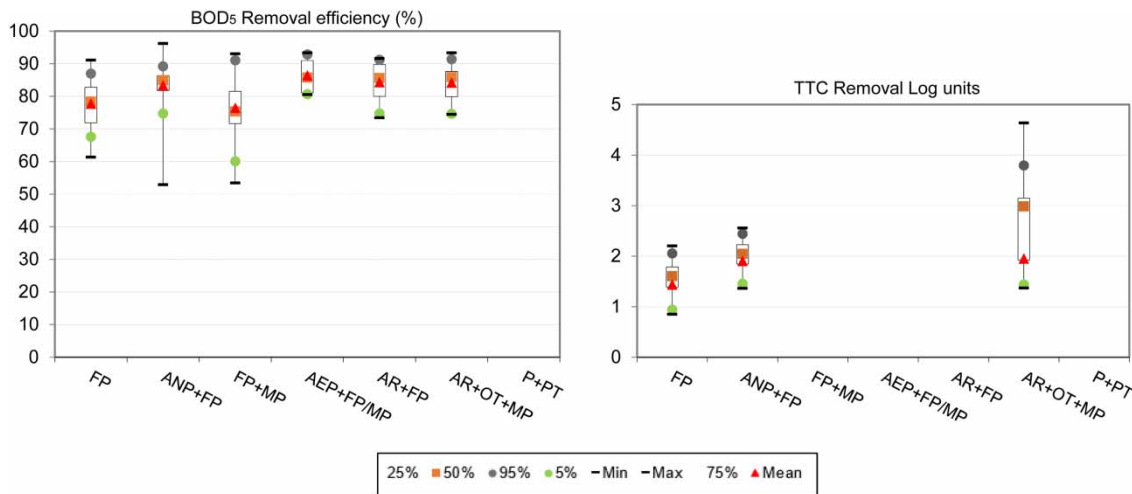


Figure 2 | Box-plot of percentage removal efficiencies of BOD₅ and log units removal for TTC for the seven configurations.

ranged from 410 mg/L to 492 mg/L. In the case of the systems with the AEP + FP/MP configuration, the median concentration was 102 mg/L, which is much lower than values reported in the literature (Faleschini *et al.* 2012; von Sperling 2014). Although the ponds in this latter configuration may not represent characteristics that are comparable to the other ones, they have been maintained in this study in order to show that this situation also occurs in practice. The influent concentrations obtained for all configurations ranged widely from 92 mg/L to 985 mg/L and the overall median was 431 mg/L. BOD₅ values of 400 mg/L would be classified as strong domestic sewage, according to Metcalf & Eddy (2014). For all configurations, the BOD₅ effluent concentrations were less than half of the influent values. There was a greater variability of concentrations between configurations. The median effluent concentration for all systems was 50 mg/L. The range obtained was from 3 mg/L to 280 mg/L. The removal efficiency ranged from 53% to 96%, with a median of 85%. The ANP + FP and AR + OT + MP were the configurations with best removal efficiency for BOD₅. Comparing these values with results from surveys of other pond systems, the overall median values for the influent and effluent concentrations are here lower than those reported by Oliveira & von Sperling (2009) with ponds in Southeast Brazil. Comparing with average values obtained by Recault *et al.* (1995) in France, the influent concentrations are higher here, and the effluent concentrations are very similar.

TSS

The ANP + FP and FP configurations showed very similar influent concentrations, with great variability, and median

values of 400 mg/L and 397 mg/L, respectively. The FP influent concentration showed to be lower than the value reported by Oliveira & von Sperling (2009). For other configurations, the medians were between 132 mg/L and 439 mg/L, and the AEP + FP/MP configuration had the lowest median influent concentration (132 mg/L). The total range for all configurations was from 57 mg/L to 806 mg/L and the overall median was 397 mg/L, which also classifies the influent as strong domestic sewage (Metcalf & Eddy 2014). This overall median value is higher than the average values reported by Recault *et al.* (1995) and Noyola *et al.* (2012), whose values were around 260 mg/L. The range of concentrations was much broader than those reported in the literature, but the median observed was lower than that reported in the literature (Oliveira 2006). For effluent concentrations, a wide variation was noted between configurations. The FP configuration showed the widest range, from 29 mg/L to 222 mg/L (percentiles 25% and 75%), and the median was similar to the ANP + FP configuration, with values of 150 mg/L and 122 mg/L, respectively. The configurations with the lowest effluent concentrations were AEP + FP/MP and P + PT, with respective medians of 27 mg/L and 26 mg/L. The overall range obtained was 3 mg/L to 498 mg/L and the overall median was 47 mg/L. The removal efficiencies had a greater variability among the configurations, presenting even negative values, which are likely to be due to the accumulation of algae and its discharge in the effluent, very common in systems with FP and FP + MP configurations. The overall interquartile range of removal was 21% to 90% and the overall median was 75%. AR + FP was the configuration with best removal efficiency for TSS. In terms of effluent concentrations, the overall median value is lower than the value reported by Oliveira & von Sperling (2009).

