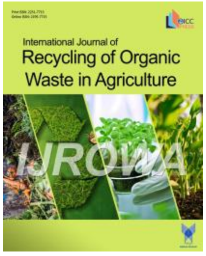

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Research Article

Release of Nitrogen, Phosphorus, and Potassium from Filter Cake, Filter Cake Biochar, and Sugarcane Bagasse Ash in a Laboratory Study

Daojarus Ketrot [1,*], Sawarin Saribut [2], Anuthida Sombatcharoennon [2], Weerawan Peungyam [1], Karuna Poomsong [1], Rathanont Jaroenchasri [1], Worachart Wisawapipat [1]

[1] *Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*

[2] *Agricultural Chemistry Program, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*

***Corresponding author:** fagrdrk@ku.ac.th

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Abstract

Purpose: This study characterized the chemical components and nutrient release patterns of filter cake, filter cake biochar, and sugarcane bagasse ash—by-products of the sugarcane industry, a globally significant crop.

Method: The chemical composition of each material was analyzed, nutrient release kinetics were examined using water extraction during 336 h, and kinetic models were applied.

Results: The studied materials were rich in various elements and exhibited alkaline properties. Carbon and Si were the primary components, followed by Ca, Al, P, and K. All materials released substantial amounts of K and P, with minimal N release. Filter cake had the highest cumulative release of water-soluble P (7,701±87.4 mg/kg), followed by filter cake biochar (2,982±27.3 mg/kg) and sugarcane bagasse ash (1,194±3.66 mg/kg), representing 32.2%, 7.8%, and 21.7%, respectively, of total P. Conversely, the cumulative release of water-soluble K was highest in sugarcane bagasse ash (7,295±418 mg/kg), followed by filter cake (3,999±124 mg/kg) and filter cake biochar (2,312±107 mg/kg), accounting for 23.3%, 30.3%, and 11.0%, respectively, of total K. The nutrient release kinetics showed that the magnitude of release was controlled by the inherent elemental concentrations of each material and exhibited good fits with the Elovich and power function models (R^2 = 0.836–0.990 and 0.810–0.996). Nutrient release depended mainly on diffusion through heterogeneous and homogeneous surfaces.

Conclusion: These sugarcane by-products have the potential to improve soil fertility through nutrient releases. Transforming filter cake into biochar slows the initial release of nutrients while ensuring a more sustained and steady long-term release.

Keywords: Plant nutrient release; Kinetic models; Sugarcane by-products, Press-mud, Ash, Biochar

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1. Introduction

Sugarcane is a globally important economic crop, cultivated in over 100 countries (FAO, 2022). Approximately 180 million tons of raw sugar are produced worldwide annually (USDA, 2024). Thailand, with a total sugarcane cultivation area of 1.78 million hectares, produced about 8.8 million tons of sugar in the 2023/2024 production year (Office of the Cane and Sugar Board, 2024; USDA, 2024), making it the world's second-largest exporter of sugarcane (USDA, 2022). The sugarcane industry generates several by-products, including bagasse (a fibrous material remaining after cane juice extraction) and filter cake, or press mud (a fine remnant after filtering the cane juice during sugar production). Bagasse constitutes approximately 50% of the composition of sugarcane by weight and is commonly recycled through incineration for energy purposes, producing a final by-product called sugarcane bagasse ash (Ungureanu et al., 2022). Reusing these by-products, especially in agriculture for plant production, would support zero-waste goals and promote sustainability in sugarcane production. Soil fertility depletion and inefficient nutrient management remain critical global challenges, particularly in intensive agricultural systems. The continuous decline in soil nutrient reserves threatens long-term soil productivity. In this context, utilizing sugarcane by-products as alternative sources of nutrients and organic matter presents a sustainable approach to improving soil fertility while also enhancing soil physical properties. Ketrot and Wisawapipat (2021) revealed that filter cake biochar and sugarcane bagasse ash are abundant in plant nutrients (including N, P, K, and S). This finding aligned with other research suggesting that filter cake biochar and sugarcane bagasse ash could improve carbon sequestration and enhance nutrient retention in soils (Eykelbosh et al., 2014; Islami et al., 2017; Speratti et al., 2017, 2018). Recent studies have further demonstrated the potential of biochar and ash derived from plant-based sources (such as coconut, wood and peanut straw) to improve soil properties as amendments and enhance nutrient availability, particularly in degraded soils, for sustainable plant production (Shamila et al., 2024; Uwiringiyimana et al., 2024; Manirakiza et al., 2025). Furthermore, Ketrot and Wisawapipat (2021) showed that incorporating filter cake biochar and sugarcane bagasse ash (1.0% and 5.0% w/w, respectively) significantly decreased the extractability of Pb and As in mining-contaminated soils. It coincided with the properties of biochar produced from other biomass sources, showing excellent adsorption capabilities for toxic elements such as Cd, Pb, and As (Jiang et al., 2012; Břendová et al., 2015; Campos and De la Rosa, 2020; Kumar and Bhattacharya, 2022).

The transformation of raw filter cake into filter cake biochar and its effects on nutrient release behavior are not yet fully understood, despite extensive research on the sorption of toxic elements by biochar and ash from the sugarcane industry and other sources. Knowledge remains limited regarding nutrient release from both raw filter cake and biochar filter cake, as well as from sugarcane bagasse ash. Therefore, the current research investigated:
1) the chemical components in raw filter cake, filter cake biochar, and sugarcane bagasse ash, and
2) the nutrient release patterns from these materials. The results from this research should shed light on the potential use of these by-products as soil amendments and green fertilizers to enhance soil fertility and serve as a source of plant nutrients, contributing to the sustainability of the sugarcane industry and agricultural production.

