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Ecological Implications of Calcium Adsorption–Desorption on Maize-Derived Biochar for Sustainable Soil Nutrient Retention

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Abstract
Biochar has emerged as a sustainable material for improving soil quality and nutrient cycling in agroecosystems. This study investigated the adsorption–desorption behaviour of calcium ions (Ca^{2+}) on maize-derived biochar produced at 400 °C and evaluated its potential role in enhancing soil nutrient retention. The adsorption characteristics were analyzed using Langmuir and Freundlich isotherm models, while adsorption kinetics were assessed using pseudo-first-order and pseudo-second-order models. The Freundlich model provided the best fit to the experimental data, indicating multilayer adsorption on a heterogeneous biochar surface. Kinetic analysis revealed that the pseudo-second-order model most accurately described the adsorption process, suggesting that chemisorption was involved during the initial sorption stage. The adsorption performance was strongly influenced by the physicochemical properties of the biochar, including porous structure, elevated cation exchange capacity, and the presence of oxygen-containing functional groups such as hydroxyl and carboxyl groups. These properties promoted Ca^{2+} retention through electrostatic attraction, ion exchange, and surface complexation mechanisms. Desorption analysis showed a hysteresis index (HI) close to unity, indicating a moderately reversible sorption–desorption process that enabled both nutrient retention and gradual nutrient release. This balanced interaction between adsorption and desorption is beneficial for sustaining nutrient availability while reducing nutrient leaching losses in soil systems. The findings highlight the ecological significance of maize-derived biochar as a sustainable soil amendment for improving nutrient cycling, enhancing soil fertility, and supporting resilient agroecosystem management.

Keyword: Biochar, Nutrient cycling, Nutrient retention, Soil ecology, Soil amendment, Agroecosystem, Hysteresis index

1. Introduction
Soil degradation and nutrient depletion are major ecological concerns that threaten agricultural productivity, food security, and ecosystem sustainability worldwide [1]. Intensive agricultural practices frequently accelerate nutrient loss, reduce soil organic matter, and disrupt natural nutrient cycling processes, thereby impairing long-term soil ecosystem functioning. Thailand, as an agricultural country where a substantial proportion of the population depends on farming activities, is particularly vulnerable to these challenges. Agricultural land accounts for approximately 54.36% of the total land area, reflecting its critical role in national economic development and food security [2]. However, agricultural productivity in Thailand has declined over the past decade, especially in maize cultivation. Between 2017 and 2020, the average maize yield was approximately 740 kg per rai, followed by a 2.20% decrease in 2021 [2]. This decline has been largely associated with soil degradation resulting from unsustainable land-use practices [3]. Such practices negatively affect soil quality by decreasing soil organic matter, disrupting microbial activity, and deteriorating soil structure, ultimately limiting root development and crop productivity [4]. Furthermore, the accumulation of contaminants such as pesticides in soil and water systems further intensifies environmental and agricultural problems [5]. Therefore, sustainable soil amendments capable of enhancing nutrient retention and regulating nutrient availability are increasingly important for maintaining resilient agroecosystems and minimizing

environmental impacts associated with excessive fertilizer application.

To mitigate soil degradation and improve soil quality, the application of sustainable soil amendments has received increasing attention in recent years. Among these materials, biochar has emerged as a promising and environmentally sustainable soil amendment due to its multifunctional properties and potential to enhance soil ecosystem functioning. Biochar is a carbon-rich material produced from biomass through pyrolysis under oxygen-limited conditions [6]. It is characterized by a porous structure, high surface area, and abundant oxygen-containing functional groups, which contribute to improved soil physicochemical properties and nutrient retention capacity [7-8]. These properties facilitate interactions between biochar surfaces and nutrient ions, thereby influencing nutrient mobility, bioavailability, and nutrient cycling processes within soil ecosystems. Functional groups such as hydroxyl (–OH) and carboxyl (–COOH) are particularly important because they promote electrostatic attraction and surface complexation with ionic species [9]. In addition, the porous structure of biochar improves soil water retention and reduces nutrient leaching losses, thereby enhancing soil fertility and environmental sustainability [7-8]. Previous studies have also demonstrated that biochar application can improve crop productivity, reduce nutrient losses in degraded soils, and lower the risk of plant toxicity, highlighting its ecological importance for sustainable agricultural systems [7,10]. Consequently, biochar application may contribute to improved soil fertility and ecological resilience in agricultural systems. Despite these advantages, the specific role of biochar surface properties in regulating calcium adsorption behaviour and nutrient retention dynamics remains insufficiently explored.

