



Beverage-Industry Wastewater Treatment Sludge as a Soil Amendment for Rice: Nutrient Enrichment, Crop Performance, and Moisture Retention

Kier Gasga* and Niño Rebuya

Natural Products Research Center, Partido State University, Goa, Philippines

*Corresponding author: kier.gasga@parsu.edu.ph

Abstract

Beverage-industry wastewater treatment sludge contains organic matter and plant nutrients that may be recovered through land application, but its agronomic performance is source-dependent. This study evaluated air-dried sludge from a beverage-production wastewater treatment facility as an amendment for rice (*Oryza sativa* L., NSIC Rc23) in an outdoor pot experiment. Five treatments were arranged in a completely randomized design with three replicate pots per treatment: unamended heavy paddy soil; a commercial fertilizer benchmark; and sludge at 2.5%, 5.0%, and 7.5% (w/w) based on the total soil-sludge mixture mass. Each pot contained one seedling. Growth and yield were measured at harvest. Moisture retention was measured for 96 hours using one soil sample from each replicate pot and summarized as the area under the water-content curve (AUC). Sludge contained 3.160% total N, 1,346.72 mg kg⁻¹ elemental P, and 30.927% organic C. Grain yield was 18.49 g pot⁻¹ in the control and 29.38 and 31.99 g pot⁻¹ at 5.0% and 7.5% sludge, respectively. These two sludge treatments shared a Tukey's HSD grouping with the commercial fertilizer benchmark (32.29 g pot⁻¹), but the shared grouping does not demonstrate equivalence. Moisture retention AUC was 36.3% and 39.9% higher than the control at sludge levels of 5.0% and 7.5%, respectively. Bulk density and total porosity did not differ among treatments. The sludge showed agronomic potential under the tested pot conditions. Field use requires contaminant and pathogen screening, salinity assessment, crop-tissue analysis, and replicated field validation.

Keywords: circular bioeconomy; industrial biosolids; NSIC Rc23; organic carbon; water conservation

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INTRODUCTION

Mineral fertilizers remain central to intensive crop production, but their manufacture and inefficient field use contribute to energy demand and nutrient losses. Organic amendments can return carbon and plant nutrients to the soil and partially replace mineral inputs; their effects vary with amendment composition, soil properties, crop demand, and the duration of use. Long-term studies have reported improvements in soil fertility and crop productivity when nutrient release from organic inputs is synchronized with crop demand (Reganold and Wachter, 2016;

Cai et al., 2019; Ippolito et al., 2021; Liu et al., 2021a). In rice, partial replacement of mineral fertilizer with organic nutrient sources has increased yield, root growth, nutrient availability, or microbial activity in field experiments (Zhang et al., 2018; Chen et al., 2021; Dai et al., 2021; Iqbal et al., 2022; Ma et al., 2022). Meta-analyses also report positive average effects on rice yield and labile soil nitrogen with substantial variation among amendment types, substitution rates, soils, and study durations (Liu et al., 2021b; Hou et al., 2023).

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Wastewater treatment sludge is a potential nutrient source. Agro-food and beverage-processing effluents contain biodegradable organic matter and nutrients that become concentrated in treatment solids (Abdulla et al., 2023; Kathi et al., 2023; Marchuk et al., 2023). Biosolids and sewage-derived amendments have increased soil organic carbon, nutrient availability, biological activity, and crop biomass or yield in a range of soils (Bai et al., 2017; Tontti et al., 2017; Rehman et al., 2018; Breda et al., 2020; Boudjabi and Chenchouni, 2021; Gutiérrez-Ginés et al., 2023). Treatment residuals have also been incorporated into organo-mineral fertilizers or composted with agricultural wastes (Kominko et al., 2019; Ucaroglu and Atalay, 2024). Recent studies continue to report agronomic potential for treated biosolids while emphasizing source-specific evaluation and field validation (Cano-Larrotta and Uggetti, 2026; Skrzypczak et al., 2026).