2. Materials and methods

2.1. Sampling of raw filter cake and bagasse ash and filter cake biochar production

Raw filter cake and sugarcane bagasse ash were collected from the sugar industry in Kanchanaburi province, located in western Thailand, which has a tropical climate. The sugarcane processed in the factory is sourced from both the western and central regions of Thailand. These sugarcane plantations are usually found in flat or gently sloping areas, with some relying on irrigation and others on rainfall. Ratooning is a common practice in these regions. The soils in this area are diverse, ranging from coarse-textured to fine-textured soils. Both Raw filter cake and sugarcane bagasse ash were air-dried and milled to pass through a 0.25 mm sieve. The filter cake biochar and sugarcane bagasse ash used were the same samples as those described by Ketrot and Wisawapipat (2021). In summary, the method for preparing biochar from the filter cake involved tightly packing moist filter cake (approximately 75% w/w moisture) into a crucible and covering with a lid to limit oxygen diffusion into the material, thus creating pyrolysis conditions. Next, the sample was combusted in a furnace (Carbolite, RWF 1200) at 600°C for 2 h and then allowed to cool to room temperature overnight in the furnace. A thin, visible layer of white and grayish ash was carefully removed with a spatula. The black carbon material remaining at the bottom of the crucible, referred to as biochar, was then milled and passed through a 0.25 mm sieve before further use.

2.2. Chemical analysis

Elemental component analyses of the raw filter cake, filter cake biochar, and sugarcane bagasse ash were conducted for total C and N using a CHNS/O elemental analyzer (2400 Series II; PerkinElmer). Other elements were

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measured on pellet-pressed samples using an X-ray fluorescence spectrometer (XRF) (Bruker S8 Tiger). The pH and electrical conductivity (EC) values in the raw filter cake, filter cake biochar, and sugarcane bagasse ash were determined using a solid-to-water ratio of 1:5. The cation exchange capacity (CEC) was measured using the 1M NH_4OAc pH 7.0 method. The organic carbon (OC) was assessed using the Walkley and Black titration. Ammonium (NH_4) and nitrate (NO_3) contents were evaluated by distillation method after the KCl extraction. The extractable P and K were analyzed using the Olsen (0.5M $NaHCO_3$ at pH 8.5) and 1M NH_4OAc at pH 7.0 methods, respectively, (Spark et al., 1996). All these parameters were measured in three replicates, except for elemental component analyses, which were conducted in one replicate.

2.3. Experiment on release kinetics of plant nutrients

The release kinetics of plant nutrients (N, P, and K) from the raw filter cake, filter cake biochar, and sugarcane bagasse ash were determined using a batch experiment. Briefly, 2.5 g of each sample was weighed in high-density polyethylene (HDPE) bottles and mixed with 250 mL of deionized (DI) water. The batch experiment was conducted in four replicates, with DI water serving as a blank. Sample suspensions were agitated horizontally on a mechanical shaker at 200 rpm for 1 h. Then, the samples were passed through Whatman No. 1 filter paper using a vacuum pump. Aliquots were collected for nutrient analysis and the sample sediments were re-suspended in an additional 250 mL of DI water. This extraction and filtration process was repeated at defined intervals of 6, 12, 24, 48, 144, 240, and 336 h. The aliquots from each interval were measured for pH and EC. The concentrations of NH_4 and NO_3 in the extracts were analyzed using the distillation method, while water-soluble P and water-soluble K were measured using the ascorbic acid method and an atomic absorption spectrophotometer (AA240; Varian), respectively (Spark et al., 1996). The concentrations of plant nutrients (NH_4, NO_3, water-soluble P, and water-soluble K) obtained in solutions were used to calculate the cumulative nutrients released over time. These data were used to describe the release characteristics based on kinetic models (Elovich, parabolic diffusion, power function, zero-order, and first-order equations). These kinetic models are commonly applied to interpret the chemical release processes of soil and organic materials (Darunsontaya et al., 2020; Zareian et al., 2018; Dey et al., 2019; Hu et al., 2019; Spark et al., 2024; Wibisono et al., 2023). The kinetic models are presented in equations 1–5:

Elovich equation	$q_t = a + b\ ln\ (t)$	(1)
Parabolic diffusion equation	$q_t = a + bt^{1/2}$	(2)
Power function equation	$ln\ (q_t) = ln\ (a) + b\ ln\ (t)$	(3)
Zero-order equation	$(q_{final} - q_t) = a - bt$	(4)
First-order equation	$ln\ (q_{final} - q_t) = a + bt$	(5)

where: q_t is the content of accumulative nutrient released at time t (mg/kg), t is the extraction time (h), q_{final} represents the total accumulated concentration at the longest release period of 336 h (mg/kg), the a coefficient is an intercept, describing the initial nutrient release magnitude (mg/kg for equations 1, 2, and 4 and *ln* (mg/kg) for equations 3 and 5), and the b coefficient is slope indicates the kinetic rates of nutrient release (mg/kg per *ln* (h) for equations 1, mg/kg/$h^{1/2}$ for equation 2, dimensionless for equation 3, mg/kg/h for equation 4, and 1/h for equation 5).
The kinetic equations were evaluated using the coefficient of determination (R^2) and the standard error of the estimate (SE) (Zareian et al., 2018), calculated as:

$$SE = [\ \sum (q_t - q_c)^2 / (n - 2)\ ]^{1/2} \quad (6)$$

where: q_c is the calculated content of accumulative nutrient released at time t (mg/kg), and n is the number of data points.

3. Results and discussion

3.1. Elemental compositions of studied materials

Based on the elemental composition analysis, the raw filter cake, filter cake biochar, and sugarcane bagasse ash contained a variety of elements. The main elements in the raw filter cake were C, Si, Ca, Al, P, N, Fe, K, Mg, and S, with concentrations of 224, 123, 47.5, 35.2, 23.9, 18.8, 15.2, 13.2, 8.37, and 3.24 g/kg, respectively (Table 1). After converting the raw filter cake into biochar, the concentrations of most elements increased by 12–76%, depending on the element, which could be attributed to the higher concentrations of elements in the more condensed structure of the biochar compared to the raw filter cake (Zhao et al., 2014; Ippolito et al., 2015; Almutairi et al., 2023). However, the concentrations of C, N, and S decreased by 32–43%, likely due to the transformation of these elements into gaseous forms through thermal decomposition and volatilization during the pyrolysis process (Zhao et al., 2014; Ippolito et al., 2015; Almutairi et al., 2023). Additionally, the fermentation process that the filter cake underwent likely depleted biodegradable non-lignin C, contributing to the overall low C yield in the biochar product and the enrichment of lignin in the filter cake itself. Although the C content of the filter cake biochar decreased in this study, the remaining C was likely in the form of stable aromatic C (Eykelbosh et al., 2014). Conversely, Si, K, Al, Ca, C, and Fe were the main components in the sugarcane bagasse ash, accounting for 330, 31.3, 27.2, 23.8, 23.4, and 11.0 g/kg, respectively (Table 1). These elemental properties suggested that all three materials had potential for enhancing the soil nutrient content. These findings aligned well with other studies demonstrating the abundance of plant nutrients from raw filter cake, its biochar, and sugarcane bagasse ash for use as soil amendments to support plant growth (Islami et al., 2017; da Mota et al., 2019; de Oliveira et al., 2023).

