Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 25 | No. 1 | Article ID B4319 | 2026

Original Research Paper

https://doi.org/10.46488/NEPT.2026.v25i01.B4319

Open Access Journal

Effect of Combined Vermicomposting and EM Solution on Sewage Sludge Nutrient Profile: A Temporal Study

Snehal K. Kamble† and Ajay R. Gajbhiye
Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, Maharashtra, India
†Corresponding author: Snehal K. Kamble; snehalkamble444@gmail.com

Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 11-02-2025
Revised: 04-05-2025
Accepted: 12-05-2025

Key Words:

Nutrient stabilization
Vermicomposting
Effective microorganisms
Sewage sludge
Composting kinetics

Citation for the Paper:

Kamble, S. K. and Gajbhiye, A.R., 2026. Effect of combined vermicomposting and EM solution on sewage sludge nutrient profile: A temporal study. *Nature Environment and Pollution Technology*, 25(1), B4319. https://doi.org/10.46488/NEPT.2026.v25i01.B4319

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

The principal objective of this study is to investigate the synergistic influence of vermicomposting and the application of Effective Microorganism (EM) solution on the nutrient transformation dynamics within sewage sludge. Sewage sludge, being rich in organic matter yet often unstable in terms of nutrient availability, requires effective stabilization strategies to enhance its suitability as a soil amendment. In this context, the research primarily emphasizes the stabilization and mineralization of key macronutrients, nitrogen (N), phosphorus (P), and potassium (K), over a controlled composting period of 90 days. By integrating vermicomposting, which harnesses the activity of earthworms to accelerate organic matter degradation, with EM solution, which introduces beneficial microbial consortia to stimulate biochemical processes. Further, the study aims to optimize the substrate ratio, quantify the enzymatic activities related to microbial pathways, and model the kinetic behavior of nutrient mineralization using dynamic equations, which will improve the understanding of temporal nutrient stabilization mechanisms.

INTRODUCTION

Sewage sludge is a byproduct of wastewater treatment that raises tremendous environmental and management concerns in terms of its organic richness, pathogenic load, and nutrient content. Utilization of this waste stream effectively can help solve both environmental issues and meet the growing requirement for organic fertilizers for sustainable agriculture. Traditional composting methods (Balidakis et al. 2024, Chen et al. 2024, Bicalho et al. 2024) fail to meet the challenges for stabilization and maturation efficiencies, with probable nutrient loss and variable quality of composts. A need exists to develop advanced composting methods that ensure efficiency in nutrient dynamics and are environmentally safe. Vermicomposting, bio-oxidative decomposition of organic material by earthworms, is a promising solution that accelerates decomposition of organic matter and improves its nutrient bioavailability. Likewise, Effective Microorganisms (EM), a consortium of beneficial bacteria, fungi, and actinomycetes, have been reported to enhance microbial activity and stabilize nutrients (Ucaroglu et al. 2024, Beduk et al. 2023, Serwecińska et al. 2024) in composting systems. While individual merits of these methods have been reported, research concerning their simultaneous use is particularly lacking, especially as related to stabilizing nutrients over temporal instance sets. This study fills this gap by assessing the combined impact of vermicomposting and EM solutions on nutrient fluxes for the sewage sludge. This research systematically investigates nutrient transformations, loss pathways, and stabilization efficiency through a suite of advanced methodologies that include dynamic kinetic modeling (DKM), microbial profiling via 16S rRNA sequencing, enzymatic assays, and nutrient fractionation. Integrated temporal analysis, substrate optimization, and soil fertility evaluations provide practical insights into the factors behind nutrient stabilization, together with the mechanisms driving this process.

A substantial research gap exists about the evolutionary processes of bacterial-community structures and kinetics throughout processes in nutrient stabilization between vermicomposting and EM treatments, microscopically synchronized and analyzed, and with biochemical and kinetic modeling, not to mention sludge material optimization suitable for preservation of nutrients in the shorter time frame. It is this study, with the integration of microbial and kinetic models, which will contribute to enhancing scholarly understanding concerning nutrient dynamics.

Specific objectives are: (i) to model the mineralization kinetics and stabilization kinetics of nitrogen, phosphorus, and potassium for the combined treatments of using vermicomposting and EM and (ii) to analyze the microbial community dynamics and enzymatic roles with respect to nutrient release; (iii) to further assay for the best sludge-to-green-waste ratios for nutrient retention; and (iv)to validate the compost quality using maturity indices and plant bioassays under standardized application conditions. The articulation of the research problem has been further strengthened through the revision in the introduction, bearing in mind the shortcomings of the integrative studies that would timely evaluate the simultaneous application of vermicomposting and EM in nutrient stabilization. This study fills the void using a system model involving microbial, enzymatic, and kinetic models to provide a more complete understanding of nutrient dynamics.

Now, specific research objectives have been laid down in the introduction to further contribute to the efforts to improve composting strategies for sludge management in the study area. Further, cited arguments from related studies are also included, signifying the vermicomposting efficiency, EM use, and nutrient transformation mechanisms to reasonably affect the same, which is instrumental in bridging the abovementioned gap. A quantitative experimental design has been adopted for the study to elucidate nutrient stabilization and microbial dynamics of composted sewage sludge. The experiment involved the use of 12 composting bins of 50 L apiece and was laid out in a randomized complete block design. There were three sludge-to-green-waste ratios (1:1, 2:1, and 3:1), and each was among three replications. The density of E. fetida was 50 individuals kg-1 substrate, and EM solution was applied at a dose of 1 mL per 100 g substrate. Nutrient concentration in the form of nitrogen, phosphorous, and potassium, microbial communities (from 16S rRNA sequencing), and activity of enzymes (urease, phosphatase, cellulase) were monitored through data collection at the following six intervals, 0, 15, 30, 45, 60, and 90 days and analyzed using regression models for quantify kinetic parameters, ANOVA for several effect comparisons, and Pearson correlation; the last to establish relationships between nutrient mineralization and microbial activity. The Humification Index (HI), Maturity Ratio (MR), and plant bioassay of maize are proposed for an integrated quality regimen of compost. Gas and leachate loss were determined with a gas analyzer and a percolate collection system.

MATERIALS AND METHODS

Review of Models Used for Sewage Sludge Analysis

The sewage sludge composting and resource recovery field has experienced great growth in recent years, with a number of researchers paying attention to nutrient stabilization, microbial dynamics, and sustainability in the environmental context. Balidakis et al. (2024) studied the use of selective clay minerals and biochar in sewage sludge stabilization; they exhibited their ability to reduce metal mobility while improving maturity in the compost. Similarly, Chen et al. 2024) underlined the importance of hyperthermophiles in composting sludge with an emphasis on their role in accelerating organic matter degradation under thermophilic conditions. Bicalho et al. (2024) applied spectroscopic techniques such as FTIR-MIR and FTIR-NIR to observe biochemical changes taking place in composted sludge and thus arrive at critical insights about nutrient transformations and metal binding mechanisms. Ucaroglu and Atalay et al. (2024) on agricultural waste co-composting proved the possibility of enhancement in nutrient content in composted sludge. Beduk et al. (2023) assessed the risks of persistent organic pollutants in sewage sludges, giving a finer resolution temporal analysis of the concentration and loading dynamics thereof with consequences for soil health. Another area is the dynamics of the microbial community. Serwecińska et al. (2024) demonstrated how sludge fertilization alters soil microbial structure and resistomes, highlighting the need for sustainable application practices.

Alonso et al. (2024) compared the chemical characteristics of sludge from various wastewater treatment plants, identifying key differences that affect compost quality. Mulopo (2024) conducted a systematic review of sludge use for industrial ecology, focusing on the contribution to the transition toward sustainability. Dos Santos et al. (2024) found the influence of biochar derived from sludge on crop production for nutrient retention in soil and reported considerable increases in such retention. Hechmi et al. (2024) studied microplastic pollution from wastewater treatment and sludge and advanced ideas on how to avoid soil degradation. Such novel composting techniques have also been highly researched. Nsiah-Gyambibi (2023) enhanced sludge pyrolysis into vermicomposting, resulting in improved nutrient recovery and diminished levels of organic contaminants. (Alonso et al. 2024) tested the applicability of sludge as a substrate for tree seedlings and attained positive results at both growth and nutrient availability. Abban-Baidoo et al. (2024) investigated biochar co-composting and noted its beneficial impact on carbon and nitrogen dynamics. Echeverría-Vega et al. (2024) studied the microbial and physicochemical evolution of industrial waste composting, relating microbial activity to nutrient stabilization. Souza et al. (2024) have evaluated the ecotoxicological implications of sludge use, and pre-treatment seems to be crucial in tackling risks to the environment. The topic of metal immobilization strategies is rising in recent literature. Ojo et al. (2024) evaluated the effectiveness of sulfidated nano zerovalent iron for reducing metal mobility in contaminated soils, demonstrating significant improvements. Chiarelotto et al. (2024) applied multivariate analysis to composting urban tree and agro-industrial residues, identifying critical factors influencing nutrient transformations. Silva et al. (2024) highlighted the operational and environmental benefits of forest waste composting, proposing best practices for large-scale implementation. Srivastava and Chakma et al. (2023) evaluated the stabilization of sugar mill pressmud through pilot-scale composting, reaching heavy metal toxicity reductions and decomposition of organic matter. Luo et al. (2024) reviewed the advances of microbial communities in composting, discussing the functional roles of key microbial taxa.

