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Influence of the Nature of the Incoming Sludge on the Performance of a Vertical Flow Reed Beds in Dakar-Senegal

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Abstract

This work investigates the influence of the type sludge on drainage, plant development, purification performances and biosolids quality. Drainage properties were measured through the frequency of clogging, the percentage of leachate recovered and the dryness of accumulated sludge. Plant development was measured through the density, the height and the stem diameter. Purification performance was evaluated from the reduction rate. Biosolids quality was measured after 3 months of maturation. The results show that the clogging frequencies were 9.5%; 0% and 3.7%; the volume of leachate recovered was 42.2%; 20.4% and 24.7% and, the dryness was 33.4%; 61.1% and 52.4% for FS-ST, FS-STT and SS respectively. Plants densities were about, with densities 197.1, 171.3 and 178.3 plants/m^2 in beds fed respectively with FS-ST, FS-STT and SS. Despite the high removal rates, the concentrations of pollutants in the leachates are above the Senegalese standard NS 05-061 for discharge into the environment. The biosolids are all mature with C/N and NH_4^+/NO_3^- ratios lower than 12 and 1 respectively. The biosolids are also rich in organic and mineral elements. The concentrations of Ascaris eggs are higher than the WHO recommendations. These biosolids should be stored for additional time or composted.

Keywords

Biosolid Quality, Dewatering Performance, Planted Drying Beds, Purification Performance, Sludge Type

1. Introduction

Planted drying beds are a simple, low-cost technology that requires little investment [1]. They reduce sludge disposal costs and produce well composted biosolids [1]. These systems are able to process different types of sludge with a dry matter content of about 0.5 to about 3 - 5% [2].

Planted drying beds have been used for several years in the treatment of effluents of various qualities such as animal manure, wastewater from food processing industries, leachate from household waste dumps, sewage sludge, industrial and mining wastewater [3]. This technology has several advantages. However, the benefits of using this technology are often offset by frequent operational problems, including slow and insufficient dewatering of sludge, poor plant growth, odor, and poor mineralization of waste sludge [4]. All these problems are largely related to the quality of the sludge or the treated wastewater.

To date, most studies on planted drying beds for sludge treatment, focus on treatment design and efficiency [2] [5] and only a few addresses the effects of sludge nature on plant growth [6], dewatering and mineralization [7] [8]. However, the composition of the sludge, e.g., fat content, ratio of organic to inorganic matter, etc., as well as the climatic conditions must be considered when sizing planted drying beds [4].

Different constituents of the sludge bind a certain amount of water. Constituents like starch (carbohydrates) or peptides (proteins) chemically bind much more water according to Nielsen and Willoughby [9]. These authors also identified the fat, starch and peptide content in the sludge, as well as the form of treatment (sludge age, sludge concentration, polymer addition, level of sludge digestion) as important parameters for dewatering. Dry matter (DM) content also plays an important role because evapotranspiration is increasingly reduced with increasing sludge dryness. In addition, water stress can compromise plant vitality [5].

All these results highlight the importance of an optimum operating strategy that ensures good drainage, efficient contaminant removal, adequate plant growth and appropriate mineralization of the accumulated sludge. This study related to the influence of sludge quality opens the possibility of formulating new guidelines for planted bed designers and operators based on field measurements. This could lead to an increase in the competitiveness of planted beds by making this technique more efficient and reliable [10]. A good development of this biotechnology in tropical conditions must also be oriented towards the definition of specific operating conditions in relation to the types of sludge. This is the aim of this work which has as objective the determination of the influence of the nature of the incoming sludge on the drainage, the purification performances and the quality of the biosolids.

2. Materials and Methods

2.1. Materials

2.1.1. Description of the Experimental Device

The experimental setup is composed of the nine 200-liter barrels [8]. Each barrel has a height of 90 cm and a diameter of 50 cm. The filter layer is composed from bottom to top by a 10 cm thick layer of coarse gravel, a 10 cm layer of fine gravel and 15 cm of sand. At the bottom of this filtering layer, there is a drainage device consisting of a perforated PVC pipe [8]. This pipe has a diameter of 4 cm. It is through this pipe that the leachate is evacuated to a collection barrel located at the bottom of each experimental bed. The sand layer is composed of beach sand. This sand has the following characteristics: a d10 of 0.35 mm, a d60 of 0.75 mm and a uniformity coefficient (UC) of 2.14 [8].

2.1.2. Different Types of Sludge Treated

1) Faecal Sludge from Septic Tanks (FS-ST)

Faecal sludge (FS) comes from onsite sanitation technologies, and has not been transported through a sewer. It is raw or partially digested, a slurry or semisolid, and results from the collection, storage or treatment of combinations of excreta and blackwater, with or without greywater [11]. It is composed of fine, non-flocculated particles in suspension and a liquid fraction in which many salts are dissolved (ammoniacal nitrogen, orthophosphates, hydrocarbonates, etc.), resulting in a high electrical conductivity. The faecal sludge used in this study was collected from the storage tank of the Camberene experimental faecal sludge treatment plant. The sludge was deposited by the emptying trucks and homogenized in the tank before being taken to feed the beds.

2) Settled and Thickened Faecal Sludge (FS-STT)

Thickened sludge is septic tank sludge that has been left to rest in Settling/thickening tanks for about one week. In settling-thickening tanks the suspended solid particles that are heavier than water settle out in the bottom of the tank through gravitational sedimentation [12]. According to these authors, particles accumulate at the bottom of the tank are further compressed through the process of thickening that. In this study, faecal sludge was deposited in the thickening settling tanks of the experimental faecal sludge treatment plant at Camberene (Senegal). The sludge was left in these tanks for one week to settle and thicken.

3) Sewage sludge (SS)

Sewage sludge is sludge, originating from the treatment process of waste water. It is the residue generated during the primary (physical and/or chemical), the secondary (biological) and the tertiary (additional to secondary, often nutrient removal) treatment [13]. The sludge used in this study is from the biological treatment. They were collected at the outlet of the secondary settling tanks of the Cambérène wastewater treatment plant.

2.2. Methods

2.2.1. Implementation of the Experimental Design

The field work lasted fifteen months, including three months of planting, acclimatization and loading; nine months to monitor the purification performance and three months for the maturation of the biosolids accumulated on the bed surface [8].