Table 1. Elemental composition (g/kg) of filter cake, filter cake biochar, and sugarcane bagasse ash

Elemental composition (g/kg)	Raw filter cake	Filter cake biochar[1]	Sugarcane bagasse ash
C	224	152 (32%)	23.4
N	18.8	10.7 (43%)	0.45
Si	123	216 (76%)	330
Ca	47.5	73.1 (54%)	23.8
Al	35.2	59.4 (69%)	27.2
P	23.9	38.1 (59%)	5.48
Fe	15.2	24.3 (60%)	11.0
K	13.2	21.1 (60%)	31.3
Mg	8.37	13.8 (65%)	9.53
S	3.24	1.84 (43%)	2.66
Ti	1.82	2.91 (60%)	1.52
Mn	1.63	2.63 (61%)	0.75
Cl	1.12	1.25 (12%)	1.61

Note: [1] Values in parentheses indicate relative change (%) in elemental concentration in filter cake biochar compared to raw filter cake.

Table 2. Chemical properties of filter cake, filter cake biochar, and sugarcane bagasse ash

Property	Raw filter cake	Filter cake biochar	Sugarcane bagasse ash
pH (1:5 H_2O)	7.50±0.01	7.88±0.04	8.77±0.02
Electrical conductivity (1:5 H_2O) (dS/m)	1.97±0.06	0.96±0.01	2.91±0.11
Cation exchange capacity ($cmol_c$/kg)	32.7±0.96	19.7±0.27	5.96±0.02
Organic carbon (g/kg)	190±5.58	148±6.65	13.5±1.85
Extractable NH_4 (mg/kg)	459±7.92	50.4±3.96	0.42±0.20
Extractable NO_3 (mg/kg)	nd	nd	nd
Extractable P (mg/kg)	1,896±36.4	1,268±4.98	906±6.21

Note: "nd" indicates "not detected".

3.2. Chemical properties of studied materials

Based on the chemical property analysis, the raw filter cake was slightly alkaline (pH 7.50±0.01), with its pH increasing when it was converted into biochar (pH 7.88±0.04). The filter cake had EC and CEC values of 1.97±0.06 dS/m and 32.7±0.96 $cmol_c$/kg, respectively, which were higher than those of the filter cake biochar (0.96±0.01 dS/m and 19.7±0.27 $cmol_c$/kg, respectively). The increase in pH of filter cake biochar is likely due to the carbonization process, which induces alkalization through the enrichment of basic cations and increased ash content (de Oliveira Paiva et al., 2024). In contrast, the decrease in EC of filter cake biochar may be attributed to the reduction in soluble S salts, as indicated by the decreased S content (Table 1). This trend is similar to the reduction in EC observed in sugarcane bagasse-derived biochar produced at 750°C, which has been linked to the thermal degradation of inorganic components and the preservation of aromatic carbon compounds (de Oliveira Paiva et al., 2024). The decrease in CEC observed in the filter cake biochar is likely a result of the high pyrolysis temperature (600°C) applied in this study. At elevated temperatures, most organic groups and bands responsible for generating negative charges are lost, leading to the removal of oxygen-containing functional groups from the biochar (Domingues et al., 2017). The sugarcane bagasse ash was strongly alkaline (pH 8.77±0.02), with an EC of 2.91±0.11 dS/m, being higher than both the filter cake and its biochar. However, the CEC for the ash was lower than for both the other materials (5.96±0.02 $cmol_c$/kg), as shown in Table 2. Most of the C content in the raw filter cake, filter cake biochar, and sugarcane bagasse ash samples was OC, with values of 190±5.58 g/kg, 148±6.65 g/kg, and 13.5±1.85 g/kg, respectively, accounting for 84.8%, 97.4%, and 57.7%, respectively, of the total C in each material. The extractable NH_4 and P showed similar trends, with the raw filter cake having the highest values (459±7.92 and 1,896±36.4 mg/kg, respectively) followed by the filter cake biochar (50.40±3.96 and 1,268±4.98 mg/kg, respectively). The sugarcane bagasse ash had a very low level of extractable NH_4 (0.42±0.20 mg/kg) and the lowest level of extractable P (906±6.21 mg/kg) for all three materials. The values for the extractable NO_3 contents in all three materials were too low to be detected using the distillation method. Conversely, the highest extractable K content was in the sugarcane bagasse ash, followed by the raw filter cake and filter cake biochar (6,390±356, 4,047±113, and 2,420±141 mg/kg, respectively). These extractable N (NH_4 and NO_3), P, and K amounts were consistent with their total concentrations (Tables 1 and 2).

However, the nutrient content and chemical properties of the filter cake, sugarcane bagasse ash, and filter cake biochar have been reported to vary substantially across different sources (Eykelbosh et al., 2014; Islami et al., 2017; Sperati et al., 2017; Pluemjai et al., 2018; Sperati et al., 2018; Hemwong and Vityakon, 2019; Inthasan et al., 2023). This large variation could be due to differences in the raw sugarcane materials and the distinct sugar production processes in each factory and region. Nevertheless, overall, these materials had alkaline properties and contained essential plant nutrients, making them suitable for improving soil fertility. Several studies have shown that raw filter cake, filter cake biochar, and sugarcane bagasse ash can ameliorate degraded soils, particularly soil chemical (pH, OC, CEC, and plant nutrients), physical (aeration, water retention, and water infiltration), and microbiological properties (Eykelbosh et al., 2014; Islami et al., 2017; Sperati et al., 2017; da Mota et al., 2019; de Oliveira et al., 2023).

3.3. pH and electrical conductivity of extracted solutions from kinetic-release experiments

Based on the analysis of the solutions extracted from all three materials at different extraction times, the solution extracted from sugarcane bagasse ash had the highest pH (8.17–9.13), with the pH levels for the filter cake biochar (pH 7.26–8.18) and the raw filter cake (pH 6.37–7.99) being lower (Fig. 1a). The temporal change in pH values revealed a surge within 12 h after extraction, followed by a gradual decline until the end of the experiment (336 h). The pH of the extracts was slightly higher than that of the original materials (Table 1), presumably due to a large variation in the solid-to-water ratio and the duration of extraction for pH measurement and nutrient release. The pH pattern of the extracted solution in this study differed from that observed by Hu et al. (2019), who reported that the pH of the distilled water-extracted solution from 10% biochar/struvite composites increased continuouslywith longer incubation time, approaching a pH of 7.5.

