Received: 28 December 2025 | Accepted: 07 January 2026 | Published online: 29 April 2026
DOI: 10.53550/ijsc.v54.i1.217

ORIGINAL ARTICLE
Indian Journal of Soil Conservation

Short-Term Effects of Solid Piggery Sludge Application on Soil Properties and Metal Accumulation In Rice and Maize under Humid Lowland Tropical Conditions in Papua New Guinea

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Handling Editor:
Dr Rajive K. Singh

Key words:
Bioaccumulation factors
Heavy metals
Oryza sativa
Piggery sludge
Soil amendment
Zea mays

ABSTRACT

The livestock industry in humid tropical regions is generating increasing amounts of piggery waste, necessitating sustainable solutions. Agricultural land application offers waste-to-resource potential, but concerns about heavy metal contamination and crop safety necessitate evaluation. This study examined short-term effects of solid piggery sludge (SPS) on soil properties and metal accumulation in rice and maize in Papua New Guinea over six months, with four SPS rates (0, 2.5, 5, and 10 t ha^{-1}) and five replicates. Soil samples were analyzed for physical, chemical, macronutrients, and heavy metals; plant tissues for metal content and bioaccumulation; and growth parameters were measured pre-reproduction. Data showed SPS increased soil organic carbon (121-185% in control vs. 1,021-1,316% at 10 t ha^{-1}), organic matter, and water holding capacity; nitrogen rose from 1,200-1,450 to 2,100-2,300 mg kg^{-1}; macro- and micronutrient levels increased dose-dependently. Heavy metals like lead, cadmium, and chromium exceeded FAO limits at higher rates. Maize benefited from SPS, with height and dry matter up by 69-83% and 55-140%, respectively; rice showed growth inhibition at higher rates despite more tillers. Tissue metal levels were higher in rice; bioaccumulation factors often below 1.0, except for Co, Zn, and Mn at higher doses. Low SPS ($\leqslant$2.5 t ha^{-1}) improved soil fertility while keeping metal levels near background; higher rates risk metal accumulation. Maize tolerated metals better than rice. Plants were harvested before grains fully matured, so actual grain safety is unknown. Six months limit long-term assessment of metal buildup and system sustainability. Results suggest 2.5 t ha^{-1} as a tentative safe maximum, but multi-year studies are needed before commercial use.

1 | INTRODUCTION

The rice (*Oryza sativa*) and maize (*Zea mays*) industries are essential to livestock for feed and to humans as food (e.g., Li, 2017; Yu *et al*., 2019; Soto-Gómez & Pérez-Rodríguez, 2022; Ding *et al*., 2023) in the humid tropics. However, production of the two crops is limited to specific farms on a small scale only, and production is always low (e.g., Wu *et al.*, 2024) due to the need for more investment, awareness, research, and development (Li & Zhang, 2023; Michael, 2023). The production of these grain crops on a large scale is expensive, requiring heavy investment and intensive production practices, one of which is the need for large quantities of inorganic (chemical) fertilizers (Xue *et al*., 2024). The supply of inorganic fertilizers is limited to certain areas, and availability and affordability are issues for most farmers, especially smallholders (Fillippo, 2022). The problems related to the supply and affordability of inorganic fertilizers allow local farmers to use piggery sludge (or other livestock wastes) as an alternative soil nutrient source (Levario *et al.*, 2025). Still, its wider use is yet to be realized (Zhang *et al*., 2011) in the wider humid tropical areas.

The livestock industry has grown, there is a demand for the need to manage waste (Zhao *et al*., 2023), and a need to know how this can be done sustainably. Not only that, the rising need to manage soil fertility in grain (rice and maize) production, using piggery sludge (livestock wastes) as an example, has broader implications (e.g., Yuan *et al*., 2021; Bertici *et al.*, 2022). Piggery waste management and its associated environmental impacts are significant global issues as the livestock industry expands (e.g., Loyon, 2018; Park *et al*., 2018; Thakur et al., 2025). Hence, the need to manage, handle, and utilize agricultural waste to meet the increasing demand for food and resource recovery has become paramount (Zhang & Jahng, 2010; Ferreira *et al*., 2023). The drive toward sustainable waste management is to understand the different types of waste and how best to manage them to protect the environment and benefit from them (Cao *et al*., 2021; Koul *et al*., 2022; Hao *et al*., 2024).

On the other hand, land use has increased, and soil nutrient availability has declined, thereby undermining sustainable agriculture (Topas & Michel, 2023); (Chakraborty *et al.*, 2024). The increased production of livestock waste and the decline in soil fertility, coupled with the high prices of chemical fertilizers (Bertici *et al.,* 2022), warrant thorough, systematic research on the agricultural use of livestock waste (Khan *et al*., 2024). The background review of the literature showed that the use of piggery wastes on farms has been well-documented (e.g., Iregbu *et al*., 2014; Roba, 2018; Machete & Chabo, 2020; Doreswamy *et al.,* 2021; Kodani, 2023; Zhao *et al.,* 2025). Still, the results are variable and cannot be extrapolated due to differences in environmental conditions and the feeding systems. There is a need to establish the sustainable use of solid piggery sludge in agriculture to assess the changes in soil chemistry induced when applied as a soil amendment from an agricultural and environmental perspective under humid lowland tropical agroclimatic conditions. Further, the need to investigate the different rates (quantities) that can be applied and the resultant impact on the performance of crops important to the livestock industry is not clearly established.