In agricultural systems, calcium (Ca^{2+}) is an essential nutrient that contributes to plant structural integrity, stress resistance, and overall crop productivity [11]. Improving calcium retention in soil is therefore particularly important under conditions of soil degradation and climate variability. Although numerous studies have investigated the adsorption behaviour of biochar toward contaminants and nutrients, limited information is available regarding the adsorption–desorption dynamics of calcium ions on maize-derived biochar and their ecological implications for nutrient cycling in agroecosystems. Most previous studies have primarily focused on heavy metal adsorption or general nutrient retention, whereas the molecular mechanisms governing calcium adsorption and desorption on biochar surfaces remain insufficiently understood. In particular, the relationship between adsorption–desorption behaviour and biochar surface chemistry for Ca^{2+} ions have not been comprehensively clarified. Understanding both nutrient retention and release mechanisms is essential because excessively strong adsorption may reduce nutrient bioavailability, whereas insufficient retention may increase nutrient loss through leaching. Therefore, this study aimed to investigate the adsorption–desorption behaviour of Ca^{2+} ions on maize-derived biochar and evaluate its ecological significance for soil nutrient retention, nutrient cycling, and sustainable agroecosystem management.

2. Materials and Methods

Maize residues were selected as biochar feedstock because maize cultivation generates substantial agricultural biomass residues worldwide, particularly in intensively cultivated agroecosystems. Converting maize residues into biochar might support circular biomass utilization while reducing agricultural waste accumulation. Calcium was selected as the target nutrient because it plays a critical role in soil fertility, plant physiological processes, and soil ecosystem stability.

2.1 Maize residue preparation

The maize residue used for biochar production was collected from local farmers in the Jedee Maekrua community, Mae Faek Mai, San Sai, Chiang Mai, Thailand. The collected maize residues were sun-dried for 7 days to remove moisture. After drying, the residues were mechanically ground at a rotational speed of 14,000 round per minute (RPM) for 3 minutes (IKA A11 basic, Germany). The ground material was then sieved through a 60-mesh screen to obtain fine maize residue powder. This powder was stored in a desiccator to prevent moisture absorption before further use.

2.2 Conversion of maize residue into Biochar

The maize residue powder, previously sieved through a 60-mesh screen, was converted into biochar by using pyrolysis process. The pyrolysis process was conducted under oxygen-limited conditions at a temperature of 400 °C for a duration of 3 hours with a heating rate of 10 °C per minute (Carbolite Gero CWF 13/13, England). This process yielded fine black biochar powder. The fine black biochar powder was subsequently sieved again using a 60-mesh screen to ensure uniform particle size. The biochar powder was then stored in a desiccator to prevent moisture absorption prior to use.

2.3 Chemical composition and physical property analysis of biochar

The chemical composition analysis of biochar was performed to identify and confirm the presence of functional groups on the biochar surface, such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O) groups, ether (–O–) and aromatic structure. This was carried out using a fourier transform infrared spectrometer (FTIR) with ATR mode (Bruker, Alpha II model, Switzerland) over a wavenumber range of 400–4000 cm-1. The chemical properties of the biochar were further assessed by measuring pH using a pH meter (Mettler-Toledo AG) and cation exchange capacity (CEC) following the method described by Intanoo and Kongklay [12]. For physical characterization, the specific surface area, pore size, and pore volume of the biochar were analyzed using a surface area and porosity analyzer based on the Brunauer–Emmett–Teller (BET) method (Quantachrome/Autosorb 1 MP).

2.4 The adsorption and nutrient release dynamics of calcium ions on the surface of biochar

The adsorption behaviour of calcium ions on the biochar surface was studied based on adsorption equilibrium theories using the Langmuir model (Eq. (1)–(2)) [13] and the Freundlich model (Eq. (3)–(4)) [14]. Both models describe the relationship between the amount of adsorbate (calcium ions) adsorbed per unit mass of adsorbent (biochar) in mg/g, and the equilibrium concentration of calcium ions remaining in the solution at a given temperature in mg/L. The adsorption and the release behaviours were investigated in two stages: (1) the determination of equilibrium sorption time, and (2) the analysis of calcium ion adsorption behaviour.