Sludge composition also constrains agricultural use. Depending on the wastewater source and treatment process, residual solids may contain potentially toxic elements, persistent organic chemicals, pathogens, antibiotics, and antibiotic-resistance determinants. Metal mobilization and plant uptake have been reported under some amendment conditions (Welikala et al., 2018; Zuo et al., 2019b; Tytła, 2020; Feng et al., 2024). Repeated sludge application can also alter soil microbial communities and the abundance of resistance genes (Urra et al., 2019; Wang et al., 2020; Humphries et al., 2023; Serwecińska et al., 2024), and transfer of antibiotics or resistance determinants to edible vegetables has been demonstrated experimentally (You et al., 2020; Patra and Dubey, 2024). Crop response alone is therefore insufficient to establish biosolid safety, particularly for food crops (Buta et al., 2021; Urionabarrenetxea et al., 2022).

Moisture retention is relevant in paddy soils because soil-water status changes during drainage and intermittent irrigation. Organic amendments may alter water storage through water adsorption, aggregation, or changes in pore-size distribution. Paddy-soil incubation studies have reported increased gravimetric water storage after the application of organic amendments (Haque et al., 2021), and sewage sludge has improved crop performance under water stress in controlled experiments (Boudjabi et al., 2019; Koutroubas et al., 2020). The response is not determined by organic carbon alone; soil texture, porosity,

amendment properties, and application rate also influence plant-available water (Libohova et al., 2018; Minasny and McBratney, 2018; Razzaghi et al., 2020). This study, therefore, measured moisture retention directly as a separate response variable.

Most agronomic sludge studies concern municipal biosolids, whereas beverage-industry treatment sludge has received less attention. Beverage-processing residues arise from relatively specific production and cleaning streams and can differ from municipal sewage sludge in nutrient content, salinity, organic matter, and contaminant profile. This study tested sludge from a beverage production facility in Camarines Sur, Philippines, in heavy paddy soil planted with NSIC Rc23 rice. The objectives were to (i) characterize the measured chemical properties of the sludge and sludge-soil mixtures, (ii) determine treatment effects on rice growth, biomass, and grain yield, and (iii) quantify soil moisture retention. The experiment was designed as a pot-scale agronomic assessment. Potentially toxic elements, pathogens, electrical conductivity, organic contaminants, and crop-tissue contaminants were not measured; consequently, the study does not establish environmental or food-safety suitability for field application.

MATERIALS AND METHOD

Study materials and experimental design

The study was conducted from July 2022 to June 2023 in Camarines Sur, Philippines. The pot experiment was maintained in an open outdoor area under ambient conditions. Wastewater treatment sludge was collected from the on-site treatment facility at a beverage production plant in Naga City. The facility treated wastewater generated during beverage formulation and routine cleaning and rinsing operations; production inputs included treated water, sweeteners, and food-grade beverage concentrates or flavorings. Heavy paddy soil was collected from an operating rice farm in San Ramon, Lagonoy, Camarines Sur. NSIC Rc23 (Katihan 1) seedlings were obtained through the Municipal Agriculture Office of San Jose, Camarines Sur. The experiment followed a completely randomized design with 5 treatments and 3 replicate pots per treatment. Each pot was an independent experimental unit. Pots measured 30 cm in diameter and 35 cm in height and initially contained 5.0 kg of soil.

Treatments were unamended soil, a commercial fertilizer benchmark, and mixtures containing 2.5%, 5.0%, and 7.5% air-dried sludge (w/w), calculated as sludge mass divided by total soil-plus-sludge mass. For 5.0 kg of soil, the corresponding sludge masses were approximately 0.128, 0.263, and 0.405 kg pot⁻¹. Sludge was air-dried for 7 days before mixing. Assuming a 0.15-m incorporation depth and a soil bulk density of 1.30 Mg m⁻³, the pot proportions correspond to approximately 50, 103, and 158 Mg dry sludge ha⁻¹. These values provide field-scale context only and are not proposed application rates. The commercial benchmark was 14-14-14 N-P₂O₅-K₂O fertilizer. The protocol also listed a target nutrient rate of 120-60-60 kg ha⁻¹, which cannot be supplied by a single rate of 14-14-14; the commercial treatment was therefore treated as a benchmark rather than a nutrient-equivalent control.

