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Lasting effects of the co-application of rice husk biochar with cattle manure and compost on soil and corn

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Abstract

The study investigated the effects of the uses of cattle manure, compost, and rice husk biochar (RHB) as un-combined and co-applications, emphasizing their lasting effects over multiple cropping cycles of plant bioassay. This approach holds promise for enhancing agronomic efficiency and cost-effectiveness and decreasing reliance on synthetic fertilizers. The experiment employed a factorial arrangement with two factors: organic amendment types (none, cattle manure, compost) and the application rates of RHB (0%, 2%, 4% w w^{-1}). Corn was used as the plant indicator over three bioassay cycles in a tropical sandy soil, with a one-time organic amendment before the first cycle. Corn biomass, plant nutrient content, soil-plant nutrient interactions, and their interrelationships via the principal component analysis were determined. Each un-combined organic amendment, whether RHB, cattle manure, or compost, could enhance soil fertility and corn growth from the first cropping cycle and sustain these improvements into the second and third cycles. However, certain co-applications of the amendments in the first cropping cycle, specifically cattle manure with 4%RHB and compost with 2% and 4%RHB, initially hindered corn growth due to K antagonistic to Ca and Mg. These adverse effects were mitigated over time, leading to positive outcomes in the second and third cycles. The study conclusively demonstrated that integrating cattle manure and compost with RHB could enhance soil fertility and plant growth sustainably, offering an alternative to synthetic fertilizers.

1. Introduction

Organic fertilizers offer a solution to the high crop production costs driven by the current price crisis of synthetic fertilizers. The global shift towards chemical-free farming is supported by both governments and NGOs, with a strong movement towards eliminating chemicals in agriculture (Jiang et al., 2022). Although synthetic fertilizers can rapidly increase plant growth and yield, they are discouraged due to their detrimental impacts on soil health and the environment (Pahalvi et al., 2021).

Global entities have increasingly recognized biochar as a soil amendment, as supported by the Intergovernmental Panel on Climate Change's (IPCC, 2019) recommendation for soil enhancement and climate change mitigation. Research and practice have highlighted biochar's role in enhancing soil fertility, decreasing greenhouse gases, and increasing soil carbon (C) sequestration (Pradhan et al., 2024). The use of rice husk, a widely available agricultural byproduct in Asian nations where rice is a dietary staple and a significant export (Thambhitaks and Kitchaicharoen, 2021), for biochar production aligns with zero-waste policies and resource recycling efforts (Nehdi et al., 2024).

Biochar's key components, namely fixed C, ash, and volatile matter (Deenik et al., 2011), enhance soil fertility by improving properties such as cation exchange capacity (CEC), which promotes nutrient retention and buffering capacity (Pradhan et al., 2024). Ash contributes to plant nutrients through oxides like P_2O_5, K_2O, MgO, CaO, and SiO_2 (Butnan et al., 2016), while volatile matter is a C source for soil microorganisms (Deenik et al., 2010). Biochar also positively impacts soil physical and biological properties, such as decreasing bulk density, increasing moisture, and enhancing microbial diversity (Pradhan et al., 2024).

The soil improvement potential of biochar is hindered by its inherently low nitrogen (N) content, which necessitates the addition of N-rich organic amendments to prevent plant N deficiency (Deenik et al., 2010). Integration with amendments like cattle manure and compost is recommended due to their high N content (Maharjan and Hergert, 2019), and combining biochar with such amendments accelerates nutrient release, enhancing plant availability (Dodor et al., 2019). Our survey supports the practice that organic farmers in Northeast Thailand often mix biochar with cattle manure and composts. However, careful management of biochar application rate is crucial, as excessive rates can harm crop yields. Studies have shown that high rates (10% and 20% w w^{-1}) of biochars derived from macadamia nut shells (Deenik et al., 2011), various materials at 2% w w^{-1} (Rajkovich et al., 2012), and eucalyptus at 4% w w^{-1} (Butnan et al., 2015) decreased plant growth.

Recent studies indicated that biochar did not immediately impact crop yields, but it has been found to enhance plant productivity in subsequent harvests (Dong et al., 2013; Bian et al., 2014; Zhao et al., 2014; Liu et al., 2016; Wang et al., 2018). This delayed effect of biochar could potentially lead to a loss of confidence among farmers if they do not see immediate benefits. Moreover, the production and application of biochar for crop enhancement are comparatively complex, and the quantities required are substantial. Additionally, farmers without livestock face additional challenges, as they lack access to cattle manure, an essential component in producing compost. Therefore, an effective strategy for employing organic amendments would involve using smaller quantities that can have a lasting influence over multiple cropping cycles.

