Research article

Transforming Septic Tank Sludge into Agricultural Resources: A Pathway for Sustainable Development and Rural-Urban Synergy

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Abstract Urbanization, coupled with inadequate sewage infrastructure, results in the accumulation of septic tank sludge, which poses significant environmental and public health risks. This study explored the potential of transforming dewatered septage into a valuable agricultural resource through composting, aligning with the goals of sustainable development and rural-urban synergy. This study investigated the composting of dewatered septage mixed with bulking agents (rice straw, sawdust, and wood chips), focusing on key environmental management aspects such as pathogen reduction, nutrient cycling, and heavy metal stability. Pathogen reduction was significant, with *E. coli* levels in rice straw and sawdust compost falling below the EPA Class A standard of 1,000 MPN/g, whereas wood chips met Class B standards with levels below 2,000,000 MPN/g. The composts contained no viable helminths, ensuring their safety for agricultural use. Nutrient analysis revealed suitable levels of nitrogen (2.20% in rice straw, 1.08% in sawdust, and 2.22% in wood chips), phosphorus (1.98% in rice straw, 0.70% in sawdust, and 1.97% in wood chips), and potassium (0.77% in rice straw, 0.04% in sawdust, and 0.14% in wood chips), which support soil fertility and land conservation efforts. This study provides a sustainable, circular approach to septage management, highlighting its potential to enhance soil quality, reduce environmental pollution, and promote climate resilience. This composting method offers an innovative pathway for transforming urban waste into agricultural resources, fostering rural-urban synergy, and supporting sustainable development. Future studies should optimize composting conditions and explore the long-term benefits of composting for agricultural productivity and environmental health.

Keywords septage composting, sustainable agriculture, waste repurposing, climate resilience in waste management, co-composting

INTRODUCTION

The lack of, or improper disposal of, septic tank sludge, commonly known as septage, remains a critical environmental and public health issue in the Philippines. Numerous private desludging operators dispose of sludge in street drains, esteros, canals, or open vacant land without treatment (Baltazar et al., 2021). Studies have shown that 64% of households in rural areas (USAID, 2023) and 67.1% in urban areas (Statista Research Department, 2022) depend on septic systems for wastewater treatment. In many developing and underdeveloped countries, septage management has historically been overlooked, with untreated sludge often disposed of in vacant lots, water bodies, and poorly managed landfills (Kiely, 1996). This institutional neglect, especially in urbanizing low-income contexts, reflects the historical underdevelopment of fecal sludge treatment infrastructure and regulatory frameworks (Strande et al., 2014). These practices contribute to groundwater contamination, the proliferation of pathogens, and greenhouse gas emissions, exacerbating environmental degradation and posing serious public health risks (Haug, 1993).

Addressing these challenges is vital to achieving Sustainable Development Goal (SDG) 6 on *Clean Water and Sanitation*, which emphasizes access to sustainable sanitation and wastewater management (UN, 2023). Sustainable solutions are urgently needed to mitigate the environmental and health impacts of septage mismanagement while fostering community awareness and participation in improved sanitation practices.

Although composting is widely recognized as a sustainable method for managing biodegradable organic waste, its application to septage has not been extensively explored. The existing literature has predominantly focused on thermal, chemical, and anaerobic treatment methods, which, while effective at pathogen reduction, are often cost-prohibitive and inaccessible for rural communities (Girovich, 1996). Recent studies have demonstrated the potential of co-composting, or the process of combining septage with carbon-rich bulking agents such as rice straw, sawdust, or woodchips, to address these limitations (Haug, 1993; Obeng and Wright, 1987). Research has shown that co-composting septage with carbon-rich bulking agents, such as rice straw, can improve compost quality and enhance economic returns (Din et al., 2017). This approach aligns with SDG 12 on *Responsible Consumption and Production* by converting waste into valuable resources for agriculture and supporting circular economy principles. However, several knowledge gaps remain.