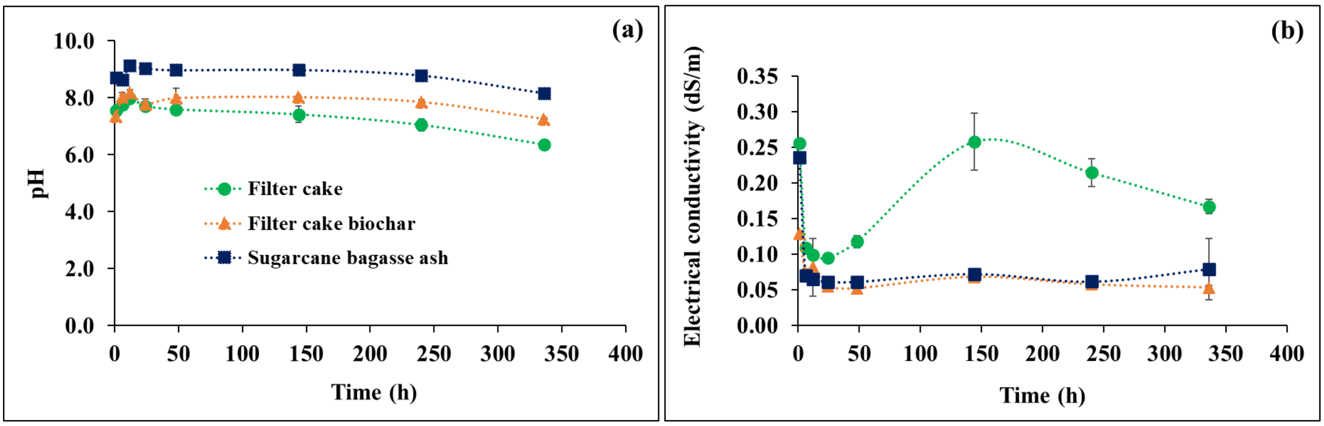

Figure 1. Extractable solution from filter cake, filter cake biochar, and sugarcane bagasse ash during continuous shaking at various time intervals: (a) pH and (b) electrical conductivity

There was a distinctly different trend in the EC of the extracted solutions compared to the pH values, with the EC being highest after 1 h of extraction, followed by an abrupt decline, and subsequent stabilization after 6 h for the filter cake biochar and sugarcane bagasse ash (Fig. 1b). In contrast, the raw filter cake EC values had a different trend from those of the biochar and ash, with an abrupt decrease at 6 h and a subsequent increase at 144 h. The large variability in EC values over time could have been due to the raw filter cake containing diverse compounds with differing solubilities, which dissolved at different rates during extraction.

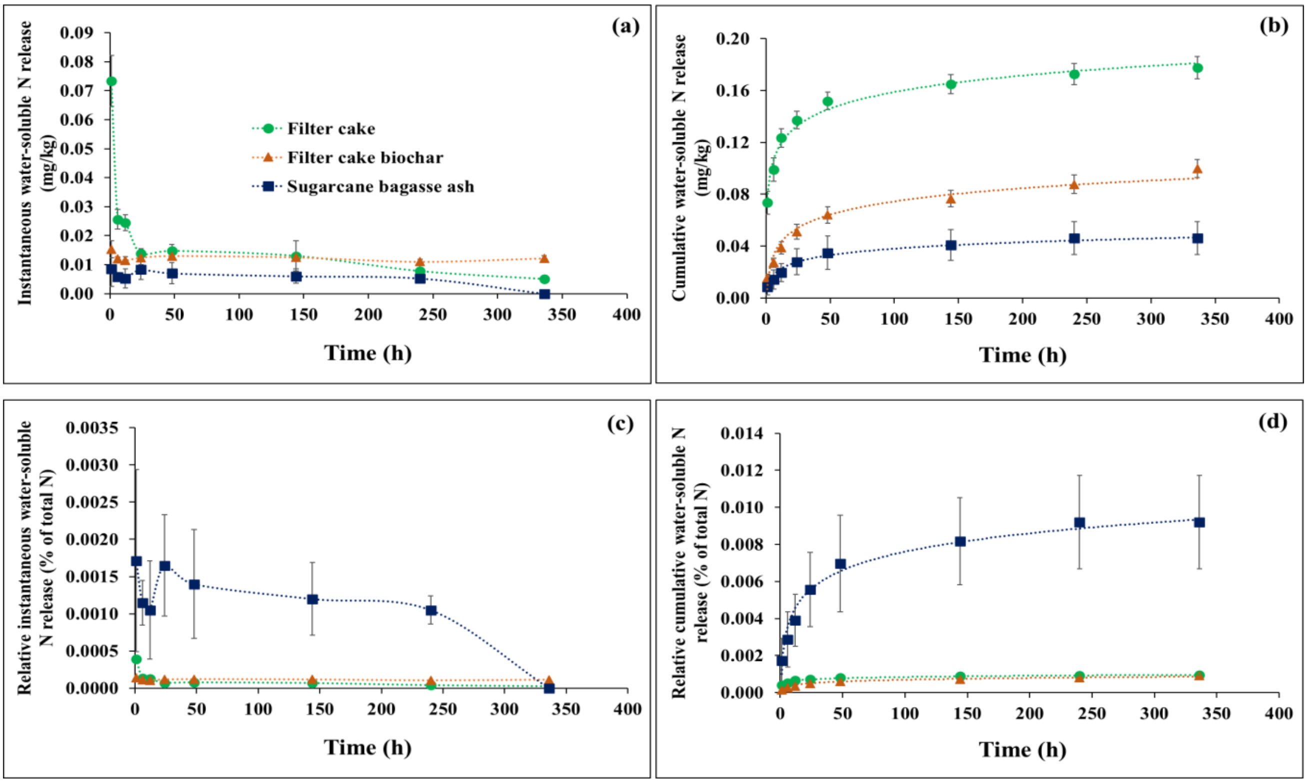

Figure 2. Water-soluble nitrogen (N) released from filter cake, filter cake biochar, and sugarcane bagasse ash during continuous shaking at various time intervals: (a) instantaneous, (b) cumulative, (c) relative instantaneous total N, and (d) relative cumulative total N