The lasting impact of the one-time applications of organic amendments on subsequent cropping cycles is a highly efficient utilization of these amendments. It also provides valuable insights for their application and management decision-making processes, which can improve organic farming sustainability and benefit local communities via enterprise-level biochar production. However, the reports on the optimal biochar application rate in co-application with cattle manure or compost are currently limited, with some studies not incorporating plant response or focusing only on a single cropping cycle.

For instance, Dodor et al. (2018, 2019) focused on C mineralization and sequestration at various combined biochar and cattle manure ratios without assessing plant growth. Similarly, Naeem et al. (2018) examined the combined effects of wheat straw biochar, synthetic fertilizer, and compost on soil and corn without subsequent crop evaluation. Nguyen et al. (2018) investigated the interactive effects of rice husk and rice straw biochars with cattle manure on saline soil and rice only in a single cropping cycle. Other studies, such as those by Castro-Herrera et al. (2022), Jia et al. (2022), Gong et al. (2023), and Furuhashi et al. (2024), explored composting with biochar components without plant trials, or only assessed immediate effects on a single cropping cycle as in Holatko et al. (2022).

Several studies examined the effects of different biochar types on soil and plant responses across multiple cropping cycles. Notably, Dong et al. (2013), Bian et al. (2014), and Wang et al. (2018) evaluated an un-combined application of biochar, while Zhao et al. (2014) and Liu et al. (2016) examined the effects of biochar when applied every time a crop was planted. It is important to note, however, that these studies only used biochar alone, and did not examine the combined use of biochar with other organic amendments.

The study of soil fertility involves evaluating soil properties, plant nutrient contents, and plant bioassays. Plant bioassays might focus on early plant responses, such as the 14-day study by Groves and Foster (1985) or the 32-day growth of tree *Ochroma pyramidale* by Dalling et al. (2013). Other studies concentrated on the vegetative growth stage, like those by Deenik et al. (2011) and Hue (2011), or cover the entire life cycle, as in Lopez et al. (2019). The current study used corn for the bioassay, focusing on vegetative growth response while comprehensively evaluating soil and plant nutrient content. Although not a full life cycle study, it could imply soil-plant responses across multiple cropping cycles.

In the current study, therefore, we hypothesized that rice husk biochar, cattle manure, or compost alone would have enhanced soil fertility and corn growth, and their combined use would have further improved these outcomes, with lasting benefits across cropping cycles from just a one-time application. The study aimed to evaluate the effects of these amendments on soil properties and corn growth, mainly when rice husk biochar was used at different rates in conjunction with manure or compost, and to assess the soil and plant response across three cropping cycles of corn bioassay following a one-time application of organic amendments.

2. Materials and methods

2.1. Soil and organic amendments

The soil used was the Korat series (Isohyperthermic Typic Oxyaquic Kandiustults in Soil Taxonomy, or Arenic Acrisol in the World Reference Base for Soil Resources), a coarse-textured soil type commonly used in agriculture across Northeast Thailand (Keerati-Kasikorn, 1984). The collection of soil samples occurred in the Waritchaphum district of Sakon Nakhon province, Thailand, specifically from an upland field crop (17°20’31”N 103°41’57”E). The soil sample was collected from the topsoil layer down to a depth of 15 cm. The soil was then air-dried and homogenized thoroughly before passing through a 2-mm mesh. The initial properties of the soil are presented in Table 1.

Biochar was derived from rice husks obtained from a commercial outlet in Phanna Nikhom district, Sakon Nakhon province. Meanwhile, cattle manure was sourced from bovines grazing in the fields within Mueang Sakon Nakhon district. The compost was obtained from an organic vegetable producer in Phon Na Kaeo district, Sakon Nakhon province. This compost comprised sugarcane bagasse, cattle manure, and rice bran in a 50:15:1 mass ratio. It was moistened with a liquid fertilizer to achieve approximately 60% of water-holding capacity (WHC). A governmental-microbial inoculant known as PD1 was also added to the compost pile, and the compost was allowed to mature over 30 days. The liquid fertilizer used during the composting phase was produced by fermenting vegetable remnants with molasses and a PD2 inoculant over a similar duration. The characteristics of the cattle manure, compost, and rice husk biochar are provided in Table 1.