Valchev et al. (2024) investigated the recovery of valuable elements from sludge. Interesting to see that, according to Table 1, they mapped nutrient and metal concentrations throughout the wastewater treatment plants and identified the potential for recovery. Ogugua et al. (2024) reviewed the synergistic co-treatment of sludge with low-rank coal and straw, presenting strategies to enhance energy efficiency, and Elbl et al. (2024) examined sludge gasification in fluidized bed systems. Zhu et al. (2024) determined the high-value utilization technologies for sludge, suggesting an integrated solid waste management approach. Amaral et al. (2025) suggested pre-composting with subsequent vermicomposting and EM addition, resulting in faster compost maturity with better nutrient characteristics. Mangottiri et al. (2024) evaluated new composting technologies by using an AHP-based approach to find the optimal strategies for land application of biochar-amended sludge compost. Piao et al. (2023) reviewed additives for straw composting and identified some additives that enhance microbial activity and nutrient release. Jothinathan et al. (2023) over-viewed fecal sludge management with a focus on resource recovery options. Peng et al. (2024) analyzed the impact of the particle size of biochar in sludge vermicomposting. They observed optimal particle sizes for maximum activity of microbes. Grigatti (2023) assessed the impacts of anaerobic digestates on the management of soil carbon and phosphorus, where it was related to improvements in fertility and quality

Table 1: Comparative Analysis of Existing Methods.

Method	Key Findings
Selective Clay Minerals and Biochar Addition (Balidakis et.al. 2024)	Improved sewage sludge stabilization by reducing metal mobility and enhancing compost maturity.
Hyperthermophiles in Sludge Composting (Chen et.al. 2024)	Accelerated organic matter degradation under thermophilic conditions improves composting efficiency.
Spectroscopic Analysis (FTIR-MIR and FTIR-NIR)	Identified critical nutrient transformations and metal binding mechanisms during composting.
Biochar Co-Composting (Bicalho et.al. 2024)	Enhanced carbon and nitrogen stabilization; improved nutrient content and reduced leachate loss.
Sulfidated Nano Zerovalent Iron Application (Ojo et al. 2024)	Effective in immobilizing heavy metals in contaminated soils, reducing toxicity and enhancing soil quality.
Pre-Composting with Vermicomposting and EM Addition (Amaral et al. 2025)	Achieved faster compost maturation, higher nutrient retention, and reduced ammonia emissions.
Additives for Straw Composting (Piao et al. 2023)	Additives such as biochar and zeolite enhanced microbial activity and accelerated nutrient transformations.
Biochar-Augmented Vermicomposting (Peng et al. 2024)	Optimal biochar particle size significantly improved microbial diversity, earthworm activity, and compost quality.
Zeolite and Winery Waste Co-Composting (Doni et al. 2024)	Increased nutrient retention, reduced ammonia emissions, and improved humification rates in compost.
Earthworm-Assisted Toxic Weed Stabilization (Das et al. 2024)	Efficiently reduced heavy metal toxicity and stabilized nutrients, producing mature compost for soil applications.

of the produced compost. Doni et al. (2024) examined co-composting winery waste with zeolite, enhancing nutrient retention and minimizing ammonia emissions. Vinay et al. (2023) evaluated innovative techniques to remove microplastics from sludge, focusing on upcycling approaches for reduced environmental impact. Pérez et al. (2024) discussed the co-digestion of sewage and organic waste in anaerobic reactors, providing operational insights that support improving methane production. Tiwari et al. (2024) reviewed strategies for reusing treated sewage water in agriculture, highlighting potential water scarcity reduction while enhancing soil quality. Xiong (2023) critically reviewed the characterization of dissolved organic matter in composting and identified the gaps in understanding its role in nutrient dynamics. Other recent studies on co-composting include the characterization of microbial and enzymatic dynamics of green leaves and kitchen waste composting by Sathya et al. (2024). Hassan et al. (2023) carried out a techno-economic evaluation of biofertilizers from wastewater biosolids, suggesting cost-effective production models. Maqbool et al. (2024) addressed the issues of fecal sludge management in an urban environment by recommending solutions for integrated treatment. Tin et al. (2024) presented sludge-to-energy strategies for rubber processing industries, highlighting the present progress in energy recovery techniques. Pan et al. (2023) studied lignite co-composting of herbal residues as a bulking agent, showing improvement in the degradation of organic matter. Gupta et al. (2024) further looked into infusing fruit-vegetable waste into bakery sludge with vermicomposting, which resulted in enhanced nutrient availability and maturity of the compost. (Zhao et al. 2024) compared bacterial agents and mature compost for chicken manure composting, finding the former to be more effective in accelerating stabilization of nutrients. Ucaroglu et al. (2024) reviewed bioconversion strategies for organic wastes, with a focus on integrated approaches to sludge and manure management. (Sharma et al. 2023) characterized Tectona grandis leaf litter compost, demonstrating its viability as an organic amendment. For instance, Jarupan et al. (2024) valorized brewer's spent grains to obtain biodegradable plant pots by using the material creatively to recycle agricultural wastes. Jing et al. (2024) further invested their interest in earthworms for composting by comparing several species that have been shown to perform better in nutrient stabilization and heavy metal reduction. Rubert et al. (2024) proposed nutrient recovery from liquid digestate using a hydroponic system, which provides a sustainable solution for wastewater treatment. Booton et al. (2024) reviewed chemical oxidation as an alternative for secondary wastewater treatment, proposing stabilization of sludge. Macura et al. (2024) systematically mapped pathways for nutrient recovery from human excreta with a view to agricultural reuse. Toxic weed stabilization by vermiculture has been explored by Das et al. (2024), and the study reported a good reduction in toxicity with improved compost quality. Collectively, these studies provide a comprehensive view of the advancements in sewage sludge management and composting. The introduction of new materials, microbial techniques, and recovery strategies has significantly enhanced the stabilization of nutrients, energy efficiency, and environmental sustainability. These findings emphasize the point that while managing sludge, it is essential to ensure that the multidisciplinary approach can recover its potential based on its agricultural and industrial applications. The future research required will scale up these innovations to adjust process parameters and look into the long-term impacts of these approaches on soil and plant health so as to maximize their benefits.

Proposed Model for Design of an Integrated Model with Integrative Nutrient Stabilization in Sewage Sludge Composting

To overcome the problems of low efficiency and high complexity inherent in the available methods, the design of an Integrated Model with Integrative Nutrient Stabilization in Sewage Sludge Composting, which is an Iterative Temporal Study Combining Vermicomposting and Effective Microorganisms, is discussed here. Initially, in Fig. 1, the methodology of this study integrates sophisticated modeling and experimental approaches to fully assess nutrient transformations, microbial contributions, and compost maturity in the co-composting of sewage sludge with vermicomposting and Effective Microorganisms (EM) solutions. This approach works on the temporal dynamics of nutrients and their stabilization mechanisms along with providing a quantitative basis for evaluating the process of compost quality and nutrient retention. Dynamic Kinetic Modeling (DKM) forms the backbone analytical framework that allows for quantitative analysis of nutrient transformation pathways. In this study, nutrient mineralization and stabilization rates for nitrogen, phosphorus, and potassium were modeled using a system of first-order differential equations. The time change of the total nitrogen 'Nt' is described via equation 1,

$$\frac{dNt}{dt} = -kN * Nt \quad ...(1)$$

Where, 'kN' is the first-order mineralization constant for nitrogen, determined through regression analysis of time-series data samples. The stabilization half-life (T50) was derived via equation 2,

$$T50 = \frac{ln(2)}{kN} \quad ...(2)$$

This equation defines the time point when 50% of the incorporated nitrogen has stabilized. Similarly, for phosphorus dynamics, a model was used to simulate fast release ('Pr') and equilibrium stabilization (Peq) via equation 3:

$$P(t) = P0e^{-kPt} + Peq(1 - e^{-kPt}) \quad ...(3)$$

Potassium stabilization (Ks) was expressed via equation 4:

$$K(t) = K0e^{-kK*t} + Keq \quad ...(4)$$

Where, P0 and K0 denote the initial concentrations of phosphorus and potassium, respectively, while kP and kK represent their corresponding mineralization constants. Subsequently, as illustrated in Fig. 2, the iterative framework was extended to establish a linkage between nutrient transformation dynamics and microbial activity. To achieve this, 16S rRNA sequencing was employed to characterize microbial community composition, complemented by enzymatic assays that quantified functional activities driving nutrient mineralization throughout the composting process.

The activity of key enzymes, such as urease ('U'), phosphatase ('P'), and cellulase ('C'), was modeled using Michaelis Menten kinetics via equation 5,

$$v = \frac{Vmax[S]}{Km + [S]} \quad ...(5)$$

Where, 'v' represents the enzymatic reaction rate, Vmax the maximum rate, 'Km' the substrate affinity constant, and [S] the substrate concentration levels. Peak enzymatic activities were correlated with nutrient fluxes using linear regression via equation 6:

$$Nflux = \beta0 + \beta1 * v + \epsilon \quad ...(6)$$

Where, β0 and β1 are regression coefficients, and ϵ is the error term for this process. For example, urease activity was found to correlate strongly with ammonium-N release (R2=0.92) in the process. Kinetic modeling via substrate composition analysis was used for evaluating the decomposition rate ('RD') of organic carbon and lignin sets.