2 | MATERIALS AND METHODS

2.1 | Description of Study Site

The study was conducted at PNGUoT Agriculture Farm (6°41” S, 146°98” E) in Lae, Morobe Province, PNG, at 65 m elevation, described in many publications (e.g., Michael, 2019a; b; 2020a; b; c; d). The climate has 3800 mm annual rainfall, evenly spread, with mean temps of 26.3°C, min 22.9°C, max 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 driest month. The soil is well-drained, sandy, alluvial, classified as Typic Tropofluents or Eutric Fluvisol (2006), with soil parameters shown in (Table 1).

2.2 | 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. A sample was sent to an analytical laboratory for mineral analysis.

2.3 | Sourcing of Planting Materials

Rice (*O. sativa*) and maize (*Z. mays*) were chosen as grain crops. The plants chosen are essential for various industries as raw materials for feed production for livestock as well as food for human consumption in PNG. The planting materials were sourced as seeds from local supplies within Lae City, Morobe Province, PNG.

2.4 | Land Preparation and Setting of Experiment

A piece of land (17 m x 13 m) on the farm was ploughed and harrowed using a tractor (Messy Ferguson, Germany). A total of 96 experimental plots (1 m x 1 m) were prepared.

HIGHLIGHTS

- Solid piggery sludge addition improved soil physical and chemical properties.
- Solid piggery sludge addition improved soil nutrient availability to maize and rice.
- Changes in soil chemistry and nutrient availability to maize and rice were dose-dependent.
- Tissue accumulation of metals was dose and crop dependent, maize being more tolerant than rice.

The plots were separated by a 0.5 m spacing within and between plots. There were four treatments: control (0), 2.5 (lowest), 5 (high), and 10 (highest) t ha^{-1} of dry piggery sludge. The treatments were arranged in a completely randomized block design with five replications. Dry sludge was applied to the soil surface and manually incorporated into the top 30 cm using handheld shovels.

2.5 | Planting and Production Management

Based on germination test results, fifteen seeds of rice and five seeds of maize were sown. Throughout the four months of running the study, watering, weeding, and pest and disease control were carried out in accordance with the farm's general practice. The maize plants were thinned to two tillers per treatment plot, and no thinning was done to the rice plants.

2.6 | Field Sampling and Preparations

2.6.1 | Sampling

All biomass (above- and below-ground) was sampled from all treatment plots. Soil and root samples were collected from the top 30 cm rhizosphere or a 10 cm radius of the pots. Each plant was gently uprooted with minimum root disturbance using a handheld shovel. The soil with intact roots was carefully shaken onto a canvas and homogenized by mixing before collecting 3 kg of soil subsample per replicate (12 kg per treatment) and bagging it into pre-labelled paper bags. The shoot and root biomasses were chopped into 1-2 cm long pieces using a gardener's clipper and bagged in pre-labelled plastic bags. The same amount of soil was collected from the other treatments; no amendment was made (control), and an amendment was made but not planted. All the samples were transported to the laboratory for further processing (cleaning, washing, and oven-drying).

2.6.2 | Sample Preparations

In the laboratory, the roots were gently washed under tap water to remove excess soil, and their fresh weight was recorded. Then the samples were air-dried at room temperature for 24 hours, and all the leaves, stems, 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 for mineral analysis. The soil samples from the field were transferred to aluminium trays, air-dried at room temperature for 7 days, and then sieved to 2.0 mm, 0.5 mm, and 0.05 mm for different measurements and analyses at the PNGUoT Analytica Laboratory.

TABLE 1 Soil parameters of the farm soil, SPS and expected range in the amended soils.

Soil parameters	Composition of parameters of the farm soil and the SPS		
	Farm (Study site)	SPS	Range
Soil organic matter (SOM, %)	2.59±0.1	22.17±0.1	3-22
Soil organic carbon (SOC, %)	1.50±0.0	12.76±0.8	2-13
pH	6.50±0.1	6.80±0.6	6-7
Cation exchange capacity (meq/100 g)	7.23	-	-
Base saturation (BS, %)	65.30±0.5	11.76±0.2	6.5-12
Electrical conductivity (EC, mS m^{-1})	0.03±0.1	1.92±1.2	0-2
Water holding capacity (WHC, %)	54.25±1.0	53.71±0.6	54-54
Bulk density (BD, g cm^{-3})	1.12±0.0	0.60±0.1	0.6-1
Total porosity (TP, %)	52.02±0.6	56.02±1.2	52-56
Particle composition (SPC, %)			
(a) Sand	89.98±2.0	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})	1500.12±0.2	17,600.45±20.3	15,000-18,000
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 four replicate samples ± standard error. Note, range is the expected change in the amended soils. An asterisk shows concentrations higher than FAO permissible limits of agricultural soil.