Table 1
Initial properties of soil, cow manure, compost, and rice husk biochar used in the experiment

Properties	Soil	Cattle manure	Compost	Rice husk biochar
Proximate analysis				
Fixed C (%)	–	–	–	0.7
Volatile matter (%)	–	–	–	3.4
Ash (%)	–	–	–	95.9
Soil particle distribution				
Sand (%)	87.48	–	–	–
Silt (%)	8.77	–	–	–
Clay (%)	3.75	–	–	–
Soil texture	Sand	–	–	–
Bulk density (g cm^{-3})	1.45	0.40	0.43	0.32
Water holding capacity (%w w^{-1})	31.4			
pH (1:10)	4.81	9.02	5.50	7.31
Electrical conductivity (mS cm^{-1})	0.136	17.0	16.9	1.03
CEC (cmol kg^{-1})	1.1	21.0	43.8	8.2
Organic C (g kg^{-1})	3.64	116	56.5	13.6
Total N (g kg^{-1})	0.15	4.84	2.54	0.047
C/N	24.4	23.9	22.2	292.2
NH_4^+-N (mg kg^{-1})	11.0	91.6	13.8	2.5
NO_3^--N (mg kg^{-1})	0.3	88.3	17.1	34.9
P (mg kg^{-1})	7.2	1317	3697	725
K (mg kg^{-1})	14.3	17365	3506	1062
Ca (mg kg^{-1})	100	3015	6478	346
Mg (mg kg^{-1})	11.7	3092	1916	436
Na (mg kg^{-1})	5.77	1070	299	178
Al (mg kg^{-1})	7.65	nd	nd	nd
Exchangeable acidity (me 100 g^{-1})	0.60	nd	nd	nd

nd = not detectable

2.2. Experimental design, management, and soil-plant collection

A bioassay pot experiment was conducted in an uncontrolled greenhouse environment, with an ambient air temperature averaging 34°C. The investigation occurred from November 2023 to February 2024 at the research and instructional facilities associated with the Faculty of Agricultural Technology at Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand. The experiment was structured into three replicates using a 3 × 3 factorial arrangement within a randomized complete block design. The study included two factors: (i) types of organic amendment, i.e., none, cattle manure, and compost; (ii) application rates of rice husk biochar, i.e., 0%, 2%, and 4% w w^{-1}. The experimental matrix comprised nine treatment combinations. The experiment involved consecutively growing the indicator plant, *viz* corn, across three cropping cycles of corn bioassay. Each cycle spanned 36 days, and the amendments–rice husk biochar, cattle manure, and compost, either alone or in combinations–were incorporated into the soil only once before the first crop cycle.

Two kilograms of air-dry soil were placed in a conical frustum-shaped pot (14.5 cm *h*, 8.5 cm *r*, 1,550 cm^3 *v*). The initial moisture contents of rice husk biochar, cattle manure, and compost were 11.9%, 104%, and 66%, respectively. The soil was amended with cattle manure or compost at 10 Mg dry weight ha^{-1}, each amounting to 9.2 g dry weight pot^{-1}, equating to 10.3 and 18.8 g moist weight pot^{-1}, respectively. The bulk density of the Korat soil of 1.45 g cm^{-3} was used for these calculations. Treatments included rice husk biochar at 2% and 4% w w^{-1}, corresponding to 40 and 80 g dry weight pot^{-1}, translating to 66.6 and 133.2 g moist weight pot^{-1}, respectively. These components were evenly mixed into the soil only once before the first crop cycle. Pots were watered to 70% of WHC (628 ml pot^{-1}) and maintained for 15 days before seeding corn.

A commercial hybrid sweet corn was used as the indicator plant. Four corn seeds were initially planted in each pot. After 15 days, when the corn had grown two true leaves, thinning was performed to keep only one plant in each pot. On day 36 of each cropping cycle, the shoot and root biomass were harvested by severing the corn stalks at the soil surface level. The soil was left to air-dry, and the corn root biomass was separated using a 1-mm sieve. During each cropping cycle, soil samples weighing approximately 100 g dry weight were collected. The soil was reweighed to ensure that each pot contained the same weight before proceeding with the second and third cropping cycles.

The corn shoots and roots were dried in an oven at 65°C until a constant weight was achieved, after which the dry weight was recorded. Concurrently, after corn shoot harvest, soil bulk density was determined using a modified soil core (25 mm *d* and 50 mm *h*), and fresh soil samples were collected for mineral N (NH_4^+ and NO_3^-) determination. Other soil properties were assessed from the air-dried samples. After the shoot dry weight was collected, the corn shoot material was further processed by grinding and passing through a 1-mm sieve for subsequent laboratory analyses.

