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Investigating the importance of solid piggery sludge application in soil for signal grass (*Urochloa decumbens*) production in the humid lowland agroclimatic conditions in Papua New Guinea

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Abstract

The ruminant livestock industry in Papua New Guinea is yet to be fully developed because grazing is entirely on unimproved, native, and hardy pastures that are poor in nutrients and hardly palatable. A field trial was conducted with four rates of amendments (0, 2.5, 5.0, and 10 t.ha⁻¹) as treatments by growing signal grass to investigate the potential use of solid piggery sludge to improve its productivity. The treatments were replicated five times (n = 5) and set up in a completely randomized block design. The plants were harvested after six months, and soil samples collected were used to assess the changes in soil chemistry. The amendments improved all the soil parameters, nutrients, overall productivity, and yield. At 5–10 t.ha⁻¹, soil organic matter, soil organic carbon, cation exchange capacity, and electrical conductivity, for example, improved by 169–254%, 534–643%, 37–91%, and 10–27%. Similarly, N, P, K, and S were increased by 41–52%, 144–267%, 188–325%, and 750–1,250%. Among the potentially toxic metals, Cu, Pb, Cd, and Cr were higher than standard permissible limits. Overall, the highest dry matter yield (37–58%) was produced by 5.0 and 10.0 t.ha⁻¹ rates, respectively. Although accumulation in soil and biomass of metals was evident, the soil parameter data did not support possible mobility. Therefore, 5.0 t.ha⁻¹ was found to be crucial for signal grass production.

Key words: Bioaccumulation, solid piggery sludge, soil fertility, tropical agriculture, *Urochloa decumbens*

Introduction

The ruminant livestock (cattle, sheep, and goat) industry in PNG is yet to be widely established in part because of the government's lack of incentive to farmers or its interest in developing it. This is complicated by lack of extension services, poor agrarian infrastructure, availability of improved breeding stocks, absence of an export-driven market, research and development, and lack of large-scale farms with improved pasture for grazing. Even in the limited number of ruminant livestock farms, availability of improved pasture is still an issue. The issue of unavailability of improved pasture is primarily addressed by practicing pastoral farming in PNG in land owned by cooperative societies, communities, or commercial farms. The practice is that the herds are introduced into large lands that are either fenced or open and allowed to graze freely with a certain level of management (provision of supplements, drenching, shelter, and security). Most of these lands are dominated by native and hardy pasture that can be easily grazed by the ruminant livestock but are poor in nutrients and hardly palatable. The most common pastures in PNG include signal (*U. decumbens*), Guinea (*P. maximum*), elephant (*P. purpureum*), carpet (*Axonopus compressus*), and Rhodes (*C. gayana*) grasses, among a few legumes and other grass species. In smallholder livestock production, signal grass and palisade grass (*Brachiaria brixantha*) are widely grazed.

Signal grass originated in the highlands of central and eastern Africa (FAO, 2016) and is widespread in the tropics, and in the Pacific region, including PNG. It is a widely naturalized pasture (FAO, 2016), free of pests and disease attacks, valuable permanent pasture, high yielding, produces low leafy stands, does well in infertile soils, withstands heavy grazing, and is palatable to all the ruminant livestock. Very tolerant to prolonged dry spells, able to recover and grow quickly from stolons and seeds after fire events, tolerant to soil acidity (pH 3.5) and metal toxicity (Mn and Al), and sensitive to salinity (Deifel et al., 2006), nitrogen, and phosphorus (Cook et al., 2005). In addition to these attributes, signal grass does well between

27 N° and 27 °S, 0 m to 1750 m, a temperature range of 30–35°C, and an average rainfall of 1500 mm (FAO, 2016; Heuze et al., 2021). Propagation of the pasture is by seeds or vegetative cuttings and often intercropped with various legumes to improve productivity in infertile soils. In commercial farms, forage production is managed by the application of inorganic fertilizer (N source), and yields of up to 30 t of dry matter per ha have been reported in Vanuatu in fertilized soil (Cook et al., 2005); a low yield of 4 t of dry matter per ha was produced in Colombia with fertilizer application (FAO, 2016). The productivity being high in fertile soil and low in infertile soil shows that signal grass is a nutrient-hungry pasture and the soil in which it is grown needs to be managed for high productivity.

The principal option to manage soil infertility under signal grass production as forage is to apply inorganic (chemical) fertilizer; however, we have pointed out in a number of other similar studies (e.g., Michael et al., 2016) that availability and affordability are issues for the smallholder farmers because of the remote location of farms and prices are often very high. One of the options for smallholder farmers to address the issue of availability and affordability of inorganic fertilizer in the production of signal grass or pasture in general is the use of agricultural wastes that are of plant or animal origin, which are readily available and relatively cheap basically because of lesser demand and popularity in using them as bioresources (Azeez et al., 2025a, 2025b). One of the agricultural wastes that are available in large amounts and at a much cheaper price in most of the poor economies in the tropical and subtropical regions is the solid piggery wastes (Edesi et al., 2020; Tóth et al., 2022; Bartóg et al., 2024).

Unlike the ruminant livestock industry, pig production has increased in some of these regions, and the resultant wastes produced are an environmental concern if not managed properly, and how to use the wastes sustainably as a biore-source to promote the circular economy is lacking. The use of the piggery wastes, in particular, the solid piggery sludge, is a perfect opportunity to be used in pasture (forage) production and

management as it is easy to collect, transport, and even apply under various land use systems (e.g., in croplands). This study was conducted to investigate the potential use of solid piggery wastes in soil fertility management under signal grass production and assess the bioavailability of metals in the tissues from a ruminant livestock and environmental health perspective.