Sludge and soil characterization

Samples of the heavy paddy soil, sludge, and each sludge-soil mixture were analyzed at the Regional Soils Laboratory in Pili, Camarines Sur. The measured parameters were total N (BSWM, 2024b), nitrate, elemental P, organic C (BSWM, 2021), and pH (BSWM, 2024a), with 3 analytical determinations for each material. Nitrate was determined by the colorimetric cadmium-reduction laboratory method. Phosphorus was determined using the Bray No. 1 method and reported as elemental P (mg kg⁻¹). The analysis did not include K, Ca, Mg, electrical conductivity, C:N ratio, potentially toxic elements, pathogens, or organic contaminants. The chemical results, therefore, describe the measured N, P, C, and pH characteristics and are not a complete fertilizer or safety profile. Analytical triplicates were summarized as mean ± standard deviation and were not used as independent experimental units for inferential analysis.

Plant measurements

One uniform 14-day-old seedling was transplanted into each pot. Pots were watered regularly throughout the experiment. Plant height and tiller number were recorded at the final growth assessment. Plants were harvested 120 days after transplanting; root length was measured after uprooting. Roots, stems, and panicles were separated and oven-dried at 70 °C for 72 hours for the determination of total dry biomass. Filled grain mass was recorded for each pot. Plant height, tiller number, root length, dry biomass,

and grain yield were analyzed with the pot as the experimental unit (n = 3 per treatment).

Water-retention measurements

After harvest, soil from each replicate pot was processed separately for the moisture retention test. Samples were air-dried, ground, and passed through a 2-mm sieve. One 100-g sample from each pot was placed in a filter-paper-lined funnel, saturated with distilled water, and allowed to drain. Gravimetric water content was recorded initially and after 24, 48, 72, and 96 hours. Thus, the 3 moisture retention samples within each treatment originated from 3 independent pots. Bulk density was measured with soil cores of known volume after oven drying, and total porosity was determined for the corresponding replicate soils. For each pot, the 0 to 96 hours water-content series was summarized as the trapezoidal area under the curve (AUC, %·h).

Statistical analysis

Plant variables and moisture retention AUC were analyzed by one-way analysis of variance (ANOVA). Pairwise comparisons were performed with Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$. Omega-squared (ω^2) was calculated as an estimate of treatment-effect magnitude. Homogeneity of variance and residual normality were examined with Levene's and Shapiro-Wilk tests, respectively. No marked violation was detected, although diagnostic sensitivity was limited by the use of 3 replicate pots per treatment. Ninety-five percent confidence intervals for treatment means were calculated for grain yield and moisture retention AUC using the *t*-distribution with 2 degrees of freedom. Nonsignificant pairwise comparisons were not interpreted as evidence of equivalence. Bulk density and total porosity were also analyzed by one-way ANOVA. Analyses were performed from the raw workbook using SciPy 1.17.0 and statsmodels 0.14.6.

RESULTS AND DISCUSSION

Nutrient characteristics of sludge and sludge-soil composites

The sludge contained higher concentrations of the measured nutrients and organic C than the heavy paddy soil (Table 1). Total N was 3.160% in sludge and 0.157% in soil; nitrate was 173.11 and 12.52 mg kg⁻¹, respectively. Elemental P was 1,346.72 mg kg⁻¹ in sludge and 25.97 mg kg⁻¹ in soil, while organic C was 30.927% and 1.267%, respectively. Concentrations increased

with the sludge proportion in the mixtures. At 7.5% sludge, total N reached 0.363%, elemental P 119.05 mg kg⁻¹, and organic C 3.440%. Similar enrichment of soil nutrient pools after biosolid amendment has been reported in other systems (Bai et al., 2017; Tontti et al., 2017; Kominko et al., 2019; Zuo et al., 2019a; Chagas et al., 2021; Ippolito et al., 2021). These data demonstrate enrichment of the measured N, P, and C pools, but they do not define the complete fertilizer value because K, Ca, Mg, and electrical conductivity were not measured.