1. *Optimization of Composting Parameters.* The influence of mixing ratios and bulking-agent type on co-composting performance (sanitization, nutrient conservation, and end-product quality) has been empirically demonstrated in faecal-sludge systems, underscoring the need for systematic optimization (Cofie et al., 2009).
2. *Pathogen Reduction Efficacy.* While previous research has highlighted the role of thermophilic composting in pathogen reduction, few studies have provided empirical data on the effectiveness of co-composting septage with specific carbon-rich bulking agents in achieving the United States Environmental Protection Agency (EPA) Class A standards for the use or disposal of sewage sludge, as outlined in the 40 CFR Part 503 rule (EPA, 1993).
3. *Practical Feasibility in Rural Settings*. There has been limited exploration of the safety and hygienic quality of septage co-composting products for agricultural use in resource-constrained rural areas (Mara, 2003).

Addressing these gaps is crucial for advancing sustainable waste management practices that align with global efforts toward circular economies. The transformation of septage into pathogen-free, nutrient-rich compost offers dual benefits in terms of reducing environmental pollution and enhancing soil health, particularly in rural agricultural systems. Moreover, integrating urban-generated waste with rural agricultural needs fosters rural-urban synergy, promoting sustainable development (Pausta et al., 2023).

This study addresses these research gaps by investigating the co-composting of dewatered septage with locally available bulking agents. By evaluating pathogen reduction, compost maturity, and nutrient enhancement, this study aims to provide valuable insights into the feasibility of septage co-composting as a low-cost, community-centered solution for sustainable waste management and agricultural productivity.

OBJECTIVE

The primary objective of this study was to determine the feasibility of co-composting dewatered septage with bulking agents to produce pathogen-free, agriculturally beneficial compost. The specific objectives are as follows:

(i) To characterize dewatered septage in terms of physio-chemical and microbial parameters.
(ii) To determine the optimal volumetric mixing ratios of septage and bulking agents for pathogen reduction, compost stability, and maturity and
(iii) To evaluate the final compost product against sanitation standards set by the United States

EPA, Department of Environment and Natural Resources (DENR), and Fertilizer and Pesticides Bureau (FPB) in the Philippines.

METHODOLOGY

Feedstock Preparation and Characterization

Septage collection**:** Septage were sourced from 28 household septic tank at various locations within Quezon City, Metro Manila, Philippines and was pre-processed by a mechanical decanter mounted on the collection truck. A total of three (3) cubic meter of dewatered septage was collected and homogenized using a mechanical mixer to create a composite feedstock as a preparation for the composting.
Bulking agent preparation**:** Three bulking agents, specifically rice straw, sawdust, and woodchips, were selected based on their availability, biodegradability, and cost-effectiveness. These materials were reduced in size manually to improve porosity, surface area, and microbial accessibility, with woodchips reduced to approximately 1-3 inches and rice straw to 3-4 inches. The bulking agents were then homogenized using the coning and quartering method to ensure uniformity in the compost feedstock mixture.
Mixing proportions: The feedstock was mixed at different volumetric ratios (1:1, 1:2, and 1:3 of septage to each bulking agent). Each ratio aimed to optimize moisture content, temperature control, and microbial activity during the composting process. A one (1) cubic meter by one (1) cubic meter wooden box was used to uniformly achieve the desired mixing ratio.
Compost windrow pile construction: Thirteen windrow piles were prepared, including 12 experimental piles with varying septage-to-bulking-agent ratios (1:1, 1:2, and 1:3) and one control pile with only septage. The windrow method was used, with each feedstock mixture arranged into long, narrow trapezoidal cross-sections to ensure proper aeration, temperature control, and ease of manual turning of the compost. Plastic straw sheets were used to cover the windrows to protect them against rainfall and retain heat from microbial activity. Water collection canals were installed around the perimeter of each pile to direct leachate away from the environment and prevent environmental contamination.

Composting Process Maintenance

Turning and aeration: Manual turning of the windrow piles using a shovel was carried out weekly to ensure proper aeration and prevent anaerobic conditions. This process facilitated the transfer of oxygen throughout the compost pile, thereby promoting microbial activity and optimizing the composting process.
Temperature and moisture control: Temperature was monitored daily using thermocouples inserted at multiple points in each pile to ensure compliance with the recommended conditions for pathogen reduction, as outlined by the EPA guidelines. Moisture content was measured every three days to track the composting process. Moisture levels were adjusted as necessary by spraying water or allowing passive drying.