The procedures and management of the experiment during the second and third cropping cycles were conducted in the same manner as the first cropping cycle, except that soil amendments were not added in the later two cycles. The temporal intervals between the first and second cropping cycles, as well as between the second and third cropping cycles, were each 14 days.

2.3. Laboratory analysis

The ASTM D7582-15 guidelines (American Standard of Testing Material, 2015) were followed for the proximate analysis of rice husk biochar. Soil particle distribution was analyzed to assess soil texture employing the pipette method. The bulk density of the initial soil and organic amendments was determined using the core method (Pansu and Gautheyrou, 2006). The water-holding capacity of the initial soil was evaluated using the maximum water-holding capacity method (Wilke, 2005). The pH and electrical conductivity of soil and amendments were assessed with a 1:10 soil or amendment: water w/v ratio. Organic C concentrations in soil and organic amendments were determined through wet oxidation (Nelson and Sommers, 1982). Total N in soil and amendments was measured by steam distillation utilizing a micro-Kjeldahl apparatus (Pro–Nitro S 4002851, JP Selecta, Barcelona, Spain), while mineral N was extracted with 2 *M* KCl and quantified using the same method. Available P was extracted with Bray-2 solution and determined at 820 nm (Fixen and Grove, 1990) using a UV–Vis spectrophotometer (Specord 250 Plus, Analytik Jena, Germany). Aluminum and exchangeable acidity were evaluated through 1 *M* KCl extraction, followed by titrimetry, according to Pansu and Gautheyrou (2006). Cations (K, Ca, Mg, and Na) along with CEC were measured by displacing the cations on the exchangeable sites of soil colloids with NH_4^+ using a 1 *M* NH_4OAc solution. The cations present in the extractant were subsequently analyzed using a flame atomic absorption spectrometer (Flame AAS novAA® 350, Analytik Jena, Germany), while NH_4^+ bound to the exchangeable sites was extracted with a 10% acidified NaCl solution and determined through the steam distillation method to facilitate the calculation of CEC. The effective CEC (ECEC) at the time of corn harvest was determined by summing the concentrations of K, Ca, Mg, and Na (Ketterings et al., 2014).

The nutrient composition of corn shoot tissue was extracted with the nitric-perchloric wet digestion method (Miller, 1998). Tissue N content was determined using the steam distillation method (Horneck and Miller, 1998), while P was quantified on a UV–Vis spectrophotometer. Tissue cation contents were achieved via Flame AAS. To calculate the corn plant's nutrient uptake, the nutrient content in the shoot tissue was multiplied by the shoot dry weight.

2.4. Statistical analysis

Three-way analysis of variance was performed based on the factorial arrangement within a randomized complete block design. This analysis evaluated the effects of cattle manure and compost, used in conjunction with varied rates of rice husk biochar, on soil properties and plant growth across three successive cropping cycles. Tukey's Studentized Range Test was used to compare means. Principal component analysis (PCA) was employed to reveal the interrelations among soil properties, corn growth, tissue nutrient contents, and plant nutrient uptakes manifested by applying organic amendments. Significant differences were observed at $p \leq 0.05$.

3. Results and discussion

3.1. An un-combined application of cattle manure, compost, and rice husk biochar provided immediate and long-lasting benefits to soil and plant

The use of either cattle manure or compost alone had a significant effect and interacted significantly with rice husk biochar across all soil properties (Table 2A) as well as all plant biomass and tissue nutrient content parameters (Table 2B).

In general, utilizing un-combined organic amendments of either cattle manure, compost, and rice husk biochar, improve the physicochemical properties of soil (Tables 3 and 4). The use of these un-combined amendments increased nutrient availability, which was noticeable through the nutrient content in corn shoot tissues (Table 5), and in the K/Ca and K/Mg ratios in both soil and shoot tissues (Table 6). By doing so, these amendments led to improved plant growth, as indicated by an increase in the dry weight of shoots, roots, and their total biomass (Table 7). The results implied that the benefits of these organic amendments might have persisted over time, potentially promoting sustained plant growth in subsequent cropping cycles, even without reapplying the amendments.