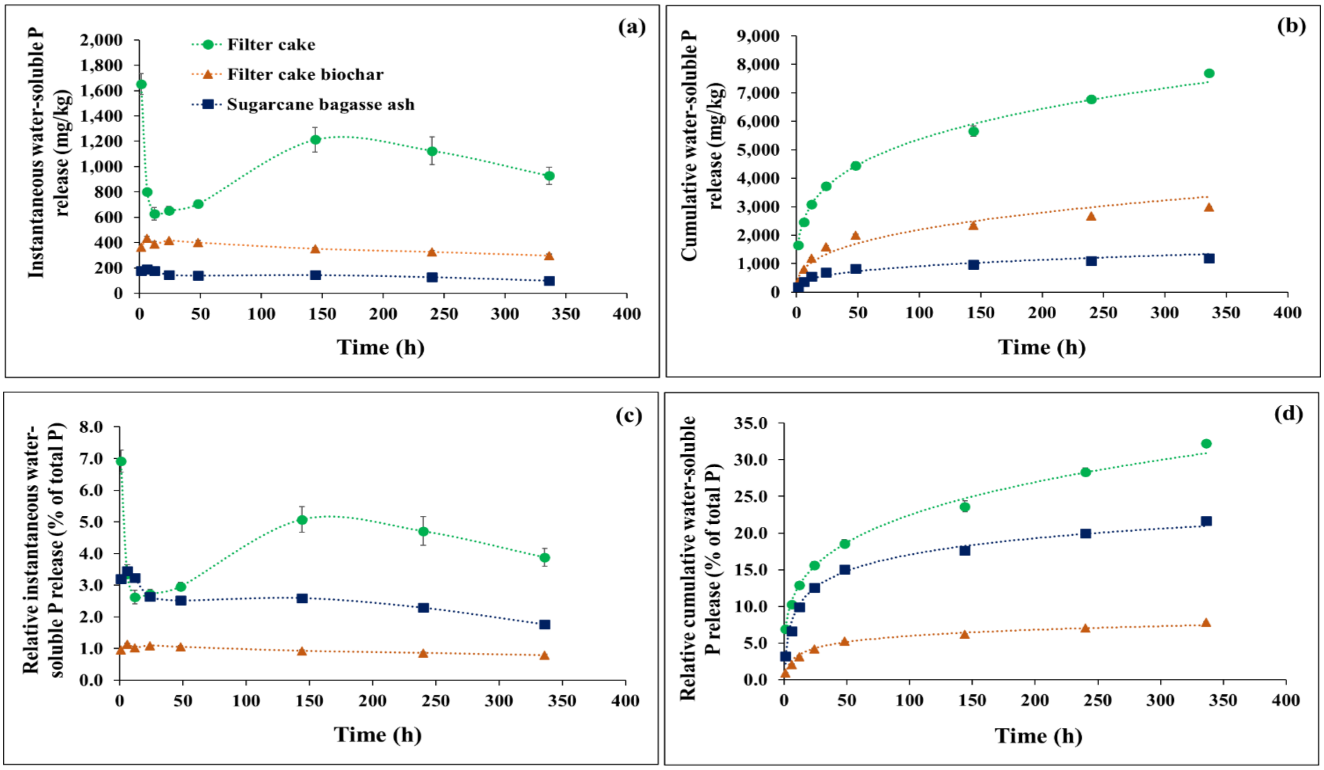

Figure 3. Water-soluble phosphorus (P) released from filter cake, filter cake biochar, and sugarcane bagasse ash during continuous shaking at various time intervals: (a) instantaneous, (b) cumulative, (c) relative instantaneous total P, and (d) relative cumulative total P

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3.4. Nutrient release profiles

The water-soluble NH_4 and NO_3 concentrations in all three material samples were very low. Therefore, the sum of the NH_4 and NO_3 concentrations was reported as the water-soluble N. A rapid release of water-soluble N from the raw filter cake occurred within 1 h, with an abrupt decline during 6–12 h, and subsequently, a gradual decline during 24–366 h. Both the filter cake biochar and sugarcane bagasse ash had similar magnitudes of water-soluble N release throughout the experiment (Fig. 2a). The filter cake biochar released water-soluble N relatively consistently until the end of the experiment at 336 h, whereas the sugarcane bagasse ash released a lower amount of water-soluble N and did not release any at the end of the experiment (336 h). Collectively, the raw filter cake had the highest total cumulative water-soluble N release (0.18±0.01 mg/kg), followed by its biochar (0.10±0.01 mg/kg) and the sugarcane bagasse ash (0.05±0.01 mg/kg), respectively (Fig. 2b). The low water-soluble N values were not unexpected and were consistent with the low total N concentrations overall. Notably, only a very small amount of water-soluble N (<0.01%) was released compared to the total N (Figs. 2c, d). The cumulative N release in the studied materials was lower than that reported by Hu et al. (2019), who found that 10% biochar/struvite composites released approximately 10% of their N in distilled water after 14 days of incubation. There was a rapid release of water-soluble P from the raw filter cake within 1 h, followed by an abrupt decrease at 6 h, an increase at 144 h, and then a gradual decrease until 366 h. In contrast, the rates of release of water-soluble P from the filter cake biochar and sugarcane bagasse ash were relatively stable, with a slight decline over time (Fig. 3a). Notably, the P release profile closely resembled the EC values (Fig. 1b), suggesting that P could be a main contributor to the soluble elements in the water extract, particularly from the raw filter cake. Furthermore, the raw filter cake had the highest total cumulative water-soluble P release (7,701±87.4 mg/kg), followed by the filter cake biochar (2,982±27.3 mg/kg) and sugarcane bagasse ash (1,194±3.66 mg/kg), respectively (Fig. 3b). The cumulative water-soluble P release was well aligned with the total P concentration. Comparing the amount of P released to the total P, the raw filter cake, its biochar, and sugarcane bagasse ash had average P release rates of 4.0%, 1.0%, and 2.7%, respectively (Fig. 3c). The cumulative P release accounted for approximately 32.2%, 7.8%, and 21.7% of the total P for the raw filter cake, its biochar, and sugarcane bagasse ash, respectively (Fig. 3d). The proportion of cumulative P release from filter cake biochar in this study was similar to that reported by Hu et al. (2019), which was approximately 6%, when compared at the same experimental duration of 14 days using water extraction. The water-soluble K was released at a rapid rate at 1 h of extraction, with amounts of 4,592±128, 2,975±133, and 926±17.3 mg/kg extracted from sugarcane bagasse ash, raw filter cake, and filter cake biochar, respectively (Fig. 4a), accounting for 14.7%, 22.5%, and 4.4% of the total K content, respectively (Fig. 4c). However, the amount of water-soluble K rapidly declined during 2–48 h and stabilized during 48–366 h. The total cumulative water-soluble K release followed a similar pattern after 366 h of extraction: sugarcane bagasse ash > raw filter cake > filter cake biochar (7,295±418, 3,999±124, and 2,312±107 mg/kg released, respectively) (Fig. 4b), accounting for 23.3%, 30.3%, and 11.0% of the total K, respectively (Fig. 4d). When comparing the cumulative K release from various modified wheat straw biochars with nutrient loading and bio-oil coating (~30–40% of K loading in 7 days), as reported by Ye et al. (2019), the K release from the sugarcane by-products in this study was lower, particularly for filter cake biochar.The highest water-soluble K in the extract is partially associated with the total K content for the sugarcane bagasse ash. Nonetheless, the water-soluble K of the raw filter cake and its biochar materials could not be directly related to their total K content (Table 1). The filter cake biochar had a lower water-soluble K release than the raw filter cake, which could be attributed to the impact of heat during pyrolysis, altering the solubility of K from highly soluble to sparingly soluble. Prakongkep et al. (2015) reported that biochar derived from diverse plant residues, including bagasse, contained diverse K-containing minerals (archerite, chlorocalcite, kalicinite, pyrocoproite, struvite-K, and sylvite) with different solubilities than the easily soluble sylvite (KCl).

