Final Manuscript Submitted to: Ecological Engineering 94 (2016) pages 617 - 621

Novel plant species for faecal sludge drying beds: Survival, biomass response and forage quality

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ABSTRACT

This study investigated the ability of forage plant species that have not previously been used in the treatment of faecal sludge to grow in planted drying beds. Experiments were conducted in 11 L and 25 L pots with layers of sand and gravel to replicate drying beds, and three loading rates (100, 200, 300 kg TS/m^2*year). Plant density with faecal sludge was increased for *Echinocloa colona, Echinochloa crus-galli, Echinochloa pyramidalis, Paspalidium geminatum*, and *Paspalum vaginatum* (196, 64, 171, 170 and 98% respectively), whereas *Eleusine indica* and *Imperata cylindrica* had reduced growth with faecal sludge (−21, −80%, respectively). Protein, minerals, nutrients and fibers as metrics of forage quality all indicated that the species in these trials improved with growth in faecal sludge drying bed conditions. Different species should be selected based on treatment objectives, for example *E. crus-galli* had optimal forage production characteristics at 200 and 300 kg TS/m^2*year loading rates, whereas *P. geminatum* and *P. vaginatum* at 100 and 200 kg TS/m^2*year. This study suggested that in addition to *E. pyramidalis* – *E. crus-galli, P. geminatum*, and *P. vaginatum* are also good candidates for treatment of faecal sludge with simultaneous forage production to offset treatment costs.

Keywords:
Planted drying bed
Resource recovery
Fodder
Sub-Saharan Africa
Wastewater

1. Introduction

Planted drying beds are a promising technology for faecal sludge treatment in low-income countries. They have low energy requirements, low operating and maintenance costs, and can generate revenue to offset treatment costs through resource recovery as fodder and soil amendments (Kengne et al., 2009). Planted drying beds have been used in Europe for dewatering and stabilization of municipal wastewater sludge since the 1980s (Steen, 2003). However, faecal sludge is highly variable, and has organic and nutrient concentrations one to two times higher than wastewater sludge (Strande et al., 2014), which creates hostile growing conditions for most plant species (Kengne et al., 2008), and means experiences from wastewater treatment are not directly transferable. Research is needed prior to full-scale uptake on how to adapt the technology to local contexts in low-income countries, including operation with indigenous plant species (Kouawa et al., 2015; Rodríguez and Brisson, 2015).

Some research has been conducted on adapting this knowledge for treatment of faecal sludge in tropical climates (Koottatep et al., 2001; Kengne et al., 2014; Sonko et al., 2014). However, of the investigated plants, *Typha* sp., *Cyperus* sp. and *Phragmites* sp. have limited economic benefit for resource recovery, and *Echinochloa pyramidalis* is the only forage plant (De Maeseneer, 1997). Forage plants need to be identified that can be used in planted drying beds for resource and cost recovery. For example, sale of *E. pyramidalis* for fodder in Cameroon can offset seven percent of annual operation and maintenance costs of treatment (Pare et al., 2012). The objectives of this study were to identify forage plants with market value that have not previously been used in planted drying beds, and to evaluate their growth potential and forage quality with increasing faecal sludge loading rates.

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The final version is availabe at Elsevier via http://dx.doi.org/10.1016/j.ecoleng.2016.05.027

Table 1
Characteristics of faecal sludge and faecal sludge effluent used in the 11 L pot experiments (Exp 1) and 25 lilter pot experiments (Exp 2), average and standard deviation.

Parameters	Units	FS effluent		FS	
		Exp 1	Exp 2	Exp 1	Exp 2
TS	g/L	1.6 ± 0.2	1.2 ± 0.2	4.0 ± 0.9	4.0 ± 0.9
TVS	(%TS)	50.4 ± 3.0	47.9 ± 2.0	55.0 ± 1.0	61.2 ± 8.7
TSS	(g/L)	0.2 ± 0.1	0.1 ± 0.1	2.4 ± 0.5	2.7 ± 1.1
pH	–	7.0 ± 0.1	6.9 ± 0.2	7.5 ± 0.3	7.4 ± 0.4
Conductivity	(μs/cm)	3663 ± 110	3557 ± 1101	3551 ± 551	2994 ± 553
Salinity	(g/L)	1.7 ± 0.2	1.6 ± 0.2	1.8 ± 0.3	1.9 ± 0.3
COD	(mg/L)	–	–	7168 ± 1527	6818 ± 1130
BOD_5	(mg/L)	–	–	1732 ± 1761	1653 ± 1614
TN	(mg/L)	–	–	523 ± 123	385 ± 246
NO_3^-	(mg/L)	–	–	45.5 ± 23.3	27.8 ± 30.6
TP	(mg/L)	–	–	83.3 ± 13.1	70.8 ± 11.4

FS: faecal sludge.

