CHEMICAL ENGINEERING TRANSACTIONS
VOL. 122, 2025
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-23-6; **ISSN** 2283-9216
DOI: 10.3303/CET25122046

Kinetic Analysis of Nutrient Release from Food Waste Compost and Leachate for Enhancing Chilli (*Capsicum frutescens* L.)

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Food waste compost and its leachate serve as a promising organic soil amendment. Both products must be assessed in terms of their nutrient release rate to determine the adequate application rate, thereby avoiding soil contamination and plant damage. Detailed kinetic studies on the individual macronutrients, specifically nitrogen (N), phosphate (P), and potassium (K), release rates of the compost and leachate, as a function of their initial nutrient contents, and their effect on plant yield are limited. This study aims to determine the individual N, P, and K release rates of compost into plants fertigated with leachate to promote chilli yield. The N, P and K release rate constants by the compost obtained could aid in estimating the ideal formulation (compost loading ratio) for optimal chilli plant growth. Additional leachate treatment increases the N, P, and K release rate constant by 2- to 10-fold higher. With or without leachate, 50 % v/v reported the highest N, P and K release rate constant, 0.1503 g of N/kg of plant media /d, 0.0640 g of P/kg of plant media /d and 0.1775 g of K/kg of plant media/d, resulting in the highest plant yield (16 – 28 g of chillies/plant). Application of compost at a concentration higher than 50 % v/v, with and without leachate, resulted in a 10 % reduction in chilli yield and a 50 % reduction in chilli weight. The nutrient release rate constants derived from this study offer a practical guide for optimising food waste compost and leachate use in chilli cultivation, supporting sustainable nutrient recycling and improved organic farming practices

1. Introduction

Food waste-derived compost and leachate contain elevated organic carbon and pollutants, which can induce phytotoxic effects and damage plant health (Bernat et al., 2021). Excessive application risks the accumulation of pollutants in soils and plants, posing hazards to ecosystems and human health (Bong et al., 2021). Optimal dosing is crucial for balancing nutrient delivery with the mitigation of contamination risks. For leachate, dilution reduces pollutant concentrations (Sanadi et al., 2021). For compost, the ideal loading ratio must be applied, depending on the plants' ability to uptake nutrients, while also considering soil conditions such as salinity or heavy metal content.

To determine the ideal compost loading ratio that maximises crop yield, the compost nutrient release kinetics, specifically N, P and K must be characterised. The rate of nutrient release from compost can significantly influence the plant nutrient uptake and growth (Chen et al., 2025). The nutrients from the compost were released by microbial degradation into a soluble form of nutrients (Sanadi et al., 2020). Detailed studies on the kinetics of N, P, and K released by food waste compost and leachate and its linked with the plant growth and yield, are lacking. Chen et al. (2025) conducted a study to characterise the release of nitrogen (N) by compost derived from crop straw, but did not established a clear linkages to the crop yield. This highlights a critical gap in the

Paper Received: 27 July 2025; Revised: 25 October 2025; Accepted: 22 November 2025
Please cite this article as: Ahmad Sanadi N.F., Lim L.Y., Woon K.S., Meng-Choung C., Ong P.Y., 2025, Kinetic Analysis of Nutrient Release from Food Waste Compost and Leachate for Enhancing Chilli (Capsicum frutescens L.), Chemical Engineering Transactions, 122, 271-276 DOI:10.3303/CET25122046

integration of nutrient release modelling with the crops yield. To address these gaps, this study investigates the rate of N, P, and K release by food waste compost and leachate, as well as their effect on the growth and yield of chilli plants (*Capsicum Frutescens* L.).

A first-order kinetic model was applied to assess the compost-driven release of nutrients into soil, enabling correlations between the release rates of N, P, and K and crop yield. First-order kinetic equation is more accurate compared to other models such as zero-order in simulating the nutrient dissolution mechanism in slow-nutrient release fertilizers such as compost in porous matrices (Lakshani et al., 2023). The correlation developed is useful for determining the ideal compost loading ratio required by the plant for maximum nutrient release rate, leading to enhanced plant growth and yield. Such insights are pivotal for advancing sustainable agricultural practices through targeted recycling of food waste resources.