Table 3 | Median values of influent and effluent concentrations and removal efficiencies for each configuration and parameter**Influent and effluent concentrations (influent/effluent)**

Configuration	Acronym	BOD ₅ mg/L	TSS mg/L	N-Ammonia mg/L	TTC ^a MPN/100 mL	<i>E. coli</i> ^a MPN/100 mL
Influent concentrations (all configurations)	–	431/50	397/47	42/6	2.84E + 07/ 3.58E + 03	4.94E + 07/ 1.56E + 04
Facultative pond	FP	492/93	400/150	42/13	2.68E + 07/ 1.27E + 05	2.66E + 07/ 6.98E + 05
Anaerobic pond + facultative pond	ANP + FP	453/69	397/122	–/17	3.14E + 07/ 1.80E + 05	9.19E + 07/ 2.28E + 05
Facultative pond + maturation pond	FP + MP	410/19	180/32	–/1	–/1.54E + 02	–/6.41E + 01
Aerated pond + facultative/ maturation pond	AEP + FP/MP	102/17	132/27	–/2	–/2.94E + 02	–
Anaerobic reactor + facultative pond	AR + FP	439/62	439/62	–	2.72E + 07/–	–/2.55E + 05
Anaerobic reactor + other treatment + maturation pond	AR + OT + MP	422/50	–	–/11	–/1.21E + 04	–/2.93E + 05
Pond + post treatment	P + PT	–/14	–/26	–/1	–/1.67E + 02	–/1.85E + 01

Removal efficiencies

Configuration	Acronym	BOD ₅ %	TSS %	N-Ammonia %	TTC ^a Log ₁₀ units	<i>E. coli</i> ^a Log ₁₀ units
Removal efficiency (all configurations)	–	85	75	57	1.74	1.63
^(a) Facultative pond	FP	78 (a < b); (a < f)	53 (a < b); (a < d); (a < e)	57	1.43 (a < b); (a < f)	1.33 (a < b)
^(b) Anaerobic pond + facultative pond	ANP + FP	85 (b > a)	71 (b > a)	–	1.90 (b > a)	1.99 (b > a)
^(c) Facultative pond + maturation pond	FP + MP	75	39 (c < e)	–	–	–
^(d) Aerated pond + facultative/ maturation pond	AEP + FP/MP	86	79 (d > a)	–	–	–
^(e) Anaerobic reactor + facultative pond	AR + FP	85	86 (e > a; e > c)	–	–	–
^(f) Anaerobic reactor + other treatment + maturation pond	AR + OT + MP	86 (f > a)	78	–	1.95 (f > a)	–
Pond + post treatment	P + PT	–	–	–	–	–

–, no data available.

^aColiform values refer to the geometric mean.

Data in parentheses tell us if there is a significant difference or not between the configurations ($\alpha = 0.05$).

However, in terms of removal efficiency, the overall value is very similar to those reported by these authors.

N-Ammonia

Data for *influent* concentrations were not available for the majority of systems, as the Department of Natural Resources

in Missouri and Georgia (USA) do not require influent concentrations to be reported, and most operators of the systems in Brazil, Ecuador, and Bolivia do not collect these data. The FP configuration was the only one with the minimum data (five) for the analysis, with a median influent concentration of 42 mg/L (ammonia as N), similar to Recault *et al.* (1995) and Faleschini *et al.* (2012). *Effluent*

concentrations were reported for all configurations. There was a large variability among the configurations, with a range from 0.02 mg/L to 51 mg/L and an overall median of 6 mg/L; 46% of the effluent N-Ammonia concentrations from all configurations were below 1.9 mg/L, 62% were below 4.8 mg/L, and 92% were below 17 mg/L, which are the thresholds for the maximum average concentrations recommended by the US EPA (2013) for 30-day, 4-day, and 1-h periods, respectively, to avoid toxicity to aquatic life in surface waters. These results demonstrate that some configurations of WSP systems are capable of meeting stringent numeric nutrient limits. The median removal efficiency for the FP configuration was 57%.