All beds were planted with 9 cuttings/m^2 of *Echinochloa pyramidalis* with at least two internodes each. After planting, the beds were fed for 15 days with tap water and for another 15 days with the supernatant of the settling/thickening tanks of the experimental treatment plant. This phase represents the acclimatization of the plants. After this stage, the sludge loads were gradually increased up to 50, 100 and 150 kg/m^2*year. This phase lasted two months. During this phase, each bed was fed with the type of sludge it was intended to receive. After these different phases the operation at nominal load started with the load of 200 kg/m^2*year. Thus, among the nine barrels, three were fed with faecal sludge from septic tanks (FS-ST), three others with settled and thickened faecal sludge (FS-STT) and the last three were fed with sewage sludge (SS). All beds were fed with a frequency of one load per week.

2.2.2. Determination of the Drainage Capacity of the Beds

The parameters used to measure the drainage capacity of the beds were the presence or absence of free water on the bed surface after one week of feeding (clogging), the amount of leachate recovered and the dryness of the sludge accumulated on the top of the bed (biosolids). All these measurements were made one week after feeding. The presence of free water on the bed surface that we consider as clogging was done empirically according to Kengne *et al*. [14].

The amount of leachate recovered is evaluated by measuring the height of the percolate collected in the previously calibrated collection barrel [8]. For the dryness measurement, samples of the accumulated were taken from three different points.

The dryness was determined from a composite sample made of the three subsample taken in each bed [8]. Dryness measurement was done through the determination of dry matter by oven dehydration at 105°C and differential weighing [15].

2.2.3. Measurement of the Morphological Characteristics of Macrophytes

The development of the macrophytes was monitored to see their behavior in relation to the nature of the incoming sludge. The parameters measured are density, size and average diameter. Density is measured by dividing each bed into 4 equal parts. The stems are counted in one of the 4 parts chosen randomly. The number of stems counted is multiplied by four and divided by the area of the pond to give the density of plants in each bed per m^2 [8]. The size of the plants is measured with a graduated ruler. Stem diameter is measured with an electronic caliper. It is measured at five centimeters from the top of the accumulated biosolids layer. The measurement of the height of the plants as well as the average diameter was done on ten plants randomly selected in each bed [8]. The corresponding value for each measurement is obtained by averaging the measurements from these ten plants [8].

2.2.4. Evaluation of the Purification Performances

For each application, raw sludge and leachates were collected. The leachates are collected one week after feeding in the recovering tank located at the bottom of each experimental bed. All samples are analyzed in the laboratory for parameters such as total solids (TS), total volatile solids (TVS), total suspended solids (TSS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonia (NH_4^+), nitrate (NO_3^-), total phosphorus (TP), orthophosphates (PO_4^{3-}) and helminth eggs. The pH, the redox potential, the conductivity and the salinity were measured directly in the incoming sludge and the leachate with a multifunctional Hach HQ 40d pH-conductivity meter equipped with specific probes. TS, TVS, TSS, COD, TKN, ammonia, nitrate, TP and orthophosphate are analyzed in triplicate through conventional methods according to the procedures indicated in the Standard Methods for the Examination of Water and Wastewater [15] [12]. The removal efficiencies were evaluated only for the physico-chemical parameters (TS, TVS, TSS, COD, TKN, NO_3^-, NH_4^+, TP, PO_4^{3-}). These removal efficiencies were calculated according to the following formula (Eq 1):

$$\text{Removal efficiency}(\%) = \frac{(C_{\text{inflow}} * V_{\text{inflow}}) - (C_{\text{outflow}} * V_{\text{outflow}})}{(C_{\text{inflow}} * V_{\text{inflow}})} * 100\% \qquad \text{Eq 1}$$

With: C: concentration in mg/l and V: volume in liter.

2.2.5. Monitoring the Quality of Biosolids

1) Sampling and sample preparation

Biosolids were collected at the end of the maturation phase, i.e., three months after the feeding was stopped [8]. Samples were taken at several different points with a hand auger in each bed throughout the thickness of the accumulated sludge layer [8]. The samples taken from each bed were mixed and dried at laboratory temperature [8]. The biosolids were then crushed and sieved through a 2 mm mesh screen prior to analysis [8]. The following parameters were evaluated: pHwater and pHKCl, salinity, redox potential, total carbon, total nitrogen, ammonia, nitrates, total phosphorus, orthophosphates, cation exchange capacity, exchangeable bases, heavy metals and helminth eggs.

2) Determination of the agronomic quality

All analyses except those for heavy metals were performed at the Laboratoire des Moyens Analytiques of the Institut de Recherche pour le Développement (IRD) in Dakar, Senegal. The pHwater and pHKCl of the dried sludge samples were measured directly with a Schott Gerate pH meter CG 818. The pHwater was determined in a 1:2.5 (Mass/Volume) suspension after a one-hour contact of dried sludge and deionized water while the pHKCl was measured in a 1:2.5 (Mass/Volume) suspension after a one-hour contact of dried sludge and KCl (1 M) [8]. The residual acidity is obtained by subtracting the pH-water value from the pHKCl value of a given sample according to Stolner [16]. According to this author, if the difference is less than 0.5, the residual acidity is low; if the difference is between 0.5 and 1, it is medium; and if it is greater than 1, it is high. In the latter case, there is a real risk of acidification of soils amended by such organic matter. Conductivity (expressed in µS/cm) and salinity (expressed in ‰)

are measured directly with a Hach CO150 conductivity meter in a 1:5 (Mass/Volume) suspension after a one-hour contact of dried sludge and deionized water [8]. Cation exchange capacity and exchangeable cations were determined by extraction with ammonia acetate (1 N) at pH 7. The determination of exchange capacity was done by colorimetry of the fixed ammonia while that of exchangeable cations was determined by atomic absorption spectrophotometry [8]. Organic carbon was determined by the Walkley and Black method while organic matter, assimilable to loss on ignition, was determined by ignition at 550°C. Inorganic nitrogen was determined by colorimetry after extraction with KCl (1 N) solution. The C/N ratio was measured using an elemental auto analyzer in gas chromatography after sample combustion and reduction of the combustion gases. The total phosphorus (TP) was determined by colorimetry after digestion under reflux in aqua regia. Assimilable phosphorus was extracted by the Olson/Dabin method using sodium bicarbonate solution and sodium fluoride and determined by colorimetry.