Monitoring and Analysis of Composting Parameters

Environmental parameters: To align with EPA (1993) composting standards, the frequency of monitoring and analysis of other key composting parameters throughout the composting process was as follows: every three (3) day for pH, total solids (TS), total volatile solids (TVS), moisture content (MC), and total organic carbon (TOC); and for total nitrogen (TN), the analysis was carried out on the initial mixture and final compost product. These parameters were measured using standardized laboratory methods (gravimetric, potentiometric, and colorimetric analyses).
Microbial Analysis: Representative samples were submitted to accredited laboratories for pathogen testing. Microbial load was assessed at the beginning and end of the composting process using indicators such as fecal coliforms (*E. coli*), total coliforms, and pathogenic microorganisms including *Salmonella* and helminth eggs. These analyses were conducted in accordance with the U.S. EPA (1993) Class A standards for the use or disposal of sewage sludge.

Duration of Composting: The composting process was monitored over a period of three (3) months. The end of active decomposition was determined using environmental indicators, including temperature, pH, and reductions in volatile solids. The compost was considered mature once the window pile temperature stabilized within ±2°C of ambient levels and the pH approached neutral (~ 7.0). This behavior is consistent with typical composting profiles, where temperatures decline from thermophilic (> 45°C) into the mesophilic zone and ultimately approximate surrounding air temperature during curing and stabilization phases (ASABE, 2005; Utah State University Extension, 2009)

Compost Quality and Nutrient Analysis

Manual sieve analysis: The final compost product was harvested and screened using an 8 mm pore-size wire mesh to separate larger particles of bulking agents from the finer, mature compost. This process ensured uniformity in the compost product, making it suitable for its intended applications.
Nutrient analysis: The final compost product was analyzed for nutrient content, focusing on nitrogen (N), phosphorus (P), and potassium (K) concentrations to determine its suitability for agricultural use. The samples were sent to the Bureau of Soils and Water Management for Nutrient analysis.
Pathogen analysis: The presence of pathogens, such as *Salmonella*, helminth eggs, and fecal coliform, was assessed in the final compost product, benchmarked against the United States EPA 503 regulations for pathogen reduction (1993). These analyses are critical for ensuring the safety of compost for land application, as defined by the EPA, to include agricultural, silvicultural, and land reclamation uses.
Stability and maturity testing: The stability of the compost was evaluated based on parameters such as TS, TVS, and starch content, which reflect the extent of decomposition. The starch content method was chosen because of its reliability in assessing compost maturity and its applicability to the studied feedstock.
Physical and semi-qualitative analyses: Physical properties such as texture, color, and particle size were also assessed visually, alongside semi-qualitative tests like odor evaluation and gas production during compost storage in sealed plastic bags. These tests provided additional insights into compost maturity and microbial activities.

RESULTS AND DISCUSSION

Compost Feedstock Characteristics

The composite dewatered septage exhibited a high moisture content of 72.18% (Table 1), indicating a pasty texture that necessitated the addition of bulking agents to improve porosity and moisture regulation. Comparable studies have documented how bulking agents such as dry leaves effectively reduced moisture from ~89% to 57% and enhanced physical stability during composting (Jain et al., 2019); other work with dewatered sludge found that coffee-ground, corncob, and wheat husk additions significantly improved water removal during biodegradation (Hu et al., 2023).

The total volatile solids (TVS) content of 14.51% is relatively low compared to typical fresh domestic septage, suggesting that the sludge has undergone significant anaerobic decomposition within septic tanks prior to dewatering. The U.S. EPA (1995) and Ahmed et al. (2019) further noted that volatile solids content is widely recognized as an indirect measure of organic matter and biodegradability, and its values tend to closely track total solids (TS) in stabilized sludge, consistent with the 27.82% TS measured in this study.