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} \qquad (1)$$

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (2)$$

$$q_e = K_F C^{\frac{1}{n}} \quad (3)$$

$$log\, q_e = log\, K_F + \frac{1}{n} log\, C_e \quad (4)$$

$$HI = \frac{1/n_{desorbed}}{1/n_{adsorped}} \quad (5)$$

Where:
q_e is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (g/g).
C_e is the equilibrium concentration of the adsorbate remaining in the solution at a given temperature (g/mL).
q_m is the maximum adsorption capacity for monolayer coverage per unit mass of adsorbent (g/g).
K_L is the Langmuir constant related to the affinity of binding sites (L/mg).
K_F is the Freundlich constant indicating the multilayer adsorption capacity (g/g).

2.4.1 Equilibrium sorption time determination
The determination of equilibrium sorption time of calcium ions onto the biochar surface was carried out by adding 30 mL of a calcium standard solution at a certain concentration to 1 gram of biochar. The mixture was then shaken at the speed of 100 round per minute (rpm) for various durations time: 4, 10, 15, 30, 60, 120, 240, 360, 480, and 900 minutes, respectively. After each specified shaking time, the samples were collected, and the solution was separated by filtration through a 0.45-micron nylon membrane filter. The amount of calcium ion adsorbed was subsequently determined using an atomic absorption spectrophotometer (GBC Scientific Equipment/SavantAA).

2.4.2 Calcium ion adsorption behavior
The study of calcium ion adsorption behavior on the biochar surface was conducted by introducing 30 mL of calcium standard solutions with the concentrations of 50, 60, 70, 80, and 90 mg/L into 1 gram of biochar. The mixtures were agitated using a shaker at a speed of 100 rpm for a duration corresponding to the previously determined equilibrium sorption time. After shaking, the solution was collected and filtered through a 0.45-micron nylon membrane filter. The amount of calcium adsorbed was then also analyzed by using an atomic absorption spectrophotometer (GBC Scientific Equipment/SavantAA).

2.5 The release of calcium ion from biochar surface
The release behaviour of calcium ions (Ca^{2+}) from biochar surface was investigated using the hysteresis index (HI) as an indicator to assess the ease or difficulty of calcium ion desorption after adsorption onto biochar [15]. The hysteresis index is calculated as the ratio of the slope of the adsorption curve to that of the desorption curve at the same equilibrium concentration, as shown in Eq. (5). In this study, the calcium-loaded biochar (obtained from the adsorption procedure described in section 2.4.2) was immersed in 30 mL of deionized water and agitated at 100 rpm using a shaker at the equilibrium sorption time. The aqueous solution was then collected and filtered through a 0.45-micron nylon membrane filter. The concentration of desorbed calcium ions was analyzed using an atomic absorption spectrophotometer (GBC Scientific Equipment/SavantAA).

3. Results and Discussion
3.1 Properties of biochar
3.1.1 Chemical and physical properties
The resulting biochar, when combined with soil at a ratio of 1:2 (biochar:soil), exhibited a cation exchange capacity (CEC) of 3,037.93 cmol/kg and a pH of 8.11, representing increases of 5.96- and 1.42-fold compared to untreated soil, respectively. These properties indicated that biochar was highly suitable as a soil amendment, particularly for mitigating soil acidity and enhancing nutrient retention. This was primarily due to its alkaline nature and high cation exchange capacity (CEC), along with the abundance of oxygen-containing functional groups, which promote proton neutralization, electrostatic interactions, and surface complexation mechanisms. These findings were consistent with previous work [12], who reported that the application of biochar at a 1:1 ratio significantly increased soil CEC by 10.33% compared to untreated soil. The enhanced CEC improved nutrient retention and availability, leading to substantial in-creases in crop yield, with kale and eggplant production rising by 43.49% and 35.25%, respectively. In addition, chlorophyll content increased by more than 50% relative to the control, indicating improved plant physiological performance. For the physical property of produces biochar, it demonstrated notable porosity, with a specific surface area of 22.51 m^2/g and a pore volume of 0.04 cm^3/g.