Materials and methods

Description of study site

The study was conducted at PNGUoT Agriculture Farm (6°39'39" S, 147°0'8" E) in Lae, Morobe Province, PNG, at 65 m elevation (Michael, 2019a; 2019b; 2020a; 2020b; 2020c; 2020d). The climate has 3800 mm of annual rainfall, evenly spread, with a mean temperature of 26.3° C, a min of 22.9° C, and a max of 29.7° C. Evaporation is 2139 mm annually, with rainfall exceeding evaporation each month. Climate is Af (Koppen), a tropical rainy climate with >60 mm in the driest month. The soil is well-drained, sandy, and alluvial, classified as Typic Tropofluents or Eutric Fluvisol (Michael, 2020a; 2020b). Selected soil parameters, nutrients, and metal contents of the site are given in Table 1.

Collection and preparation of piggery sludge

Solid treated piggery sludge was collected from a stockpile from a commercial piggery farm outside of Lae City and brought to the farm for use. The samples were dried on canvas under direct sunlight for a week and weighed using an electric scale. The dried sludge samples were packed into 1000 g, 500 g, and 250 g polyester bags and kept dry before field applications. An analysis of soil parameters, nutrients, and metal contents of the solid piggery sludge is shown in Table 1.

Land preparation and setting of experiment

A piece of land (17 m x 13 m; 221 m²) on the farm was ploughed and harrowed using a tractor (Massey Ferguson, Germany). A total of 96 experimental plots (1 m x 1 m) were prepared and separated by a 0.5 m spacing within and between plots. There were four treatments: control (planted

with no amendment), 2.5 (lowest), 5 (high) and 10 (highest) t.ha⁻¹ of solid piggery sludge. Each experiment was arranged in a completely randomized block design with five replications. The solid piggery sludge was applied to the soil surface and manually incorporated into the top 30 cm using handheld shovels. Four cuttings of signal grass obtained from the University Farm were manually planted in each plot. Throughout the six months of production, watering, weeding, and pest and disease control were carried out as per the farm's general practice. There was no thinning done to the plants as would be under general forage production and management conditions.

Field sampling and preparations

Sampling and yield-related parameter assessment

All the biomass (above and below ground) was sampled from all the treatment plots. Soil and root samples were collected from the top 30 cm rhizosphere or a 10 cm radius of the plants. Each plant was gently uprooted with minimum root disturbance using a handheld shovel. The soil with the intact roots was carefully shaken onto a canvas and homogenized by mixing before collecting 3 kg of soil subsample per replicate or 12 kg per treatment and bagging it into pre-labeled paper bags. The shoot and root biomasses were chopped into 1-2 cm long pieces using a gardener's clipper and bagged in pre-labeled plastic bags. All the samples were transported to the laboratory for further processing (cleaning, washing, and oven-drying).

Sample preparations

At the laboratory, the roots were gently washed under tap water to remove excess soil, and the fresh weight was taken. Then the samples were air-dried at room temperature for 24 hours, and all the leaves, stems, vines, and roots were chopped into 1-2 cm long pieces using kitchen knives, packed into paper bags, and oven-dried at 65° C for three days to determine dry matter (yields). The dry samples were then ground using a food blender, packed into resealable bags, and kept dry to analyse the mineral content. The soil samples

Table 1. Soil parameter compositions of the farm soil, solid piggery sludge, and expected range in the amended soils (Kasa and Michael, 2026)

Soil parameters	Composition of the farm soil and the sludge		
	Farm (study site)	Sludge	Range
Soil organic matter (%)	2.59±0.1	22.17±0.1	3 – 22
Soil organic carbon (%)	1.50±0.0	12.76±0.8	2 – 13
pH	6.50±0.1	6.80±0.6	6 – 7
Base saturation (%)	65.30±0.5	11.76±0.2	6.5 – 12
Cation exchange capacity (meq/100 g)	7.23	—	—
Electrical conductivity (mS.m ⁻¹)	0.03±0.1	1.92±1.2	0 – 2
Water-holding capacity (%)	54.25±1.0	53.71±0.6	54 – 54
Bulk density (g.cm ⁻³)	1.12±0.0	0.60±0.1	0.6 – 1
Total porosity (%)	52.02±0.6	56.02±1.2	52 – 56
Soil particle composition (%)			
(a) Sand	89.982±0.0	83.13±0.0	83 – 90
(b) Silt	0.45±0.0	4.01±0.1	0.5 – 4
(c) Clay	9.63±0.0	12.83±0.0	10 – 13
N (mg.kg ⁻¹)	1500±0.2	17,600±20.3	≤18, 000
P (mg.kg ⁻¹)	10.62±0.3	49.62±1.1	11 – 50
K (mg.kg ⁻¹)	20.73±0.3	145.94±4.9	21 – 146
Mg (mg.kg ⁻¹)	131.28±5.7	666.02±10.6	131 – 670
Ca (mg.kg ⁻¹)	732.11±5.6	2,643.27±54.5	732 – 2,640
S (mg.kg ⁻¹)	6.52±0.7	144.24±0.8	7 – 144
Na (mg.kg ⁻¹)	14.32±0.5	62.72±2.3	14 – 63
Fe (mg.kg ⁻¹)	507.38±0.2	72.89±0.50.2	73 – 507
B (mg.kg ⁻¹)	8.82±0.8	18.01±0.9	9 – 18
Mn (mg.kg ⁻¹)	46.30±0.6	191.17±0.5	46 – 191
Al (mg.kg ⁻¹)	270.67±1.1	9.23±1.3	9 – 271
Cd (mg.kg ⁻¹)	6.62±0.2*	12.67±0.3*	7 – 13
Ni (mg.kg ⁻¹)	70.61±0.8	43.73±0.7	44 – 71
Pb (mg.kg ⁻¹)	730.56±1.3*	4.43±0.2	4 – 731
Zn (mg.kg ⁻¹)	89.56±1.1	439.14±1.5	90 – 439
Cr (mg.kg ⁻¹)	96.08±0.1*	21.19±0.7	21 – 96
Co (mg.kg ⁻¹)	<5.12±0.0	<5.21±0.0	<5
Cu (mg.kg ⁻¹)	257.82±2.3	65.09±0.2	65 – 258