Important soil physical and chemical properties that influence soil fertility, mineral, and nutrient availability were determined according to Michael (2020a; b; c; d). Ground biomasses were analysed using laboratory analytical equipment, and the standard equations (Eqns. 1 to 10) were used to assess them. 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 sulfuric acid at 300 – 400 C (H_2SO_4 reduces nitrogen as ammonium sulphate $(NH_4)_2SO_4$). The sample solution was distilled using 60% sodium hydroxide (NaOH), where ammonium (NH_4^+) was converted to ammonia (NH_3) 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 (NO_3^- N) was determined using the salicylic acid method with UV light after extraction with 0.027 M $Ca(OH)_2$. Available phosphorus (P) was determined by the Olsen method using a spectrophotometer (UV1800, Shimadzu Corporation, Japan) with 0.5 M sodium bicarbonate ($NaHCO_3$) after adjusting the pH to 8.5 with NaOH. Extraction was for 30 minutes using a 200-rpm shaker at 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 CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0. 001 M EDTA) in 1:10 (soil: extractant ratio) and analysed using an ICP OES. The data was calculated as per Melich3 18F1 standard as follows:

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

Ve is effective volume used in the extraction calculation (1:20 soil is to solution),
Where N is nutrient, e.g., K, C is concentration, B is blank ((mg element/dm^3), and Ws is the weight of the sample. The

data in milli-equivalent (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 nutrient data. 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) with the same solutions (Michael, 2020a-d).

The bulk density (g cm^{-3}) was calculated by oven-drying the cores at 105 °C for 48 hours, followed by weighing again (Michael, 2020a-d). The oven-dry weights were divided by the core volume and estimated as follows:

$$BD = (Odw \div \pi r^2 h) \quad (3)$$

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

The soil organic carbon (SOC) content was analyzed using the weight-loss-on-ignition method (Schulte & Hopkins, 1996). 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:

$$SOC (\%) = [((Wf - Fw) \div Wf) \div 1.724)100] \quad (4)$$

The conversion factor was used to convert soil organic matter content to organic C, assuming 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) x Cf and expressed as a percentage as per Michael (2020) as follows:

$$SOC_{stock} (\%) = [((SOC/100) \times BD \times SP) \times Cf] \quad (5)$$

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

$$SOM (\%) = [(SOC) \times Cf)] \quad (6)$$

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 (W_w), dried in an oven at 105 ˚C for 24 hours, and reweighed to obtain the oven-dry weight (OD_w). The WHC was estimated as follows:

$$WHC (\%) = [((W_w - OD_w) \div OD_w) 100] \quad (7)$$

The total porosity was determined as follows:

$$P = [(1- \left(\frac{BD}{d}\right) 100] \quad (8)$$

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:

$$SOM (tons) = [(SOC \times BD \times SP \times ha) 1.72] \quad (9)$$

Where SOC is in %, BD is in g cm^{-3}, SP is in m and ha is hectare (10 000 m^2).

Bioaccumulation factors (BiF) were calculated as:

$$BiF = [Metal]plant\ tissue / [Metal]soil \quad (10)$$

Values >1 indicate metal accumulation, while values <1 suggest limited uptake or exclusion mechanisms.

2.7 | Statistical Analysis

Data from four replicates were used for analysis. The fifth replicate served as a backup and was excluded from statistical analysis to maintain a consistent sample size across parameters. Treatment means and standard errors were calculated for all parameters. For each response variable, assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were tested. Data were log-transformed where necessary to meet assumptions. To test for main effects and interactions, two-way ANOVA with crop type and amendment rate as fixed factors was performed. When a significant interaction was detected ($p<0.05$), one-way ANOVA for each crop species was performed. For one-way ANOVAs with significant treatment effects, Tukey's HSD post hoc test for pairwise comparisons was used. Significance level was set at $\alpha=0.05$ for all tests. All analyses were conducted using JMP Pro 16 (SAS Institute Inc., Cary, NC, USA).

3 | RESULTS AND DISCUSSION

3.1 | Changes in Soil Properties

The changes in soil properties measured under rice are shown in Table 2. Generally, an increase in sludge improved all the soil properties except electrical conductivity, pH, and particle composition. The measured changes in soil properties were as follows: organic carbon was 1.65 – 96.69%, organic matter was 18.84 – 138.45%, base saturation was 4.62 – 10.77%, and moisture and water-holding capacity in the soil amendment with the highest amount were 50% and 76.47%, respectively. All three rates significantly improved water-holding capacity and total porosity, except for bulk density. The highest sludge-only rate significantly increased this.

The changes in soil properties under maize production were similar to those under rice production (Table 2), except for some notable differences. All the different rates significantly increased soil organic carbon and organic matter contents, the highest being recorded in the soil amended with the highest amount of sludge. Base saturation, moisture level, and water holding capacity were highest at higher rates. Soil electrical conductivity, pH, bulk density, and soil texture remained nearly unchanged under maize. The different rates significantly increased total porosity, while the bulk density remained unchanged (Table 2).