3.5. Release kinetics modeling of plant nutrients

The release kinetics of nutrients (N, P, and K) from the studied materials, based on various kinetic models, were best described by the Elovich equation. This model exhibited the highest coefficient of determination for water-soluble N (R^2 = 0.968–0.983), water-soluble P (R^2 = 0.936–0.987), and water-soluble K (R^2 = 0.836–0.990), along with the lowest prediction error for N release (SE = 0.003–0.006) (Table 3 and Fig. 5). These results suggested that the release of N, P, and K from these materials was primarily governed by heterogeneous diffusion (Spark et al., 2024). The power function equation was the second most accurate model for describing N, P, and K release kinetics, with R^2 values ranging from 0.956–0.981, 0.955–0.996, and 0.810–0.977, respectively. It also exhibited the lowest SE values for P and K release (0.034–0.155 and 0.025–0.076, respectively). This further supports nutrient release through homogeneous diffusion in all materials (Spark et al., 2024). The initial rapid phase could be attributed to the release of nutrients located on the outer surface of particles, from where the nutrients are released more rapidly than from the micropores of the particles (Zhao et al., 2018). However, the later slow-release phase could be attributed mainly to the dissolution of the less soluble minerals or nutrients present in the micropores, which being less accessible were therefore released at a slower rate than those in the mesopores (Zhao et al., 2018). The *a* and *b* coefficients revealed that the raw filter cake released a greater magnitude at a faster release rate of extractable N and water-soluble P than the other materials. Conversely, sugarcane bagasse ash had a higher magnitude and faster rate of water-soluble K release compared to the others. The b coefficient of the power function equation for all three materials was less than 1, suggesting a decrease in release rate over time (Zareian et al., 2018), as shown in Table 3 and Fig. 5.

In addition to the Elovich and power function models, the first-order equation ($R^2 = 0.800–0.975$) was superior to the zero-order equation ($R^2 = 0.348–0.900$), suggesting that nutrient release was not linear but rather had an exponential decline based on the natural logarithm function. This decline depended on the inherent concentration of nutrients in each material.