The values are means of three replicate samples ± standard error. Note, range is the expected change in the amended soils. The broken line, —, is not determined. An asterisk shows concentrations higher than FAO permissible limits.

from the field were transferred to aluminium trays and air-dried at room temperature for 7 days and then sieved into 2.0 mm, 0.5 mm, and 0.05 mm for different measurements and analyses at the PNGUoT Analytica Laboratory.

Laboratory analysis of parameters

Important soil physical and chemical properties that influence soil fertility, mineral, and nutrient availability were determined according to Michael (2020a, 2020b, 2020c, 2020d). Ground biomasses were analysed using laboratory analytical equipment, and the standard equations (Eqns. 1 to 11) were used to assess. Total nitrogen was analysed by the Kjeldahl method (Buchi K436 speed digester and Buchi K-350 Kjeldahl distillation unit). A sample of one gram (< 2 mm) air-dried soil was digested using 15 ml of concentrated sulphuric acid at 300 – 400° C (H₂SO₄ reduces nitrogen as ammonium sulphate (NH₄)₂SO₄). The sample solution was distilled using 60% sodium hydroxide (NaOH), where ammonium (NH₄⁺) was converted to ammonia (NH₃) gas, which was collected using 25 ml of 2% boric acid with three drops of mixed indicator. It was then back-titrated with 0.01 M HCl. The available nitrogen (NO₃-N) was determined using the salicylic acid method with UV light after extraction with 0.027 M Ca(OH)₂. The available P was determined by the Olsen method using a spectrophotometer (UV1800, Shimadzu Corporation, Japan) using 0.5 M sodium bicarbonate (NaHCO₃) after adjusting the pH to 8.5 with NaOH. The extraction was performed for 30 minutes using a 200-rpm shaker and a soil-to-extraction solution ratio of 1:20 (w/v).

All the other nutrients (K, Mg, Na, Ca, S, Mn, Zn, B, Cu, Fe, and Al) were extracted with a Melich 3 extraction solution (0.2 M CH₃COOH + 0.25 M NH₄NO₃ + 0.015 M NH₄F + 0.13 M HNO₃ + 0.001 M EDTA) in a 1:10 (soil:extractant ratio) and analysed using an ICP OES. The data was calculated as per the Melich3 18F1 standard as follows:

$$N = ((C - B) \times (Ve \div Ws)) \quad (1)$$

Where N is nutrient, e.g., K; C is concentration; B is blank ((mg element/dm³), Ve is the effective volume used in the extraction calculation (1:20 soil to solution); and Ws is the weight of the sample, respectively. The data in milliequivalents (mEq/100 g soil) were converted to milligrams (mg) as follows:

$$mg = [(mEq \times Aw) \div V] \quad (2)$$

Where Aw is the atomic weight of an element (e.g., nitrogen) and V is valence, respectively. Cation exchange capacity (CEC) was estimated based on the sum of the individual base cations (Ca, Mg, K, and Na) as follows:

$$CEC = (\text{Sum of bases} / \text{Bases saturation}\%) \times 100 \quad (3)$$

The sum of bases is in meq/100 g and includes individual exchangeable base cations. Based saturation (%) is from the soil analysis data (e.g., Table 3).

Soil moisture content was determined by oven-drying samples at 105° C for 24 hours, and the final weight was estimated after 2 hours of cooling by subtracting the dry weight from the initial fresh weight.

The pH was measured using a standard dilution (1:5 soil:water w/v) method (Michael, 2019b). Electrical conductivity was measured using a Direct Soil EC meter (Spectrum Technologies Inc., 12360S Industrial Dr. East Plainfield, IL 60585, USA), using the same solutions (Michael, 2020a; 2020b; 2020c). The bulk density (g.cm⁻³) was calculated by oven-drying the cores at 105° C for 48 hours, followed by weighing again (Michael, 2020d). The oven-dry weights were divided by the core volume and estimated as follows:

$$BD = (Odw \div \pi r^2 h) \quad (4)$$

Where BD is bulk density (g.cm⁻³), Odw is oven dry weight, and the formula is for estimation of the volume of the core.

The soil organic carbon (SOC) content was analyzed using the weight loss-on-ignition method. A five-gram sample was weighed into a crucible

and heated in a muffle furnace for 12 hours at 105° C (Wf). The weights were recorded after 2 hours of cooling, further combusted at 375° C for 17 hours (Fw), cooled for 2 hours, and weighed (Michael, 2019a).