TTC and *E. coli*

Similar to N-Ammonia, there was a lack of information available for the *influent* concentrations for TTC and *E. coli*. Based on the data available for the three configurations with complete information, the geometric mean values of the TTC *influent* concentrations were 2.7×10^7 MPN/100 mL (FP and AR + OT + MP) and 3.1×10^7 MPN/100 mL (ANP + FP), and the total range obtained was from 7.6×10^6 MPN/100 mL to 2.5×10^8 MPN/100 mL, which are similar to ranges reported previously in the literature for Brazil and the United States (von Sperling & Chernicharo 2005; Metcalf & Eddy 2014). The overall geometric mean was 2.84×10^7 MPN/100 mL, which is lower than the values reported in Oliveira & von Sperling (2009) and Noyola et al. (2012). The FP + MP, AEP + FP/MP and P + PT configurations had similar *effluent* concentrations, with geometric mean values below 300 MPN/100 mL. For the other configurations, the variability in the *effluent* concentrations was greater. The overall range for all configurations was between 7.1 MPN/100 mL and 4.2×10^6 MPN/100 mL, and the overall geometric mean was 3.6×10^3 MPN/100 mL. The range of removal efficiencies for TTC was 0.9 to 4.6 \log_{10} units, with an overall geometric mean of 1.74 \log_{10} units.

The results for *E. coli* were very similar to TTC. Only the FP and ANP + FP configurations presented *influent* concentration data. The geometric mean values of the *influent* concentrations were 1.06×10^6 MPN/100 mL and 3.11×10^{10} MPN/100 mL, and the overall geometric mean was 4.9×10^7 MPN/100 mL, which are within the range of reported values in the literature (von Sperling & Chernicharo 2005; Metcalf & Eddy 2014). For *effluent* concentrations, there was a great variability among the configurations, resulting in a very wide range of geometric mean

values, from 1.0 MPN/100 mL to 6.2×10^8 MPN/100 mL. The overall geometric mean obtained was 1.6×10^4 MPN/100 mL. The removal efficiency was very similar to TTC, with a range of 1.02 and 3.23 \log_{10} units and an overall geometric mean removal of 1.64 \log_{10} units.

The values of the removal efficiencies for TTC and *E. coli* indicate that the *effluent* of systems with the FP and ANP + FP configurations would be suitable for restricted irrigation (of crops not typically consumed raw), using sub-surface irrigation; the *effluent* of the systems with the ANP + FP configuration would be suitable for unrestricted irrigation of high-growing crops (that may or may not be consumed raw) if drip irrigation is used (WHO 2006).

For the P + PT configuration, the *effluent* concentrations for the parameters studied were always lower than those from the other configurations. The interpretation of the performance of this configuration is difficult and limited, due to the variability of post treatment methods employed. However, it is interesting to present their data and information, in order to highlight that different *effluent* qualities can be achieved, depending on the post treatment process employed.

WSP are natural treatment systems, whose performance depends on operational and environmental factors. Table 4 shows a summary of the environmental factors (ambient temperature and isolation) for each location and operational factors (hydraulic retention time – HRT – only for the configurations that had at least five systems with this information, and surface organic loading rate – only for primary facultative ponds). This table shows the wide diversity of conditions in the pond systems included in this survey. A study of the influence of these factors on treatment performance has been done as part of this overall research (Espinosa 2016), but was not included in this article due to space limitations. An important conclusion of this part of the study is that none of the factors, taken separately, was able to explain the performance of the pond systems, demonstrating that the performance of these systems is a result from a multitude of factors interacting simultaneously.