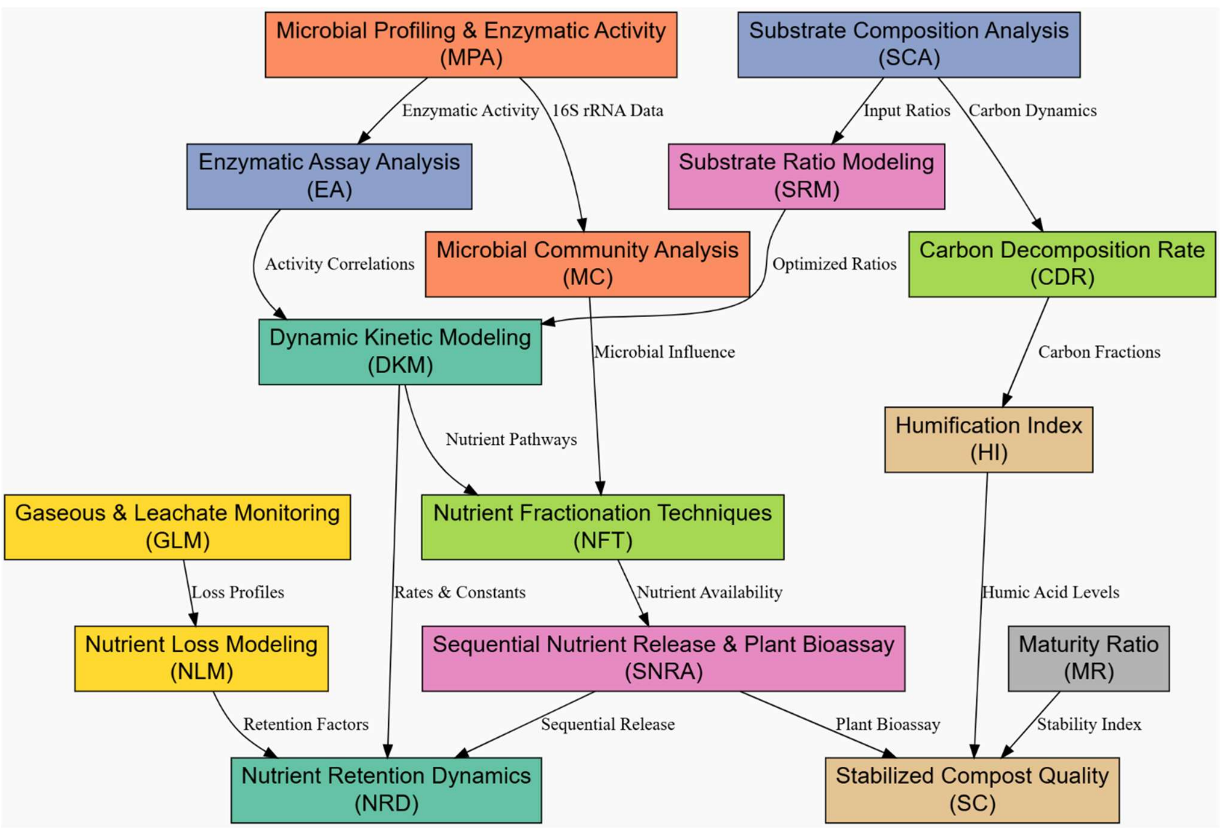

Fig. 1: Model Architecture of the Proposed Analysis Process.

The temporal degradation of cellulose (‘Ct’) was modeled via equation 7:

$$\frac{d\dot{C}t}{dt} = -kD * Ct \qquad ...(7)$$

With kD being the decomposition rate constant for this process. Stabilization of the carbon-to-nitrogen ratio (C/N) was analyzed via equation 8:

$$\frac{d\left(\frac{C}{N}\right)}{dt} = -kCN\left(\frac{C}{N} - \frac{C}{Neq}\right) \qquad ...(8)$$

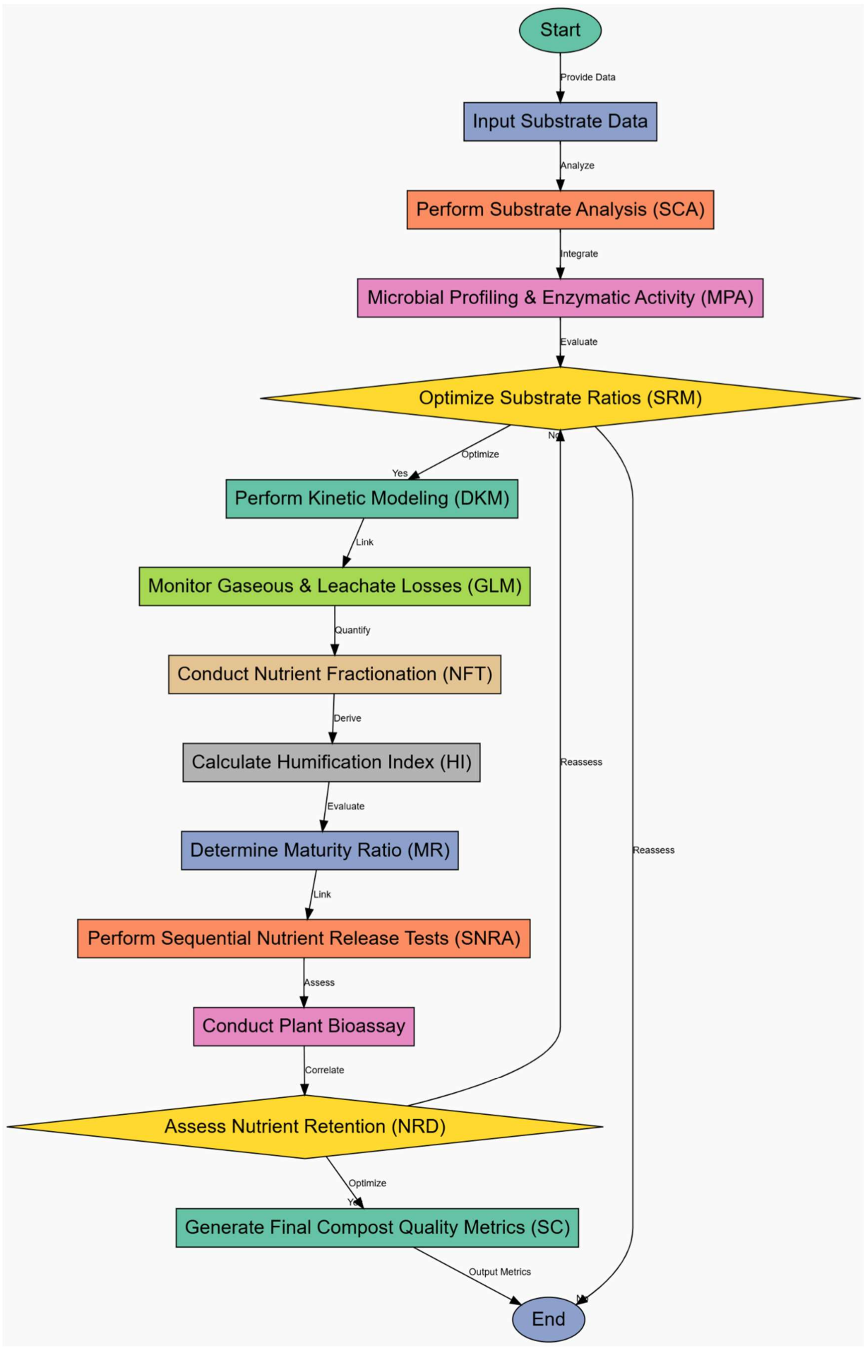

Fig. 2: Overall Flow of the Proposed Analysis Process.

Where, C/Neq is the equilibrium ratio for this process. A 2:1 sludge-to-green waste ratio resulted in a stabilization of C/N at 15:1 by Day 30 in the observations. Sequential releases of nutrients and plant bioassays provided practical validation of levels of quality of compost via equation 9; the process modeled the residual availability of the nutrient in the soil over time as follows:

$$Na(t) = Nmin + (N0 - Nmin)e^{-kloss*t} \quad ...(9)$$

Where, Nmin is the residual nutrient concentration, and kloss represents nutrient loss rates. Crop nutrient use efficiency (NUE) was quantified via equation 10,

$$NUE = \frac{\Delta Y}{Napplied} \quad ...(10)$$

Where, ΔY is the yield increase, and Napplied is the total applied nutrient for the process. Gaseous and leachate monitoring quantified nutrient losses. Ammonia (NH3) emissions were modeled based on diffusion dynamics via equation 11:

$$\frac{dNgas}{dt} = kgas * \Delta C \quad ...(11)$$

Where, kgas is the diffusion coefficient, and ΔC is the concentration gradient for the process. The cumulative nutrient loss (Lt) via leachate was modeled via equation 12:

$$Lt = \int_0^t kleachN(t)dt \quad ...(12)$$

Where, kleach represents the leachate loss coefficient in the process. Compost maturity was assessed using the Humification Index ('HI') and Maturity Ratio ('MR') sets. 'HI' was calculated via equation 13:

$$HI = \frac{HA}{FA} \quad ...(13)$$

Where, HA and FA are humic and fulvic acid concentrations. 'MR' was derived from stabilized carbon and nitrogen ratios via equation 14:

$$MR = \frac{Cfinal}{Cinitial} \times \frac{Nfinal}{Ninitial} \quad ...(14)$$

The final output integrated all these equations into a composite nutrient retention efficiency model ('NRE') via equation 15:

$$NRE = \frac{(Napplied - Nloss) + Nmineralized}{Napplied} \quad ...(15)$$

It captures the culmination of nutrient dynamics, stabilization efficiency, and practical utility in terms of optimized composting, contributing to nutrient conservation and agricultural productivity. The integration of the most advanced techniques and models complements the traditional composting studies through a temporal, mechanistic, and scalable framework for the stabilization of nutrients. We then discuss the efficiency of the proposed model based on different metrics and compare it to other methods under various scenarios.