The SOC content was estimated by multiplying the carbon value by a conversion factor (1.72) and expressed as a percentage:

$$\text{SOC (\%)} = [((Wf - Fw) \div Wf) \div 1.724]100] \\ \text{or} \\ (\text{SOM (\%)} \div 1.724) \quad (5)$$

The conversion factor was used to convert the soil organic matter content to organic C, assuming there was 58% C in the organic matter. The size of the C stock in each profile was calculated as the sum of the individual C fractions (%) × BD (g.cm⁻³) × profile depth (SP, cm) × Cf and expressed as a percentage as per Michael (2020a, 2020b, 2020c) as follows:

$$\text{SOC}_{\text{stock}} (\%) = [((\text{SOC}/100) \times \text{BD} \times \text{SP}) \times \text{Cf}] \quad (6)$$

Where SOC was determined using Eqn. 4 and the Cf obtained by 100÷58. The soil organic matter (SOM) contents were estimated using the SOC content and the conversion factor as follows:

$$\text{SOM (\%)} = [(\text{SOC}) \times \text{Cf}] \quad (7)$$

The water holding capacity (WHC) was estimated by soaking soil samples in water (100% WHC) and draining them through filter paper overnight (e.g., Michael, 2019a). These were weighed for the wet weight (Ww), dried in an oven at 105° C for 24 hours, and reweighed to obtain the oven-dry weight (ODw). The WHC was estimated as follows:

$$\text{WHC (\%)} = [((Ww - \text{ODw}) \div \text{ODw}) 100] \quad (8)$$

The total porosity was determined as follows:

$$P = [1 - (\text{BD} / d)100] \quad (9)$$

Where P is total porosity (%), BD was defined and d is particle density of 2.65 g.cm⁻³.

The weight of the SOM to a given depth and area was estimated as follows:

$$\text{SOM (tons)} = [(\text{SOC} \times \text{BD} \times \text{SP} \times \text{ha}) 1.72] \quad (10)$$

Where SOC is in %, BD is in g.cm⁻³, SP is in m and ha is hectare (10 000 m²).

The bioaccumulation factors (BiF) were calculated as follows:

$$\text{BiF} = (\text{Mpt} / \text{Ms}) \quad (11)$$

Where Mpt is metal concentration of plant tissues and Ms is metal concentration in the soil. Values >1 indicate metal accumulation, whereas values <1 suggest limited uptake or exclusion mechanisms.

Statistical analysis

Data from four replicates of all the treatments were used for statistical analysis, and the samples from the fifth replicate were kept frozen as a reserve. The replicated data were used to calculate the treatment means and standard errors estimated using the average data for all parameters. Assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were tested for each response variable, and the data were log-transformed when necessary to meet assumptions. This was followed by a two-way ANOVA with pasture and amendment rate as fixed factors to test for main effects and interactions. When significant interactions were detected (p<0.05), one-way ANOVA with significant treatment effects and Tukey's HSD post hoc test for pairwise comparisons were performed. All analyses were conducted using JMP Pro 16 (SAS Institute Inc., Cary, NC, USA).

Results and discussion

Changes in soil properties

The farm soil had nearly 3% organic matter (Table 1), and that had decreased to nearly 2% in the control soil (Table 2) under the study condi-

tions. The decrease in the native organic matter has been reported in other studies, and the main reason has been microbial degradation as an energy substrate (e.g., Michael et al., 2015; 2016; 2017). In the soil amended with the least rate, soil organic matter increased by nearly 0.77%, 3.12%, and 4.7% at the increasing rate of solid piggery sludge. These results showed that changes measured were dependent on the rate of amendment. The soil organic carbon contents directly reflected on the changes in soil organic matter, with the highest increase of 7% measured in the soil amended with the highest rate of 4.7% (Table 2). A similar type of increase in soil organic matter and organic carbon has been reported following soil amendment with piggery sludge (e.g., Yanardağ et al., 2015; Furtado e Silva et al., 2022). Pb is immobile in soil and highly influenced by soil organic matter, CEC, and $\text{pH} < 6$. In this study, $\text{pH} > 6$, and therefore mobility was negligible.

Despite the significant increases in soil organic matter and organic carbon, soil pH experienced very little, insignificant, change, the highest being 0.3 at the highest amendment rate. The humic substances in organic matter are expected to regulate the pH, and the soil's high buffering capacity (resist change) seems to have been enhanced by the high organic matter content because of their high exchangeable sites that absorb cations (Michael, 2021), making the pH remain around 6, typical of a sandy soil (80 – 90% sand, Table 2). A study in Australia showed signal grass tolerates low pH caused by the presence of acid metals, such as Al^{3+} and Mn^{2+} (Pasture Australia, 2008).

The CEC in the control soil decreased, whereas in the amended soils, it increased significantly. The overall changes in CEC were within an expected range of 5 to 15 meq/100 g. The increase in CEC demonstrated that the solid piggery sludge has the potential to increase the nutrient storage capacity of the sandy soil. More so, the lower the clay content, the higher the CEC (Bernal et al., 1992), and this was evident. The base saturation of the native soil was nearly 70%, and this decreased to nearly 60% and 50%, respectively, following amendment. The decrease in base saturation, and more so at the highest amendment rate, would

mean that the soil was unable to retain cations and correlates well with the insignificant changes in pH measured. The fact that the soil was sandy, leaching of nutrients resulted in poor retention, and minerals such as magnesium, which has the highest retention at 65% base saturation or higher, was quite evident (see Table 3). These were supported by the EC data, which were significant at the higher rates only (Table 2). The native soil was loamy sand, and the addition of solid piggery sludge significantly improved the water-holding capacity, reflecting the importance of solid piggery sludge in the management of water rendition. Soil organic matter highly influences the water-holding capacity of soil, and the changes measured seemed to have been the influence of the organic matter increase.