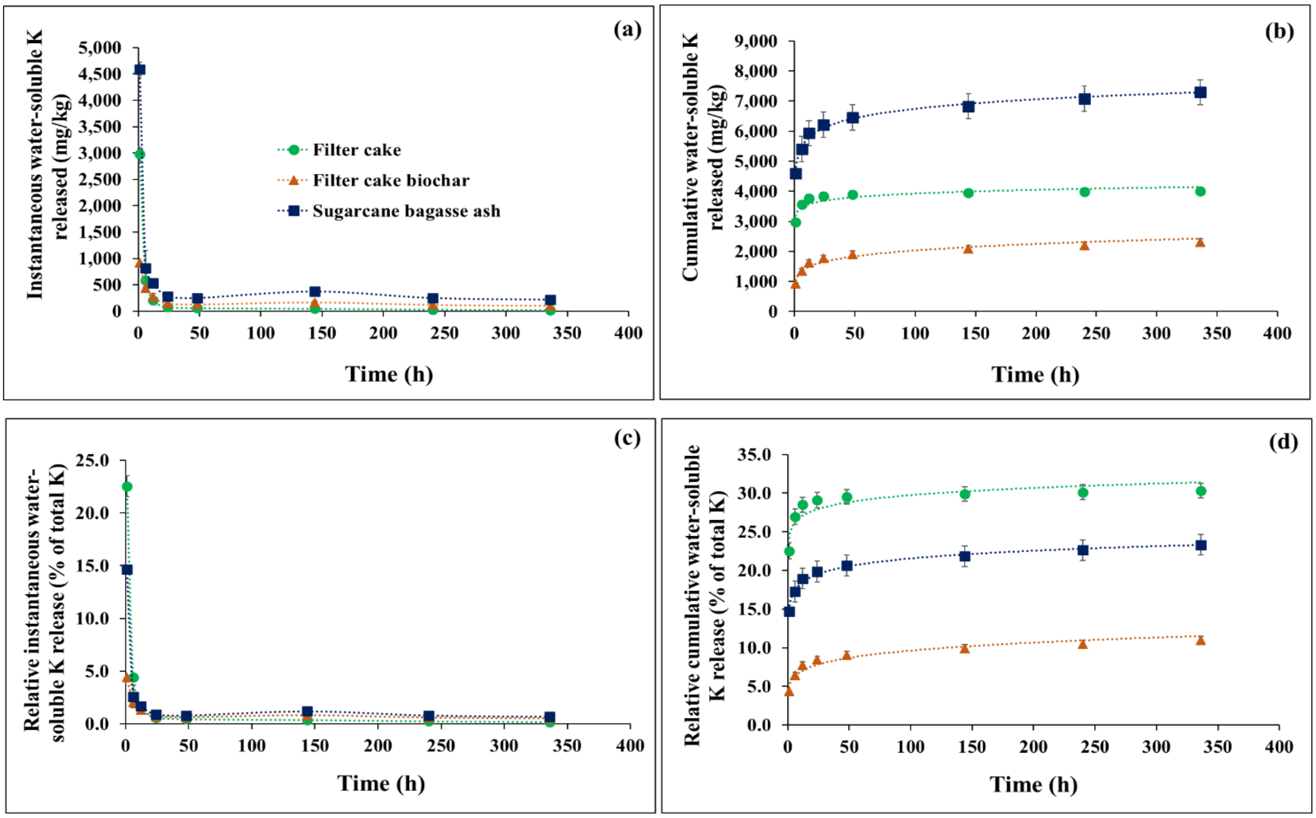

Figure 4. Water-soluble potassium (K) released from filter cake, filter cake biochar, and sugarcane bagasse ash during continuous shaking at various time intervals: (a) instantaneous, (b) cumulative, (c) relative instantaneous total K, and (d) relative cumulative total K

The parabolic diffusion model also effectively described the release of P from all three materials ($R^2 = 0.900–0.983$), indicating diffusion-controlled phenomena, including intraparticle and surface diffusion, which are rate-limiting processes (Almaroai et al., 2013). However, Dey et al. (2019) demonstrated that nutrients released from different organic fertilizers (composts and manure) were well described by the zero-order equation, suggesting that nutrient release from these organic materials was constant and independent of their inherent concentrations. Furthermore, Zhao et al. (2018) reported that nutrient release from biochar derived from pig manure and sewage sludge, under simulated landfill conditions using the toxicity characteristic leaching procedure, was rapid in the initial phase and could be better explained by the second-order model than the first-order model, suggesting that the early-stage release process was dominated by chemical desorption and the diffusion of labile nutrients.

3.6. Environmental impact and study limitations

The utilization of sugarcane by-products (raw filter cake, filter cake biochar, and sugarcane bagasse ash) presents significant benefits for enhancing soil fertility and promoting sustainable agriculture. However, their environmental implications require careful evaluation. One primary concern is the risk of nutrient leaching, particularly P (which is abundant in the studied materials).

During heavy rainfall or improper application, excess P may enter water bodies, leading to nutrient pollution and eutrophication (Dengia and Lantinga, 2018). To mitigate this, converting filter cake into biochar before field application could be an effective strategy to slow nutrient release and reduce environmental risks. Additionally, proper application rates and regular monitoring of nutrient levels in runoff are crucial for preventing excessive leaching. Another key aspect is the impact of these by-products on soil microbial communities. These materials can promote beneficial microbes (de Oliveira et al., 2023), similar to other organic amendments (Guo et al., 2022), potentially improving soil health and nutrient cycling (Gonfa et al., 2018). However, further research is needed to assess their long-term effects on microbial communities across different soil environments. Although the laboratory-based kinetic models used in this study offer valuable insights into the release behavior of water-soluble nutrient forms, they do not reflect the total nutrient-supplying potential of the materials. Likewise, the laboratory findings provide valuable insights, they may not fully capture the complexity of field conditions. To address this, future studies should validate these results through field trials, considering factors such as weather conditions, soil heterogeneity, and crop interactions. Moreover, as this study focused on short-term nutrient release, long-term field studies are necessary to evaluate the sustained effectiveness of these materials, their impact on soil health, and their influence on crop productivity over extended periods.

Table 3. Parameters of kinetic equation used to describe release of nitrogen, phosphorus, and potassium from filter cake, filter cake biochar, and sugarcane bagasse ash

Kinetic Equation	Filter cake				Filter cake biochar				Bagasse ash			
	Intercept (*a*)	Slope (*b*)	R^2	SE	Intercept (*a*)	Slope (*b*)	R^2	SE	Intercept (*a*)	Slope (*b*)	R^2	SE
Nitrogen												
Elovich	0.074	0.018	0.983	0.006	0.007	0.015	0.968	0.006	0.005	0.007	0.971	0.003
Parabolic diffusion	0.096	0.005	0.808	0.018	0.021	0.005	0.941	0.010	0.013	0.002	0.887	0.005
Power function	-2.542	0.151	0.956	0.070	-4.106	0.312	0.981	0.099	-4.694	0.301	0.967	0.120
Zero-order	0.064	-0.0002	0.633	0.027	0.064	-0.0002	0.820	0.015	0.027	-0.0001	0.725	0.010
First-order	-2.691	-0.011	0.927	0.321	-2.702	-0.007	0.939	0.193	-3.505	-0.013	0.908	0.252
Phosphorus												
Elovich	880.9	1,030	0.936	582.9	162.7	459.2	0.979	143.6	120.1	177.7	0.987	44.36
Parabolic diffusion	1792	327.4	0.983	299.0	635.7	137.7	0.916	290.6	308.3	52.63	0.900	121.7
Power function	7.379	0.263	0.996	0.034	6.076	0.351	0.960	0.155	5.358	0.316	0.955	0.148
Zero-order	4,883	-15.94	0.900	765.0	1890	-6.452	0.777	501.9	709.3	-2.451	0.755	202.7
First-order	8.562	-0.007	0.975	0.114	7.600	-0.008	0.934	0.218	6.628	-0.009	0.938	0.226
Potassium												
Elovich	3,204	156.8	0.836	149.8	982.3	230.3	0.986	58.36	4671	450.8	0.990	96.3
Parabolic diffusion	3,436	38.18	0.516	257.2	1256	64.51	0.805	220.4	5,197	127.51	0.824	409.5
Power function	8.070	0.045	0.810	0.047	6.939	0.147	0.946	0.076	8.464	0.076	0.977	0.025
Zero-order	416.5	-1.594	0.348	322.7	831.8	-2.927	0.641	320.9	1,659	-5.817	0.663	606.7
First-order	5.901	-0.013	0.800	0.636	6.758	-0.009	0.897	0.306	7.457	-0.009	0.910	0.284