2. Materials and methods

2.1. Identification of forage plants

Plants were collected from five field sites (shown in graphical abstract and supplemental information) during September 2011 at the end of the rainy season, based on growth in wetlands alongside common planted drying bed species, or areas impacted by anthropogenic contaminants (e.g. open ditches with wastewater). Only forage plants were selected. Following the collection of plants, interviews were carried out with vendors and urban livestock holders to verify market values.

2.2. Ability of plants to grow in faecal sludge conditions

Growth assays with faecal sludge were carried out during July to August 2012 at the Cambérène Wastewater and Faecal Sludge Treatment Plant in Dakar, Senegal. Dakar has a semi-arid climate (Sahelo-Soudanian), with a dry season from November to May, and rainy season June to October. The average annual rainfall is 300–400 mm, and average temperature 22–25 °C from December to April and 27–32 °C from May to November. Faecal sludge was obtained from vacuum trucks that collect it from septic tanks and discharge it at the treatment plant.

As a first screen, each of the species was grown in eleven liter pots filled with washed gravel (5 cm; Ø:5–10 mm), and washed sand (5 cm; Ø:0.2–0.6 mm) to replicate planted drying bed conditions. Five young shoots were planted into each pot, with six repetitions for each species (i.e. three treatment, three control). During acclimatization, plants were watered with tap water once a day for two weeks, followed by effluent from faecal sludge settling tanks (characteristics in Table 1) three times per week for four weeks. Following acclimatization, plants were irrigated with faecal sludge effluent for an additional four weeks, during which time plant growth was measured weekly by shoot height, and plant density and mortality were visually observed. At the end of four weeks, total biomass was recorded as dry weight and root growth as number of main roots for each plant reported as density.

Faecal sludge samples were kept in a cooler on ice and transported to the lab within one hour for analyses. pH, conductivity and salinity were measured directly with Hach HQ 40 d multi pH-conductivity meter probes. Total solids (TS), total volatile solids (TVS), total suspended solids (TSS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), Ammonia (NH_3), Nitrate (NO_3^-) and total phosphorus (TP) were analysed following Standard Methods (APHA, 2005).

2.3. Effect of faecal sludge loading rate on plant growth and forage quality

Plant species were selected for further trials based on: ability to grow in faecal sludge effluent, market value, and they had not previously been used for planted drying beds. These plants were then grown in 25 L pots filled with washed gravel and sand during October–December 2012. Following acclimization with tap water and faecal sludge effluent, plants were then irrigated with faecal sludge (Table 1) at loading rates of 100, 200 and 300 kg TS/m^2*year for four weeks. Plants were grown in triplicate. Measurements were the same as above.

Potential plant fodder quality was measured by total mineral (ash), protein, fiber, TP, and TKN concentrations. A composite sample was made for the three repetitions of each treatment from above ground dried biomass. Ash content as a measure of the total amount of minerals was determined by dry ashing. TKN was determined by the Kjeldahl digestion method (AOAC, 2000), crude protein (CP) calculated as TKN*6.25 (AOAC, 2000), acid digestion fiber (ADF) was measured by boiling a sample of forage in a detergent under acid (pH = 2) conditions and filtering the boiled sample through filter paper. Crude cellulose (CC) was determined by the AFNOR (1993) method. The sample is first digested in sulfuric acid (0,26N), and then potassium hydroxide (0,23N) in the unit (Tecator Fibertec M6). TP was extracted by dry ashing in a muffle furnace diluted with an acid mix (HCL/HNO_2) and analyzed by molybdate procedure (Murphy and Riley, 1962).