2.2.6. Determination of the Sanitary Quality of Biosolids

The concentration of Ascaris eggs was chosen as an indicator of the hygienic quality of biosolids. The choice of Ascaris eggs as an indicator of health risk is related to the fact that Ascaris eggs are highly resistant and can survive various treatments, as indicated by several authors [17]. Furthermore, according to WHO, these nematodes have a very high prevalence in developing countries [18]. Ascaris eggs were determined on samples taken from the full thickness of the accumulated sludge layer at the end of the maturation phase. Ascaris eggs were analyzed using the method developed by Water SA [19].

For each sample, 10 g of biosolids were suspended in ammonia bicarbonate. The solution was mixed for a few minutes using a magnetic stirrer and then filtered through a series of two 100- and 20-micron sieves arranged from top to bottom respectively [19]. For the liquid sludge, one liter was directly filtered through the series of sieves. The sieve residue of the lower sieve is then collected with a Pasteur pipette in one or several centrifugation tubes of 25 or 50 ml, depending on the quantity of residue [19]. These tubes are centrifuged at 3000 rpm for 3 minutes. At the end of the centrifugation, the supernatant is poured out and the pellet is resuspended by vortexing after addition of a few milliliters of zinc sulfate solution having a density higher than 1.3 [19]. The tubes are centrifuged again at 2000 rpm for another 3 minutes. After this second centrifugation, the supernatant of the tubes is then filtered through the 20-micron mesh sieve [19]. The sieve residue is then washed with water to remove the zinc sulfate and collected in other centrifuge tubes. These are then centrifuged for a final time at 3000 rpm for 3 minutes. At the end of the centrifugation, the supernatant is poured [19].

The determination of the Ascaris eggs content is done in the pellet deposited at the bottom of the centrifuge tubes. Ascaris eggs are counted by placing a drop of the pellet on a microscope slide. This drop is covered with a slide before counting under the microscope. Several slides are used depending on the quantity of pellet [19].

2.2.7. Determination of Heavy Metal Concentration

This analysis was performed using HACH analytical techniques (Anonymous, 2000). Biosolids samples were previously diluted in a solution of sulfuric and hydrochloric acid at a rate of 1 g of biosolids in 3 ml of nitric acid and 9 ml of hydrochloric acid. The samples were then boiled on a hot plate for 15 - 20 min. After heating in a 500 ml Erlenmeyer flask, the volume of the flask is made up to the mark. Four 10 ml reading samples (including blank) are then made up for each type of biosolid. Prior to the reading, the Hach manufactured reagent of the desired parameter is added (except in the tube containing the blank). The reading was done on the DR 4000 spectrophotometer.

3. Results and Discussion

3.1. Characteristics of the Sludge Used in the Study

The average characteristics of the sludge used in this study are shown in **Table 1**.

Table 1 shows that faecal sludge from septic tanks (FS-ST) is very low in concentration compared to settled/thickened faecal sludge (FS-STT) and sewage sludge (SS) for all parameters measured. This may have an implication on the quantities of sludge to be load on the beds. Indeed, in relation to the TS concentration, the volumes of sludge that were applied were much higher in the case of FS-ST than with FS-STT and SS. According to the calculation of the quantity of sludge to be applied each week, the average volume applied is 115.52 liters for FS-ST against 10.40 liters for FS-STT and 20.03 liters for SS. These large differences can have various influences on the drainage capacity of the beds and the developments of macrophytes.

Table 1. Average characteristics of sludge used.

Parameters	Unit	FS-ST	FS-STT	SS
TS	(mg/l)	6533.92 ± 3123.75	72599.62 ± 13792.75	37690.69 ± 10391.14
TVS	(%)	51.53 ± 4.66	53.68 ± 3.47	53.56 ± 3.49
TSS	(mg/l)	5613.85 ± 2557.64	71643.00 ± 13667.68	36390.90 ± 110075.44
COD	(mg/l)	6922.31 ± 2884.38	74263.31 ± 14611.47	38725.30 ± 11056.39
TKN	(mg/l)	240.45 ± 100.47	1985.38 ± 382.38	956.21 ± 372.53
NH_4^+	(mg/l)	122.59 ± 32.3	321.00 ± 114.41	208.31 ± 58.03
NO_3^-	(mg/l)	82.81 ± 15.61	238.46 ± 87.43	276.63 ± 171.56
PT	(mg/l)	57.96 ± 15.32	634.54 ± 383.97	205.71 ± 66.19
PO_4^{3-}	(mg/l)	33.58 ± 6.06	48.98 ± 10.94	33.98 ± 14.52
Conductivity	(µS/m)	1693.31 ± 281.68	3189.62 ± 932.88	5370.08 ± 1172.71
Salinity	(g/l)	1.15 ± 0.28	1.65 ± 0.49	2.75 ± 0.73
Ascaris eggs	(n/l)	2028.14 ± 1503.74	7049.14 ± 1824.43	837.28 ± 267.62

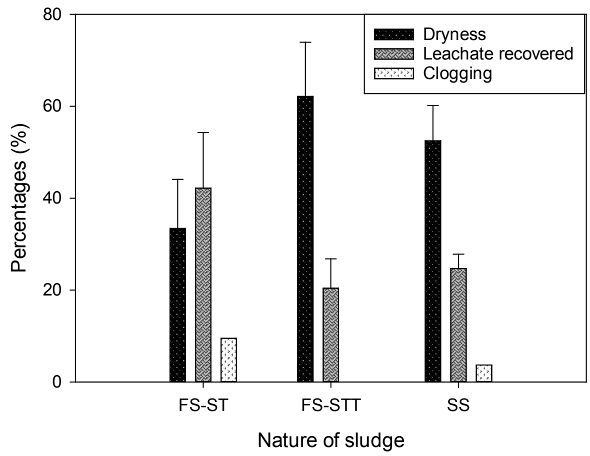
FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge.

3.2. Influence of the Nature of the Incoming Sludge on the Drainage Properties of the Bed

The dryness, proportion of percolate collected, and percentage of bed clogging that determine the drainage properties of the beds are shown in **Figure 1**.