2. Materials and methods

2.1 Preparation And Physicochemical Properties Of Food Waste Compost And Leachate

The food waste compost and leachate were collected from the Bio-Baja Zambri composting centre, Layang-Layang, Johor, Malaysia (1°49'42.9"N, 103°30'03.9"E). About 200 kg of food waste was collected around the Layang-Layang suburban area, consisting of rice, fruits, meats, and vegetable waste. A two-stage composting system was used in the composting centre, a combination of in-vessel composting (1st stage) and windrow composting (2nd stage), with each stage lasting five weeks. The nutrient properties of the generated food waste compost and leachate are listed in Table 1.

Table 1: Nutrient properties of the food waste compost and leachate

Parameter	Compost (g/kg)	Leachate (mg/L)
N	6.64	2,400
P	11.64	596
K	6.80	2,750

2.2 Greenhouse field trial for chilli plant growth

The planting preparation and experiment were conducted in a greenhouse located at the School of Biomedical Engineering and Health Science, Universiti Teknologi Malaysia (UTM) (1°33'54.6"N, 103°39'15.7"E). One 4-week-old cultivated seedling was transferred into a 4 – L polybag filled with planting medium consisting of cocopeat from BERNAS, Malaysia and food waste compost, as shown in Table 2. Each sample contained five replicates.

Table 2: Planting medium composition for each treatment

Treatment: Compost and leachate				Treatment: Compost		
Sample	Food waste compost v/v (%)	Cocopeat v/v (%)	Leachate (mL of leachate/L of water)	Sample	Food waste compost v/v (%)	Cocopeat v/v (%)
C0	-	100	10	XC20	20	80
C20	20	80	10	XC50	50	50
C50	50	50	10	XC70	70	30
C70	70	30	10	XC100	100	-
C100	100	-	10			

All plants were irrigated with water at a rate of 750 mL/min, six times per day. For plants treated with leachate,10 mL of leachate per litre of water was applied via irrigation on day 28, and the treatment was continued every 2 weeks thereafter. The test duration was 105 days, from the time the chilli plants reached maturity (Kumar et al., 2016).

2.3 Chilli yield, and nutrient release analysis

Chilli yield was measured at full maturity (day 105) by measuring the total chilli weight per plant using the measuring balance model EK-1200A from company A & D. The planting media samples were collected starting from day 56, when flowering and fruiting began, and continue at two weeks interval to monitor the trend of available inorganic N (NO_3^- and NH_4^+), P, and K. (Kumar et al., 2016). The planting media sample was collected at a depth of 0-20 cm from three randomly chosen positions in the polybag. The planting media sample is extracted to obtain a liquid sample, which is then measured in a photometer Spectroquant NOVA 60 (Merck, Germany). The extraction samples used in this study were based on the Food and Agriculture Organization of the United Nations (FAO) standards (Azadnia et al., 2023).

2.4 Kinetic nutrient release rate from planting media

The first-order kinetic equation is used to assess the amount of individual N, P, and K released from the food waste compost as a function of time (Lakshani et al., 2023). The equation was shown in Eq(1):

$$ln(b) = ln\,(a) - kt \tag{1}$$

Where *a* = amount of N, P or K in the compost initially (g of nutrient/kg of planting media) (at the beginning of the fruiting stage/day 56) (g of nutrient/kg of planting media); *b* = amount of N, P or K available in the soil at a certain time *'t'* (g of nutrient/kg of planting media), *k* is the rate of nutrient released constant (g of nutrient/kg of planting media/time). A one-way ANOVA test was conducted to determine the *p*-value that evaluates the degree of effect of the food waste compost and leachate amendment on the chilli yield, and rate of nutrient release from the plant. All data were analysed using Minitab 16 (version 16.1)

3. Results and discussion

3.1 Plant growth and chilli yield

Chilli yield is an important indicator representing the performance of the compost and leachate in relation to the chilli plant. Figure 1 shows the cumulative chilli yield from all treatments on day 105. All values shown in Figure 1 were the average value with a maximum of 20 % standard deviation.