TABLE 2 Changes in Soil Properties Following Six Months of Piggery Sludge Amendment

Parameter	Crop	Control (0)	Low (2.5 t ha^{-1})	Medium (5 t ha^{-1})	High (10 t ha^{-1})	Effect Size[1]
Organic Carbon (%)	Rice	1.21±0.04^a	3.23±0.02^b	6.75±0.03^c	10.38±0.02^d	856%
	Maize	1.85±0.02^a	3.05±0.02^b	7.09±0.03^c	13.16±0.02^d	711%
Organic Matter (%)	Rice	2.09±0.10^a	2.55±0.03^b	3.15±0.02^c	4.91±0.20^d	235%
	Maize	3.19±0.03^a	2.79±0.02^b	3.81±0.02^c	5.09±0.03^d	160%
pH	Rice	6.50±0.10^a	6.60±0.10^a	6.50±0.10^a	6.70±0.03^a	NS
	Maize	6.42±0.10^a	6.62±0.10^a	6.54±0.10^a	6.52±0.10^a	NS
Moisture (%)	Rice	6.10±0.04^a	6.90±0.30^b	6.72±0.50^b	8.70±0.10^c	143%
	Maize	6.42±0.10^a	8.13±0.30^b	10.42±0.20^c	17.32±0.10^d	270%
WHC (%)	Rice	33.70±0.50^a	45.65±0.70^b	50.35±0.70^c	59.61±0.50^d	177%
	Maize	56.34±0.50^a	54.63±0.60^a	61.04±0.70^b	65.65±0.70^c	117%
Base Saturation (%)	Rice	64.50±0.50^a	67.57±0.50^b	67.37±0.80^b	71.77±0.80^c	111%
	Maize	64.41±0.60^a	66.77±0.80^{ab}	69.27±0.70^{bc}	74.63±0.70^c	116%
EC (mS m^{-1})	Rice	120.02±0.20^a	130.03±0.10^b	145.73±0.30^c	240.56±0.20^d	200%
	Maize	130.23±0.10^a	145.24±0.10^b	158.14±0.20^c	185.44±0.20^d	142%
Bulk Density (g cm^{-3})	Rice	1.16±0.10^{ab}	1.20±0.02^a	0.56±0.10^b	0.29±0.10^c	25%
	Maize	1.11±0.04^a	1.24±0.10^a	1.25±0.10^a	1.17±0.04^a	NS
Porosity (%)	Rice	48.12±0.40^a	56.22±1.20^b	64.21±1.10^c	72.24±1.30^d	150%
	Maize	50.12±0.40^a	44.22±1.10^b	44.21±1.10^b	46.23±1.30^{ab}	NS

Notes: [1]Effect size = (High treatment / Control) × 100%, [2]Decrease from control, WHC = Water Holding Capacity; EC = Electrical Conductivity. The different letters within a row indicate statistical differences at $p<0.05$.

The farm soil and sludge served as good sources of organic matter, with the sludge enhancing water-holding capacity. The particle composition showed a high proportion of clay (Table 1). When sludge was added to the soil, it significantly increased organic matter, thereby positively affecting organic carbon content. This boost in organic matter further improved soil moisture, water-holding capacity, and pH under rice and maize cultivation. Soil electrical conductivity indicates the soluble salt content (salinity) and is an important marker of soil mineral content, influencing whether salt ions could limit crop growth. This parameter was very low, ranging from 0.03 to 0.05 mSm^{-1}, similar to the normal pH range, suggesting the soil was suitable for crop growth. Bulk density improved notably after sludge amendment, as reflected by increased soil porosity observed under each crop. This increase in porosity was partly due to the high sand content in the sludge. Particle composition remained fairly stable, showing little impact from sludge on this property. In a long-term study spanning 2004–2020, Ferreira *et al.*, (2022) examined the effects of piggery sludge and litter, finding that adding a unit increased soil C content and raised soil pH. Over a 17-year period, Tavares *et al.*, (2019) applied various rates of piggery sludge and measured changes in soil carbon balance, organic matter mineralization, humic substance formation, and soil aggregation. In a shorter 10-year study, the addition of liquid swine manure improved soil porosity, organic matter content, and exchange cations in soybean production (Antoneli *et al.*, 2019). Our findings, based on a shorter timeframe, generally agree that applying piggery wastes in slurry, liquid, or solid form enhances overall soil properties, regardless of application timing, duration, or agroecological conditions.

3.2 | Changes in Soil Mineral and Metal Compositions

Table 3 shows the changes in soil mineral content. The most notable increase was in soil nitrogen, which was also significantly higher than P and K, the other main macronutrients. Among secondary macronutrients, Ca, Mg, and Na showed significant increases, while sulfur decreased, especially in soils amended with the highest sludge amount. For micronutrients, higher sludge rates raised their levels, and even the lowest rate caused significant increases in Zn, Mn, Pb, and Cr. Cu, Co, and Al showed no significant change except at the highest application rate. Compared to pre-amendment levels, the overall changes in soil nutrients, especially nitrogen, B, and Cu were relatively smaller.