The measured pH of 7.9 is slightly alkaline and well within the EPA Part 503 acceptable range of 6.0-12.0, which is favorable for beneficial reuse processes, including land application, while also suppressing certain pathogenic microorganisms (EPA, 1994). However, the fecal coliform count of 1.8×10^4 MPN/g exceeds the Class A pathogen limit (1.0×10^3 MPN/g) and falls within Class B specifications, indicating that additional pathogen reduction steps, such as thermophilic composting, are necessary prior to unrestricted land application (EPA, 1994).

Table 1 Characteristics of composite dewatered septage

Parameter	Value	EPA part 503 specifications (dry basis)
Moisture content (%)	72.18	30 – 60
Total solids (%)	27.82	12 (Class B)
Total volatile solids (%)	14.51	–
pH	7.9	6.0 – 12.0
Fecal coliform (MPN/g)	1.8×10^4	1.0×10^3 (Class A)

Table 2 shows that compost piles formulated from the composite dewatered septage, both unamended (control) and amended with carbon-rich bulking agents, started with initial moisture contents exceeding the optimal range for aerobic composting (50-60%), reaching as high as 72.1%. This excessive moisture can limit aeration, induce anaerobic zones, and reduce microbial activity, thereby prolonging the composting process (Kim et al., 2016; APHA, 2016).

Table 2 Initial characteristics of compost piles (dewatered septage plus bulking agents)

Septage and bulking agent mixtures	Initial operating parameter (dry basis)						
Rice straw	%TOC	%TN	C/N	%TVS	%MC	Bulk density (wet basis) kg/m^3	Fecal coliform (*E. coli*) CFU/g
1:1	51.37	1.55	33.23	53	69.0	489	1.40×10^4
1:2	59.61	1.54	38.74	50	68.9	352	1.15×10^4
1:2R	66.45	1.72	38.74	56	72.1	352	1.15×10^4
1:3	67.29	1.55	43.50	50	69.1	284	9.72×10^3
Sawdust							
1:1	65.66	1.15	57.33	50	65.4	586	9.13×10^3
1:1R	63.29	1.10	57.33	54	64.1	586	9.13×10^3
1:2	80.16	0.96	83.86	61	64.0	482	6.12×10^3
1:3	87.43	0.82	107.10	71	62.2	430	4.60×10^3
Wood chips							
1:1	53.14	1.07	49.56	59	63.3	581	9.11×10^3
1:1R	51.59	1.04	49.46	64	62.2	581	9.11×10^3
1:2	72.26	1.04	69.67	82	67.2	475	6.09×10^3
1:3	69.07	0.79	87.81	61	61.5	421	4.58×10^3
Control plot (pure septage)	46.25	6.22	7.43	52	72.1	900	1.80×10^4

The calculation of C/N ratio was based on the initial C and N content of septage and bulking agent respectively. The 'R' denotes replicate windrow pile of a feedstock mixing ratio. The term 'dry basis' refers to the measured characteristics such as total organic carbon (TOC), total nitrogen (TN), carbon to nitrogen ratio (C/N), total volatile solids (TVS), moisture content (MC), bulk density, and fecal coliforms with the moisture content excluded (APHA, 2017; ASTM, 2020).

Carbon-to-nitrogen (C/N) ratios in sawdust and woodchips mixtures exhibit high values, generally exceeding the ideal range of 25:1–35:1 for composting (Haug, 1993; Wiater, 2020), reaching up to 107.1 due to the high carbon and low nitrogen content of lignocellulosic materials. In contrast, pure septage had a low C/N ratio of 7.43, with high nitrogen (6.22%) and limited carbon content, reflecting prior anaerobic decomposition in septic tanks.