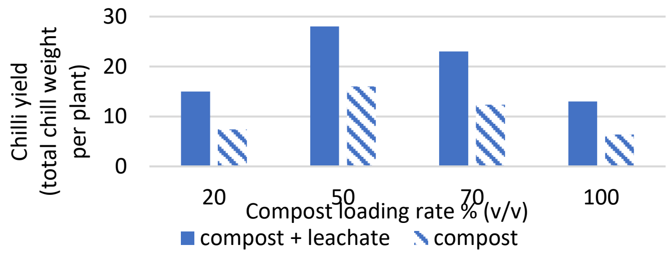

Figure 1: Cumulative chilli yield of plants at day 105 treated with different compost loading ratios with and without leachate fertigation

Figure 1 clearly highlights that combining compost and leachate treatment shows a 50 % increase in chilli yield for all compost loading ratios. The additional nutrient content in the leachate significantly improves (p <0.05), the chilli yield. The plant treated with 50 % v/v compost with (C50) and without leachate (XC50) reported the highest chilli yield (28 g of chillies/plant for C50 and 16 g of chillies/plant for XC50). The average chilli yield treated with 50% v/v compost reported in this study align with the findings by Kumar et al. (2016) who reported an average 26 g of chillies / plant for *Capsicum frutescens* L. treated with vermicompost during matured stage. Plants treated with 70 % and 100 % v/v compost with and without leachate (C70, C100, XC70, XC100) showed a reduction in chilli yield of 14 – 30 % (5-7 g of chilli per plant),indicating that compost levels above 50% negatively affect growth and yield . The decline in chilli plant's growth is due to the excess trace element content in the planting media such as Ca, Mg, Na, Cu, Pb, Fe, and Ni (Rahim et al., 2024). Table 3 compares the nutrient content in the food waste compost used in this study with the maximum nutrient threshold in the soil set by the Food and Agriculture Organization of the United Nations (FAO) standards (Stavi et al., 2021) and the Department of Standards Malaysia (2012).

Table 3: Comparison of the trace element content in the food waste compost

Macronutrient	This study	Malaysia	FAO
Ca (g/kg)	20	ND	10.02
Mg (g/kg)	5	ND	0.47
Fe (g/kg)	1	ND	2.5
Na (g/kg)	6	ND	1.3
Pb (mg/kg)	99	300	ND
Cu (mg/kg)	11.20	ND	ND
Ni (mg/kg)	4.20	150	ND

The findings in Table 3 clearly shows that the Ca, Mg, Fe, and Na content in the food waste compost used in this study exceeded the threshold value set by FAO. Excess accumulation of these elements, such as Na in the soil can disrupt plant growth by suppressing potassium absorption in the plant roots, leading to poor root formation (Farooq et al., 2024). Therefore, the compost must be applied in an ideal amount to prevent excessive accumulation of trace elements in the soil. From this study, 50 % v/v is the optimal amount, and applying more than 50 % v/v results in a reduction in plant growth performance due to excessive Ca, Mg, and Fe in the compost.

3.2 Kinetic nutrient release rate from the compost

This study applied a first-order kinetic model (based on Lakshani et al., 2023) to assess the release rates of nitrogen (N), phosphorus (P), and potassium (K) from food waste compost between days 56–70. The *k* value was used as an indication in evaluating the capability of the food waste compost to release the N, P, and K. Higher *k* values reflect rapid nutrient release suitable for short-term crops, while lower *k* values support longer-duration growth (Basak et al., 2021). Table 4 presents the N (k_N), P (k_P), and K (k_K) released from the compost with varying loading ratios. Each sample was measured in five replicates for each batch of planting, with a standard deviation of less than 5 %.

Table 4: N (k_N), P (k_P) and K (k_K) released from the compost with different loading ratios of compost with or without leachate treatment

Treatment: Compost and leachate				Treatment: Compost			
Sample	k_N	k_P	k_K	Sample	k_N	k_P	k_K
C0	0.1296	0.217	0.1374	XC20	0.0157	0.1896	0.1469
C20	0.1316	0.2131	0.1565	XC50	0.0495	0.1960	0.1231
C50	0.1503	0.2224	0.1775	XC70	0.1396	0.1436	0.1055
C70	0.1405	0.1765	0.1645	XC100	0.2044	0.1369	0.0654
C100	0.2085	0.1747	0.0909	XC20	0.0157	0.1896	0.1469

Table 4 clearly shows that the plant treated with combined compost and leachate has a higher k_N, k_P, and k_K release rate than the plant treated with compost only. The finding indicates that addition of leachate treatment can significantly ($p < 0.05$) improve the nutrient release rate capability of the plant. It is likely the soluble macronutrient in the leachate can be easily absorbed by the plant, increasing the rate of nutrient release.