Increasing soil amendment rates elevated all primary and secondary macronutrients in maize and enhanced nearly all other mineral levels, except cadmium and cobalt (Table 4). For every mineral, the lowest amendment rate had no significant effect on P, K, Ca, S, B, Ni, Pb, Cr, and Co concentrations. Comparing the two grain crops revealed notable differences—for instance, with aluminum. Soil aluminum was markedly higher under rice at elevated amendment rates. In maize, soil aluminum levels rose across all soil types. Conversely, sulfur decreased in rice but increased under maize. Additionally, soil boron content remained low for both crops.

TABLE 3 Changes in soil mineral and metal compositions under rice production

Element ($mg\ kg^{-1}$)	The different rates of the amendment ($t\ ha^{-1}$)			
	0	2.50	5.00	10.00
N	1200±0.0	1400±0.0*	2000±0.0*	2100±0.0*
P	8.21±0.5	9.43±0.4	12.77±0.7*	16.46±0.5*
K	15.74±0.8	32.66±0.9*	34.48±0.4*	44.84±0.8*
Ca	515.65±0.9	1068.71±0.9*	1168.71±0.6*	1349.26±0.8*
Mg	112.04±0.8	175.00±0.9*	190.43±0.9*	240.58±0.9*
Na	11.29±0.8	30.41±0.8*	68.83±0.8*	97.68±0.6*
S	5.77±0.3	15.71±0.3*	33.87±0.2*	43.79±0.4
B	6.11±0.7	11.43±0.9*	18.51±0.9	22.30±0.6
Fe	394.55±0.9	597.26±0.9	650.52±0.9*	773.44±0.9*
Cu	192.73±0.9	177.47±0.5	275.85±0.8	307.83±0.9*
Zn	84.95±0.9	105.79±0.2*	216.63±0.8*	311.3±0.8*
Mn	33.69±0.8	64.53±0.6*	79.40±0.8*	114.07±0.8*
Cd	4.70±0.3	6.45±0.8	10.01±0.0*	17.01±0.0*
Ni	55.65±0.8	64.22±0.6*	76.30±0.9	94.23±0.2*
Pb	407.47±0.1	539.86±0.9*	692.15±0.6*	723.02±0.9*
Cr	88.29±0.9	92.77±0.8*	106.27±0.7*	115.38±0.9*
Co	0.06±0.0	0.10±0.0	0.17±0.0	0.95±0.0*
Al	135.17±0.9	143.08±0.7*	196.42±0.8*	210.80±1.0*

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference ($p<0.05$) between the control and the treatment.

TABLE 4 Changes in soil mineral and metal compositions under maize production.

Element ($mg\ kg^{-1}$)	The different rates of the amendment ($t\ ha^{-1}$)			
	0	2.50	5.00	10.00
N	1450.00±0.0	1670.00±0.0*	2100.00±0.0*	2300.00±0.08*
P	8.63±0.3	10.53±0.2	13.37±0.2*	21.36±0.1*
K	17.81±0.9	21.68±0.9	23.39±0.8*	36.61±0.8*
Ca	645.66±0.9	754.34±0.7	836.32±0.6*	915.63±0.7*
Mg	124.75±0.9	145.82±0.6*	156.42±0.5*	215.44±0.5*
Na	9.63±0.6	30.99±0.9*	47.50±0.8*	63.13±0.5*
S	3.83±0.2	10.97±0.2	24.50±0.2*	64.70±0.1*
B	5.57±0.5	10.23±0.2	14.96±0.5	21.38±0.1*
Fe	415.21±0.6	443.56±0.8*	458.93±0.9*	473.53±0.8*
Cu	156.54±0.9	168.09±1.0*	175.59±1.0*	208.30±0.8*
Zn	66.38±0.8	109.17±0.8*	145.93±1.0	226.06±0.6*
Mn	35.34±1.0	57.56±0.6	73.40±0.9*	108.77±0.8*
Al	152.17±0.8	166.85±0.9*	223.52±0.9*	261.07±0.6*
Cd	5.06±0.7	8.72±0.1	12.50±0.3	16.36±0.3
Ni	64.47±0.9	69.89±0.9	76.06±0.8*	101.09±0.9*
Pb	516.65±0.8	562.89±0.9*	672.85±0.9*	722.88±0.9
Cr	83.37±0.5	93.00±0.7*	98.87±0.9*	112.78±0.9*
Co	0.05±0.0	0.07±0.0	0.18±0.0	0.25±0.0

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference ($p<0.05$) between the control and the treatment.