The proportion of leachate collected is higher in beds fed with septic tanks faecal sludge (FS-ST) (42.2% of the applied sludge volume) than in beds fed with settled/thickened faecal sludge (FS-STT) (20.4%) and sewage sludge (SS) (24.7%). These results show that sludge having a high TS content (FS-STT and SS) release less water at the outlet than sludge having a low TS content as FS-ST; certainly, due to the large volumes applied when the TS concentration is low. These findings are similar to those of Dominiak *et al.* [10]. Indeed, according to these authors, the volume of water removed by percolation through the drying beds is related to the volumes of sludge applied. When a large volume of sludge is applied, the pressure is increased at the same time. This high pressure will lead to a higher percolation rate, thus increasing the volume of water lost by percolation.

In this study, the volumes applied with the FS-ST feed are largely more important than those applied with the FS-STT and SS. The latter two types of sludge being more concentrated (**Table 1**), the volumes calculated on the basis of their concentration in total solids are largely less important than those calculated for the FS-ST for the same load of 200 kg/m^{2}*year. The average volume of sludge applied to the beds was 115.52 liters for FS-ST, 10.40 liters for FS-SST and 20.03 liters for SS. These volumes resulted in average sludge heights of 59 cm, 5 cm and 10 cm for FS-ST, FS-STT and SS respectively. As a result, the hydrostatic pressure induced by the amount FS-ST applied was greater than that induced by the other types sludge leading to the large volume of leachate recovered. However, the recovered volumes of leachate are generally less than 50% confirming the results of Stefanakis and Tsihrintzis [20] who showed that on planted drying beds the water was lost mainly by evapotranspiration.



FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge

Figure1. Hydraulic characteristics measured according to the nature of the sludge.

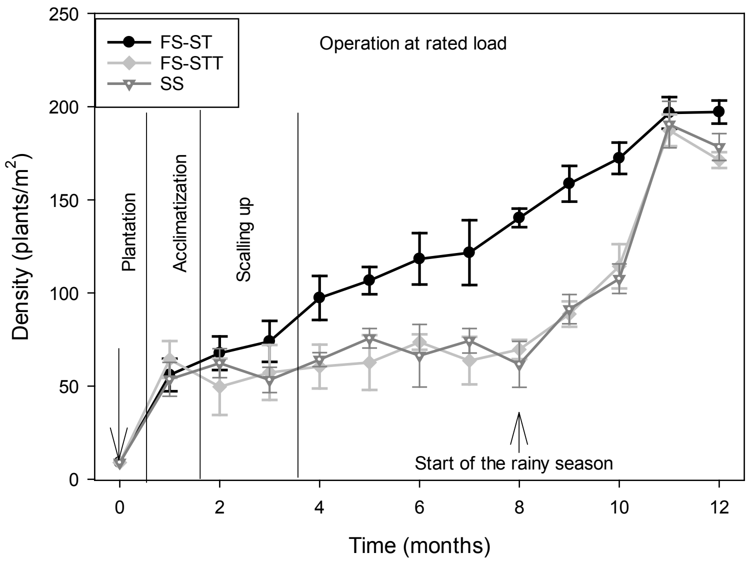
Through evapotranspiration, the macrophytes remove the water trapped in the biosolids (sludge accumulated on the surface of the bed) and contribute by this process to the increase of the dryness. The dryness levels obtained in this study before each week reloading are higher in beds fed with FS-STT (62.1% on average) and SS (52.48%) than in those fed with FS-ST (33.40%). Thus, with the most concentrated sludge, higher dryness levels were obtained in accordance with the results of Uggetti *et al.* [21]. However, these first two types of sludge contain higher organic matter loads (OM) (**Table 1**). Organic matter is considered by Kopp and Dichtl [22] to have an influence on sludge dewatering. These authors studied the binding of water to the sludge and found a dependence of the sludge dewatering with the total volatile solid contents (TVS). Kopp and Dichtl [22] additionally showed that the dewatering of sludge applied increases with decreasing TVS content. Compared to these results, biosolids from FS-STT and SS should then have had lower dryness levels. Unfortunately, this is not the case. In fact, dryness levels of about 62.1% and 52.48% for FS-STT and SS respectively are higher than the dryness of FS-ST (33.40%). However, such results were found by Vincent *et al.* [7]. Indeed, when testing the feasibility of dewatering sewage sludge in comparison with faecal sludge on small-scale planted drying beds in France, Vincent *et al.* [7] showed that despite a low dewaterability of sewage sludge, it dried intensively due to the lower hydraulic load applied. These authors worked with two different loads of sewage sludge. Their results can explain the fact that the dryness levels of biosolids from FS-STT and SS are higher because these sludges are applied with much lower hydraulic loads than FS-ST.

Clogging is only reported in beds fed with SS and FS-ST. The percentage of clogging is about 3.7% and 9.5% in beds fed with SS and FS-ST respectively. This result shows that beds fed with low concentrated sludge clog more frequently than those fed with high concentrated sludge as FS-STT. Indeed, according to several authors, drainage is strongly dependent on the volume of sludge applied and the TSS concentration of the sludge [10] [20] [23] [24]. According to Dominiak *et al.* [23], when a large amount of sludge is applied to a bed, drainage will proceed very slowly, or even stop, in extreme cases leading to clogging. This may be the reason of the high clogging frequencies recorded in beds fed with FS-ST that received high volume of sludge as demonstrated by Langergraber *et al.* [24]. However, despite the low volumes applied compared to the one applied for FS-ST, a clogging frequency of about 3.7% was recorded for beds fed with sewage sludge. These results a priori contradictory may be related to the drainage difficulties associated with the high organic matter concentration of sewage sludge (SS) (**Table 1**). This result is consistent with the findings of Kopp and Dichtl [22].

These results show that with loads calculated based on the TS concentration of sludge, beds fed with thickened sludge and sewage sludge drain better than beds fed with raw faecal sludge. Although this can be considered as an advantage for wastewater treatment, but it can become an issue if the lack of water should result in a water deficit for macrophytes [7].