3.1.2 FTIR Spectra
Figure 1 presents the FTIR analysis of produced maize derived biochar. It was found that produced biochar revealed the presence of several key functional groups on its surface. These included hydroxyl groups (O–H stretching at 3,700-2,700 cm-1), carboxylic acid-carboxylate ion (C=O stretching at 1,700–1,566 cm^{-1}), and ether groups (C–O stretching at 1,163–1,075 cm^{-1}) (Bruker, Alpha II model, Switzerland). Additionally, aldehyde aromatic and ketone aromatic structures (C=C, C=O stretching at 1,795-1674 cm^{-1}) and amine tertiary aromatic (C=C, C–N stretching at 1,390-1,250 cm^{-1}) were also detected (Bruker, Alpha II model, Switzerland). The dominant oxygen-containing functional groups mostly found on biochar surface [16-17]. They were attributed to partial oxidation reactions during the pyrolysis of maize residue under low-temperature (400°C) and oxygen-limited conditions. Under such conditions, biochar retained some hydrogen (H) and oxygen (O) element, leading to the development of new surface functional groups. Whereas high temperature (more than 500°C), both H and O were lost causing low chemical reactivity. The preservation of oxygen-containing functional groups at relatively low pyrolysis temperatures may enhance nutrient interactions within soil environments and improve nutrient retention capacity in agroecosystems. These functional groups are particularly important for regulating nutrient exchange processes and maintaining nutrient availability in biologically active soils. For the porosity of biochar, it originated from the thermal decomposition of organic structures as cellulose and hemicellulose, which generates volatile compounds such as CO, CO_2, CH_4, H_2, and water vapor under oxygen-limited conditions. When volatiles compound released, they left behind the cavities within the carbon matrix, by which creating the porous structure. These

features collectively enhanced the functionality of biochar in improving soil structure, water holding capacity, and nutrient-retaining capacity.

The presence of various functional groups on the biochar surface had attracted significant attention due to their role in enhancing the soil's cation exchange capacity (CEC). These surface functional groups, such as carboxylic (–COOH), hydroxyl (–OH), and carbonyl (C=O), can dissociate to form negatively charged sites (e.g., R–COOH → R–COO⁻), thereby enabling the adsorption of nutrient cations from soil solution. Therefore, incorporating biochar into agricultural soils may enhance nutrient retention by reducing leaching losses, as the negatively charged sites on the biochar surface bind positively charged nutrient ions. Furthermore, elevated CEC contributed to improve fertilizer use efficiency, enriches soil fertility, and ultimately increases crop productivity [15].

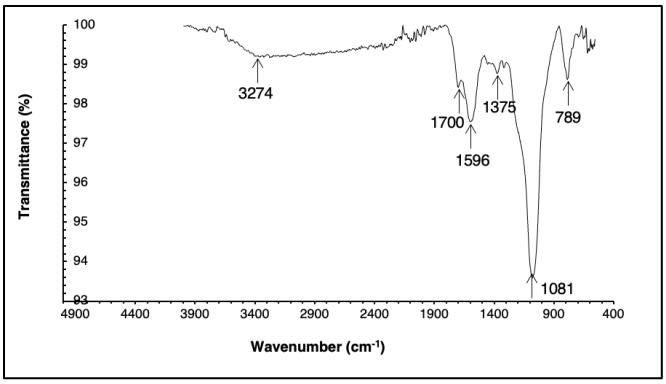

Fig 1: FTIR spectra of biochar produced from maize residue at 400 °C for 3 hours.

3.2 Calcium ion adsorption behavior on the surface of biochar

Several experimental procedures were conducted focusing on equilibrium time, ad-sorption capacity, and kinetic parameters to comprehensively evaluate the adsorption behavior of calcium ions on the biochar surface. Isotherm analysis elucidated the nutrient interaction mechanism and surface characteristics, whereas estimating equilibrium sorption time was essential for identifying the point at which adsorption reaches a steady state. Moreover, kinetic modeling elucidated the characteristics of the adsorption process and the rate-limiting mechanisms. Therefore, as discussed in the subsequent sections, equilibrium sorption time measurement, adsorption isotherm analysis, and kinetic modeling were employed to systematically investigate the adsorption behavior of calcium ions.