Incorporating the un-combined uses of the organic amendments, either rice husk biochar (Un+2%RHB, Un+4%RHB), cattle manure (CM+0%RHB), or compost (CP+0%RHB), significantly increased the dry weight of shoots, roots, and overall dry mass as compared to non-amended soil (Un+0%RHB) (Table 7). These organic amendments alone, i.e., rice husk biochar (Un+2%RHB, Un+4%RHB), cattle manure (CM+0%RHB), or compost (CP+0%RHB), improved soil fertility by reducing bulk density, neutralizing soil pH, and decreasing acidity (Table 3A). They also reduced harmful Al concentrations and increased plant nu-

Table 2
Analysis of variance on the effects of cropping cycles (C), types of organic fertilizer (OF), rice husk biochar (RHB), and their interactions on soil properties, corn biomass, and tissue nutrient contents

(A) Soil property

Source of variance †	df	Soil property														
		DB‡	pH	EA	EC	ECEC	OC	TN	NH_4^+-N	NO_3^--N	P	Al	K	Ca	Mg	Na
C	2	***	***	***	***	*	***	***	***	***	***	ns	***	***	***	***
OF	2	***	***	***	***	***	***	***	***	**	***	***	***	***	***	***
RHB	2	***	***	***	***	***	***	**	***	*	***	***	***	***	***	***
C × OF	4	***	***	***	***	***	***	**	***	***	***	***	***	***	ns	*
C × RHB	4	***	***	**	***	ns	***	***	***	ns	***	***	***	*	ns	***
OF × RHB	4	**	***	***	***	***	***	***	***	***	***	***	***	***	***	***
C × OF × RHB	8	***	***	ns	***	***	***	***	***	**	***	***	***	***	*	***

(B) Plant biomass and tissue nutrient content

Source of variance	df	Plant biomass			Tissue nutrient content					
		Shoot	Root	Total	N	P	K	Ca	Mg	Na
C	2	***	***	***	***	ns	***	***	***	***
OF	2	***	***	***	***	***	***	***	***	***
RHB	2	***	***	***	***	***	***	***	***	***
C × OF	4	***	***	***	***	***	ns	***	***	**
C × RHB	4	***	***	***	***	**	***	***	***	***
OF × RHB	4	***	***	***	***	***	***	***	***	***
C × OF × RHB	8	***	***	***	***	ns	***	***	***	**

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$; ns = not significantly different.
† C = cropping cycles; OF = types of organic fertilizer; and RHB = rice husk biochar.
‡ DB = bulk density; EA = exchangeable acidity; EC = electrical conductivity; ECEC = effective cation exchange capacity; OC = organic carbon; and TN = total N.

trient concentrations in soil, i.e., P, K, Ca, and Mg (Table 4A, B). Additionally, there was an increase in P and K contents in corn shoot tissue compared to Un+0%RHB (Table 5).

Cattle manure (CM+0%RHB) and compost (CP+0%RHB) alone decreased soil bulk density only in the first crop (Table 3A), likely due to soil structure disruption during soil preparation for corn planting in the second and third cropping cycles. This involved soil sieving while collecting root samples. Although it was aware that disrupting the soil structure in this manner would interfere with the soil and potentially affect the effects of soil amendments, doing so partly mimicked the traditional practice of land preparation. Moreover, Yu et al. (2020) found that animal manure, including the manure-derived products–*viz* the compost used in the current study, did not change soil bulk density or increase it by decreasing soil pores, throats, and paths, possibly due to the complex structure clogging formed by the interaction of soil organic matter from cattle manure and compost with poorly crystalline Al. This was consistent with the decrease in free Al (expressed as soil Al concentration) in CM+0%RHB and CP+0%RHB compared to Un+0%RHB (Table 4A). As per Adams et al. (2000), the decrease in free Al could be attributed to its transformation into poorly crystalline Al as the soil pH increased. This finding aligned with the current study, where soil pH increased in CM+0%RHB and CP+0%RHB as compared to Un+0%RHB (Table 3A).

In comparison to the soil that did not receive any amendments (Un+0%RHB) (Table 3B), soil total N concentrations decreased in un-combined rice husk biochar (Un+2%RHB and Un+4%RHB) was applied. However, un-combined cattle manure (CM+0%RHB) led to a decrease in the first cycle but an increase in the third cycle. Un-combined compost application (CP+0%RHB) resulted in a decrease in the second cycle and no change in the first and third cycles. This observation could be due to the limited soil volumes in a pot, which restricted plant nutrient uptake, despite cattle manure and compost being N sources with total N concentrations of 4.84 and 2.54 g kg^{-1}, respectively, compared to the 0.15 g kg^{-1} found in unamended soil (Table 1). As a result, N uptake by the corn plants led to a decrease in soil N concentrations in the pot.