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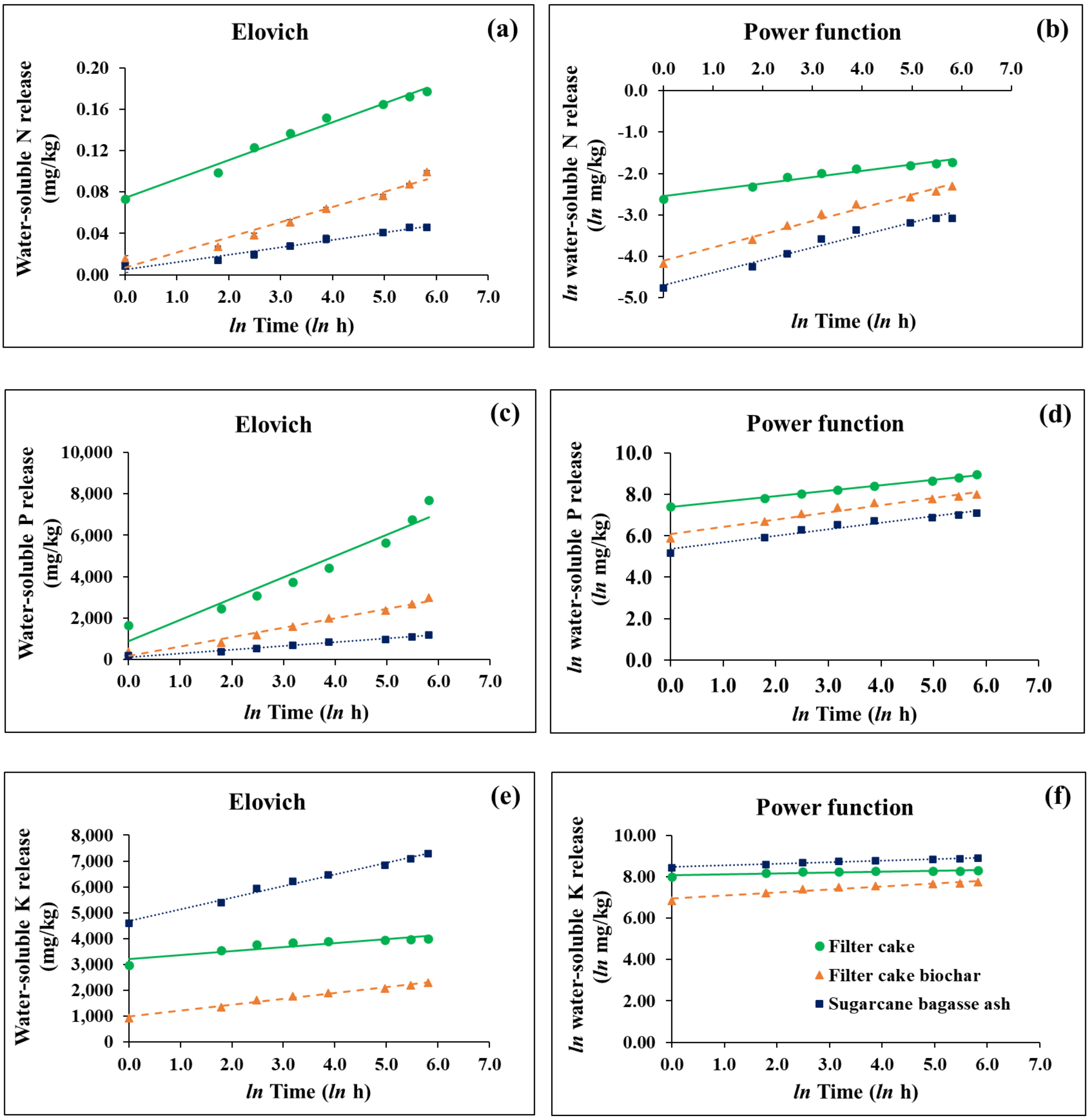

Figure 5. Data fitted to Elovich and power function models describing nutrient release from filter cake, filter cake biochar, and sugarcane bagasse ash: (a) and (b) nitrogen, (c) and (d) phosphorus, and (e) and (f) potassium, respectively

4. Conclusion

This study revealed that by-products from the sugarcane industry (raw filter cake, filter cake biochar, and sugarcane bagasse ash) were rich in various plant nutrients and had alkaline properties. The main elements were C and Si, followed by Ca, Al, P, and K. These materials showed high potential as soil amendments, improving plant nutrient availability, and alleviating soil acidity. The results of the NPK release indicated that these by-products released high amounts of K and P, whereas N was released in a very small concentration. The raw filter cake released the highest levels of water-soluble N and P, followed by the filter cake biochar and sugarcane bagasse ash. Conversely, the sugarcane bagasse ash released the highest amount of water-soluble K. Notably, the release kinetics profiles of NPK had a more rapid initial nutrient release from the raw filter cake than its biochar form. The best descriptions of the release kinetics for all three materials were the Elovich and power function equations, indicating that nutrient release was governed by multiple chemical processes, particularly heterogeneous and homogeneous diffusion. Typically, nutrient release commences at a high rate and tapers off over time, with the nutrient release magnitudes governed by the inherent concentrations of each nutrient in the material. Overall, this study underscored the dual role of filter cake, filter cake biochar, and sugarcane bagasse ash as fast- and slow-release sources of P and K fertilizers, supporting green and sustainable agricultural production. We recommend that farmers incorporate these by-products into soil management, particularly in areas with soil acidity and nutrient deficiencies. Policy-makers should promote their use and provide support to encourage farmers in adopting these sustainable practices. Future research should focus on field trials to validate laboratory findings and long-term studies on nutrient release and soil health to assess the sustainability and effectiveness of these materials.

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Authors Contribution

All authors were involved in the conceptualization and study design. Laboratory analysis and data curation were carried out by S. Saributt, A. Sombatcharoennon, W. Peungyam, K. Poomsong, R. Jaroenchasri, and D. Ketrot. Data analysis and result interpretation were performed by D. Ketrot and W. Wisawapipat. Writing—original draft, review, and editing were carried out by D. Ketrot and W. Wisawapipat. Project administration and funding acquisition were handled by D. Ketrot All authors contributed to the final approval of the publication.

Availability of data and materials:

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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