Mixture pH did not increase monotonically at the 2 lower sludge rates. Soil, 2.5% sludge, and 5.0% sludge had mean pH values of 6.99, 6.88, and 7.13, respectively, whereas the 7.5% mixture reached pH 8.30. Thus, the highest sludge rate combined the largest measured enrichments of N, P, and organic C with a shift toward alkalinity. Rate-dependent changes in soil chemistry can alter nutrient availability and trace-element mobility (Jin et al., 2017; Tytla, 2020; Gutiérrez-Ginés et al., 2023). Electrical conductivity was not measured, so the pH data cannot be used to infer salinity.

Rice growth, biomass, and grain yield

ANOVA detected treatment effects for all 5 plant endpoints (Table 2). Omega-squared ranged from 0.59 for plant height to 0.87 for tiller number. Grain yield differed among treatments ($F(4, 10) = 12.25$, $p < 0.001$, $\omega^2 = 0.75$). Mean yield was 18.49 g pot⁻¹ in the unamended control and 25.20, 29.38, and 31.99 g pot⁻¹ at 2.5%, 5.0%, and 7.5% sludge, respectively. The 95% confidence intervals were 15.86–21.12, 18.99–31.41, 21.88–36.88, and 24.36–39.62 g pot⁻¹; the commercial fertilizer benchmark averaged 32.29 g pot⁻¹ (95% CI: 22.73–41.85). The yield at 7.5% sludge was approximately 73% above the control. Tukey's HSD test placed the 5.0% and 7.5%

sludge treatments above the control and in the same grouping as the commercial benchmark. A shared Tukey group indicates that a difference was not detected at $\alpha = 0.05$; it does not establish equivalence.

Dry biomass and tiller number followed the yield response. Dry biomass increased from 37.63 g plant⁻¹ in the control to 65.73 and 69.40 g plant⁻¹ at 5.0% and 7.5% sludge, respectively. Tiller number increased from 7.67 to 13.67 and 14.67 over the same treatments, respectively. Root length was also greater at the higher sludge rates, whereas the 2.5% treatment generally showed an intermediate response. Figure 1 summarizes these relative treatment responses, with values normalized to the unamended control. Increased nutrient supply provides a plausible explanation for greater tillering, root growth, biomass accumulation, and grain production, although nutrient uptake was not measured. Similar rice responses to organic or combined organic-mineral nutrition have been reported previously (Zhang et al., 2018; Chen et al., 2021; Dai et al., 2021; Iqbal et al., 2022; Ma et al., 2022; Medina Litardo et al., 2022). Treated biosolids have also produced growth responses in recent controlled crop trials (Cano-Larrotta et al., 2026).

Comparable crop responses to biosolids have been reported for wheat, sunflower, sorghum, and other species (Rehman et al., 2018; Boudjabi et al., 2019; Zuo et al., 2019a; Koutroubas et al., 2020; Boudjabi and Chenchouni, 2021). The present response should not be extrapolated beyond the tested 7.5% mixture. The approximate field-equivalent loads calculated for context are high, and the 7.5% mixture also produced the highest pH. Practical field rates should therefore be established based on nutrient requirements, soil response, contaminant limits, and replicated field trials rather than by direct scaling of pot concentrations.