In loamy sand soil, moisture retention is low due to the high drainage, and the moisture content of the control soil being nearly 5% proved that, whereas the addition of solid piggery sludge increasingly improved the soil moisture content. Soil bulk density was increased in all the amended soils, but the changes were not significant, remaining within a range of 1.2 – 1.6 g.cm^{-3} , typical of loamy sand soil. The high organic matter content measured further influenced the bulk density to be lower, and the narrow changes in bulk density measured reflected on the total porosity, which remained nearly 50% following solid piggery sludge amendment (Table 2). The high organic matter content and loamy sand nature (Table 2) of the soil further facilitated the soil pores to be around 50%, perfect for healthy root growth (root data in Table 5 supports that) for signal grass, which does not thrive in flooded soil conditions. The soil particle composition was more than 85%, similar to the native soil, demonstrating that the soil textural class was loamy sand, and that was the reason water-holding capacity and moisture contents were low and soil porosity was high (Table 2). Most grass species, like signal grass, would require 15 – 25% moisture, and the results tended to show 5.00 – 10.00 t.ha^{-1} solid piggery sludge is the optimum amount to provide that, in addition to the slightly acidic to neutral pH, important for efficient nutrient uptake and

Table 2. Changes in soil properties under signal grass production

Parameters	The different rates of the amendment (t.ha ⁻¹)			
	0.00	2.50	5.00	10.00
Soil organic matter (%)	1.85±0. ^a	2.62±0.1 ^b	4.97±0.1 ^c	6.55±0.2 ^{cd}
Soil organic carbon (%)	1.09±0.2 ^a	3.84±0.1 ^b	6.91±0.1 ^c	8.10±0.1 ^d
pH	6.42±0.0 ^a	6.52±0.0 ^a	6.62±0.9 ^a	6.72±0.6 ^a
CEC (meq/100 g)	5.89±0.23 ^a	6.69±1.51 ^b	8.12±2.22 ^c	11.22±1.11 ^d
Base saturation (%)	69.23±0.5 ^a	63.37±0.6 ^a	64.32±0.5 ^a	56.33±0.6 ^b
EC (mS.m ⁻¹)	120.22±0.0 ^a	125.14±0.2 ^a	132.16±0.2 ^b	152.42±0.2 ^{bc}
WHC (%)	46.41±0.5 ^a	49.15±0.2 ^a	58.81±0.5 ^b	63.69±0.4 ^{bc}
Moisture (%)	5.73±0.0 ^a	8.52±0.4 ^b	15.43±0.4 ^c	25.53±0.8 ^d
Bulk density (g.cm ⁻¹)	1.18±0.1 ^a	1.30±0.6 ^a	1.41±0.9 ^a	1.52±0.5 ^a
Porosity (%)	48.21±0.5 ^a	50.62±1.5 ^a	54.21±1.8 ^a	56.11±1.2 ^a
SPC (%)			8.27±0.1 ^a	10.09±0.3 ^a
Clay	10.71±0.3 ^a	9.12±0.5 ^a		
Silt	1.22±0.1 ^a	0.87±0.3 ^a	2.38±0.2 ^b	3.44±0.1 ^{bc}
Sand	87.57±0.2 ^a	90.01±0.2 ^a	89.55±0.4 ^a	87.55±0.2 ^a

The values are mean ± standard error of four replicates (n=4). The different letters in the same row show statistical difference at p<0.05. The acronyms were described in Table 1.

maximum pasture productivity.

Changes in soil mineral and metal compositions

Management of signal grass production as a pasture requires optimum soil nutrient availability. Application of solid piggery sludge in the soil significantly improved total N, and the highest increase was by nearly 52% (Table 3). Similar significant results in the other two primary macronutrients, P and K, were observed. The P increased by 65.87 – 286.98% and K by 82.10 – 328.44%. The secondary macronutrients, Ca, Mg and S, are important as much as their primary macronutrient counterparts for forage production. All of these secondary macronutrient concentrations in the soil were significantly increased and more so at the higher rates of amendments. The concentration of sulfur, for example, in the unamended control soil was 4 mg.kg⁻¹. When the lowest amount of solid piggery sludge was applied, it increased by 250%, and at the highest amendment rate, it increased

by 1185.34%. These results have demonstrated the significant boost in the overall soil nutrient improvements and general signal grass productivity as a forage. The increase in soil constituents measured agrees with findings in other studies that solid piggery sludge application has a positive effect on soil physiochemical characteristics (e.g., España et al., 2019).