The sludge's mineral and metal contents were high for all the primary and secondary macronutrients and for Cd and Zn, and the farm soil was high in Al, Ni, Pb, and Cu, agreeing with the results of previous studies. When fermented piggery sludge was applied to pasture land, Bertici et al. (2022) noted a positive influence on total nitrogen and available P and K, with a lesser influence on Cu and Zn. All the primary and secondary macronutrients were improved when sludge was added under the two-grain crops. Under the highest amendment rate, N, P, and S were low under rice, whereas the rest of the primary and secondary nutrient contents were higher than those of maize. These nutrient differences could mean different affinities for the two-grain crops. Under the same amendment rate, Fe, B, Mn, Ni, Pb, Cr, and Al were higher under rice than in the soils planted with maize. The low concentrations measured under maize could mean crop uses of these soil minerals. Still, tissue concentrations of Al and other metals raise concerns about bioavailability to livestock and humans, especially when above the minimal standard limits (FAO, 2025). This could mean establishing the most effective application rate under agricultural conditions, especially when increases in soil mineral content, including heavy metals, were measured under each crop. The Cd, Cr, and Pb contents (0.86, 22, and 400 mg kg^{-1}) were outside, whereas Zn, Cu, and Ni were within the FAO permissible limits, which could be a concern for the environment. The estimated bioaccumulation factors for all metals were less than 1, except for Co, Zn, and Mn, which suggests that the bioavailability of these metals may be a concern. Under glasshouse conditions, Seo *et al*., (2011) added swine slurry continuously for five years at 50%, 100% and 200%, and planted tomato (*Lycoperscion esculentum*) and cucumber (*Cucumis sativus*). The results showed no positive influence on phosphate and trace elements, but high K and Na. The effect on yield was not much of that of the chemical fertilizer treatment. The disparity between our study results and those reported by Tavares *et al*., (2019), Antoneli *et al*., (2019), and Ferreira *et al.*, (2022) indicates that piggery wastes positively influence soil mineral and metal compositions and are largely influenced by prevailing agroecological conditions.

3.3 | Metal Concentrations in Biomass

Table 5 shows the metal compositions in forage tissues. In plants grown on unamended soil, high levels of Pb, Al, Fe, and Cu were observed, with maize showing higher Cu levels than rice. Applying 2.5 t ha^{-1} of sludge raised the tissue concentrations of Zn, Pb, Mn, Cu, Fe, and Al in both forages by at least 50 mg kg^{-1}. Metals like Cd and Co remained below 5 t ha^{-1}, with levels under 20 mg kg^{-1}. Increasing the amendment to 5 t ha^{-1} reduced Al, Cu, Fe, and Pb in rice tissues, while other metals increased, except Al and Pb in maize, which decreased. The highest tissue concentration increases above 5 t ha^{-1} were observed for Zn, Mn, Pb, Al, and Cu, especially in rice. At 10 t ha^{-1} amendment, metal levels declined overall, except for Cu. Despite this, Mn, Zn, and Al remained high in rice, and Cu, Fe, Zn, and Mn remained elevated in maize (Table 5).

The bioaccumulation factor (BiF), an indicator of the crop's capacity to accumulate the metals, was determined as the ratio of the concentrations in the crops' biomass. Generally, the BiF were less than 1 except for Zn and Mn at 5 and 10 t ha^{-1}, respectively. The bioaccumulation patterns revealed three distinct groups:

Group 1 - Limited Uptake (BiF < 0.5): Al, Cr, Cu, Fe, and Ni showed restricted translocation to above-ground tissues in both crops, suggesting active exclusion mechanisms or low phytoavailability. These metals remained predominantly in root tissues or were sequestered in soil.

Group 2 - Moderate Accumulation (BiF 0.5-1.0): Cd and Pb showed intermediate uptake efficiency. The BiF values <1 indicate that soil-to-plant transfer was limited, but tissue concentrations still approached or exceeded safe consumption limits (FAO, 1996), particularly at higher amendment rates.

TABLE 5 Metal concentrations in biomass of rice and maize following different rates of sludge amendment

Metals (mg kg^{-1})	← Amendment rates (t ha^{-1}) and crops →							
	0		2.50		5.00		10.00	
	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize
Al	125±0.2	115.22±0.3	130.54±0.1*	109.22±0.4*	73.42±0.4*	50.11±0.2*	60.13±0.2*	15.52±0.8*
Cd	1.54±0.2	1.45±0.3	12.51±0.4*	7.13±0.2*	8.20±0.2	5.11±0.4*2	2.64±0.4*	3.22±0.5*
Co	4.52±0.4	4.14±0.3	7.11±0.1*	8.12±0.6*	8.64±0.6*	8.82±0.4*	8.89±0.4*	9.65±0.3*
Cr	7.23±0.1	11.10±0.3	22.99±0.2*	19.26±0.2*	10.11±0.4*	16.45±0.3*	1.24±0.6*	3.12±0.5*
Cu	61.33±0.1	95.18±0.4	135.06±0.4*	153.34±0.6*	46.14±0.4*	140.22±0.2*	14.64±0.5*	114.06±0.2*
Fe	109.44±0.5	81.55±0.3	80.55±0.3*	130.27±0.2*	27.12±0.3*	119.33±0.4*	6.27±0.6*	103.11±0.9*
Ni	12.22±0.3	5.55±0.4	39.03±0.6*	32.22±0.5*	25.65±0.4*	26.89±0.5*	10.23±0.7*	3.65±0.5*
Pb	221.26±0.2	211.19±0.4	185.24±0.6*	162.15±0.4*	115.22±0.4*	95.60±0.5*	36.55±0.2*	39.33±0.5*
Zn	4.23±0.5	3.09±0.3	419.64±0.3*	410.62±0.2*	299.31±0.4*	381.54±0.2*	212.44±0.3*	295.55±0.6*
Mn	10.55±0.4	8.65±0.4	165.55±0.4*	176.22±0.3*	149.55±0.2*	160.35±0.5*	119.44±0.4*	125.21±0.2*

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference ($p<0.05$) between the control and the treatment.