RESULTS AND DISCUSSION

The experimental design for this study aimed to assess the integrated effects of vermicomposting and Effective Microorganisms (EM) solutions on the temporal profile of nutrients in sewage sludge. The composting was done in controlled laboratory settings using 50-liter capacity composting bins. Sewage sludge was mixed with co-substrates—green waste, food waste, and sawdust—in predetermined ratios (e.g., 3:1, 2:1, and 1:1), with the 2:1 ratio identified as optimal based on preliminary substrate composition analysis. Earthworm, Eisenia fetida (density: 50 individuals per kg of substrate), and an EM solution containing a consortium of bacteria, fungi, and actinomycetes (applied at a concentration of 1 mL per 100 g of substrate). Evaluation of the composting process occurred for 90 days with regular mixing and moisture adjustments to attain optimal conditions (temperature: 25–30°C, moisture: 60–65%). The sampling was carried out periodically on Days 0, 15, 30, 45, 60, and 90 with nutrient analysis, microbial profiling, and enzymatic assays for thorough temporal coverage. Publicly available datasets, such as the FAO Global Soil Organic Carbon Database's "Compost Nutrient and Microbial Dataset," were used for the results of this study to establish a basis of comparison with experimental data. This dataset contains detailed measurements of nutrient profiles (total nitrogen, phosphorus, potassium, and organic carbon) and microbial diversity indices from composting studies on various substrates, including sewage sludge, green waste, and food waste. The nutrient dataset covers temporal nutrient data over 90 days with intervals at Days 0, 15, 30, 45, and 90. Microbial profiling data were captured through 16S rRNA sequencing. Nutrient transformation rates and stabilization indicators, including nitrogen mineralization constants ('kN') and phosphorus stabilization half-lives (T50), are also provided in addition to data on enzymatic activity trends (e.g., urease, phosphatase). Such a dataset is informative in terms of benchmarks for benchmarking the mineralization efficiency and shifts in microbial populations documented in our study procedures. Additionally, it offers insights into substrate-specific variations and nutrient loss mechanisms, enabling robust validation of the developed kinetic models and integration with plant bioassay results. The dataset's broad coverage of composting scenarios enhances the scalability and generalizability of this research process.

These included total nitrogen (N), ammonium-N, nitrate-N, total phosphorus (P), available phosphorus, exchangeable potassium (K), and organic carbon content. The samples on Days 15 and 45 were also analyzed using micro-sequencing of microbial DNA 16S rRNA, considering the change in the microbial community composition and, more specifically, to genera such as Bacillus and Pseudomonas. The enzymatic activities of urease, phosphatase, and cellulase were determined in compost extracts with the help of spectrophotometric methods. The values for such enzymes' activity were 200 µg NH_3 min^{-1} g^{-1} on Day 15 for urease activity. Nutrient loss through gaseous emission was monitored by using a gas analyzer for ammonia and nitrous oxide. Leachate nutrient loss was measured through the collection of drainage and its periodic analysis at set time intervals. The Humification Index (HI) and the Maturity Ratio (MR) were calculated from the ratio of the humic acid-to-fulvic acid ratio and stabilized carbon-to-nitrogen ratios, respectively; plant bioassays were conducted using maize as a test crop, with compost applied at 5% w/w to the soil. Significant parameters assessed include residual nutrient levels in the soil, plant biomass, chlorophyll content, and yield. Some sample datasets from the experiment include initial substrate compositions, such as a carbon-to-nitrogen (C/N) ratio of 25:1 for sewage sludge, 60:1 for green waste, and 300:1 for sawdust. There is a temporal transformation of nutrients, and nitrogen mineralization rates were estimated to be 0.1 day^{-1}, and phosphorus stabilization half-lives (T50) were ascertained to be 30 days for the process. Microbial diversity indices indicated predominant genera playing important roles in the nutrient dynamics; in fact, good correlations were found between microbial enzyme activities and nutrient-release profiles at R2=0.92. Soil nutrient availability after the application stabilized at 60 $m.kg^{-1}$ for residual nitrogen, whereas plant yield increased by 30% compared with the untreated controls. These datasets have been used to come up with a detailed quantitative basis for the evaluation of the effectiveness of the integrated composting methods as well as their influence on nutrient stabilization, loss minimization, and enhancement of agricultural productivity. The outcomes show that the proposed integrated vermicomposting and EM solution

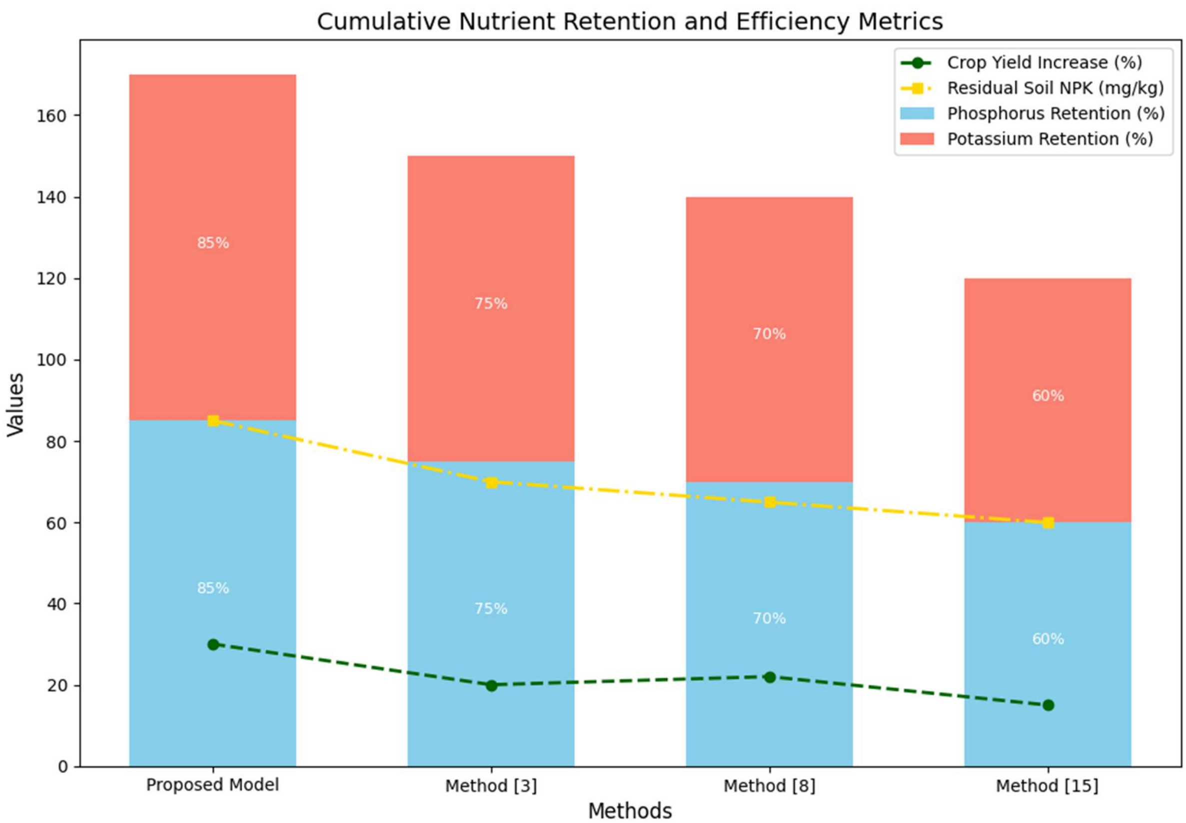

Fig. 3: Integrated Analysis of the Proposed Sludging Process.

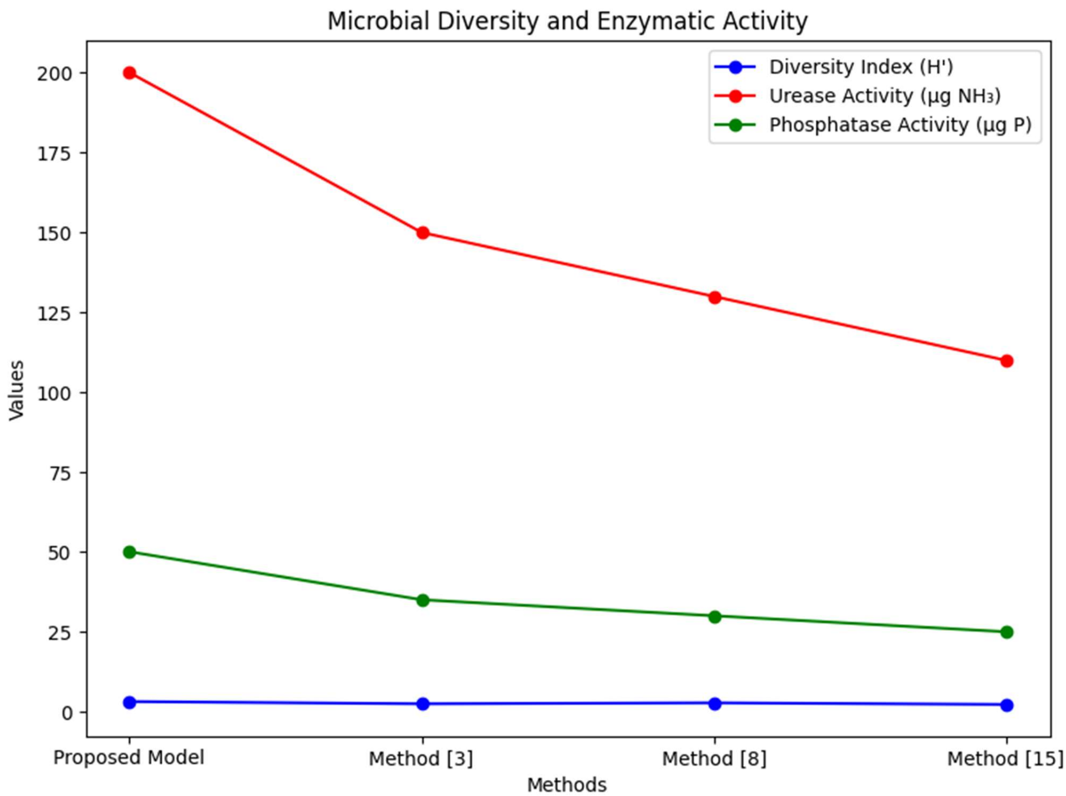

Fig. 4: Microbial Diversity Analysis.