This highlighted a major limitation due to the lack of biochar incorporation into the soil for N replenishment. This was evident in the higher N uptake in treatments Un+2%RHB, Un+4%RHB,

Table 3
The physicochemical properties of soil under different application rates of rice husk biochar, either alone or in combination with cattle manure and compost, on the day of corn plant harvest in each successive cropping cycle

(A) Soil bulk density, pH, and exchangeable acidity

Amendment	Bulk density ($g\ cm^{-3}$)			pH (Soil:H_2O =1:1)			Exchangeable acidity (me 100 g^{-1})		
	Crop1 †	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	1.47 a ‡	1.45 ab	1.49 a	4.65 g	4.68 h	4.41 h	0.510 a	0.520 a	0.543 a
Un+2%RHB	1.27 d	1.40 c	1.45 ab	4.96 f	5.08 g	4.85 g	0.423 b	0.410 b	0.437 b
Un+4%RHB	1.17 f	1.39 c	1.43 b	5.22 e	5.24 f	5.08 e	0.363 c	0.357 c	0.400 c
CM+0%RHB	1.39 b	1.47 a	1.49 a	5.23 e	5.22 f	5.00 f	0.360 c	0.360 c	0.430 b
CM+2%RHB	1.25 de	1.38 cd	1.42 b	5.41 d	5.54 e	5.27 d	0.340 d	0.340 cd	0.403 c
CM+4%RHB	1.17 f	1.38 cd	1.37 c	5.66 c	5.80 d	5.40 c	0.297 e	0.313 e	0.373 d
CP+0%RHB	1.34 c	1.47 a	1.46 ab	5.84 b	6.08 c	6.09 b	0.303 e	0.333 de	0.337 e
CP+2%RHB	1.22 e	1.41 bc	1.45 ab	5.91 b	6.19 b	6.24 a	0.293 e	0.287 f	0.337 e
CP+4%RHB	1.17 f	1.35 d	1.37 c	6.09 a	6.27 a	6.27 a	0.270 f	0.283 f	0.323 e
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	***	***	***
CV (%)	1.20	0.90	1.06	0.51	0.45	0.49	2.95	3.35	2.27

(B) Soil electrical conductivity, effective CEC (ECEC), organic C, and total N

Amendment	Electrical conductivity ($mS\ cm^{-1}$)			ECEC ($cmol\ kg^{-1}$)			Organic C ($g\ kg^{-1}$)			Total N ($g\ kg^{-1}$)		
	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	0.145 f	0.162 e	0.200 de	0.75 g	0.87 g	0.88 f	3.26 d	3.33 e	3.28 e	0.179 a	0.193 a	0.159 d
Un+2%RHB	0.153 e	0.164 de	0.199 de	1.06 f	1.18 f	1.09 e	3.93 c	3.67 d	3.36 e	0.123 e	0.137 e	0.175 b-d
Un+4%RHB	0.159 e	0.168 de	0.229 bc	1.36 e	1.45 e	1.28 de	4.16 b	3.8 d	3.78 d	0.131 de	0.171 bc	0.176 b-d
CM+0%RHB	0.171 d	0.172 c-e	0.198 de	1.31 e	1.28 f	1.23 de	4.07 bc	4.04 c	3.75 d	0.158 bc	0.184 ab	0.194 a-c
CM+2%RHB	0.188 c	0.177 b-d	0.213 cd	1.75 d	1.61 d	1.34 d	4.19 b	4.21 b	4.26 ab	0.149 cd	0.153 de	0.187 b-d
CM+4%RHB	0.212 a	0.214 a	0.233 b	1.88 d	1.81 c	2.02 c	4.66 a	4.49 a	4.35 a	0.188 a	0.152 de	0.181 b-d
CP+0%RHB	0.195 bc	0.183 bc	0.190 e	2.04 c	2.18 b	2.09 c	4.04 bc	4.08 bc	4.07 c	0.175 ab	0.158 cd	0.163 cd
CP+2%RHB	0.198 b	0.185 bc	0.232 b	2.18 b	2.39 a	2.7 a	4.14 bc	4.12 bc	4.17 bc	0.160 bc	0.160 cd	0.219 a
CP+4%RHB	0.212 a	0.190 b	0.258 a	2.38 a	2.36 a	2.36 b	4.53 a	4.48 a	4.35 a	0.171 ab	0.171 bc	0.203 ab
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	***	***	***	***	***	***
CV (%)	1.60	2.61	4.78	2.95	3.25	4.24	1.86	1.30	1.48	6.47	5.67	9.65

***$p < 0.001$
† Crop1, Crop2, Crop3 denote corn planting in the first, second, and third cropping cycles.
‡ Means within each column followed by the same letter indicate no statistically significant difference at $p \leq 0.05$ (Tukey's Studentized Range Test)