Group 3 - Enhanced Accumulation (BiF > 1.0): Co, Zn, and Mn at rates ≥5 t ha⁻¹ showed bioaccumulation factors exceeding unity, indicating these elements were actively concentrated in plant tissues relative to soil content. This pattern is consistent with their roles as essential micronutrients with active uptake mechanisms. The declining BiF values at 10 t ha⁻¹ for most metals (except Co) suggest toxicity-induced reduction in root function or activation of metal tolerance mechanisms at high soil concentrations.

Rice produced an increasing number of tillers and leaves, shorter plants, and fewer roots with an increasing sludge concentration. In other words, higher amounts of the amendment retarded the growth and development of the rice plants. The tiller number (only two were maintained), plant height, and root length of maize were not affected, except that leaf number decreased as the amendment rate increased. The dry matter of the two-grain crops was significantly higher across all three rates, particularly at 10 t ha^{-1} of sludge. These results show that rice is sensitive to high concentrations of heavy metals and Al toxicity. Santos *et al*., (2018) showed that piggery sludge application favours pasture biomass production (Santos *et al*., 2018), but did not consider an actual rate. Fahad *et al*., (2019) reported that soil accumulation of Cd, Pb, Cu, and Ni decreased rice seedling emergence and growth, consistent with the findings in this study, which indicate that heavy metal accumulation affected the roots. The higher tiller and leaf number produced by the shorter plants could be an adaptive response to metal and Al in the soil.

On the other hand, maize seems to have a certain degree of tolerance and tissue accumulation (Atta *et al*., 2023). This ascertainment is based on the fact that the concentration of heavy metals and Al was lower in all the amended soils, and the effects of these metals on the roots needed to be more evident. The fewer leaves produced by the maize plants could mean more tissue accumulation in the leaves. These results agree with those of Ruiz-Huerta et al. (2022), who found that high levels of heavy metal accumulation significantly reduced maize growth when planted in mine-contaminated soil. Overall, the tissue concentrations of Cd, Co, Pb, and Zn were outside the FAO (1996) permissible limits of heavy metals in soil and plants. These results could hinder the potential agricultural use of piggery sludge, which is increasingly produced in PNG, and highlight the need for more research to determine how much and how to apply it to avoid crop loss and minimize environmental, livestock, and human toxicity concerns. Piggery sludge application under field conditions improved pea (Pisum sativum) yield without affecting soil pH (Hlisnikovský *et al*., 2022), further indicating the bioresource's broader applications.

3.4 | Plant Biomass Production

The plant growth characteristics for the assessed crops are shown in (Table 6). Sludge amendment increased the number of tillers in rice at all rates, except for maize, which was thinned to just two plants and kept throughout. The rice plants became stunted—as seen by a decrease in height—as sludge rates increased, while the opposite trend was observed in maize plants. Higher sludge rates resulted in much taller maize plants. Root biomass decreased in rice but increased in maize. As the amendment rate was high, both plants produced more leaves, and their dry matter reflected in the biomass produced. Yield data are not shown because plants were harvested at the tillering stage (rice) and tasseling stage (maize).

This study provides preliminary evidence for short-term soil chemical changes following piggery sludge application, but has several important limitations. The six-month duration captured initial soil responses but cannot assess: (i) long-term metal accumulation trajectories, (ii) organic matter stabilization and mineralization dynamics, (iii) multi-season cumulative effects, or (iv) chronic toxicity impacts on soil biota. Plants were harvested at vegetative stages (rice at tillering, maize at tasseling) to assess early growth responses and metal uptake patterns. Consequently, grain yield data—critical for evaluating practical agricultural value—were not obtained. The vegetative dry matter results indicate growth potential but cannot be extrapolated to predict grain production. Results from a single location under humid lowland tropical conditions may not apply to other soil types, climatic zones, or piggery

TABLE 6 Biomass production by rice and maize at different rates of sludge amendment