Compliance with different effluent quality and system performance goals

The percent of systems in compliance with the established goals for water quality (concentrations of pollutants in the final *effluent*) and system performance (percent removal of pollutants) was evaluated for each of the seven configurations. Each system was rated as having *high* ($\geq 90\%$), *medium* ($> 50\%$ and $< 90\%$), or *low* ($\leq 50\%$) compliance

Table 4 | Range (5 and 95 percentiles) and median (in parentheses) values of environmental factors in each location and operational factors in each configuration**Environmental factors**

	Location							
	BO	EC	GA	MO	MG	RN	SP	FD
Ambient temperature (°C)	NS	L	16.6–16.6 (16.6)	10.6–14.1 (11.9)	20.8–24.5 (23.2)	25.8–26.5 (26.2)	21.0–24.8 (23.8)	L
Insolation (kWh/m ² d)	NS	L	4.3–4.4 (4.4)	4.0–4.2 (4.1)	4.8–5.5 (5.3)	5.8–6.4 (6.3)	5.0–5.3 (5.2)	L

Operational factors

	Configuration						
	FP	ANP + FP	FP + MP	AEP + FP/MP	AR + FP	AR + OT + MP	P + PT
Hydraulic retention time (d)	13–64 (33)	12–40 (23)	11–143 (72)	L	21–59 (36) ^a	NA	18–131 (87) ^b
Surface organic loading rate (kgBOD/ha d)	95–638 (316)	NA	36–831 (344)	NA	NA	NA	NA

NS, not specified; NA, not applicable; L, less than five data.

HRT values correspond to the complete system (all units). Surface organic loading rate corresponds to the primary facultative pond.

^aValues correspond only to the pond (not considering the HRT of the upflow anaerobic sludge blanket (UASB)).

^bValues correspond to the first pond.

with four different goals (least stringent, less stringent, more stringent and most stringent), as shown in Figures 3 and 4, respectively. When considering the water quality goals for the final effluent concentrations (Figure 3), the P + PT configuration had the best performance of all configurations for all pollutants, which is likely due to the additional unit process used for post treatment in these systems. In Figure 4, despite the lack of information for some configurations, it is clear that most WSP systems have difficulty in meeting the established goals for percent removal of the different pollutants.

For BOD₅, most configurations had low compliance (<50%) with the most stringent goals for effluent concentration (≤ 20 mg/L) and removal efficiency ($\geq 90\%$), where more than 85% of the WSP systems had less than 50% of instances with removal efficiencies higher than 90%. For the less stringent BOD₅ quality goals, the results were more acceptable for most of the WSP systems. The FP + MP, AEP + FP/MP and P + PT configurations had high compliance with 93%, 100% and 100% of all WSP systems, respectively. For example, 90% of the measurements of BOD₅ effluent concentration were lower than 100 mg/L for 93% of WSP systems with the FP + MP configuration. For the other configurations, the compliance is also high but only with 36% or less of all WSP systems. For BOD₅ removal efficiency goals, the compliance improves from

the less stringent goal (70%); in this goal medium compliance prevails in all configurations with more than 50% of their WSPs. High compliance appears with less than 45% of the WSP systems, except configuration AR + FP that presents high compliance with 67% of their WSP systems. For the least stringent goal (60%), all configurations achieved a high level of compliance ($\geq 90\%$), except for FP and FP + MP, which reached a medium level of compliance ($>50\%$ and $<90\%$).

For TSS, the results showed that the two lowest goals for the final effluent concentration (20 mg/L and 60 mg/L) were difficult for WSP systems to meet; perhaps due to the presence of algae in the final effluent, which is common in these types of systems. Systems from all seven configurations had mostly low compliance for the most stringent level (20 mg/L); systems with the FP + MP, AEP + FP/MP and P + PT configurations achieved mostly high compliance for the more stringent level (60 mg/L), and for the other two goals (100 and 140 mg/L), the compliance was more acceptable for systems with the AR + FP configuration. Systems with FP and AP + FP did not achieve high compliance with even the least stringent goal for effluent concentration. The AR + FP configuration was the only configuration with data that had mostly medium or high compliance with the TSS removal efficiency goals.