Table 1. Chemical properties of heavy paddy soil, beverage-industry wastewater treatment sludge, and sludge-soil mixtures (mean±SD; 3 analytical determinations)

Parameter	Soil	Sludge	2.5% SSC	5.0% SSC	7.5% SSC
Total N (%)	0.157±0.006	3.160±0.147	0.217±0.012	0.320±0.020	0.363±0.023
Nitrate (mg kg ⁻¹)	12.52±1.45	173.11±6.70	16.64±1.72	21.97±2.26	24.69±2.33
Elemental P (mg kg ⁻¹)	25.97±1.90	1,346.72±70.74	67.09±1.06	91.42±12.06	119.05±7.06
Organic C (%)	1.267±0.067	30.927±1.782	1.970±0.069	2.623±0.312	3.440±0.144
pH	6.99±0.71	7.92±0.47	6.88±0.69	7.13±0.85	8.30±0.68

Note: SSC = Sludge-soil composite. Analytical triplicates were summarized descriptively and were not treated as independent experimental units

Table 2. Rice growth and yield responses to commercial fertilizer and sludge-soil mixtures (mean±SD, n = 3 independent pots)

Variable	Control	Commercial	2.5% SSC	5.0% SSC	7.5% SSC	ANOVA p ; ω^2
Plant height (cm)	91.45±4.87 ^{bc}	113.53±14.56 ^{ab}	88.22±3.21 ^c	102.07±8.73 ^{abc}	114.05±4.16 ^a	0.008; 0.59
Tillers (no.)	7.67±0.58 ^c	16.00±1.00 ^a	11.33±1.15 ^b	13.67±1.15 ^{ab}	14.67±1.53 ^a	< 0.001; 0.87
Root length (cm)	24.54±0.83 ^c	32.44±0.97 ^a	26.72±2.18 ^{bc}	30.27±0.95 ^a	29.57±0.20 ^{ab}	< 0.001; 0.83
Dry biomass (g plant ⁻¹)	37.63±0.82 ^c	70.55±8.15 ^a	51.81±3.23 ^b	65.73±5.63 ^a	69.40±3.44 ^a	< 0.001; 0.86
Grain yield (g pot ⁻¹)	18.49±1.06 ^b	32.29±3.85 ^a	25.20±2.50 ^{ab}	29.38±3.02 ^a	31.99±3.07 ^a	< 0.001; 0.75

Note: Within a row, means sharing at least one letter were not significantly different by Tukey's HSD at $\alpha = 0.05$. ω^2 = Omega-squared; SSC = Sludge-soil composite

Soil moisture retention and physical properties

Moisture retention AUC differed among treatments ($F(4, 10) = 38.99$, $p < 0.001$, $\omega^2 = 0.91$; Table 3). Mean AUC was 2,276.4 %·h in the control, 2,561.2 %·h with commercial fertilizer, and 2,682.6, 3,103.5, and 3,184.2 %·h at 2.5%, 5.0%, and 7.5% sludge, respectively. Corresponding 95% confidence intervals were 1,967.6–2,585.2, 2,425.3–2,697.1, 2,372.3–2,992.9, 2,777.8–3,429.2, and 3,021.7–3,346.7 %·h. Relative to the control, AUC was 36.3% higher at 5.0% sludge and 39.9% higher at 7.5% sludge. These 2 treatments shared the same Tukey's HSD grouping. At 96 hours, gravimetric water content averaged 26.24% and 26.52% for sludge at 5.0% and 7.5%, respectively, compared with 16.54% in the control.

Bulk density ($p = 0.810$) and total porosity ($p = 0.267$) did not differ among treatments. The increase in moisture retention AUC, therefore, cannot be attributed to a measured reduction in bulk density or increase in total pore volume. Water adsorption associated with added organic matter, aggregate formation, and redistribution of pore sizes are possible explanations, but none were measured directly. Previous studies likewise show that organic amendments can increase water storage in paddy soil, while the magnitude of the response varies with texture and amendment characteristics (Libohova et al., 2018; Minasny and McBratney, 2018; Razzaghi et al., 2020; Haque et al., 2021).

The higher grain yield and greater retained moisture observed at the 2 highest sludge rates are agronomically relevant, but the pot experiment did not reproduce field hydrology. Pots were watered regularly, and irrigation volume and water-use efficiency were not measured. Field trials are required to determine whether the observed moisture persistence reduces irrigation demand or stabilizes yield under intermittent drying in paddy systems.