In terms of k_N, it was observed that compost treated with 100 % v/v from both treatments has the highest N release rate, followed by 50 % v/v (C50, XC50), 70 % v/v (C70, XC70), 20 % v/v (C20, XC20) and 0 % v/v (C0). The high N release rate from the 100 % v/v is due to the high organic N content in the compost, enhances microbial activity and nitrification, leading to increased mineralised and soluble nitrogen (Araújo et al., 2020). Biruntha et al. (2020) also reported a higher N release rate in compost with a higher organic N content compared to those with lower organic N content. The results indicate a positive correlation between k_N and the compost's organic nitrogen content.

The highest k_P and k_K release rates were observed at the 50% v/v compost loading ratio. The low k_P and k_K values at 20 % v/v are typically due to the low organic P and K content present in the compost. At 70% - 100%, the k_P and k_K might be attribute to the excess Ca and Na which exceeded the threshold value set by FAO (10 g/kg) (refer to Table 3). Excess Ca content in the planting media caused P immobilisation by the available Ca in the compost, via the formation of Ca-P complexes (Vanden Nest et al., 2021). Na competes with the K element to be absorbed in the plant's root (Farooq et al., 2024). Excess Na content can hinder the K absorbed by the plant through its roots, reducing the K release from the compost (Ait-El-Mokhtar et al., 2021). This study demonstrates that a 50 % v/v loading ratio is the ideal ratio for achieving a high P and K release rate while minimising Ca and Na accumulation.

To established a link between the nutrient release rate and the yield of the chilli plant, an individual graph was created that relates the k_N, k_P, and k_K results from Table 4 to the chilli yield results from Figure 1. The ideal compost loading ratio, which gives the highest chilli yield and nutrient release rate, can be estimated from the analysis. Figure 2 and 3 illustrates the relationship between the composts' N, P, and K release rate with the chilli yield from plants treated with compost and leachate and those treated with compost only.

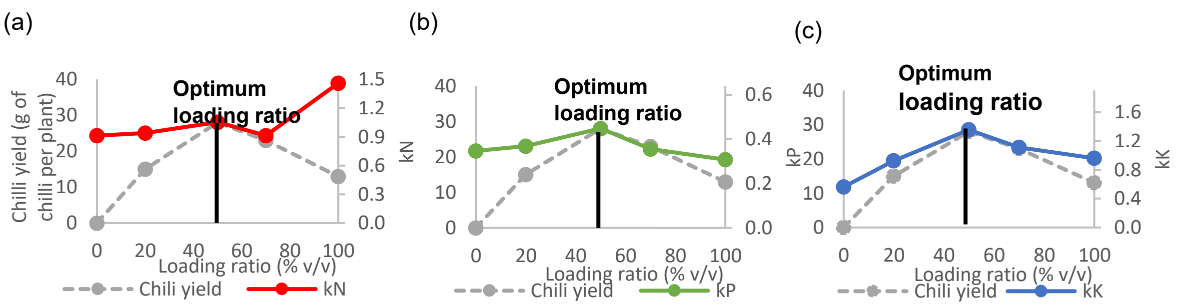

Figure 2: Relationship between the chilli yield with (a) nitrogen release rate (kN), (b) phosphate release rate (kP), (c) potassium release rate (kK) from plants treated with compost and leachate

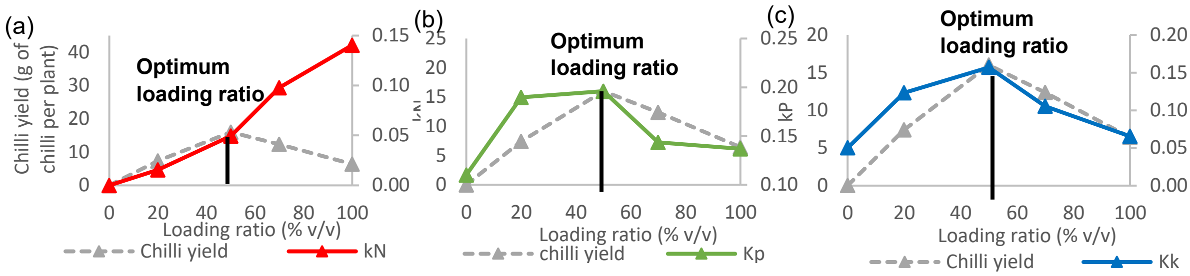

Figure 3: Relationship between the chilli yield with (a) nitrogen release rate (kN), (b) phosphate release rate (kP), (c) potassium release rate (kK) from plants treated with compost