For N-Ammonia, there was great variability between the different configurations in terms of their compliance with

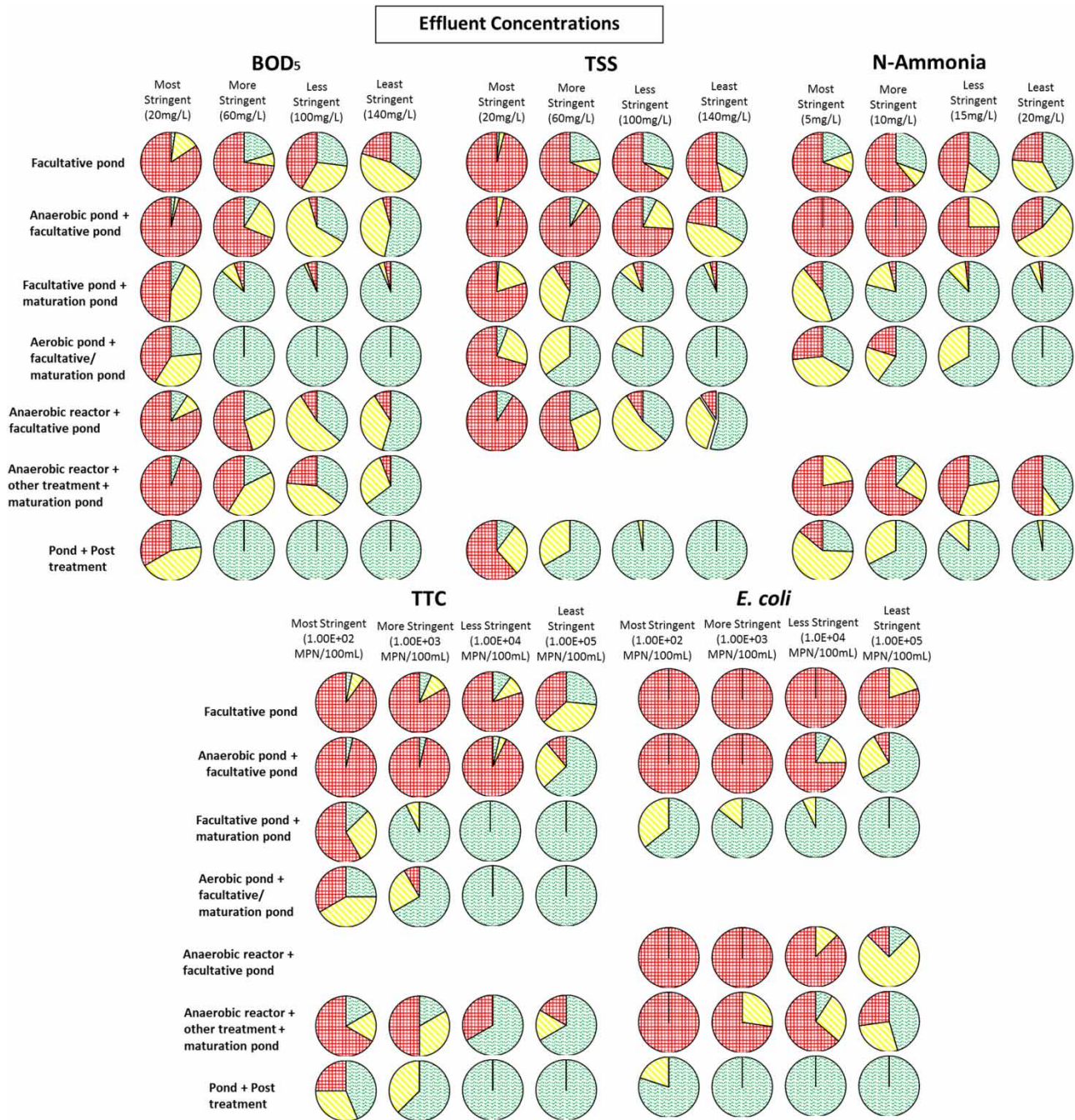


Figure 3 | Percentage of compliance with the effluent concentration goals: most stringent, more stringent, less stringent and least stringent for the seven configurations, according to the criteria: High ($\geq 90\%$ compliance), Medium ($> 50\%$ and $< 90\%$ compliance), and Low ($\leq 50\%$ compliance).

effluent concentration goals. All configurations had low compliance for the most stringent goal of 5 mg/L, and mostly medium or high compliance for the least stringent goal (20 mg/L); the configurations reached high compliance with more than 40% of their WSP systems, except ANP +

FP, which reached high compliance only with 13% of their WSP systems. Analysis of compliance to the removal efficiency goals for N-Ammonia was not possible due to the lack of available influent concentration data for this parameter (Figure 4).