3. Results and discussion

3.1. Species identified

The following seven species of Poaceae (grass) were identified in the field: *Echinochloa colona, Echinochloa crus-galli, E. pyramidalis, Eleusine indica, Imperata cylindrical, Paspalidium geminatum and Paspalum vaginatum*. Only *E. pyramidalis* had previously been evaluated for use in planted drying beds for treatment of faecal sludge (Kengne et al., 2008). The Poaceae family has a worldwide distribution, are highly adaptable, have rapid growth, and are good forage plants (Saarela, 2005), indicating their relevance for forage production and treatment with planted drying beds.

3.2. Economic potential for forage

A total of 107 interviews were conducted with urban livestock handlers (49%), livestock traders (23%) and forage traders (28%) at local markets. Based on the interviews, other uses for plants, such as weaving for roofs and fences, were not considered as these uses do not have as consistent demand as forage. Urban livestock is

Table 2
Plant growth characteristics following initial screening for four weeks with faecal sludge effluent, average and standard deviation. Control plants were irrigated with tap water.

Species	Shoot density (Number of Shoot/m^2)		Shoot height (cm)		Root density (Number of Root/m^2)	
	Control	Treatment	Control	Treatment	Control	Treatment
E. colona	347 ± 95	1027 ± 201	53 ± 8	115 ± 8	480 ± 178	647 ± 117
E. crus-galli	187 ± 76	307 ± 46	68 ± 8	100 ± 16	293 ± 90	740 ± 156
E. Pyramidalis	227 ± 50	613 ± 95	87 ± 8	142 ± 5	353 ± 42	813 ± 42
E. indica	160 ± 53	127 ± 110	28 ± 7	21 ± 7	187 ± 12	207 ± 12
I. cylindrica	100 ± 20	20 ± 20	37 ± 4	16 ± 29	147 ± 61	173 ± 46
P. geminatum	287 ± 58	773 ± 194	61 ± 4	107 ± 11	567 ± 103	713 ± 70
P. vaginatum	353 ± 114	700 ± 111	46 ± 2	90 ± 7	313 ± 61	493 ± 50