3.2.1 Equilibrium sorption time determination

A correlation between the amount of calcium ions adsorbed per unit mass of biochar at a given time (q_t) and adsorption time was established to determine the equilibrium sorption time, as shown in Figure 2. The results indicated that calcium adsorption in-creased rapidly with time and gradually approached a plateau after approximately 240 minutes, suggesting that further adsorption beyond this point did not significantly enhance calcium uptake. This behavior implied that the available adsorption sites became saturated, leading to the establishment of a dynamic equilibrium in which adsorption and desorption processes occurred simultaneously. Partial desorption of previously adsorbed ions created newly available sites for subsequent adsorption. This observation was consistent with the desorption analysis, where the hysteresis index (HI) was 1.1471 (>1.00), indicating partial hysteresis of Ca^{2+} ions. Such hysteresis reflected the presence of high-energy binding sites and strong interactions, including surface complexation and ion exchange, which limited desorption reversibility. Overall, these findings confirmed that equilibrium was effectively reached after approximately 240 minutes.

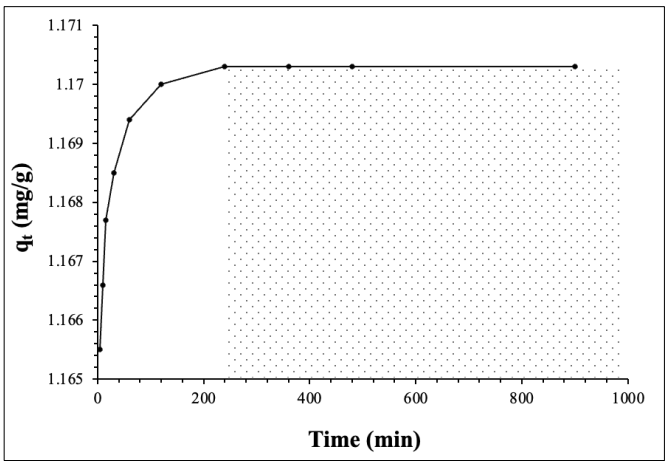

Fig 2: The adsorption of calcium ions on biochar surface at different contact times at room temperature.

3.2.2 Analysis of calcium ion adsorption behaviour

The adsorption behaviour of calcium ions on the biochar surface was examined using adsorption equilibrium theories based on the Langmuir and Freundlich models. According to the Langmuir model, when the linearized relationship in Eq. (2) was applied, a linear trend was observed, as illustrated in Figure 3(a). The constants q_m and K_L were derived from this linear relationship, as shown in Table 1. The q_m indicated the theoretical maximal monolayer nutrient retention potential of calcium ions on biochar. Both q_m and K_L were determined to be negative, signifying that the calcium ion adsorption be-havior on the biochar surface did not conform to the Langmuir model [18], suggesting that monolayer adsorption on a homogeneous surface was not applicable in this system. Furthermore, the correlation coefficient (R^2) for the Langmuir model was 0.85, which is inferior to the value derived from the Freundlich model (R^2 = 0.98), as illustrated in Eq. (4) and Figure 3(b) [19].

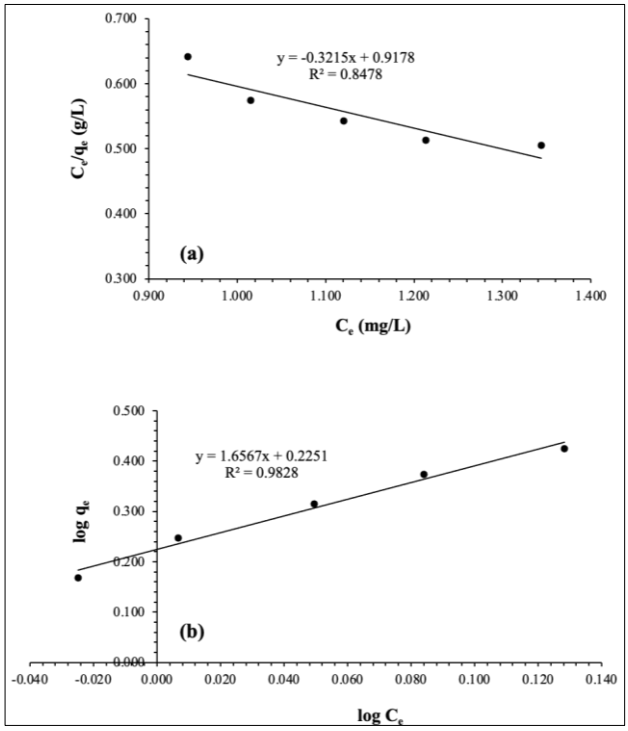

Fig 3: (a) Langmuir and (b) Freundlich isotherm model for Ca^{2+} adsorption on biochar.