Plant growth parameters	← The different rates of amendment ($t\ ha^{-1}$) and crops →							
	0		2.50		5.00		10.00	
	Rice	Maize	Rice	Maize	Rice	Maize	Rice	Maize
Tillers (number)	64.67±0.2	2.00±0.6	100.33±0.5*	2.00±04	114.32±0.5*	2.00±0.6	121.67±0.4*	2.00±0.9
Plant height (cm)	91.67±0.1	146.67±0.3	81.30±0.7	248.33±0.5*	54.32±0.4*	271.67±0.4*	42.45±0.6*	268.67±0.7*
Root length (cm)	32.33±0.0	10.33±0.1	32.28±0.3	40.21±0.2*	27.35±0.3*	48.23±0.8*	24.33±0.7*	60.25±0.6*
Leaf (number)	152.32±0.5	35.22±0.2	175.62±0.8*	27.32±0.4*	203.20±0.2*	19.24±0.9*	230.36±0.9*	11.67±0.8*
Dry matter (g)	129.28±0.4	119.11±0.4	164.23±0.4*	184.24±0.6*	175.37±0.4*	232.03±0.5*	181.92±0.8*	286.33±0.4*

The values are mean ± standard error of four replicates (n=4). An asterisk indicates a significant difference ($p<0.05$) between the control and the treatment.
Note that dry weight is the difference between the fresh weight and moisture content.

operations with different feeding regimes and waste characteristics. Several metals (Pb, Cd, Cr) exceeded FAO permissible limits, raising concerns about food safety. However, without grain analysis, we cannot assess actual human or livestock exposure risks through feed/food consumption. Nevertheless, based on these preliminary findings, we offer cautious recommendations: (i) application rates ≤2.5 t ha^{-1} appear relatively safe for soil properties improvement while minimizing metal accumulation concerns, (ii) pre-application sludge analysis is essential to characterize metal content, (iii) crops intended for direct human consumption should be avoided until grain metal concentrations are verified, and (iv) further research is needed with multi-year field trials with complete grain harvest and yield analysis, economic viability assessment comparing sludge application to conventional, fertilization, food safety evaluation with grain metal analysis against international standards, and investigation of metal remediation strategies (phytoremediation species, and also soil amendments to reduce bioavailability.

4 | CONCLUSIONS

This six-month trial offers initial evidence on soil chemical responses to solid piggery sludge in humid tropical lowlands. Key findings: i) sludge consistently improved soil organic carbon (up to 10x), water holding capacity (77%), and base saturation across crops, quickly (within six months) and dose-dependently; ii) macronutrients (N, P, K) and secondary nutrients (Ca, Mg, Na) increased significantly with amendment rate, with the highest rate (10 t ha^{-1}) providing about 21,000 kg N ha^{-1}, surpassing crop needs; iii) soil Pb, Cd, and Cr exceeded FAO limits at multiple rates, with metal levels strongly linked to sludge rate; iv) maize tolerated metal stress, maintaining growth, while rice showed growth inhibition at ≥5 t ha^{-1}, indicating species sensitivity; v) metals mostly had bioaccumulation factors <1, showing limited soil-to-plant transfer, except Co, Zn, and Mn at higher rates, requiring monitoring for feed use. Based on initial findings, applying rates ≤2.5 t ha^{-1} improves soil quality and maintains metal levels near their natural baseline. Maize is more appropriate than rice for systems amended with sludge. - Rice grown on sludge soils should be limited to ≤2.5 t ha^{-1}. The six-month window captures initial reactions but doesn't reveal long-term sustainability, cumulative metal effects, or seasonal variation. Since harvest occurs before reproductive stages, it can't assess grain yield, quality, or the actual nutritional value of the grain. Conducted at a single site with specific soil and climate, limiting broader application. Total metal content measurement doesn't reflect plant-available fractions, so toxicity risks may differ. The study lacks a cost-benefit analysis comparing this method to traditional fertilization or waste management. For piggery sludge as a sustainable soil amendment, future research should focus on: 1. Completing crop cycles and evaluating yields. 2. Monitoring over 3-5 years for long-term effects. 3. Analyzing grain quality for metals, nutrition, and safety. 4. Comparing costs, labor, and returns of sludge versus fertilizers. 5. Multi-site trials across different soils and climates in PNG and tropical regions. 6. Studying metal speciation for bioavailability and risks. 7. Investigating soil microbiology's impact on beneficial organisms and decomposition. 8. Developing metal contamination remediation strategies like phytoremediation or amendments. 9. Exploring treatments like composting or biochar to reduce metal availability. 10. Setting policies for safe application, monitoring, and farmer training. While initial evidence suggests piggery sludge can boost soil and fertility crop yields at low rates, long-term data on this aspect of sustainable soil management is needed.

ACKNOWLEDGMENTS

The study was supported by funding from the Papua New Guinea University of Technology and the Eastern Highland Provincial Administration. The authors are grateful to colleagues and fellow students from the PNG University of Technology who have contributed directly or indirectly to the study.

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 CONTRIBUTION

Conceptualization, Methodology, Supervision, and Writing draft and editing: PM; Formal analysis, Data collection, analysis, and investigation: LK. All authors read and approved the final manuscript.

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How to cite this article: Kasa, Levy., Michael, S, Patrick., 2026. Short-Term Effects of Solid Piggery Sludge Application on Soil Properties and Metal Accumulation in Rice and Wheat Maize under Humid Lowland Tropical Conditions in Papua New Guinea . *Indian J. Soil Cons.*, **54(1): 44-54**