Agronomic potential and safety boundaries

Taken together, the pot data show that the sludge increased the measured N and P concentrations of the soil mixture, increased rice biomass and grain yield at the higher rates, and prolonged soil moisture retention. Similar agronomic responses have been reported for long-term biosolid use, sludge-derived fertilizers, and other organic amendments (Alvarez-Campos and Evanylo, 2019; Hu et al., 2019; Shao et al., 2019; Cristina et al., 2020; Cano-Ruiz et al., 2021; Chagas et al., 2021). Rice responses to sewage

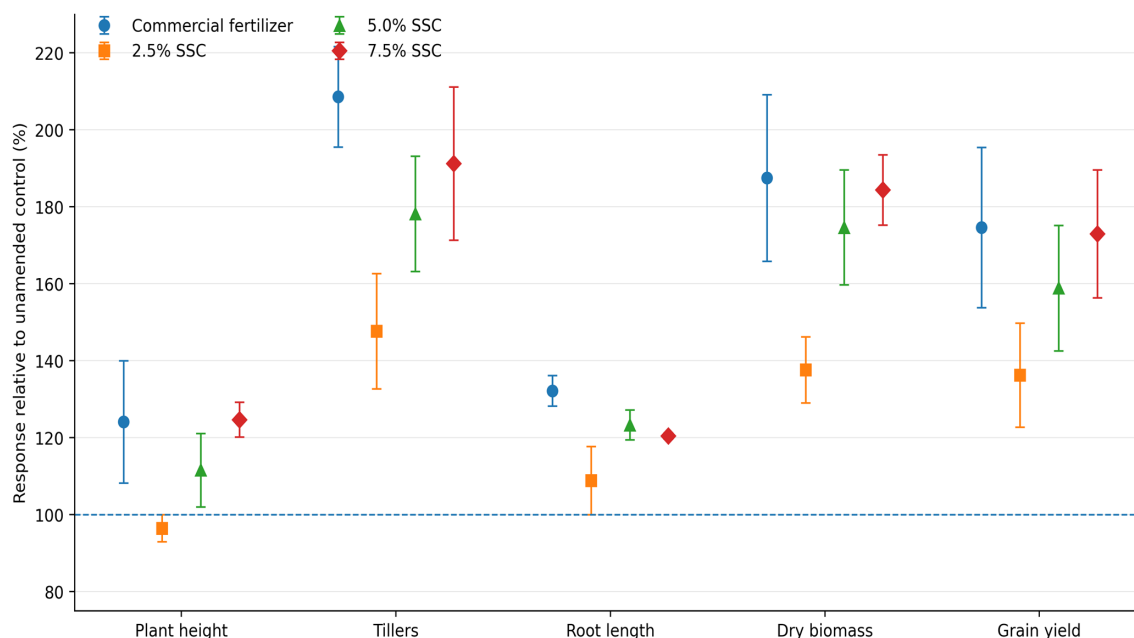


Figure 1. Rice growth and yield responses normalized to the unamended control (100%)

Note: Points show treatment means and error bars show $\pm$ SD ($n = 3$ independent pots). The dashed horizontal line denotes the control reference. Values are descriptive; inferential comparisons are reported in Table 2

Table 3. Moisture retention, AUC, and soil physical properties (mean $\pm$ SD, $n = 3$ independent pots)