The results indicated that the adsorption of calcium ions onto the biochar surface is better described by the Freundlich isotherm model, suggesting multilayer adsorption on a heterogeneous surface [20]. This behaviour can be attributed to the pyrolysis conditions used for biochar production, particularly the relatively low temperature of 400 °C under oxygen-limited conditions [21]. Such conditions favoured the preservation of oxy-gen-containing functional groups rather than the formation of highly condensed aromatic structures [22]. These functional groups, including hydroxyl (–OH) and carboxyl (–COOH), provided diverse adsorption sites with varying binding affinities for Ca^{2+} ions, thereby contributing to surface heterogeneity. In addition to surface chemistry, the porous structure of biochar played a critical role in adsorption performance. Previous studies had demonstrated that pore networks facilitated ion diffusion and retention within internal structures, while functional groups enhanced adsorption through electrostatic attraction and surface complexation. The present findings were consistent with these observations, indicating that the synergistic effects of surface heterogeneity and porosity governed the multilayer adsorption behaviour. Furthermore, the high cation exchange capacity (CEC) of biochar promoted ion exchange processes, enhancing Ca^{2+} retention and regulating nutrient exchange within soil systems. The multilayer adsorption behaviour observed from the Freundlich model suggested that maize-derived biochar could function as a dynamic nutrient reservoir within soil systems. Such adsorption behaviour might contribute to more stable nutrient cycling processes by reducing rapid nutrient loss while maintaining nutrient accessibility for plant uptake.

Table 1: Parameters describing adsorption behaviour based on the Langmuir and Freundlich isotherm models.

Langmuir adsorption isotherm			Freundlich adsorption isotherm		
q_m (mg/g)	K_L (L/mg)	R^2	K_F (L/g)	$1/n$	R^2
-3.1104	-0.3503	0.8478	1.6792	1.6567	0.9828

Based on these characteristics, the nutrient interaction mechanism could be described as a combination of chemisorption and physisorption. Initially, Ca^{2+} ions were strongly adsorbed onto the biochar surface via chemisorption involving functional groups. Subsequently, additional adsorption layers were formed through weaker adsorbate–adsorbate interactions, including van der waals forces and dipole–dipole interactions, which were classified as physisorption [23]. This dual mechanism explained the multilayer adsorption behaviour observed in this study. The Freundlich constants further supported this interpretation. The value of $1/n_{adsorped}$ obtained in this study (1.6567) suggested cooperative adsorption behaviour, indicating that adsorption became more favourable as surface coverage increased. This might be associated with adsorbate–adsorbate interactions that promoted multilayer formation, consistent with the proposed nutrient interaction mechanism. However, rapid surface saturation might limit the availability of high-energy binding sites, reducing nutrient retention efficiency at later stages. Nevertheless, increasing Ca^{2+} concentration in solution can sustain adsorption through continued multilayer formation.

3.2.3 Adsorption kinetics

The kinetics of calcium ion adsorption on the biochar surface were examined to explain the fundamental nutrient interaction mechanisms. The adsorption rate might be influenced by either the diffusion of calcium ions to the biochar surface, as described by the pseudo-first-order kinetic model (Eq. (6)), or by chemisorption, which involved the establishment of chemical bonds between calcium ions and surface functional groups, as illustrated by the pseudo-second-order kinetic model (Eq. (7)). Comparing these models enabled the identification of the dominant rate-controlling step governing calcium adsorption on the biochar surface.

$$log(q_e - q_t) = log\, q_e - \frac{k_1}{2.303} t \quad (6)$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (7)$$

Where:
k_1 is the rate constant of the pseudo-first-order kinetic model (min^{-1}).
q_t is the amount of adsorbate adsorbed per unit mass of adsorbent at time t (mg/g).
q_e is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g).
t is the adsorption time (minutes).

In this study, linearized plots of both pseudo-first-order and pseudo-second-order kinetic models were constructed, yielding different correlation coefficients (R^2), as presented in Figure 4 and Table 2. The pseudo-second-order model exhibited a higher correlation coefficient (R^2~1.00) compared to the pseudo-first-order model, indicating that the adsorption process was better described by pseudo-second-order kinetics. Furthermore, the rate constant (k_2) of the pseudo-second-order model was significantly greater than that of the pseudo-first-order model (k_1), suggesting a more efficient adsorption process. The calculated equilibrium nutrient retention potential ($q_{e_{cal}}$) from the pseudo-second-order model closely agreed with the experimental value ($q_{e_{exp}}$= 1.170 mg g^{-1}), further supporting the validity of this model.