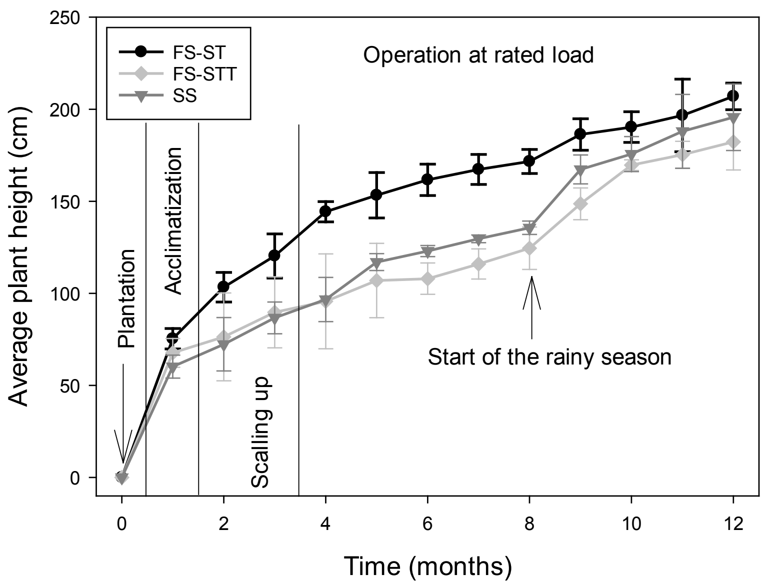
3.3. Influence of the Nature of the Incoming Sludge on the Development of Macrophytes

Changes in density, mean size, and mean diameter of Echinochloa pyramidalis macrophytes over the experimental period are recorded in **Figures 2**, **Figure 3** and **Figure 4** respectively.



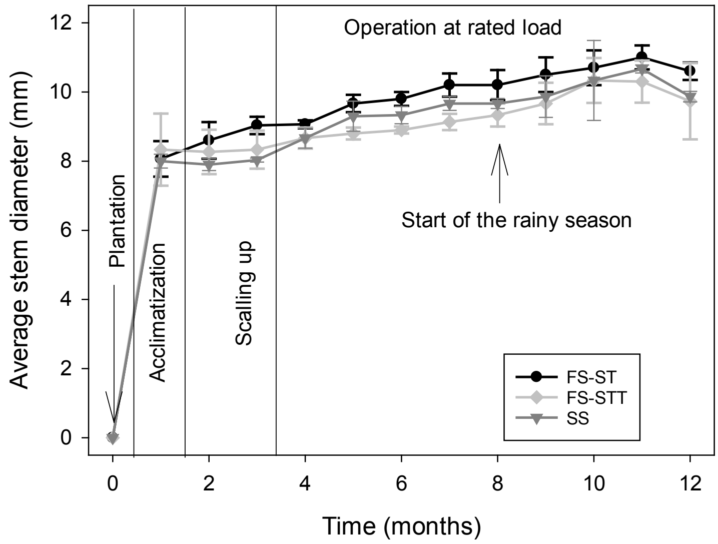
FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge

Figure 2. Densité moyenne d'Echinochloa pyramidalis en fonction de la nature des boues entrantes.



FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge

Figure 3. Taille moyenne d'Echinochloa pyramidalis en fonction de nature des boues entrantes.



FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge.

Figure 4. Diamètre moyen des tiges d'Echinochloapyramidalis en fonction de la nature des boues entrantes.

The monitoring of plant density (**Figure 2**) shows that in beds fed with septic tanks faecal sludge (FS-ST) macrophyte densities are higher. Indeed, from 9 cuttings/m^2 on all beds at the beginning, the density was 56.0; 64.3 and 53.7 plants/m^2 at the end of acclimation phase in the beds fed with FS-ST, FS-STT and SS respectively. During the scaling-up densities varied between 67.7 and 74.0 in beds fed with FS-ST; 49.7 and 57.3 in beds fed with FS-STT and, 62.3 and 53.3 plants/m^2 in beds fed with SS. At the end of the monitoring, the density recorded was 197.1 plants/m^2; 171.3 plants/m^2 and 178.3 plants/m^2 in beds fed respectively with FS-ST, FS-STT and SS.

The macrophytes in the beds fed with raw sludge also show larger height. The average height recorded (**Figure 3**) at the end of the monitoring period are 207.0; 182.3 and 195.7 cm at the beds fed with FS-ST, FS-STT and SS respectively.

In addition to the higher densities and plant heights, the plants in the beds fed with FS-ST also have a larger average stem diameter. The average diameter measured at the end of the monitoring is 10.6 mm compared to 9.7 and 9.8 mm for the plants from the beds fed with FS-STT and SS respectively (**Figure 4**). These results show that the macrophytes in beds fed with FS-ST develop better, followed by those in beds fed with SS and finally those in beds fed with FS-STT.

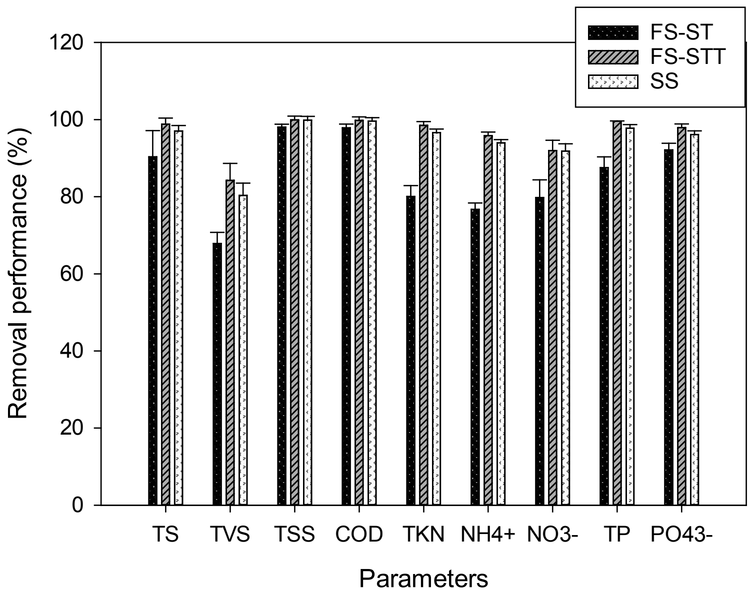
In the beds fed with thickened sludge (FS-STT) and sewage sludge (SS), the macrophytes faced water stress that had negative consequences on their development. This water stress may be related to the fact that both types of sludge are much more concentrated in TS than faecal sludge from septic tanks (FS-ST). Therefore, these sludges are applied with low hydraulic loads resulting in a deficiency of water for the plants. Such results have been reported by several authors. Indeed, by comparing the purification performance of planted beds receiving sewage sludge and others receiving septic tank sludge, Vincent *et al*. [7] have shown that the high concentrated sludge (sewage sludge) dried intensively because of the low hydraulic load applied, in contrast to faecal sludge that was less concentrated and therefore applied with a higher hydraulic load. These authors further stated that the low hydraulic loads could induce water stress during the summer and could lead to premature death of the macrophytes. Furthermore, according to Koottatep *et al*. [5], the temporary deficit of water in the filter media and biosolids can lead to a decrease in plant density. Such results are illustrated in **Figure 2**, which shows low densities in beds fed with FS-STT and SS. The densities have, moreover, increased from the 9th month (July) corresponding to the rainy season.