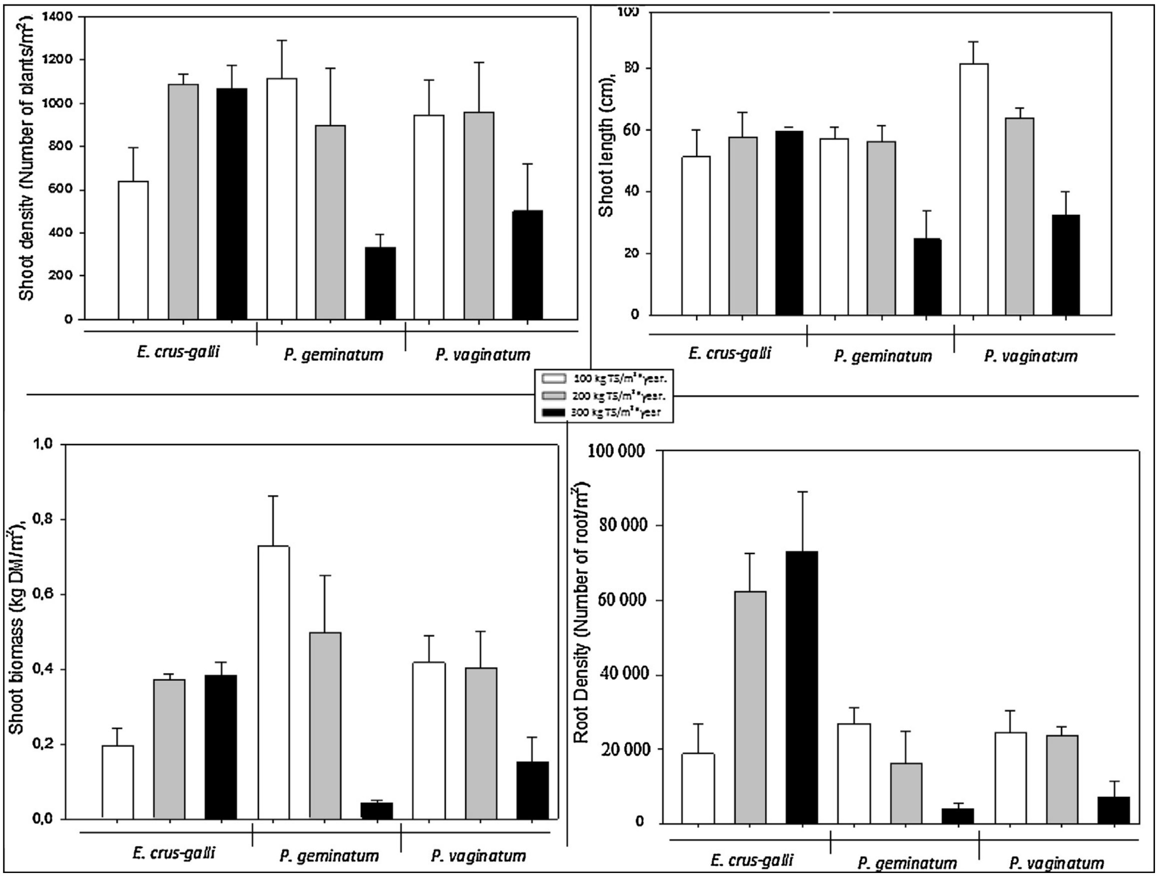

Fig. 1. Sludge loading rate and resulting measurements of plant growth, including shoot density, shoot length, shoot biomass, and root density.

very common in Senegal, with 45% of households in Dakar having small ruminants (Missohou et al., 1995), and 60% of interviewees in this study able to solely support themselves with urban livestock. Interviewees also confirmed that the bulk of forage is available in the rainy season, with shortages common throughout the rest of the year. Keepers of livestock and traders reported buying 3–7 and 10–30 kg per day of fresh fodder, respectively. Forage is sold by the "heap" (~500 g fresh) for 0.10 USD (50 FCFA). These results indicate there is significant demand for urban forage production.

3.3. *Ability of plants to grow with faecal sludge conditions*

Five of the seven screened plants had increased shoot density and shoot height with faecal sludge effluent over tap water, as shown by growth measurements in Table 2. The greatest increase in growth compared to controls was *E. colona*. The differences between treatments and controls was statistically significant at $P < 0.05$ for all species other than *E. crus-galli* (all results of statistical analyses are reported in the Supplemental Information). The five species with increased biomass also had increased shoot biomass, root density and stem diameter.

As shown in Table 2, five of the seven plants also had increased root density over the control. However, for the two species with decreased plant growth in the treatment, *E. indica* and *I. cylindrical*, the difference was not significant ($P < 0.05$). Increased plant growth with nutrients that are present in faecal sludge over tap water is not surprising, however, it was an important first screening, as many plants are not able to grow in planted drying bed conditions with faecal sludge, and is why *E. indica* and *I. cylindrica* were eliminated from further studies.

3.4. *Plant growth with faecal sludge loading rate*

Further pot studies were conducted to evaluate optimal faecal sludge loading rates for growth and forage quality of *E. crus-galli, P. geminatum and P. vaginatum.* As shown in Fig. 1, overall

Table 3
Crude protein (CP), ash, total kjeldahl nitrogen (TKN), total phosphorus (TP), acid digest fiber (ACD) and crude cellulose (CC) concentrations of plant shoots, reported as% of dry matter (DM).

Species	Protein		Mineral contents	
	FS-LR (kg TS/m^2*year)	CP	Ash (% DM)	TKN
E. crus-galli	100	17.53 ± 0.25	14.43 ± 1.58	2.80 ± 0.04
	200	17.23 ± 0.07	13.13 ± 0.39	2.76 ± 0.01
	300	17.03 ± 0.04	12.36 ± 0.21	2.72 ± 0.06
P. geminatum	100	18.41 ± 0.01	11.37 ± 0.38	2.95 ± 0.01
	200	20.41 ± 0.34	12.46 ± 0.08	3.26 ± 0.06
	300	21.25 ± 0.13	16.50 ± 0.14	3.40 ± 0.02
P. vaginatum	100	15.84 ± 0.09	11.60 ± 0.02	2.53 ± 0.01
	200	14.97 ± 1.43	12.59 ± 0.59	2,39 ± 0,23
	300	18.29 ± 0.31	12.49 ± 0.05	2.93 ± 0.05