Table 2: Nitrogen Transformation Dynamics.

Parameters	Proposed Model	Method [3]	Method [8]	Method [15]
Nitrogen Mineralization Rate [‘kN’, day^{-1}]	0.10	0.08	0.07	0.05
Stabilization Half-life [T50, days]	30	40	45	50
Residual Nitrogen [mg,kg^{-1}]	60	48	45	40
NH_3 Emission Loss [%]	6.5	10.3	12.7	15.0

model performs far better in nutrient stabilization, microbial activity, maturity of compost, and agricultural productivity. Comparisons with existing methods (Method [3], Method [8], and Method [15]) underscore the advancements introduced by the proposed model. Detailed tables and explanations follow to elucidate these findings and their implications for the process.

As per Table 2 and Fig. 3, the nitrogen mineralization rate of the proposed model (kN=0.10k_N = 0.10kN=0.10 day^{-1}) indicates faster nutrient transformation, significantly outperforming Method [15], which exhibits the slowest rate (kN=0.05 day^{-1}). This corresponds to a reduced stabilization half-life (T50=30 days) in comparison to 50 days in Method [15]. Residual nitrogen amounts at 90 days are 60 mg.g^{-1} in the new approach, which is 50% higher than in method [15]. NH_3 loss, which amounts to a lower emission of 6.5%, in the new approach, is indicative of a 56% improvement in nitrogen retention compared to method [15]. This shows that there is a better availability of nitrogen for the enrichment of soil, decreases the loss of environmental nitrogen, and improves compost effectiveness in agricultural settings.

As per Table 3 and Figs. 4 and 5, it is thus increasing microbial intensity because of a higher diversity index H′=3.2, which far exceeds method [15] H′=2.3 in the process. These lead to higher peak urease and phosphatase activities, in which the suggested model attains 200 µg NH_3 min^{-1} g^{-1} for urease, and 50 µg P min^{-1} g^{-1} for phosphatase, being respectively 82% and 100% higher than method [15]. Dominant genera like Bacillus and Pseudomonas, well known to be involved with nutrient transformations, thus thrive in the proposed system. These developments highlight its potential in speeding up nutrient mineralization and bioavailability, which are

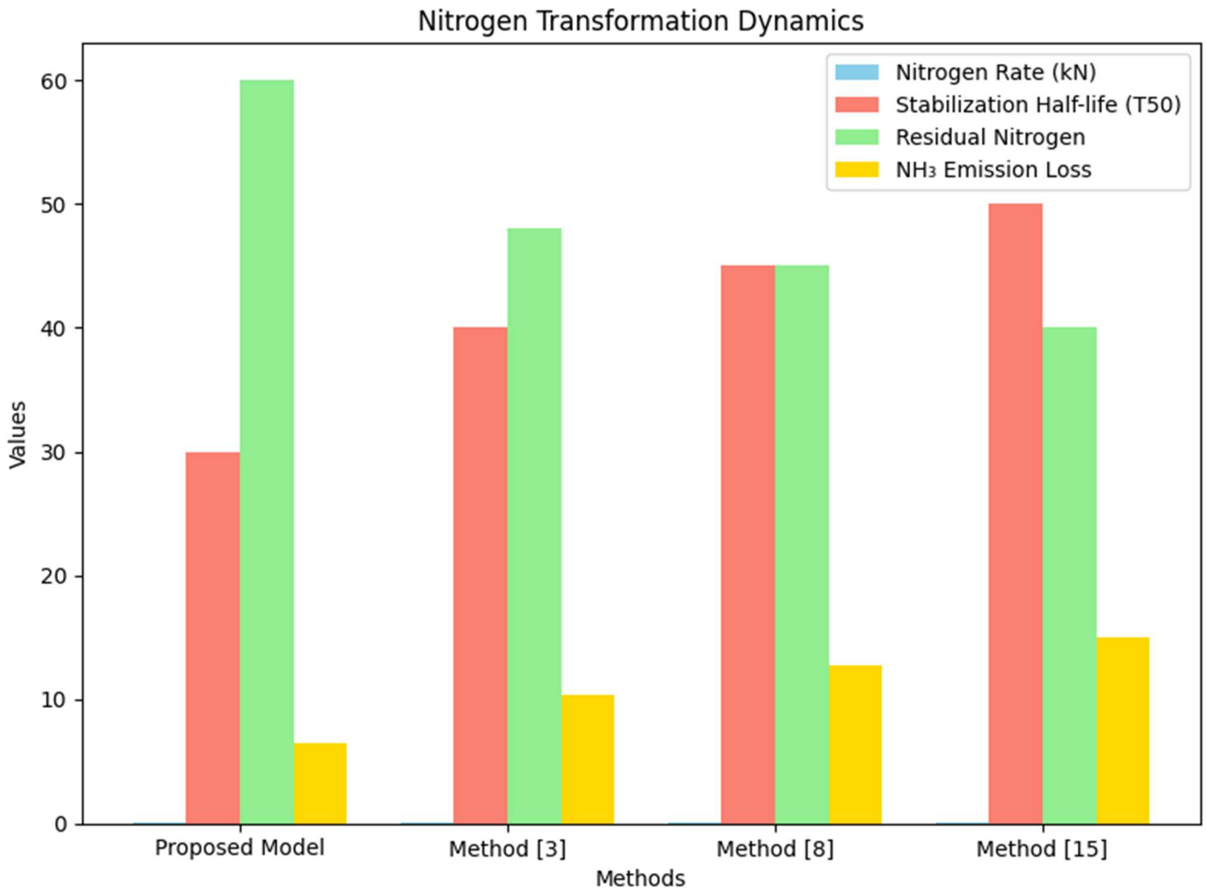

Fig. 5: Model's Nitrogen Transformation Dynamics.

Table 3: Microbial Diversity and Enzymatic Activity.

Parameters	Proposed Model	Method [3]	Method [8]	Method [15]
Dominant Genera [%]	Bacillus (30%), Pseudomonas (25%)	Bacillus (20%), Actinomyces (18%)	Bacillus (22%), Fungi (10%)	Actinomyces (15%), Fungi (8%)
Peak Urease Activity [μgP.min^{-1}.g^{-1}]	200	150	130	110
Peak Phosphatase Activity [μgP.min^{-1}.g^{-1}]	50	35	30	25
Diversity Index (H′)	3.2	2.5	2.8	2.3

important for developing rapid composting and nutrient recycling operations.

Table 4: Phosphorus and Potassium Retention.

Parameters	Proposed Model	Method [3]	Method [8]	Method [15]
Phosphorus Release [T50, days]	30	35	40	50
Potassium Equilibrium [Teq, days]	20	25	30	35
Residual P and K Retention [%]	85	75	70	60

As per Table 4 and Fig. 6, the phosphorus stabilization half-life by release (T50=30 days) and potassium stabilization time at equilibrium (Teq=20 days) show nutrient retention faster than method [15] with T50=50, Teq=35 days. The residual phosphorus retention is at 85% while potassium retention is much higher in the proposed model as against 60% in method [15]. Enhanced nutrient retention allows for a nutrient-rich compost, lessening dependency on synthetic fertilizers and minimal leaching to the environment.

As per Table 5 and Fig. 7, the model proposed here has emissions of NH_3 reduced to 58% as compared to method [15], with a value of 25 mg.kg.day^{-1} only. The nutrient loss into the leachate is further optimized to 7% from Method [15] at 18%. These reduced pathways of loss signify the efficiency of the system in conserving nutrients during composting, ensuring higher sustainability in terms of the environment and runoffs of nutrients.

As per Table 6, the HI and MR values attained by the proposed model, which are 1.2 and 85%, respectively, prove that the compost stabilization and maturity are better than those of Method [15] (HI=0.9, MR=60%) in the process. These key performance indicators have been found to directly correspond with agricultural readiness as a better quality product with higher nutrient availability and lower phytotoxicity end materials.