The water stress could be the reason of the smaller plant diameters and low average heights recorded in the beds fed with FS-STT and SS because the plants in the beds fed with FS-ST had a better development due to a higher hydraulic load. Indeed, Li *et al*. [25] showed that high soil water content enhanced vegetative growth through increased productivity yield, plant height and stem diameter.

3.4. Influence of the Nature of the Incoming Sludge on the Purification Performance

3.4.1. Purification Performances

The purification performances of the beds according to the nature of the sludge treated are shown in **Figure 5**. This figure represents the averages of the depollution rates obtained during the 13 campaigns.



FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge.

Figure 5. Percentage reduction of pollutants according to the type of sludge.

The percentages of pollutants removal are high for all parameters, regardless of the nature of sludge. They are higher than 65% for all the monitored parameters. The yields in TS, TSS and COD are close whatever the nature of the sludge applied with depollution rates above 90% for each of these parameters. Similar efficiencies have been reported by Kengne *et al.* [26] on experimental beds in Cameroon using *Echinochloa pyramidalis* as macrophytes for the treatment of faecal sludge.

TSS and COD are reduced in the same proportions whatever the type of sludge applied. The removal rates are higher than 97% for these two pollutants for all types of sludge. However, TSS is 12 and 5 times more concentrated and COD 11 and 6 times more concentrated in FS-STT and SS respectively than in FS-ST. The removal of TSS and COD does not therefore depend on the nature of the sludge. According to Kuffour *et al.* [27], their elimination is due to the capacity of the filtering media to block the solids contained in the sludge. In fact, according to several other authors, the main process of TSS removal is physical filtration by the filter media due to the high proportion of particulate elements in the sludge [28] [29]. Suspended solids are also removed by sedimentation and trapping [30]. Both of these processes could be responsible for COD removal. Indeed, COD removal is comparable to that of TSS. This indicates that COD removal is mainly due to physical processes, such as filtration through the filter substrate, rather than biological processes [29]. This good removal by filtration may be due to the characteristics of the Dakar'sfaecalsludge which has 93% COD in particulate form, according to Walker [31].

TS is also removed with high percentages of reduction. From 90.3% in beds fed with FS-ST, the removal rates are about 98.8% and 97.1% for FS-STT and SS respectively. These results show that TS is removed together with TSS and COD during the filtration of the sludge through the filter media of the drying beds.

The removal rates of TVS are between 60 and 85%. However, beds fed with FS-ST have lower removal rates for TVS. Indeed, the rate of TVS reduction was 67.90% for beds fed with FS-ST against 84.26 and 80.34% for beds fed with FS-STT and SS respectively.TVS represent the organic fraction of the TS. Their removal is therefore closely linked to that of the TS. Then, the higher removal rates obtained in beds fed with FS-STT and SS could be related to their higher concentrations in TS (**Table 1**) and the lower removal rates of TS in beds fed with raw sludge (**Figure 5**).

Regarding nutrients, pollution reduction rates are higher than 70% for all pollutants. However, removal rates recorded in beds fed with FS-ST are lower for TKN (80.10%), ammonium (76.72%), nitrate (79.78%), total phosphorus (87.53%) and phosphates (92.15%) compare to those recorded in beds fed with FS-STT (98.51%, 95.84%, 91.98%, 99.58%, 97.94% for TKN, ammonium, nitrate, total phosphorus and phosphates respectively) and SS (96.61%, 96.97%, 91.82%, 97.78%, 96.14% for TKN, ammonium, nitrate, total phosphorus and phosphates respectively). In fact, pollution reduction rates are more than 10 times higher in beds fed with FS-STT and SS. The higher removal rates recorded in these beds may be due to their high concentration on TS which enhances their physical retention on the bed surface. Such results were reported by Lee *et al*. [32] who showed that high removal rates of TKN were related to physical processes such as filtration and adsorption. Paing and Voisin [33] also argued that TKN removal was mainly due to retention, ammonification and partial nitrification of organic nitrogen. It is probably through this process that ammonium, total phosphorus and nitrate are removed.

The lower treatment performance recorded for beds fed with FS-ST may be related to the larger volumes of sludge applied as a result of the low TS contents of these types of sludge. Indeed, on average 115.5 liters of raw sludge were applied each week against 10.4 liters for FS-STT and 20.3 liters for SS. The amount of sludge applied strongly influences the drainage rate which is responsible for leaching. Ouyang *et al*. [34] showed that the overall removal efficiency of a planted drying bed was more or less controlled by leaching. Sludge with a low concentration (which is applied with large volumes) would accelerate drainage, which can result in the leaching of solids [10]. In addition, Rousseau *et al*. [28] stated that dissolved nutrients can be transferred slowly by diffusion. This may be the cause of the low removal rates of TKN, ammonia, nitrate and total phosphorus noted in beds fed with FS-ST.