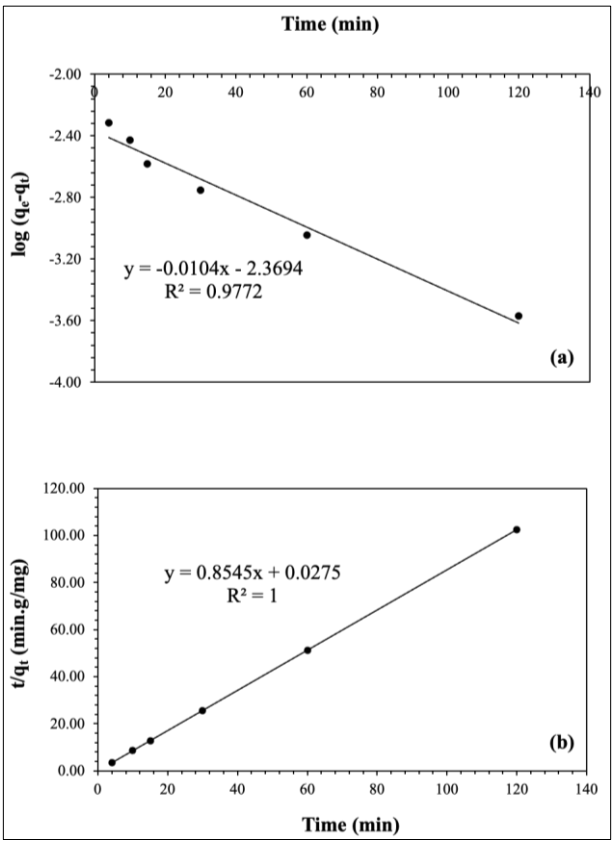

Fig 4: (a) Pseudo-first-order and (b) pseudo-second-order kinetic model for Ca^{2+} adsorption.

These findings indicated that chemisorption was the dominant mechanism controlling the initial adsorption stage, involving ion exchange and the formation of chemical bonds between negatively charged functional groups and Ca^{2+} ions. This was consistent with the previously discussed role of oxygen-containing functional groups, such as hydroxyl and carboxyl groups, in providing active binding sites. Moreover, when considered together with the Freundlich isotherm results, the kinetic behaviour confirmed that calcium adsorption on the biochar surface occurred through a combination of chemisorption and subsequent physisorption, supporting the proposed multilayer nutrient interaction mechanism. This integrated interpretation highlighted the synergistic role of surface chemistry and adsorption dynamics in controlling calcium retention on biochar under the studied conditions. The coexistence of chemisorption and physisorption mechanisms might be ecologically beneficial because it enabled both nutrient stabilization and gradual nutrient release. This balanced sorption behaviour might help maintain nutrient availability during plant growth while reducing nutrient fluctuations within agricultural ecosystems.

Table 2: Kinetic constants for calcium ion adsorption on biochar based on pseudo-first-order and pseudo-second-order models.

$q_{e_{exp}}$[1] (mg g^{-1})	pseudo-first order reaction rate			pseudo-second order reaction rate		
	$q_{e_{cal}}$[2] (mg g^{-1})	k_1 (min^{-1})	R^2	$q_{e_{cal}}$[2] (mg g^{-1})	k_2 (g mg^{-1} min^{-1})	R^2
1.170	0.00427	0.0239	0.9772	1.170	26.56	1.00

[1] Calcium nutrient retention potential at equilibrium obtained from the experiment.
[2] Calcium nutrient retention potential at equilibrium obtained from the calculation.