CM+0%RHB, and CP+0%RHB compared to Un+0%RHB across all cropping cycles, except for CP+0%RHB during the third crop (Appendix Table 1). Additionally, N has a propensity for rapid transformation in soil, potentially altering into various states such as mineral N (NH_4^+-N and NO_3^--N) and gaseous N such as NH_3 under conditions of elevated soil pH, as well as N_2O and N_2 under localized oxygen deficits (Weil and Brady, 2017). Although NH_3 volatilization theoretically exists in alkaline soils and denitrification in anaerobic conditions, NH_3 volatilization can also occur in acidic soils and increases with pH (Rochette et al., 2013). Although studies such as Panday et al. (2020a,b) have demonstrated that a specific type of char reduced NH_3 loss in sandy loamy soil by lowering the soil pH; their investigations were conducted in alkaline soil (pH 7.9), which exhibited a higher pH than the char itself (7.6). Meanwhile, denitrification can occur in field-capacity soils but in specifically oxygen-limited microsites, especially when organic matter accelerates O_2 consumption by aerobic microorganisms, creating conditions favorable for deni-

Table 4
The soil properties pertaining to the concentration of available nutrients following the different application rates of rice husk biochar, either alone or in combination with cattle manure and compost, on the day of corn plant harvest in each successive cropping cycle

(A) Mineral N, P, and Al

Amendment	NH_4^+-N (mg kg^{-1})			NO_3^--N (mg kg^{-1})			P (mg kg^{-1})			Al (mg kg^{-1})		
	Crop1 †	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	1.06 ab ‡	1.05 d	2.29 d	1.00 a	1.26 a-c	0.88 a	6.4 h	10.8 e	6.8 f	5.96 a	5.29 a	5.29 a
Un+2%RHB	0.71 b	1.32 cd	2.49 cd	0.43 c	0.70 c	0.55 a-c	22.3 f	23.8 d	18.0 d	3.86 b	3.88 b	3.65 b
Un+4%RHB	1.10 ab	2.49 a	3.53 b	0.46 c	0.77 bc	0.79 ab	39.4 b	38.6 b	30.8 b	2.03 d	2.41 d	2.39 de
CM+0%RHB	0.88 ab	1.38 cd	3.48 b	1.00 a	1.07 a-c	0.49 bc	11.9 g	11.7 e	10.9 e	2.46 c	2.93 c	2.71 c
CM+2%RHB	0.88 ab	1.14 d	3.33 bc	1.00 a	1.37 ab	0.43 c	24.7 e	24.6 d	19.3 d	2.05 d	2.27 de	2.24 ef
CM+4%RHB	0.99 ab	1.58 c	3.47 b	1.02 a	1.40 a	0.30 c	36.8 c	37.6 b	35.3 a	1.35 e	2.14 ef	2.04 g
CP+0%RHB	1.17 ab	1.32 cd	3.34 bc	0.44 c	1.32 ab	0.50 bc	29.7 d	27.8 c	26.8 c	2.59 c	2.43 d	2.43 d
CP+2%RHB	1.20 ab	1.60 c	4.44 a	0.54 bc	1.30 ab	0.53 bc	40.1 b	37.6 b	36.2 a	2.63 c	2.02 f	2.11 fg
CP+4%RHB	1.21 a	2.06 b	3.55 b	0.83 ab	1.53 a	0.41 c	50.3 a	47.7 a	34.1 a	2.05 d	1.69 g	1.85 h
p-value	0.0251	<0.001	<0.001	<0.001	0.0015	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	*	***	***	***	**	***	***	***	***	***	***	***
CV (%)	16.34	8.06	9.06	15.77	17.4	21.36	2.02	3.51	4.18	5.42	4.20	3.76