Treatment	0–96 h AUC (%·h)	96 h water content (%)	Bulk density (g cm ⁻³)	Total porosity (%)
Control	2,276.4 $\pm$ 124.3 ^c	16.54 $\pm$ 1.21	1.420 $\pm$ 0.144	47.87 $\pm$ 5.33
Commercial	2,561.2 $\pm$ 54.7 ^b	18.10 $\pm$ 1.83	1.303 $\pm$ 0.067	45.77 $\pm$ 4.79
2.5% SSC	2,682.6 $\pm$ 124.9 ^b	21.87 $\pm$ 1.67	1.330 $\pm$ 0.185	53.09 $\pm$ 1.77
5.0% SSC	3,103.5 $\pm$ 131.1 ^a	26.24 $\pm$ 1.83	1.310 $\pm$ 0.164	48.60 $\pm$ 6.09
7.5% SSC	3,184.2 $\pm$ 65.4 ^a	26.52 $\pm$ 2.54	1.377 $\pm$ 0.085	52.19 $\pm$ 0.80
ANOVA <i>p</i>	< 0.001	< 0.001	0.810	0.267

Note: AUC = Trapezoidal area under the gravimetric water-content curve from 0 to 96 hours; SSC = Sludge-soil composite. Each moisture retention replicate originated from a different experimental pot. AUC means with different letters differ by Tukey's HSD test at $\alpha = 0.05$. The 96-hour *p*-value is a secondary time-specific comparison

sludge amendment have also been documented at the physiological and molecular levels (Calzone et al., 2024), and recent work with treated biosolids supports further agronomic testing (Cano-Larrotta et al., 2026). These comparisons support continued evaluation of the material; they do not justify direct transfer of the pot rates to field use.

Environmental and food safety were not evaluated in this experiment. Before use in rice fields, the sludge should be analyzed for potentially toxic elements, particularly As, Cd, Pb, Cr, Ni, Cu, Zn, and Hg, as well as pathogens, electrical conductivity/salinity, and relevant organic or emerging contaminants. Arsenic requires particular attention in flooded rice because reducing conditions can alter its mobility

and plant uptake. Contaminants were not measured in roots, shoots, or grain. Recent assessments of sludge-derived fertilizers similarly identify heavy metals, pathogens, microplastics, pharmaceuticals, and other emerging contaminants as components of risk evaluation (Skrzypczak et al., 2026). The present results are therefore limited to agronomic responses under pot conditions.

Study limitations

Chemical characterization was restricted to total N, nitrate, elemental P, organic C, and pH; therefore, nutrient balance and salinity could not be fully assessed. The commercial fertilizer was a benchmark rather than a nutrient-equivalent control because the 120-60-60 kg ha⁻¹ protocol

target is not directly comparable to a single rate of 14-14-14 fertilizer. The experiment also used one heavy paddy soil, one sludge source, one rice variety, and three pots per treatment. Fresh biomass, tissue nutrient uptake, contaminant accumulation, and field water-use efficiency were not measured. Field studies should establish application rates from nutrient budgets and safety thresholds, characterize the sludge more comprehensively, and evaluate repeated applications across contrasting paddy soils.

CONCLUSIONS

Beverage-industry wastewater treatment sludge increased measured soil N, elemental P, and organic C and improved rice biomass, grain yield, and 0- to 96-hour moisture retention under the tested pot conditions. Grain yield at 5.0% and 7.5% sludge exceeded that of the unamended control; the shared Tukey's HSD grouping with the commercial fertilizer benchmark does not demonstrate equivalence. Moisture retention AUC increased by 36.3% and 39.9% at 5.0% and 7.5% sludge, respectively, while bulk density and total porosity were unchanged. The sludge, therefore, showed potential as a soil amendment in this pot study. The tested mixture proportions represent high field-equivalent loads and should not be interpreted as recommended application rates. Agricultural use requires more detailed nutrient characterization, electrical conductivity/salinity measurements, screening for potentially toxic elements and pathogens, crop tissue and grain analyses, and replicated field trials to establish safe agronomic rates and field performance.

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DECLARATION OF GENERATIVE AI USE

OpenAI ChatGPT (GPT-5.6 Sol) was used to assist with statistical code verification, manuscript organization, and language editing. Statistical values reported in the manuscript were

recalculated from the supplied raw dataset and checked using reproducible statistical software. The authors independently verified the analyses, references, interpretation, and final wording, and have final responsibility for the submitted manuscript.

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