3.3 Calcium ion desorption from biochar surface

The desorption behaviour of calcium ions (Ca^{2+}) from the biochar surface was evaluated using the hysteresis index (HI), which provided insight into the reversibility of the adsorption–desorption process. An HI value lower than 0.60 indicated weak retention, suggesting that adsorbed nutrients could be readily released and might be susceptible to leaching losses under environmental conditions such as rainfall, thereby reducing nutrient availability for plant uptake [24]. In contrast, an HI value greater than 2.00 reflected excessively strong retention, implying limited desorption and reduced nutrient bioavailability to plants. In this study, the HI value was 1.1471, approximately 1.00, indicated a slight but discernible hysteresis effect, suggesting that the adsorption and desorption processes were not entirely reversible. However, as the HI value was close to unity, the sorption–desorption behaviour could be considered largely reversible with moderate retention strength. This reflected a balanced interaction between Ca^{2+} ions and the biochar surface, involving both strong binding mechanisms, such as surface complexation and ion exchange, and weaker interactions associated with physisorption. Consequently, Ca^{2+} ions were sufficiently retained while remaining available for gradual release. The hysteresis index (HI) close to unity indicated a moderately reversible sorption–desorption process, reflecting a balanced interaction between nutrient retention and nutrient release. Such behaviour was advantageous in agricultural ecosystems because nutrients can be retained sufficiently to reduce leaching losses while remaining available for gradual plant uptake. By moderating nutrient mobility, biochar application might also reduce nutrient transport to surrounding environments, thereby mitigating potential ecological impacts associated with nutrient runoff and soil degradation. This controlled nutrient release mechanism might contribute to improved nutrient use efficiency and more sustainable nutrient management practices. The observed sorption–desorption behaviour was consistent with the previously discussed nutrient interaction mechanisms, in which chemisorption contributed to strong

binding, whereas physisorption facilitated partial desorption and gradual nutrient release.

Surface modification of biochar could be considered to enhance calcium availability. For example, increasing the pH of biochar through treatment with alkaline solutions such as sodium hydroxide (NaOH) or calcium hydroxide ($Ca(OH)_2$) could promote the dissociation of surface functional groups, thereby increasing the density of negative charges and facilitating the release of positively charged Ca^{2+} ions [25]. In addition to chemical modification, environmental factors such as increased soil moisture could enhance ion diffusion and exchange processes, as water acted as a medium that improved ion mobility and promoted nutrient desorption [7]. Furthermore, the incorporation of organic materials, particularly organic fertilizers, could improve soil structure and stimulate adsorption–desorption dynamics, thereby enhancing nutrient availability and supporting plant growth. In agroecosystem applications of biochar, it is essential to evaluate both nutrient retention capacity and the ability to release nutrients in accordance with plant demand. Nutrients should not be excessively retained on the biochar surface to the extent that they become unavailable for plant uptake. An optimal hysteresis index (HI) range for agricultural use was typically between 1.00 and 1.50, which reflected a balanced adsorption–desorption behaviour. This range supported sustained nutrient availability by enabling both effective retention and gradual release of nutrients in soil.

This study demonstrated that the HI value of 1.1471 falls within the optimal range, indicating the potential of maize-derived biochar to function as a nutrient reservoir within soil systems. The observed sorption–desorption behaviour suggested that nutrients can be retained on the biochar surface while remaining available for gradual release in response to plant demand. Such controlled nutrient release might contribute to improved nutrient use efficiency and reduced nutrient losses through leaching. Consequently, these properties highlighted the ecological potential of biochar for supporting sustainable nutrient management and enhancing nutrient cycling in agricultural ecosystems.

4. Conclusions

This study demonstrated that maize-derived biochar produced at 400 °C possesses favourable physicochemical properties for Ca^{2+} adsorption and controlled nutrient release. The adsorption behaviour was best described by the Freundlich isotherm model, indicating multilayer adsorption on a heterogeneous surface, while kinetic analysis suggested the involvement of chemisorption during the initial sorption stage. The presence of oxygen-containing functional groups, porous structure, and elevated cation exchange capacity contributed to enhanced nutrient retention through electrostatic attraction, ion exchange, and surface complexation mechanisms. Desorption analysis further revealed a hysteresis index close to unity, indicating a moderately reversible sorption–desorption process that supported both nutrient retention and gradual nutrient release. This balanced interaction was ecologically important because it might enhance nutrient cycling efficiency, reduce nutrient leaching losses, and maintain nutrient availability within agricultural soils. Overall, the findings highlighted the ecological potential of maize-derived biochar as a sustainable soil amendment for improving soil fertility, supporting resilient agroecosystems, and promoting environmentally sustainable nutrient management strategies.

5. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.5281/zenodo.20051193.

6. Acknowledgements

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