Species	Mineral contents		Fiber contents	
	FS-LR (kg TS/m^2*year)	TP	ADF (% DM)	CC
E. crus-galli	100	0.17 ± 0.01	36.74 ± 6.31	31.80 ± 4.56
	200	0.17 ± 0.01	31.36 ± 1.11	27.75 ± 0.34
	300	0.17 ± 0.01	31.10 ± 0.27	28.36 ± 1.28
P. geminatum	100	0.15 ± 0.01	32.13 ± 1.31	29.33 ± 0.04
	200	0.17 ± 0.01	30.91 ± 0.51	24.70 ± 0.96
	300	0.20 ± 0.03	31.19 ± 0.17	25.82 ± 0.05
P. vaginatum	100	0.12 ± 0.00	30.14 ± 4.31	24.30 ± 4.35
	200	0.15 ± 0.00	33.66 ± 2.17	29.27 ± 1.56
	300	0.19 ± 0.02	32.69 ± 0.63	24.67 ± 0.12

FS-LR: faecal sludge loading rate.

plant growth was optimum for *E. crus-galli* with 200 and 300 kg TS/m^2*year, and for *P. vaginatum* and *P. geminatum* at 100 and 200 kg TS/m^2*year. Based on shoot biomass *P. geminatum and P. vaginatum* appear to have the greatest potential for use in planted drying beds with a loading rate of 100 kg TS/m^2*year. However, based on shoot and root density, *E. crus-galli* appears to be a better candidate for planted drying beds based on its rigorous growth, and potential for increased nutrient uptake. Plant density results for *E. crus-galli* were different from those observed in Cameroon with *E. pyramidalis*, where reduction of plants densities were observed at a faecal sludge loading rate of 300 kg TS/m^2*year (Kengne et al., 2008).

3.5. *Forage quality*

Results of protein, mineral and fiber analyses are presented in Table 3. Protein, ash, nitrogen and phosphorus concentrations were similar among treatments. There was a slight trend similar to growth parameters, decreasing with increasing faecal sludge loading rate for *E. crus-galli*, and vice versa for *P. geminatum* and *P. vaginatum*, with the greatest concentrations at 300 kg TS/m^2*year. The observed crude protein concentrations were two to three times higher than those reported for grasses grown in natural areas of 4.37–9.42% DM (Zeki et al., 2009). Ash concentrations in this study (14.97–21.25% DM) were higher than those observed with 20 grass species growing in natural areas (7.36–13.16% DM) (Zeki et al., 2009). The TKN concentrations were much greater than those observed by Kengne et al. (2008) of 2.2–2.3, however the TP concentrations were much lower (0.53–0.63). There was no statistical difference for fiber analyses among plant species or faecal sludge loading rate, and the values were comparable to those reported for natural forage. Based on these measurements, all of the plants grown in this study meet recommended nutritional requirements of livestock, and were well below levels of toxicity (NRC, 2001).

4. Conclusions

These results indicate that indigenous fodder plants can be adapted for use in planted drying bed treatment of faecal sludge, with simultaneous forage production for resource recovery. Identifying plants based on their growth in the environment was not adequate to predict growth in drying beds, pot studies like the ones in this study are required prior to scaling up. Protein, minerals, nutrients and fibers as metrics in general indicated that fodder quality of *E. crus-galli P. geminatum* and *P. vaginatum* improves in faecal sludge drying bed conditions. However, species should be selected based on treatment objectives, for example *E. crus-galli* had optimal forage production characteristics at 200 and 300 kg TS/m^2*year loading rates, whereas *P. geminatum* and *P. vaginatum* had optimal forage production characteristics at 100 and 200 kg TS/m^2*year. Higher loading rates increase treatment plant capacity, which can reduce the required land in urban areas where space is limited. However, selection of forage plants should also be based on the local market demand.

Acknowledgements

The authors are very grateful to Moritz Gold and Chuck Henry for their review. Funding was provided through the Volkswagen Foundation, the Swiss Agency for Development and Cooperation (SDC), the Eawag partnership program (EPP), the USAID/ERA Local Scholarship Program of Excellence Fellowship, and the International Foundation for Science (IFS) grant No W/5705-1.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2016.05.027.

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