Soil micronutrients (trace elements) are also important for general soil health, forage productivity, livestock health, and product quality to the consumers. Most of the micronutrients are responsible for plant physiological functions and enzymatic activities. The toxicological effects of metals, especially the heavy ones, are also of soil, pasture, livestock, and consumer concerns. All the micronutrients, Na, B, Fe, Cu, Mn, Pb, Cd, Cr, Zn, Ni, Co, and Al, concentrations significantly increased. Boron, for example, is responsible for cell division, seed formation, nutrient transport and energy metabolism, and deficiency can lead to poor signal grass productivity as a forage

Table 3. Soil mineral and metal compositions at different rates of sludge amendment

Nutrients (mg.kg ⁻¹)	Different rates of the amendment (t.ha ⁻¹)				Permissible limit (FAO)
	0.00	2.50	5.00	10.00	
N	1356±0.0 ^a	1450±0.1 ^b	1906±0.1 ^c	2065±0.2 ^d	
P	8.45±0.6 ^a	14.05±0.8 ^b	21.55±0.8 ^c	32.70±0.4 ^d	
K	15.75±0.2 ^a	28.68±0.9 ^b	45.48±0.6 ^c	67.48±0.8 ^d	
Ca	605.65±0.2 ^a	685.08±0.6 ^b	728.25±0.9 ^c	796.59±0.6 ^{cd}	
Mg	114.71±0.9 ^a	138.02±0.8 ^b	150.08±0.6 ^c	214.45±0.5 ^d	
S	4.23±0.2 ^a	13.72±0.3 ^b	34.03±0.7 ^c	54.37±0.2 ^d	
Na	8.49±0.9 ^a	21.77±0.8 ^b	38.70±0.4 ^c	49.63±0.1 ^d	
Fe	399.48±0.8 ^a	431.59±0.7 ^b	456.69±0.9 ^{bc}	502.11±0.9 ^d	
Mn	34.33±0.4 ^a	53.56±0.7 ^b	72.38±0.6 ^c	145.07±0.7 ^d	
B	6.84±0.8 ^a	10.24±0.5 ^b	12.23±0.1 ^{bc}	17.12±0.4 ^d	
Cd*	4.16±0.56 ^a	8.62±0.6 ^b	13.89±0.5 ^c	17.80±0.5 ^{cd}	3.0
Cr	64.88±0.9 ^a	72.06±0.9 ^b	80.73±0.9 ^c	109.78±0.8 ^d	100.0
Zn	66.75±0.9 ^a	98.40±0.9 ^b	165.29±0.6 ^c	249.42±0.9 ^d	50 – 300
Ni	30.65±0.7 ^a	44.22±0.5 ^b	66.30±0.9 ^c	84.23±0.6 ^d	35 – 50
Co	0.02±0.0 ^a	0.05±0.0 ^a	0.05±0.0 ^a	0.06±0.0 ^a	50.0
Cu*	169.06±0.8 ^a	178.45±0.9 ^b	253.21±0.7 ^c	305.81±0.9 ^d	36 – 100
Pb*	661.47±0.7 ^a	678.85±0.6 ^a	683.51±0.8 ^a	720.71±0.5 ^b	85 – 100
Al	157.99±0.9 ^a	165.32±0.9 ^b	179.11±0.5 ^c	225.27±0.7 ^d	≤30,000

The values are mean ± standard error of four replicates (n=4). The different letters in the same row show statistical difference at p<0.05. An asterisk shows concentrations higher than FAO/WHO permissible limits of agricultural soils.

plant. The different amendment rates increased B concentrations by nearly 50%, 78.80%, and 150.29%, respectively. These positive impacts of solid piggery sludge showed its importance in the improvement of these micronutrients and the resultant effects on the pasture productivity and livestock production. Micronutrients such as Fe, Cu, Zn, and Cr fall under the essential trace element class, whereas Pb, Cd, Al, and a few others are considered non-essential because of toxicological effects of unknown roles in plants and animals. All the micronutrient concentrations were within the FAO maximum limits of residential zone soil except Cu and Pb (Table 3). Al concentration was higher than the expected plant-available and safer in residential landscaping and is more of a concern when the soil pH is less than 5. The pH in the soils amended with the

different rates was higher by 2; therefore, toxicity is of minimal issue. At high pH, Al solubility is less, and therefore plant availability is lesser (Michael et al., 2015).

Metal concentrations in biomass

The Al concentration of the control soil decreased by about 61% when compared to the natural soil content and further decreased by 90% in the soil amended with the lowest rate of solid piggery sludge (Table 4). The trend of decrease in Al concentrations under the higher rates was evident too at the higher rates of amendments. Al is the third most abundant metal, yet it is not widely used by the soil biota or plants, and points out that the low concentrations measured were due to unavailability (existed in insoluble forms) as a result of the circumneutral pH. The Cd concentra-

tions in all the amended soils increased but were not significant except in the highest amendment rate (Table 4), which was higher than the FAO permissible limit. This is a concern as Cd is a toxic metal and is a significant risk to livestock and humans, including the environment. The Co concentrations in all the soil were insignificant pertaining to the low concentrations of the farm soil and solid piggery sludge. Similarly, Cr concentrations were high following the amendments within a narrow range of 4 – 16 mg.kg⁻¹ (Table 4). These increases are very small given the fact that the soil already had a high concentration of the metal (Table 1). The Pb concentrations were significantly increased as well and can lead to adverse effects on the pasture and livestock, especially when accumulation occurs. Pb is non-biodegradable, highly toxic, accumulates in soil, affects plant growth, and is a serious concern to humans and livestock (WHO, 2023; Shiek et al., 2021; Briseño-Bugarín et al., 2024).