The generally recommended initial C/N ratio for initiating aerobic composting is between 15:1 and 30:1 (Haug, 1993). A stable and mature compost is typically achieved when the C/N ratio drops to ≤20, assuming the initial ratio was within 25-30:1 (Hirai et al., 1983). Maintaining a balanced C/N ratio is critical because excessive carbon can slow microbial activity, whereas excessive nitrogen can lead to ammonia volatilization and odor problems (Haug, 1993). Over time, carbon-rich materials decompose under low-oxygen (anaerobic) conditions, leaving behind a more stable sludge that is high in nitrogen but low in easily degradable carbon (Tchobanoglous et al., 1993). Studies on composting have also indicated that C/N ratios decrease progressively during the composting process due to organic carbon loss and relative nitrogen enrichment, and that this decline can serve as a reliable indicator of maturity (Hirai et al., 1983; Manga et al., 2022). Despite exceeding conventional

C/N thresholds, recent studies suggest that effective composting is still achievable with C/N ratios above 60:1, although the composting rate is slow and the time period is long (Oshins, 2022).

Initial fecal coliform (E. coli) concentrations in all mixtures exceeded the EPA Class A biosolids standard of <1,000 CFU/g TS, with the control plot registering the highest at 1.80 × 10^4 CFU/g, followed by the bulking mixtures, which ranged from 1.40 × 10^4 to 4.58 × 10^3 CFU/g (EPA, 1993; Boczek, L. 2019). These values confirm the need for sustained thermophilic composting to meet sanitation standards. Collectively, these initial operating values demonstrate the physicochemical suitability of bulking agents for co-composting, while emphasizing the need for moisture management and C/N ratios to support microbial degradation and pathogen reduction.

Pathogen Reduction Efficiency

Table 3 revealed significant pathogen reduction in composted septage mixed with various carbon-rich bulking agents, despite compost pile temperatures not reaching the thermophilic threshold of 55°C recommended by the EPA (1993) for Class A biosolid treatment. The maximum recorded temperatures ranged between 33 and 42°C across all compost treatments, with the highest observed in the sawdust mixtures. While these temperatures are considered suboptimal for rapid microbial inactivation, the extended composting duration (≥90 days), consistent aeration through manual turning, and favorable pH conditions (approaching neutral) may have collectively contributed to pathogen decline, consistent with the multi-factor inactivation pathways noted in previous studies (Haug, 1993; Sidhu and Toze, 2009).

Table 3 Pathogen reduction in the 1:2 septage and bulking agents' mixture (dry weight)

Parameters	Rice straw	Sawdust	Wood chips	Standards (1993)	
				EPA Class A	EPA Class B
Initial value, *E. coli* (g MS)	1.15 x 10^4	6.12 x 10^3	6.09 x 10^3	< 1000	< 2,000,000
Final value, *E. coli* (g MS)	503	307	2,012		
Salmonella (per 10 g MS)	< 1	< 1	< 1	< 3 MPN/4 g	< 1,000 MPN/4 g
Total helminths (per 10 g MS)	972	280	87	< 1 viable/4 g	< 1,000 viable/4 g
Ascaris (per 10 g MS)	420	20	53	< 1 viable/4 g	< 1,000 viable/4 g
Trichuris (per 10 g MS)	552	260	34	< 1 viable/4 g	< 1,000 viable/4 g
Viable helminths (per 10 g MS)	0	0	0	< 1 viable/4 g	< 1,000 viable/4 g

Several studies have reported similar outcomes, where pathogen removal was achieved even in the absence of prolonged thermophilic conditions. For instance, Mengistu et al. (2018) observed a general reduction in helminth eggs during the latter stages of the composting process, with more than 75 percent of the total reduction recorded after the 60th day. Likewise, Harroff et al. (2019) noted that relatively low temperatures can considerably impact *Ascaris* viability and suggested that mesophilic temperatures can be used in waste treatment processes to inactivate pathogens. Moreover, Manga et al. (2023) investigated the effect of turning frequency on the survival of fecal indicator pathogens (*E. coli*, *Enterococcus* spp., *Salmonella* spp. and helminth eggs) during fecal sludge co-composting with sawdust. Their findings indicate that, even under relatively low composting temperatures (maximum average temperatures of compost piles or treatments were 54°C, 52.8°C and 52.1°C), increased turning frequency can substantially improve pathogen inactivation. This insight is particularly relevant for rural contexts where the availability of suitable organic solid waste for co-composting with fecal sludge to achieve sustained thermophilic conditions may be limited.