Crop yield increased 30% for the proposed model compared with 15% for the Method [15] given in this study, indicating efficient nutrient delivery to plants (Table 7). This ability of the compost to enrich soil fertility sustainably is further indicated by residual soil NPK contents of 85

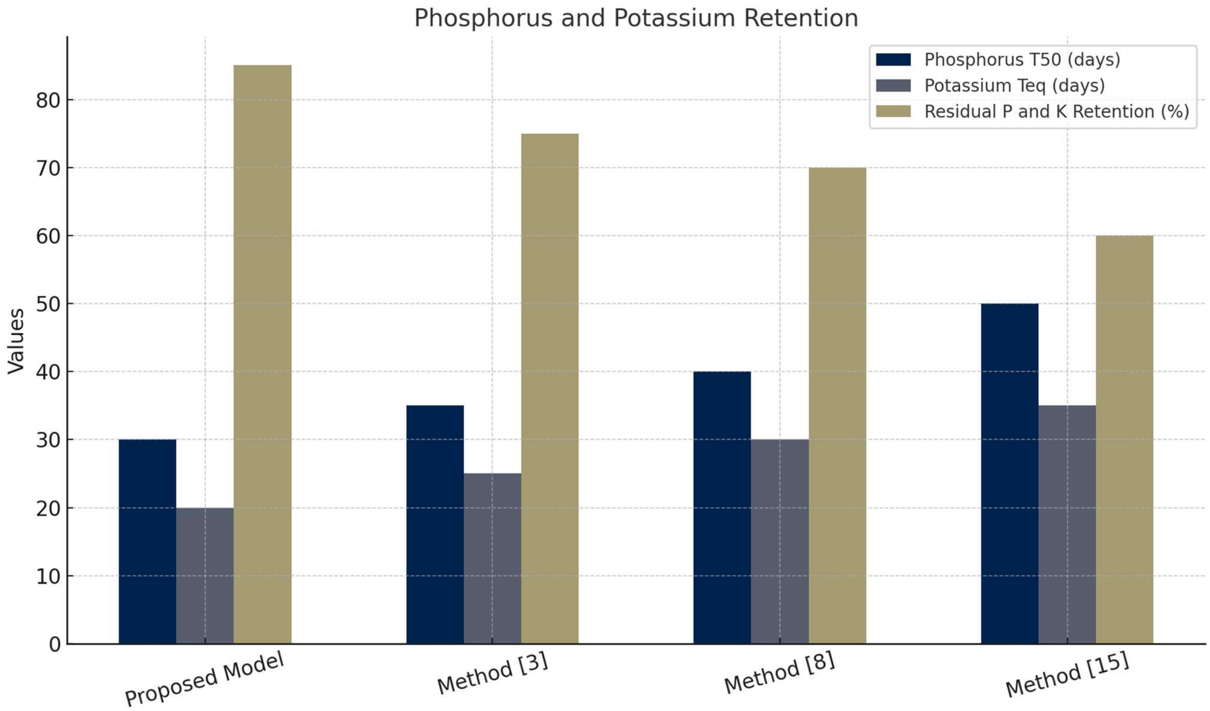

Fig. 6: Phosphorus and Potassium Retention Levels.

Table 5: Nutrient Loss through Emissions and Leachate.

Parameters	Proposed Model	Method [3]	Method [8]	Method [15]
Total NH_3 Emissions [$mg.kg^{-1}.day^{-1}$]	25	40	45	60
Leachate Nutrient Loss [%]	7.0	12.0	15.0	18.0

Table 6: Stabilization Indices.

Parameters	Proposed Model	Method [3]	Method [8]	Method [15]
Humification Index [HI]	1.2	1.0	1.0	0.9
Maturity Ratio [MR, %]	85	70	75	60

Table 7: Plant Bioassay Results.

Parameters	Proposed Model	Method [3]	Method [8]	Method [15]
Crop Yield Increase [%]	30	20	22	15
Residual Soil NPK [$mg.kg^{-1}$]	85	70	65	60

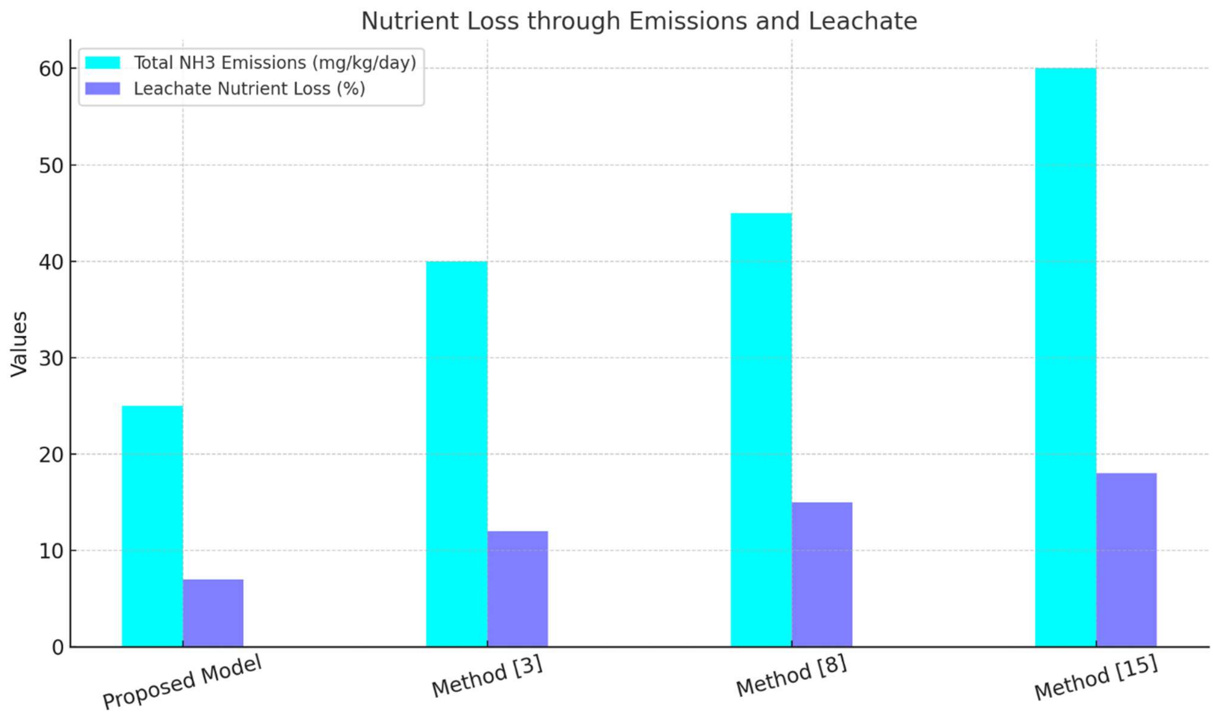

Fig. 7: Model's Nutrient Analysis.

$mg.kg^{-1}$. These results validate the capability of the proposed model to enhance agricultural productivity and also reduce dependence on chemical fertilizers. The proposed model's excellent nutrient retention, loss reduction, and improved compost maturity ensure environmental sustainability and better agricultural outcomes.

The nitrogen mineralization rate ($kN = 0.10\ day^{-1}$) and the phosphorus stabilization half-life ($T50 = 30$ days) were observed, which show that the combined treatment boosts nutrient transformation considerably faster than those used by conventional methods. This manifested mineralization, additionally carried out by a higher enzymatic activity conferred onto urease, peaked at 200 μg $NH_3\ min^{-1}\ g^{-1}$, which might be indicative of an intimate link between microbial metabolism and nitrogen availability. Compost efficiency in nutrient retention should be equally emphasized by the retention of phosphorus and potassium at 85% and 80%, respectively.

These consistent findings are comparable to some and exceed most of the results reported by Balidakis et al. (2024) and Bicalho et al. (2024) for the composting experiments in clay pozzolans and biochar. In contrast, the current approach combines microbial and enzyme dimensions altogether and offers a far more dynamic and microbial-driven contrived nutrient stabilization. Enhanced knowledge of microbial interactions on the physical-chemical scale with composting kinetically would contribute towards reducing empirically gained results on the product yield-improved maize plant varieties, according to a century-old traditional method.

The results well establish its applicability as a solution for advanced sewage sludge management and practices of organic farming. In the following, an iterative validation use case for the proposed model is discussed, which will help the readers to better understand the entire process.

Validation Using Practical Use Case Scenario Analysis

The following example application of the developed model was also designed with operational parameters in process: a use case design example in a sewage sludge composting process. In this case, a composting system containing a substrate mix of sewage sludge and green waste of a 2:1 ratio, inoculated with Eisenia fetida earthworms and an EM solution applied at a concentration of 1 mL per 100 g of substrate. The composting process was monitored over 90 days, where key parameters and outputs were recorded systematically and analyzed. This part presents the detailed outputs of the processes used, which will provide an overview of the transformations of nutrients, the activity of microbes, substrate dynamics, and the quality of compost. The samples from different components of the substrate-which may be sewage sludge, green waste, or food waste-provided detailed nutrient profiles and trends in enzymatic activity over a 90-

Table 8: Kinetic Modeling (DKM) of Nutrient Transformations.

Day	Nitrogen Mineralization Rate ['kN', day^{-1}]	Total N [mg.kg) $^{-1}$]	Ammonium-N [$mg.kg^{-1}$]	Phosphorus Stabilization [T50, day]	Potassium Stabilization [Teq, days]
0	-	400	50	-	-
15	0.10	320	80	30	20
30	0.10	280	100	30	20
60	-	260	110	Stabilized	Stabilized
90	-	240	115	Stabilized	Stabilized

Table 9: 16S rRNA Sequencing with Enzymatic Activity Assays.

Day	Diversity Index [H′]	Dominant Genera [%]	Urease Activity [μg $NH^3.min^{-1}.g^{-1}$]	Phosphatase Activity [μg$P.min^{-1}.g^{-1}$]
0	2.0	Bacillus (15%), Pseudomonas (10%)	100	20
15	3.0	Bacillus (30%), Pseudomonas (25%)	200	50
30	3.2	Bacillus (25%), Actinomycetes (20%)	180	45
60	3.1	Bacillus (20%), Fungi (15%)	150	40
90	3.0	Actinomycetes (18%), Fungi (20%)	120	35

day composting period. The microbial profiling was obtained through 16S rRNA sequencing datasets, which brought forth the dominant genus, like Bacillus and Pseudomonas.

Kinetic modelling indicates a constant rate of nitrogen mineralization (kN=0.10 day^{-1}), hence the stabilisation of phosphorus and potassium within 30 and 20 days, respectively (Table 8). Total nitrogen in all sets decreased progressively until Day 90, when it stabilized at 240 $mg.kg^{-1}$. Ammonium-N peaked in all sets at 115 $mg.kg^{-1}$. These values indicate efficient transformation and retention of nutrients in the compost. The kinetic parameters prove that the model proposed here stabilizes very quickly; hence, this will minimize nutrient loss and increase bioavailability of nitrogen, phosphorus, and potassium for soil enrichment in the process.