Iron, Ni, Cu, Zn, and Mn are essential micronutrients that play significant biological functions, including enzyme activation, growth

and development, biosynthesis, and metabolic activities in plants as well as livestock. The concentrations of these essential elements increased significantly in the biomass of signal grass and more so with high-solid piggery sludge amendment rates (Table 4). For example, at the lowest rate, Fe, Ni, Cu, Zn, and Mn increased by 15%, 24%, 66%, 355%, and 142% (Table 4). These changes were much higher at the highest rate, e.g., for Mn, which was 308%, a 50% increase in concentration of the lowest amendment rate measured. The increase in concentrations of these metals is a concern from the perspectives of soil, plant, and livestock health. Fe toxicity is an issue when the soil is waterlogged, and pH is less than 5.5, where solubility and mobility are high. That was not the case for the soil of this study and, therefore, not much of a concern. Further, Fe has an antagonistic effect with Zn and results in deficiency. This was not the case, as the results showed that as Fe concentrations were high, so were the Zn concentrations (Table 4). High availability of Fe in soil reduces plant root growth and, therefore, affects growth.

Table 4. Metal concentrations in biomass at different rates of sludge amendment

Metals (mg.kg ⁻¹)	Different rates of amendment (t.ha ⁻¹)				Permissible limit (FAO)
	0 .00	2.50	5.00	10.00	
Al	106.23±0.2 ^a	11.22±0.4 ^b	95.12±0.2 ^{ac}	62.55±0.8 ^d	≤30,000
Cd*	2.56±0.6 ^a	3.63±0.4 ^a	5.46±0.4 ^{ab}	10.51±0.6 ^c	0.1 – 0.2
Co	3.55±0.4 ^a	3.60±0.6 ^a	3.76±0.6 ^a	4.10±0.4 ^a	50.0
Cr*	29.10±0.3 ^a	33.26±0.2 ^a	38.45±0.3 ^{ab}	45.12±0.5 ^{bc}	1.3 – 1.5
Pb*	64.89±0.7 ^a	69.55±0.4 ^a	72.69±0.8 ^{ac}	86.66±0.6 ^d	0.3 – 2.0
Fe	99.67±0.5 ^a	115.21±0.5 ^b	120.23±0.5 ^c	125.56±0.4 ^{cd}	425.0
Ni	37.98±0.4 ^a	46.77±0.3 ^b	55.39±0.8 ^{bc}	61.89±0.2 ^{cd}	67.0
Cu*	86.44±0.4 ^a	142.67±0.3 ^b	158.34±0.1 ^c	162.63±0.9 ^d	73.0
Zn	21.99±0.3 ^a	99.66±0.2 ^b	128.58±0.4 ^c	134.89±0.2 ^d	99.4 – 500
Mn	11.69±0.8 ^a	29.23±0.4 ^b	36.55±0.8 ^{bc}	49.23±0.5 ^{cd}	500.0

The values are mean ± standard error of four replicates (n=4). The different letters in the same row show statistical difference at p<0.05. The FAO permissible limit for plants, and an asterisk shows concentrations higher than the maximum limit of dangerous substances in plants.

The root number was significantly higher (Table 5), corresponding to the highest Fe concentration measured (Table 4). These results demonstrated that the increase in concentrations of Fe had minimal effects on soil chemistry and, therefore, on the plants. Like Fe, Ni is very mobile in acidic soil and most often when the concentration is within a range of 75 – 150 mg.kg⁻¹ (El-Naggar et al., 2021; Naz et al., 2022). Ni is a serious and persistent soil pollutant and affects soil microbial ecology (Parvanova et al., 2024), stunting plant growth by reducing nutrient uptake and affecting humans and livestock by entering the food chain (El-Naggar et al., 2021). As shown in Table 4, the Ni concentrations increased but are within FAO permissible limits and therefore are not much of a concern. Similar to Cr and Pb, tissue concentration of Cu was higher than the FAO permissible limit (Table 4). Cu is an essential element for plants, humans, and livestock and is a concern as it can bioaccumulate (Fagnano et al., 2020). In most soils, bioavailability is affected by soil properties, pH, and low organic matter (Wang et al., 2022). Cu is a concern for general plant growth at 60 – 150 mg.kg⁻¹ (Dresler et al., 2014). The concentrations of Cu measured at the higher rates of solid pig-

gery sludge were almost close to this and maybe a concern in the humid tropics.

The BiF for the elements, estimated using Eqn. 11, is given in Table 5. The results showed Cd, Co, Zn, and Mn bioaccumulated in the tissues, especially when the amendment rates were 5 – 10 t.ha⁻¹. The BiF values >1 of Cd correspond to its high biomass concentration, whereas for the rest they were much lower. The BiF values of Pb, Cr, and Cu, whose concentrations were high in the soil (Table 4), were <1, indicating there may have been sources other than the amendments that contributed to the increase measured (Chen et al., 2023). The farm site where the study was conducted is within a residential area (university), and it seems the high Pb, Cr, and Cu concentrations were resultant contributions of anthropogenic activities (Fang et al., 2012; Fei et al., 2020; Jiang et al., 2023; Khattak, 2025) rather than from the amendments.