Referring to Figure 2 (part a) and 3 (part a), chilli yield and nitrogen uptake (kN) increase with compost loading up to 50% v/v, regardless of leachate treatment. After 50 % v/v, the k_N continue to increases, but the chilli yield decreases due to nitrogen (N) overaccumulation in the planting media, causing toxicity and growth suppression. Excess nitrogen released in planting media can be toxic to plants by inducing oxidative stress, which reduces the accumulation of photosynthetic pigments, disrupts the photosynthesis process, and hinders plant growth. (Niu et al., 2024). According to the Department of Malaysian Standards (2012), the threshold limit for N in the organic fertiliser is 15 g/kg. The high N content (N = 15.42 – 22.03 g/kg) and high N release rate from the compost in 70 % v/v and 100 % v/v solutions cause N accumulation in the planting media, leading to N toxicity and suppression of plant growth and yield. A similar case was reported by Mondal et al. (2023), where the grain yield of maize (*Zea mays L.*) was reduced by 30 % when treated with N fertiliser at a rate higher than 160 kg/ha. The study demonstrates that a 50 % v/v compost ratio is the optimal ratio for achieving a high nitrogen (N) release rate while minimising N toxicity.

According to Figure 2 (part b and c) and Figure 3 (part b and c), in both leachate and without leachate treatment, the chilli yield and *k* value (k_P and k_K) increase with a higher loading ratio until they reach 50 % v/v. Application of compost at a concentration above 50 % v/v results in a reduction of the *k* value and chilli yield. This indicates that the P and K release rate is directly correlated with the chilli yield. Compost with a high P and K release rate can supply sufficient P and K nutrients to the plant quickly, thereby increasing the plant's P and K uptake rate and yield. Billah et al. (2020) found that compost with a high potassium release rate enhances K uptake and wheat yield. However, when compost loading exceeds 50 % v/v, the P and K release rates decrease due to the accumulation of Ca (14 – 20 g/kg) and Na (1.4 – 2.0 g/kg), which in turn reduces nutrient uptake and plant yield. This finding was supported by Farooq et al. (2024), who state that the growth and yield of wheat (*Triticum aestivum L.*) decrease with a high application rate of Na (more than 1.30 g/kg) in the soil. A study by Wen et al. (2021) showed that the application of Ca fertiliser at a rate higher than 0.4 g/kg could significantly decrease the growth of peanut seedlings. The finding from this study shows that the excess Ca and Na in the planting media can indirectly disrupt the growth and yield of the plant. This study demonstrates that the P and K release rates have a significant influence on chilli yield.

4. Conclusion

This study examines the impact of the nutrient release rate of compost on chilli yield when treated with leachate through fertigation. A first-order kinetic model effectively describes the release of nutrients during the fruiting stage. Applying 10 mL/L of leachate significantly enhances the release of nitrogen (N), phosphorus (P), and potassium (K), resulting in a 2–10 times increase in chilli yield. The compost loading ratio has a strong influence on nutrient release and plant growth, with optimal results at a 50 % v/v ratio (N = 11.02 g/kg, P = 1.49 g/kg, K = 11.05 g/kg). Above this threshold, P and K release and yield decline. Nutrient release significantly drops after day 70, suggesting compost should be replenished at that point. The study highlights the potential of food waste compost and leachate as effective biofertilisers, providing both economic and environmental benefits by reducing fertiliser use and food waste disposal. The limitation of this study is it focuses only on macronutrients (N, P, K), excluding micronutrients and potentially harmful elements such as heavy metals, which could affect long-term soil and crop health. The findings are specific to chilli cultivation and may not be directly transferable to other crops or soil types. Future research should incorporate trace elements and the C:N ratio to enhance the model's predictive accuracy. Long-term field trials with various crops are needed to further validate the findings. Moreover, integrating advanced modelling approaches, such as machine learning, may improve nutrient release prediction and support precision fertigation practices.

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