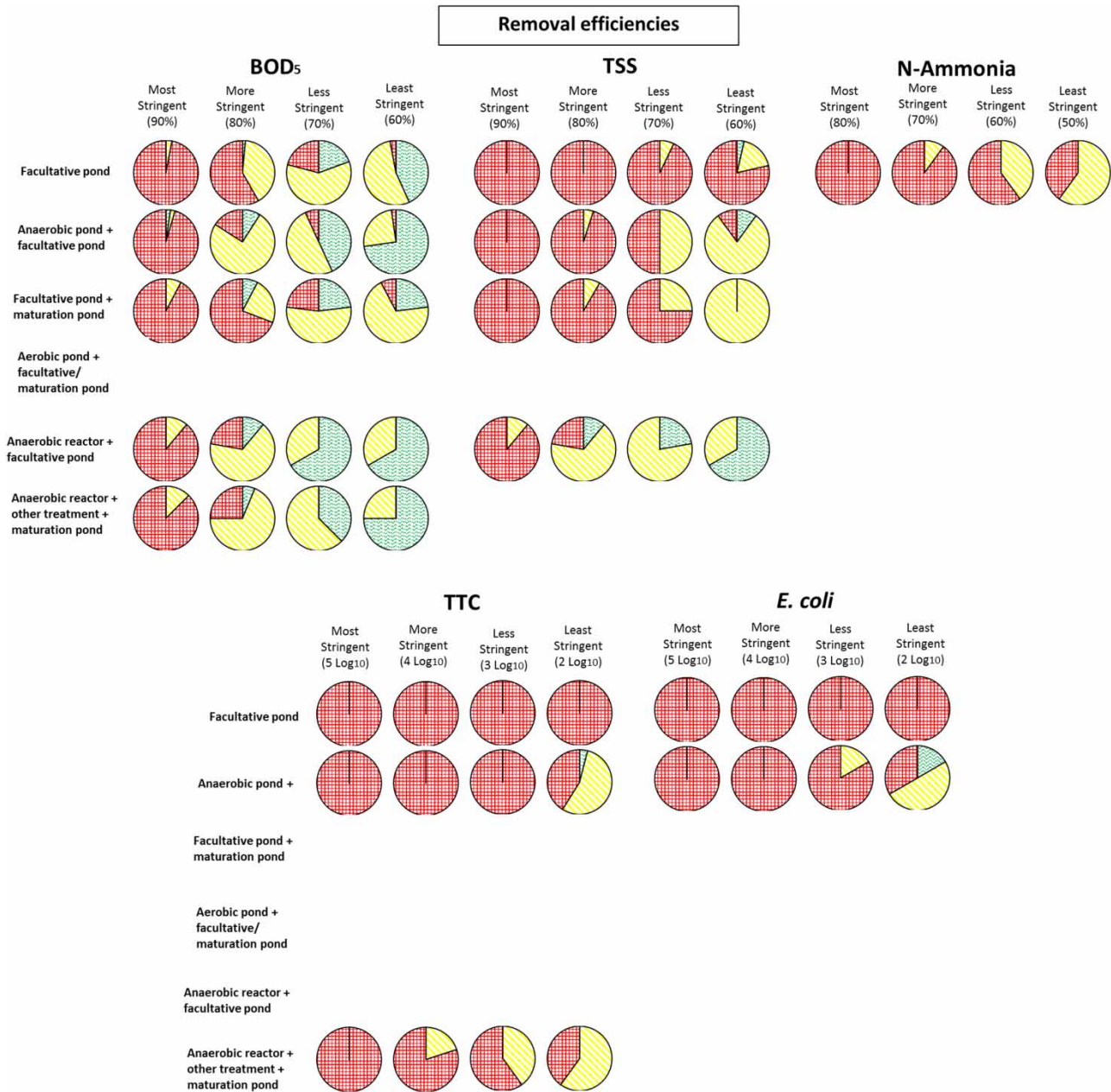


Figure 4 | Percentage of compliance with the removal efficiency goals: most stringent, more stringent, less stringent and least stringent for the seven configurations, according to the criteria: High ($\geq 90\%$ compliance), Medium ($> 50\%$ and $< 90\%$ compliance), and Low ($\leq 50\%$ compliance).