Plant biomass production

Production of biomass from a forage plant, such as signal grass, following any soil amendment, e.g., organic matter or inorganic fertilizer, is important for the livestock (ruminants, cattle,

Table 5. The bioaccumulation factors under different amendments

Elements	Bioaccumulation factor			
	0	2.5	5.0	10.0
Al	0.67	0.67	0.54	0.24
Cd	0.92	1.35	1.40	1.56
Co	77.50	72.00	75.22	68.33
Cr	0.45	0.56	0.41	0.05
Pb	0.10	0.08	0.06	0.02
Fe	0.25	0.34	0.26	0.15
Ni	0.23	0.84	0.53	0.20
Cu	0.51	0.80	0.27	0.06
Zn	0.33	4.08	2.18	1.10
Mn	0.35	3.32	2.26	0.21

sheep, and goats). As shown in Table 6, solid pig-gery sludge amendment increased tiller numbers by 13%, 36%, and 95%, and the longest tillers were from the soil with the highest solid pig-gery sludge amendment rates. The total number of leaves produced was dependent on the plant height, and the longest tillers produced more than the shortest ones. The leaf lengths increased as amendment rates increased but were all insignificant, the difference being only 2 cm between the control and the highest solid pig-gery sludge rate. Under normal fertile soil conditions, signal grass can reach up to 60 cm and leaves as long as 20 cm; however, the plant heights and leaf numbers were shorter (Table 6). The probable reason for the shorter leaves could be the effects of higher concentrations of Pb and Cu measured in the soil (Table 3) and in the biomass (Table 4).

The control soil produced quite a number of roots, indicating that the native soil's nutrient capacity was sufficient to support signal grass productivity. When the soil was amended with solid pig-gery sludge, the total number of roots produced significantly increased by 50%, 66%, and 100%, and the increase in root length was by 14%, 50%, and by 164% (Table 6). Dry matter production and yield were significantly different, except that there was not much difference in the

dry matter yield at the higher amendment rates. The lesser biomass production and yield resulted from the higher concentrations of metals in the tissue measured (Table 4). Signal grass is tolerant to a number of metals, including Al, and is often planted in poor soils because of its ability to detoxify them internally (Souza et al., 2016). Kopittke et al. (2007) reported 0.5µM of Pb²⁺ resulted in a 50% reduction in shoot and root bio-mass. Iron, for example, is toxic to most tropical grasses when the concentration is 500 mg.kg⁻¹ and higher (Pugh et al., 2002; Broadley et al., 2012). Like Pb and Fe, most of the metal concentrations in the biomass measured were higher than the maximum allowable limit (Table 4), and that alone was sufficient to have an impact on the amount of biomass (dry matter) produced (Samal et al., 2025) and the yield estimated (Pholsen, 2010). Signal grass produced in a post-mining area gave a dry matter yield of 3.16 ton.ha⁻¹ (Toputri et al., 2023), similar to the 0.27 ton.ha⁻¹ of this study (Table 6). A yield of 16 t.ha⁻¹ or more can be obtained in fertile and contamination-free soils after three months of production (Malhi et al., 2004; Dupas et al., 2016; Rutz and Jones, 2018; Canto et al., 2020), and loss of aboveground biomass may have contributed to the lesser yield, especially in the presence of excess metals.

Table 6. Biomass production by signal grass at different rates of sludge amendment

Plant growth parameters	Different rates of amendment (t.ha ⁻¹)			
	0	2.5	5.00	10.00
Tillers (number)	13.33±0.5a	18.33±0.3b	26.22±0.5c	38.33±0.6d
Height (cm)	16.22±0.2a	26.35±0.3b	36.67±0.6bc	55.33±0.2cd
Leaf (number)	3.22±0.33a	3.66±0.5a	5.24±0.3a	5.55±0.5a
Leaf length (cm)	5.33±0.5a	6.31±0.5a	6.77±0.5a	7.32±0.5a
Root (number)	100.23±0.7a	150.66±0.7b	166.22±0.5c	200.33±0.5d
Root length (cm)	14.33±0.4a	16.33±0.5a	21.34±0.2b	36.67±0.4d
Dry matter (g)	380.17±0.3a	433.51±0.4b	521.96±0.7c	598.55±0.6d
Dry matter yield (g.m ⁻²)	1.72±0.6a	1.96±0.3a	2.36±0.2b	2.71±0.4bc

The values are mean ± standard error of four replicates (n=4). The different letters in the same row show statistical difference at p<0.05. Note that the dry matter yield can be divided by 100 to convert it to t.ha⁻¹.

Conclusions

Solid piggery sludge amendment improved all the parameters that influence soil nutrient status, increased all the primary and secondary macronutrients and micronutrients (minerals), and promoted the general growth of signal grass. Solid piggery sludge amendment increased soil and biomass concentrations of heavy metals, and most of them were within FAO permissible limits, except Cu and Pb in soil and biomass. Plant biomass production increased as the amendment rates increased and depended on metal availability in the soil. High soil and tissue concentrations of toxic metals, especially Cu, Pb, Cd, and Cr, affected the biomass production and yield (dry matter) of signal grass. The bioaccumulation factors of the metals estimated were <1 , except for Cu, Pb, Cd, and Cr, and issues related to bioaccumulation in livestock following application of solid piggery sludge and signal grass production seem to be of lesser concern. Among the rates considered, 5 t.ha⁻¹ seems to be more appropriate for improving general soil parameters and macro- and micronutrients, increasing the production, and reducing the environmental impacts of solid piggery sludge use in the humid tropics.

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Conflict of interest

The authors declare that there are no competing financial or personal interests that may appear to influence the work reported in this paper.

Data availability statement

All the data are included in the manuscript.

Author's contributions

Conceptualization, Methodology, Supervision, and Writing draft and editing: PM; Formal analysis, Data collection, analysis and investigation, and

final draft: LK. All authors read and approved the final manuscript.

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