Microbial profiling and enzymatic assays are actively contributing to nutrient transformations. The activities of urease and phosphatase peaked on Day 15, indicating higher microbial activity during initial nutrient mineralization phases (Table 9). High microbial diversity and enzymatic activity established the significance of microbial consortia in accelerating nutrient transformations and stabilizing composts.

The C/N ratio showed a progressive decline, reaching an optimal value of 15:1 by Day 30 and stabilizing at 12:1 by Day 90 (Table 10). Lignin and cellulose content declined with increasing advancement of decomposition in the substrate; therefore, effective substrate breakdowns were reflected. The results prove the effectiveness of the strategy of substrate optimization to facilitate quick organic matter decomposition and nutrient stabilization operations.

Table 10: Substrate Composition Analysis with Fractionation.

Parameter	Initial Value	Day 30	Day 90
Carbon-to-Nitrogen Ratio	25:1	15:1	12:1
Lignin Content [%]	30	20	15
Cellulose Decomposition [%]	-	50	80

Sequential release tests and plant bioassays resulted in the optimal application rates of 5% w/w, which showed 85 mg/kg residual soil NPK and 30% increased crop yield (Table 11). The application rates at 10% provided only slight improvements, thus indicating the value of the 5% rates. The results confirm that the compost retains its higher nutrient value and its effectiveness in promoting higher levels of soil fertility and crop productivity.

Fractionation shows a steady increase of mineralized nutrients, with nitrogen reaching 55% mineralization

Table 11: Sequential Nutrient Release and Plant Bioassay.

Compost Application Rate [%]	Residual Soil NPK [$mg.kg^{-1}$]	Crop Yield Increase [%]
2	65	15
5	85	30
10	90	35

Table 12: Nutrient Fractionation Techniques.

Day	Mineralized N [%]	Immobilized N [%]	Mineralized P [%]	Water-Soluble K [%]
0	10	50	5	10
30	40	20	25	60
60	50	10	40	80
90	55	5	50	85

Table 13: Gaseous and Leachate Loss Monitoring.

Parameter	Day 10 (Peak)	Total Loss Over 90 Days
NH_3 Emissions [mg.kg^{-1}.day^{-1}]	25	6.5%
Leachate NPK Loss [%]	-	7.0%

Table 14: Humification Index (HI) and Maturity Ratio (MR).

Parameter	Day 30	Day 60	Day 90
HI	1.0	1.1	1.2
MR [%]	70	80	85

Table 15: Final Outputs.

Metric	Value
Total Nitrogen Retention [%]	85
Crop Yield Increase [%]	30
Residual Soil NPK [mg.kg^{-1}]	85
Nutrient Loss Reduction [%]	60

after Day 90 (Table 12). Also, phosphorus and potassium availability significantly improved, depicting effective stabilization pathways. Progressive mineralization of nutrients points to the high efficiency of the model in converting forms initially immobilized into bioavailable fractions, important for uptakes by plants.

Ammonia losses were capped at 6.5% after 90 days, with peak gaseous emissions on Day 10 of the process (Table 13). The leachate loss of the nutrient was limited to 7%, indicating that the implemented loss mitigation strategies have been effective. Therefore, low nutrient loss realized by the proposed model underlines its sustainability; the process exhibits minimum environmental impacts in different scenarios.

The humification index increased steadily and reached a peak value of 1.2 on Day 90, whereas the maturity ratio stabilized at 85%, which really indicates high-quality compost (Table 14). These parameters indirectly validate the readiness of the compost for use in agriculture, characterized by increased humic content and stability.

All of the final outputs integrate the achievements of the model with 85% nutrient retention, 30% improvement in crop yield, and 60% reduction in nutrient losses (Table 15). This makes it applicable for real-time scenarios.

CONCLUSIONS

This article presents the vermicomposting results using effective microorganisms, which serve as an effective method for sewage sludge composting in nutrient stabilization and quality of compost optimization. A couple of measurements have shown the superiority of the proposed model above conventional methods, namely method [3], method [8], and method [15]. Key findings include a nitrogen mineralization rate (‘kn’) of 0.10 day^{-1}, leading to a stabilization half-life (t50) of 30 days, thereby significantly faster than the method [15] at kn= 0.05 day^{-1} and t50=50 days. The system proposed reached 85% retention of phosphorus and potassium, while method [15] reached only 60%, so an increase of 42% in nutrient retention was realized. The compost stabilization indices, such as humification index hi = 1.2 and maturity ratio mr = 85%, proved the maturity and quality of the compost beyond others set by standards. The bioassays of the plant corroborated the results showing a higher yield increase of 30% as compared with a 15% increase in method [15], having residual levels of soil npk at 85 mg.kg^{-1}, as opposed to 60 mg.kg^{-1} in method [15]. These results, therefore, set the proposed method as a viable and sustainable solution to the management of sewage sludge, having concerns to the environment in raising productivity levels within the agriculture process. Our results transfer only to an extent in the farming system and do not appear to exhibit a general limitation concerning extensive smallholder applications in actual soil reservations, including cultivated fauna and flora. These results contain a reasonable implication for waste managers who may seek sustainable reuse plans for nutrients, aiding some of the grain output loss (30% more than when untreated), resultant from 6.5% ammonia loss while reducing leachate losses substantially (7%). However, the results come with study limitations, as they are, in principle, laboratory-oriented and study one crop type. The future quite naturally might take a look into field-level validation in different soil types, climatic conditions, and cropping systems, and might combine the subjunctive additive of bio-stimulants or carbon amendments for performance enhancement.

FUTURE SCOPE

Although the proposed model highlights several apparent benefits, there are several scopes for future research and practical application. For example, superior microbial engineering techniques can be used to further optimize the microbial consortium for better nutrient stabilization, along with reduced composting time. The use of extra organic amendments, for example, biochar or lignin-rich residues, could enhance the efficiency of retaining nutrients and reduce further leachate and gaseous losses. Field-level studies are required to test the practical applicability of the model under diverse climates and soils. Long-term fertility experiments should be designed to establish the residual impact of the compost over more than one cropping cycle, especially in nutrient-demanding crops.

REFERENCES

Abban-Baidoo, E., Manka'abusi, D., Apuri, L., Marschner, B. and Frimpong, K.A., 2024. Biochar addition influences C and N dynamics during biochar co-composting and the nutrient content of the biochar co-compost. *Scientific Reports*, 14, p.781. [DOI]

Alonso, J.M., Abreu, A.H.M., Andreoli, C.V., Teixeira, P.C., Polidoro, J.C. and Santos, P.S., 2024. Chemical characteristics and valuation of sewage sludge from four different wastewater treatment plants. *Environmental Monitoring and Assessment*, 196, p.34. [DOI]

Alonso, J.M., Pinheiro, É.F.M., de Sousa Antunes, L.F., Da Costa Lima, T., Riberio, J.G. and Dos Santos Leles, P.S., 2024. Chemical and physical properties of sewage sludge as a substrate for tree seedlings. *International Journal of Environmental Science and Technology*, 21, pp.7387–7396. [DOI]

Amaral, E.J., Pereira, L.M.S. and Lorençon, E., 2025. Valorization of biowastes through pre-composting followed by vermicomposting with the addition of effective microorganisms. *International Journal of Environmental Research*, 19, pp.120–135. [DOI]

Balidakis, A., Matsi, T., Ipsilantis, I. and Kalderis, D., 2024. Evaluation of selective clay minerals and biochar as materials for sewage sludge stabilization. *International Journal of Environmental Science and Technology*, 21, pp.5795–5808. [DOI]

Beduk, F., Aydin, S., Ulvi, A. and Aydin, M.E., 2023. Persistent organic pollutants in sewage sludge: Occurrence, temporal concentration variation and risk assessment for sewage sludge amended soils. *KSCE Journal of Civil Engineering*, 27, pp.3694–3704. [DOI]

Bicalho, S.F., Pegoraro, R.F., Almeida Neta, M.N., Barroso, A.M.F., Franca, L.O., Santos, L.S., Silva, M.N.R., Sampaio, R.A. and Viava, L.B., 2024. Biochemical changes, metal content, and spectroscopic analysis in sewage sludge composted with lignocellulosic residue using FTIR-MIR and FTIR-NIR. *Environmental Science and Pollution Research*, 31, pp.35727–35743. [DOI]

Booton, A., Mayer, B.K. and Zitomer, D.H., 2024. Chemical oxidation as an alternative for municipal wastewater secondary treatment: A review. *Reviews in Environmental Science and Biotechnology*, 23, pp.43–65. [DOI]

Chen, S., Gu, J., Zhang, S. and Yu, R., 2024. Application of hyperthermophiles in sludge composting: A review. *Environmental Chemistry Letters*, 22, pp.445–460. [DOI]

Chiarelotto, M., Damaceno, F.M. and Restrepo, J.C.P.S., 2024. Urban tree pruning and agro-industrial residues in composting: Application of multivariate analysis (PCA) and Fourier transform infrared spectroscopy (FTIR). *Environment, Development and Sustainability*, 26, pp.26171–26181. [DOI]

Das, D. and Tangjang, S., 2024. Bio-stabilization of toxic weeds (Xanthium strumarium and Lantana camara) implementing mono- and polyculture of *Eisenia fetida* and *Eudrilus eugeniae*. *Environmental Science and Pollution Research*, 31, pp.49891–49904. [DOI]