The performance of the configurations to the compliance of the TTC effluent concentration goals was variable. The FP and ANP + FP configurations had the lowest levels of compliance with the established goals. This makes sense, considering that these configurations are not designed to eliminate fecal indicators and pathogens, since they lack post treatment unit processes like maturation ponds, wetlands or disinfection. The FP + MP and P + PT configurations had the best compliance with TTC effluent concentration goals (Figure 3). Other

configurations had mostly low compliance ($\leq 50\%$) with the effluent quality goals of $1.00E + 03$ MPN/100 mL and $1.00E + 04$ MPN/100 mL. For the least stringent goal ($1.00E + 05$ MPN/100 mL), the compliance was generally high, with more than 60% of WSP systems from all configurations, except the FP configuration, which still presented mostly low or medium compliance. Furthermore, for the TTC removal efficiency goals (Figure 4), there were only three configurations (FP, ANP + FP and AR + OT + MP)

with complete data. The compliance with the two most stringent goals (4 and 5 log₁₀ units) was very low. For the FP configuration, low compliance prevailed in both cases with 100% of WSP systems; systems with the ANP + FP configuration reached medium compliance with the least stringent goal (2 log₁₀ units) for 55% of WSP systems; and low compliance for all other goals with 100% of their WSPs.

Finally, for *E. coli*, like for TTC, the performance of the different configurations was variable. For the most stringent effluent concentration goal, only the FP + MP and P + PT configurations reached high compliance with 60% and 80% of systems. All systems with other configurations showed low compliance ($\leq 50\%$) with this most stringent goal. Once again, this demonstrates the need to have a maturation pond or another kind of post treatment unit process in WSPs to comply with goals for the concentration of fecal indicator microorganisms. For the least stringent goal (1.00E + 05 MPN/100 mL), the compliance was better, and the FP configuration was the only one that did not have any systems that reached high levels of compliance. For the removal efficiency goals, it was not possible to evaluate differences between systems with different configurations due to the lack of data available for this parameter at the influent points. Only the FP and ANP + FP configurations had systems with complete information. Systems with the FP configuration had low compliance for all four removal goals, and systems with the ANP + FP configuration had low compliance to the three most stringent removal goals (3, 4 and 5 log₁₀ units), but had 50% of systems reach medium compliance for the least stringent goal (2 log₁₀ units).

CONCLUSIONS

To the authors' knowledge, this is the broadest evaluation to date of the performance of WSP systems, based on the number of plants and treatment configurations. A database with seven configurations of WSPs from 388 different systems was created and analysed. The configuration with the greatest number of systems was facultative pond followed by maturation pond, whereas systems with anaerobic reactors were the least common in the database. The overall median BOD₅ and TSS influent concentrations were consistent with strong domestic sewage, and the range of influent concentrations for TTC and *E. coli* were also consistent with values previously reported in the literature. The effluent concentrations of N-Ammonia, TTC and *E. coli* demonstrate that some configurations of WSP systems are indeed capable of meeting stringent effluent limits for these parameters. The

overall median removal efficiencies for all configurations were 85% for BOD₅, 75% for TSS and 57% for N-Ammonia (N-Ammonia results based on the FP alone), and the overall geometric mean removals of TTC and *E. coli* for all configurations were 1.74 and 1.63 log₁₀ units, respectively. The FP and FP + MP configurations generally had lower removal efficiencies than other configurations, particularly the AEP + FP/MP, AR + FP and AR + OT + MP configurations. Compliance with the most stringent effluent quality and removal efficiency goals was very low, but improved for the less stringent goals. Systems with facultative ponds followed by maturation ponds, and systems with WSPs followed by post treatment unit processes had better compliance with the effluent quality goals. Future research is needed to better understand the design, operational, or environmental factors (such as hydraulic retention time, temperature, and solar insolation) that enable some WSP systems to provide more efficient removal of pollutants than others. This is especially important for the sustainability of wastewater management in tens of thousands of small towns throughout the world that currently rely on this technology (and many more that will rely on it in the future) for wastewater treatment.

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