Orthophosphate removal rates are high and close regardless of the type of sludge used in the bed feed. This may be related to the good adsorption of phosphates by the filter media of the beds. In fact, Arias and Brix [35] had shown on pilot scale planted drying beds that sand was very effective in removing phosphate. This chemical adsorption of the drying bed filter media is enhanced, according to Prochaska *et al*. [36], by a high retention time often materialized by low infiltration. The high phosphate removal rates in beds fed with FS-STT and SS may be related to the high concentration of these sludges, compared to FS-ST. This characteristic increases the retention time of these sludges with the result of poor drainage. Indeed, according to Dominiak *et al*. [10], the thicker the sludge, the longer it takes to infiltrate. Drainage is also highly dependent on the volume of sludge applied and the concentration of TSS in the sludge [23] [24]. If a large amount of sludge is applied to a bed, drainage will proceed very slowly, or even stop, in extreme cases [10] leading to clogging. These phenomena of reduced infiltration and clogging will result in increased retention time in the bed. This may be responsible for the high depollution rates recorded in beds fed with FS-ST that are applied with high loads.

3.5. Physicochemical Characteristics of Leachates

The characteristics of the leachates collected at the outlet of the planted drying beds, fed with FS-ST, FS-ST and SS are reported in **Table 2**. These results, expressed as average concentrations, are compared with the limit values of the Senegalese Standard NS 05-061 relating to the discharge of wastewater into the receiving environments.

Table 2. Average concentrations with standard deviations of leachate recovered for each type of sludge used in comparison with Standard NS 05-061.

Parameters	Units	FS-ST	FS-STT	SS	NS 05-061
TS	(mg/l)	1400.69 ± 1836.10	4096.62 ± 2484.25	4424.64 ± 1591.16	-
TVS	(%)	36.75 ± 5.24	40.76 ± 8.24	42.09 ± 7.44	-
TSS	(mg/l)	242.56 ± 109.54	247.67 ± 90.98	219.64 ± 40.98	50
COD	(mg/l)	326.95 ± 179.47	723.12 ± 297.82	591.12 ± 143.60	200 - 100
TKN	(mg/l)	106.32 ± 37.17	142.45 ± 35.90	129.68 ± 80.12	30
NH_4^+	(mg/l)	63.39 ± 20.47	64.35 ± 21.42	50.18 ± 31.63	-
NO_3^-	(mg/l)	37.20 ± 15.16	92.24 ± 78.70	90.44 ± 49.14	-
TP	(mg/l)	16.05 ± 3.90	12.81 ± 12.81	18.27 ± 12.06	10
PO_4^{3-}	(mg/l)	5.86 ± 2.94	4.88 ± 1.73	5.24 ± 2.82	-
Conductivity	(µS/m)	2062.69 ± 1591.53	4050.05 ± 2224.90	4694.31 ± 1587.65	-
Salinity	(g/l)	1.17 ± 0.89	2.08 ± 1.32	2.47 ± 0.84	-

FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge

The leachates from the beds fed with FS-ST are weakly concentrated in TS, COD and nitrate and have much lower salinities and conductivities levels than the leachates from FS-STT and SS. Moreover, it is noted that the leachates have concentrations higher than the limit values of the Senegalese standard, NS 05-061. These waters cannot therefore be discharged into the receiving environments. They must therefore be treated before being released into the environment.

3.6. Agronomic and Sanitary Quality of Biosolids

3.6.1. Agronomic Value of Biosolids

The characteristics of the biosolids collected from the drying beds are presented in Table 3. These are average values representing the 3 replicates of the planted beds fed with FS-ST, FS-STT and SS.

These biosolids are slightly acidic with pHwater of about 6, regardless of the nature of the sludge treated. Similar pHwater were found by Kengne *et al.* [37] on Echinochloa pyramidalis beds treating faecal sludge in Cameroon. Their residual acidity is low because the differences between pHwater and pHKCl are less than 0.5; the limit value below which residual acidity is considered low according to Stolner [16]. The differences between these two pHs found, in this study, are 0.14; 0.04 and 0.10 for FS-ST, FS-STT and SS respectively. Biosolids are also less concentrated in salt with concentrations of lower than 2 ‰ regardless of the nature of the sludge.

The biosolids have C/N ratios below 12; the limit value below which a compost can be considered, according to Bernal *et al.* [38], as mature. The C/N ratios obtained are about 9.01, 9.05 and 10.05 for FS-ST, FS-STT and SS respectively. These biosolids can then be considered as mature. This maturity is corroborated by the NH_4^+/NO_3^- ratios that are below 1, the threshold value defined by Ko *et al.* [39] as evidence of a mature compost.

Table 3. Physico-chemical characteristics of biosolids according to the nature of sludge.

Parameters	Units	FS-ST	FS-STT	SS
pH H_2O	-	6.54 ± 0.06	6.45 ± 0.03	6.46 ± 0.01
pHKCl	-	6.40 ± 0.02	6.41 ± 0.02	6.36 ± 0.00
Conductivity	µS/cm	1762.67 ± 577.41	3308.67 ± 409.75	3165.33 ± 129.37
Salinity	‰	0.87 ± 0.31	1.73 ± 0.25	1.60 ± 0.08
$N(NO_3)$	mg/kg	393.47 ± 193.46	1093.23 ± 104.75	714.22 ± 51.24
$N(NH_4)$	mg/kg	183.90 ± 32.49	546.99 ± 107.47	242.48 ± 41.60
$N(NH4)/N(NO_3)$	-	0.46	0.50	0.33
Total N	%	2.80 ± 0.21	2.59 ± 0.15	2.35 ± 0.19
Total C	%	25.20 ± 1.77	23.44 ± 1.79	23.55 ± 1.72
C/N	-	9.01 ± 0.08	9.05 ± 0.24	10.05 ± 0.11
Organic C	g / kg	217.45 ± 16.43	199.41 ± 10.65	201.97 ± 15.61
Total P	P g/kg	10.95 ± 0.14	9.21 ± 0.09	10.82 ± 0.10
Available P	P g/kg	2.54 ± 0.13	1.97 ± 0.08	2.14 ± 0.13
Ca	méq%	55.15 ± 7.93	103.85 ± 5.72	100.62 ± 8.49
Mg	méq%	3.87 ± 0.70	5.15 ± 0.95	5.16 ± 0.99
Na	méq%	2.35 ± 0.21	3.23 ± 1.22	3.37 ± 1.07
K	méq%	1.34 ± 0.16	2.07 ± 0.46	1.28 ± 0.26
Cation exchange capacity	méq%	44.44 ± 2.39	36.77 ± 2.96	39.50 ± 2.39

FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge.