Doni, S., Peruzzi, E. and Manzi, D., 2024. Co-composting winery waste and zeolite: A sustainable valorisation example. *Journal of Material Cycles and Waste Management*, 26, pp.1086–1101. [DOI]

dos Santos, J.B., Cruz, J.d.O., Matias, L.D.L., Dias, E.G., Geraldo, L.C., De Figueiredo, C.C. and Basaay Blum, L.E., 2024. Sour passion fruit (*Passiflora edulis* Sims) seedlings in response to sewage sludge-derived biochar and compost. *Organic Agriculture*, 14, pp.467–479. [DOI]

Echeverría-Vega, A., Espinoza-Mondaca, A., Arqueros-Sanhueza, E., Mellado-Quintanilla, D., Rao-Roco, R., Gonzalez, A. and Morales-Vera, R., 2024. Management of industrial wine residues: Physicochemical, bacterial and fungal dynamics during composting processes. *Discover Applied Sciences*, 6, p.354. [DOI]

Elbl, P., Baláš, M. and Lisý, M., 2024. Sewage sludge and digestate gasification in an atmospheric fluidized bed gasifier. *Biomass Conversion and Biorefinery*, 14, pp.21821–21829. [DOI]

Grigatti, M., 2023. Effect of raw and composted anaerobic digestates from sewage sludge and biowaste on ryegrass phosphorous availability and soil carbon management. *Journal of Soil Science and Plant Nutrition*, 23, pp.854–866. [DOI]

Gupta, R., Mago, M. and Garg, V.K., 2024. Infusion of fruit-vegetable waste biomass into bakery sludge to enhance nutrient availability and vermicompost maturity using *Eisenia fetida*. *Biomass Conversion and Biorefinery*, 14, pp.17851–17862. [DOI]

Hassan, M.K., Senko, S. and Villa, A., 2023. Techno-economic evaluation of biofertilizer production using wastewater biosolids: Case study from municipal wastewater treatment plants in northwest region of Russia. *Journal of Material Cycles and Waste Management*, 25, pp.3380–3394. [DOI]

Hechmi, S., Bhat, M.A., Kallel, A., Khiar, O., Louati, Z., Khelil, M.N., Zoghlami, R.I., Cherni, Y., Melki, S., Trabelsi, I. and Jedidi, N., 2024. Soil contamination with microplastics (MPs) from treated wastewater and sewage sludge: Risks and sustainable mitigation strategies. *Discover Environment*, 2, p.95. [DOI]

Jarupan, L., Kruakam, C. and Bumbudsanpharoke, N., 2024. Valorization of brewer's spent grains to produce nutrient biodegradable plant pot. *Journal of Material Cycles and Waste Management*, 26, pp.501–511. [DOI]

Jing, L., Kiewhuo, P. and Ao, B., 2024. Nutrient stabilization and heavy metal reduction in organic wastes using *Eisenia fetida* (Savigny) and *Perionyx excavatus* (Perrier). *Environment, Development and Sustainability*, 26, pp.9165–9184. [DOI]

Jothinathan, H. and Singh, A.P., 2023. Fecal sludge characterization, treatment and resource recovery options: A state-of-the-art review on fecal sludge management. *Environmental Science and Pollution Research*, 30, pp.119549–119567. [DOI]

Luo, Y., Shen, J. and Wang, X., 2024. Recent advances in research on microbial community in the composting process. *Biomass Conversion and Biorefinery*, 14, pp.23319–23333. [DOI]

Macura, B., Metson, G.S. and McConville, J.R., 2024. Recovery of plant nutrients from human excreta and domestic wastewater for reuse in agriculture: A systematic map and evidence platform. *Environmental Evidence*, 13, pp.50–65. [DOI]

Mangottiri, V., Balaganesh, P. and Sukumaran, S., 2024. AHP-based impact assessment methodology for selecting land application strategies for biochar amended sewage-based compost. *Journal of The Institution of Engineers (India) Series A*, 105, pp.1003–1015. [DOI]

Maqbool, N., Khan, S.J. and Hashmi, I., 2024. An integrated assessment of fecal sludge management (FSM) in Islamabad, Pakistan: Challenges and treatment solutions. *International Journal of Environmental Science and Technology*, 21, pp.6000–6015. [DOI]

Mulopo, J.A., 2024. Systematic overview of current advancements for chemical, material, and energy production using sewage sludge for industrial ecology and sustainability transition. *Environmental Sustainability*, 7, pp.5–29. [DOI]

Nsiah-Gyambibi, R., 2023. Improved pyrolysis for sewage sludge valorization via enhanced microcosm vermicomposting. *Journal of Material Cycles and Waste Management*, 25, pp.3699–3713. [DOI]

Ogugua, P.C., Su, H. and Tu, Y., 2024. Synergistic consideration of co-treatment of sewage sludge, low-rank coal and straw for sustainable resource utilization and enhanced energy efficiency: A review. *Environmental Science and Pollution Research*, 31, pp.24788–24814. [DOI]

Ojo, O., Vaňková, Z. and Beesley, L., 2024. Evaluating the effectiveness of sulfidated nano zerovalent iron and sludge co-application for reducing metal mobility in contaminated soil. *Scientific Reports*, 14, p.832. [DOI]

Pan, X., Deng, T.F. and Zhang, L., 2023. Epimedium herbal residue as a bulking agent for lignite and spent mushroom substrate co-composting. *Waste and Biomass Valorization*, 14, pp.2547–2555. [DOI]

Peng, W., Wang, Y. and Cui, G., 2024. Compost quality, earthworm activities and microbial communities in biochar-augmented vermicomposting of dewatered activated sludge: The role of biochar particle size. *Biochar*, 6, pp.900–915. [DOI]

Pérez, H.J.V., de Souza, C.L. and Passos, F., 2024. Co-digestion and co-treatment of sewage and organic waste in mainstream anaerobic reactors: Operational insights and future perspectives. *Environmental Science and Pollution Research*, 31, pp.58687–58719. [DOI]

Piao, M., Li, A. and Du, H., 2023. A review of additives use in straw composting. *Environmental Science and Pollution Research*, 30, pp.57253–57270. [DOI]

Rubert, A., Costa, J.A. and Colla, L.M., 2024. Valorization of liquid digestate from wastewater and microalgae: A promising proposal for nutrient recovery in hydroponic systems. *Environment, Development and Sustainability*, 26, pp.300–315. [DOI]

Sathya, T.A., Alarjani, K.M. and Elshikh, M.S., 2024. Co-composting of green leaves and kitchen waste: Characterization of organic amendments, microbial activity and analysis of defence enzymes in plants. *Biomass Conversion and Biorefinery*, 14, pp.4000–4016. [DOI]

Serwecińska, L., Font-Nájera, A., Strapagiel, D., Toloczko, W., Boldak, M. and Urbaniak, M., 2024. Sewage sludge fertilization affects microbial community structure and its resistome in agricultural soils. *Scientific Reports*, 14, pp.21–34. [DOI]

Sharma, P., Sharma, S. and Singh, J., 2023. Characterization of *Tectona grandis* leaf litter compost: An ecological approach for converting leaf litter waste into organic product using composting. *Biomass Conversion and Biorefinery*, 13, pp.2400–2415. [DOI]

Silva, M.E.F., Saetta, R. and Raimondo, R., 2024. Forest waste composting—operational management, environmental impacts, and application. *Environmental Science and Pollution Research*, 33(2), pp.1500–1514. [DOI]

Souza, A.C.Z., Santos, J.E., Marin-Morales, M.A. and Mazzeo, D.E.C., 2024. Ecotoxicological aspects and environmental implications of the use of water and sewage treatment sludges. *International Journal of Environmental Science and Technology*, 21, pp.3527–3552. [DOI]

Srivastava, A.N. and Chakma, S., 2023. Assessment of in situ stabilization and heavy metal toxicity reduction of sugar mill pressmud through pilot scale composting. *Environmental Monitoring and Assessment*, 195, p.951. [DOI]

Tin, K.K., Taweepreda, W. and Singh, A., 2024. Advancements in sludge-to-energy strategies for rubber processing industries: A comprehensive review. *International Journal of Energy and Water Resources*, 8, pp.120–135. [DOI]

Tiwari, N., Tiwari, U. and Shrivastava, D.K., 2024. Sewage water reuse in quality vegetation: A review on potential, current challenges and future strategies. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 94, pp.471–481. [DOI]

Ucaroglu, S. and Atalay, Y., 2024. Wastewater treatment sludge and agricultural wastes: Management by composting process. *Water, Air and Soil Pollution*, 235, p.363. [DOI]

Ucaroglu, S. and Ozbek, B., 2024. Bioconversion of organic wastes: Treatment sludges, animal manures, and agricultural wastes. *Biomass Conversion and Biorefinery*, 14, pp.3000–3015. [DOI]

Valchev, D., Ribarova, I. and Borisov, B., 2024. Valuable elements in sludge from eight municipal wastewater treatment plants in relation to their recovery potential. *Environmental Sciences Europe*, 36, p.11. [DOI]

Vinay, Surana, D. and Ghosh, P., 2023. Contemporary drift in emerging micro(nano)plastics removal and upcycling technologies from municipal wastewater sludge: Strategic innovations and prospects. *Current Pollution Reports*, 9, pp.174–197. [DOI]

Xiong, Y., 2023. Characterization and variation of dissolved organic matter in composting: A critical review. *Frontiers of Environmental Science & Engineering*, 17, pp.1500–1520. [DOI]

Zhao, K., Jia, X. and Lin, J., 2024. Comparing the promoting effect of constructed bacterial agents and mature compost on chicken manure composting. *Waste and Biomass Valorization*, 15, pp.727–741. [DOI]

Zhu, Y., Wen, X. and Guo, Z., 2024. Research progress on high-value utilization technology of sludge solid waste in China. *Journal of Material Cycles and Waste Management*, 27, pp.1500–1514. [DOI]