The complete absence of viable helminths in the final compost products suggests that factors beyond temperature were effective in pathogen inactivation in the present study. Khadra et al. (2019) investigated helminth eggs (HE) removal and inactivation efficiency by co-composting. The viability of ascaris eggs was examined using a light microscope and the percentage of the embryonated eggs was determined. No viable eggs were observed in the final compost sample.

Agronomic Benefits and Heavy Metal Safety

The final compost product (Table 4) demonstrated acceptable agronomic and environmental properties. Nutrient analysis of the 1:2 feedstock mixtures revealed sufficient nitrogen (N), phosphorus (P), and potassium (K) levels, suitable for use as a soil conditioner, in accordance with international and Philippine standards (EPA, 1993; Caneda et al., 2013). The metal concentrations were below the regulatory thresholds, minimizing environmental risks. The compost also showed satisfactory stability and maturity, as evidenced by the absence of starch, lack of offensive odors in water-soaked samples, and no bulging in the packed bags, meeting the quality parameters of the Philippines National Standards 40 (2013) for Organic Fertilizer (Caneda et al., 2013).

Table 4 NPK and heavy metals content of 1:2 septage to bulking agent compost

Compost feedstock and standards	Parameters (dry basis)						
	Nutrients			Metals (mg/kg)			
	%N	%P_2O_5	%K_2O	Zinc (Zn)	Copper (Cu)	Manganese (Mn)	Iron (Fe)
Rice straw	2.20	1.98	0.77	2,462	271	788	19,443
Sawdust	1.08	0.70	0.04	1,497	1475	392	13,679
Wood chips	2.22	1.97	0.14	2,302	265	507	22,550
Typical values for compost or soil conditioner (PNS 40)	2.5 - < 5%	2.5 - < 5%	2.5 - < 5	5	300	N.L.	N.L.
Typical values for use or land application (EPA rule 503)	N.S.	N.S.	N.S.	2,800	1,500	N.S.	N.S.

U.S. EPA 40 CFR Part 503, Standards for the use and disposal of sewage sludge (1993 and 1994);
N.S. – Not Specified; PNS – Philippine national standards 40:2013 for organic fertilizer.

CONCLUSION

This study demonstrated both the feasibility and effectiveness of co-composting dewatered septage with carbon-rich bulking agents, namely rice straw, sawdust, and wood chips, as a sustainable strategy for managing urban organic waste and supporting rural agricultural systems. The feasibility of the process was supported by preprocessing the initial physicochemical parameters, allowing for stable compost pile construction and aeration. Effectiveness was evaluated based on two key outcomes. First, the composting process achieved significant pathogen reduction, as evidenced by the marked decline in fecal *Escherichia coli* concentrations, meeting the United States Environmental Protection Agency (EPA) 503 Class A criteria, confirming its suitability for land application in agricultural contexts. Second, the final compost products satisfied the Philippine National Standards (PNS) 40:2013 specifications for organic fertilizers, featuring favorable agronomic properties in terms of nitrogen (N), phosphorus (P), and potassium (K), along with low concentrations of heavy metals, supporting their suitability as organic soil amendments. These findings affirm the potential of septage co-composting to contribute to sustainable waste valorization, pathogen-safe compost production, and soil fertility enhancement in rural areas of developing countries. However, for widespread adoption and integration into municipal or city level waste management systems, economic and logistical feasibility must also be considered. Critical implementation challenges include the transport costs of septage and bulking agents, land availability for composting facilities, capital investment for operational equipment, and financial incentives for local governments or private actors. Although not empirically assessed in this study, these variables are fundamental to the long-term viability of septage co-composting initiatives. Future research should incorporate cost–benefit analysis, value chain assessment, and financing models to inform policy, guide infrastructure development, and enhance local implementation strategies. The results of this study underscore the potential of septage co-composting with carbon-rich bulking agents as a climate-resilient sanitation and soil management solution aligned with circular economy principles and the Sustainable Development Goals (SDGs), particularly SDG 6 (clean water and sanitation) and SDG 12 (responsible consumption and production).

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