Moreover, the ammonium concentration seems to confirm this maturity. Indeed, the ammonium concentrations of about 0.18; 0.55 and 0.24 g/kg are below or close to the threshold value (<0.4 g/kg) defined by Bernal *et al*. [40]. These three parameters among those used for monitoring compost maturity show that the biosolids obtained in this study are all mature. However, the cation exchange capacity (CEC) of the biosolids is below the limit value (> 60 meq/100 g) identified by Harada and Inoko [41] as that of a mature compost. The CEC has been considered as an important factor by several authors, as it gives an indication of the humification of the compost [41]. Since the maturity of a compost cannot be determined by a single parameter [40], these low values of CEC of biosolids from different types of sludge cannot put into question the maturity of these.

Biosolids have a high agronomic value, regardless of the nature of the sludge. Their concentrations on various nutrients such as total carbon, organic carbon, total nitrogen, nitrate, total phosphorus, P_2O_5, Ca, Mg, Na and K are close to the values obtained by Kengne *et al*. [37] and Sonko *et al*. [8] on mature biosolids from planted drying beds after six or three months of maturation respectively. These results show that regardless their nature, the sludge are well transformed into a stable humus with comparable characteristics. They are in contradiction with the work of Vincent *et al* [7] who found that sewage sludge (SS) had lower mineralization rates than faecal sludge (FS-ST) when testing the feasibility of treating FS-ST on planted drying beds in France.

Table 4. Trace metal concentrations in collected biosolids compared to European standards.

	Cr	Cu	Zn
Unit	ppm	ppm	ppm
FS-ST	38 ± 6.16	395.17 ± 11.71	113.33 ± 44.98
FS-STT	58.17 ± 9.83	424.33 ± 43.96	142.50 ± 70.32
SS	36.83 ± 62.90	403 ± 24.39	110.50 ± 38
EUC standards	100	1000 - 1750	2500 - 4000

FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge.

3.6.2. Heavy Metal Concentration of Biosolids

The concentrations of heavy metals and trace metals in the collected biosolids are given in **Table 4**.

The concentrations in heavy metals are quite similar regardless of the nature of the sludge treated. The average Cr concentrations were 38, 58, 17 and 36.83; Cu concentrations were 395.17, 424.33 and 403.24 and, Zn concentrations were 133.33, 142.50 and 110.50 ppm for FS-ST, FS-STT and SS respectively. These concentrations are lower than the European Union Commission guidelines. These biosolids can therefore be safely used as an agricultural amendment.

3.6.3. Sanitary Quality of Biosolids

The concentration of Ascaris eggs in the biosolids collected after 3 months of maturation is recorded in **Table 5**. This table also mentions the temperature of the biosolids and the dryness of the biosolids at the time of sampling.

The high parasite egg concentrations in the biosolids are due to the retention of 100% of parasite eggs by the filter media according to Kengne *et al.* [26] and Sonko *et al.* [8]. Indeed, the total Ascaris egg concentrations are 209.5 eggs/g TS in these biosolids compared to 87.3 and 49.1 eggs/g TS in biosolids from beds fed with FS-ST and SS respectively. The high concentrations of Ascaris eggs in biosolids from FS-STT are due to their settling in the settling/thickening tanks.

Ascaris eggs are highly inactivated with reduction rates about 85.5, 82.4 and 82.7% in biosolids from beds fed with FS-ST, FS-STT and SS respectively. Despite these high inactivation rates, the concentrations of Ascaris eggs remain above the WHO guidelines of less than one viable nematode egg/g TS [18]. Indeed, biosolids collected from beds fed with FS-ST, FS-STT and SS, after three months of maturation, have concentrations of 12.6, 37.7 and 8.5 fertile eggs/g TS respectively. These results show that the three-month maturation period is insufficient to inactivate Ascaris eggs. In tropical climatic conditions, Kengne *et al.* [37] have stated that helminth inactivation can be linked to the adverse environmental conditions such as dryness rather than temperatures which are often low as in this study where they are around 30°C. In planted drying beds longer storage times can result in increased inactivation of helminth eggs, with a minimum of six months storage for planted drying beds required for the adequate reduction of helminth eggs in tropical countries [37].

Table 5. Temperature, dryness and concentration of Ascaris eggs in biosolids collected from the surface of the planted beds according to the nature of the incoming sludge.

			Ascaris eggs (egg/g TS)		
Type of sludge	Dryness (% TS)	Temperature (°C)	Fertile	Non fertile	Total
FS-ST	80,6	29 ± 0.21	12.6	66.7	87.3
FS-STT	78,4	30 ± 0.91	36.7	172.8	209.5
SS	75,6	29 ± 0.83	8.5	40.6	49.1

FS-ST: septic tanks faecal sludge, FS-STT: settled/thickened faecal sludge, SS: sewage sludge.

These biosolids, despite their high agronomic value, cannot be used directly as an agricultural amendment because of their high health risk. They must therefore be stored for an additional period of time in order to eliminate their parasitic load.

4. Conclusion

Planted drying beds are capable of treating several categories of sludge. In this study, the beds were used to treat FS-ST, FS-STT and SS. Overall, the results were encouraging for all categories of sludge. In details, the study shows that planted beds treating FS-STT and SS clog less frequently than beds fed with raw sludge and biosolids from the first two types of sludge have much higher dryness rates than the biosolids from the beds fed with FS-ST. These high dryness rates could be the reason for the poor plant development with law plant densities, plant heights and plant stem diameters recorded in beds fed with FS-STT and SS. The treatment performance for TS, TSS and COD is not influenced by the nature of the sludge. Treatment performances for TVS, nitrogen, ammonium and nitrate are lower in the beds fed with FS-ST than in the beds fed with FS-STT and SS. However, leachate concentrations of TS, COD and nitrate are significantly higher in the thickened sludge and sewage sludge beds. Furthermore, for all parameters, the leachates have concentrations higher than the Senegalese discharge standard. The biosolids are all stable and mature after three months. However, they have concentrations of Ascaris eggs higher than the WHO recommendations and must be stored for an additional period of time in order to ensure the proper elimination of Ascaris eggs.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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