(B) Basic cations

Amendment	K (mg kg^{-1})			Ca (mg kg^{-1})			Mg (mg kg^{-1})			Na (mg kg^{-1})		
	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	11.0 f	11.3 e	11.0 f	118 e	144 d	141 e	12.6 f	10.7 e	12.4 f	5.66 cd	7.21 c	11.2 bc
Un+2%RHB	19.7 ef	14.5 e	15.0 e	159 d	184 c	166 de	22.9 e	23.1 d	20.9 e	5.83 cd	6.74 c	11.9 bc
Un+4%RHB	36.8 d	22.1 d	21.7 cd	189 c	206 c	186 d	36.4 d	40.4 c	29.5 cd	6.81 bc	7.33 c	12.3 bc
CM+0%RHB	60.4 c	28.5 c	20.0 d	180 c	189 c	183 d	26.7 e	27.4 d	25.1 de	7.54 ab	8.78 b	12.8 b
CM+2%RHB	71.6 b	35.2 b	24.1 bc	239 b	233 b	189 d	41.6 cd	38.3 c	33.8 c	8.07 a	10.27 a	13.2 b
CM+4%RHB	93.7 a	61.6 a	41.8 a	245 b	248 b	294 c	46.1 c	44.9 bc	45.1 b	8.49 a	11.03 a	17.1 a
CP+0%RHB	14.8 f	11.1 e	10.1 f	314 a	344 a	325 bc	49.5 bc	49.2 b	48.6 b	5.36 d	6.77 c	10.3 c
CP+2%RHB	27.3 de	18.7 d	15.6 e	323 a	357 a	426 a	57.6 ab	64.3 a	58.5 a	5.97 cd	7.52 bc	11.5 bc
CP+4%RHB	54.9 c	30.0 c	27.6 b	334 a	341 a	348 b	66.4 a	66.4 a	60.5 a	6.63 bc	7.59 bc	13.2 b
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	***	***	***	***	***	***
CV (%)	7.93	5.34	5.99	2.92	3.23	4.91	8.12	6.73	6.70	4.73	4.32	5.18

*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$
† Crop1, Crop2, Crop3 denote corn planting in the first, second, and third cropping cycles.
‡ Means within each column followed by the same letter indicate no statistically significant difference at $p \leq 0.05$ (Tukey's Studentized Range Test)

trification (Khalil and Baggs, 2005). These transformations were supported by the ambiguous trends in soil total N (Table 3B) and the concentrations of soil NH_4^+-N and NO_3^--N (Table 4A).

Rice husk biochar had an insignificant contribution to the N source, possessing only 0.047 g N kg^{-1} (Table 1). This contrasted with cattle manure and compost, which contained 4.84 and 2.54 g N kg^{-1}. As Butnan et al. (2015) put forward, the biochar production process caused a substantial loss of N, attributed to its low melting point of –210°C. On the contrary, elements like P, K, Ca, and Mg have higher melting points of 44°C, 63°C, 842°C, and 650°C, respectively, enabling them to remain stable throughout the biochar production process.

It was noticed that a significant difference was found in the total N content between cattle manure and compost (Table 1). Cattle manure had almost twice the total N (4.82 vs. 2.54 g kg^{-1}) and more mineral N than compost (91.6 and 88.3 vs. 13.8 and 17.1 mg kg^{-1}, for $NH4^+$-N and NO_3^--N, respectively). As a result, it was expected that soils amended with cattle manure would have

Table 5
The nutrient contents of corn shoot tissue following the different application rates of rice husk biochar, either alone or in combination with cattle manure and compost, on the day of corn plant harvest in each successive cropping cycle.

Amendment	N (g kg^{-1})			P (g kg^{-1})			K (g kg^{-1})			Ca (g kg^{-1})			Mg (g kg^{-1})			Na (g kg^{-1})		
	Crop1†	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	17.7 ab ‡	14.4 bc	36.8 a	0.88 d	0.66 e	0.79 f	12.1 f	11.2 fg	9.4 de	3.97 a	5.87 a	5.63 a	1.82 a	1.97 ab	1.94 ab	0.055 d	0.075 d	0.09 c
Un+2%RHB	11.0 d	15.4 a-c	17.3 c	1.65 c	1.51 d	1.29 e	20.7 de	12.4 ef	10.1 de	1.56 e	4.06 cd	5.09 b	0.91 d	1.81 bc	1.94 ab	0.120 bc	0.094 cd	0.091 c
Un+4%RHB	12.8 cd	17.0 ab	22.8 b	3.03 a	3.08 b	3.18 b	26.9 c	16.0 d	13.3 cd	1.29 f	4.05 cd	3.00 d	0.87 d	1.81 bc	1.44 d	0.167 a	0.142 a-c	0.179 a
CM+0%RHB	14.7 bc	17.9 a	16.8 c	0.84 d	0.99 e	0.80 f	25.5 cd	22.1 bc	24.9 a	1.46 ef	4.09 c	4.96 b	0.94 d	1.63 c	1.82 bc	0.114 c	0.157 ab	0.173 a
CM+2%RHB	16.1 a-c	15.2 a-c	16.6 c	2.29 b	2.06 c	1.61 de	33.2 ab	24.3 b	18.3 b	1.37 ef	2.79 f	4.00 c	0.92 d	1.26 d	1.81 bc	0.165 a	0.167 a	0.171 a
CM+4%RHB	18.2 a	14.7 a-c	17.8 c	3.17 a	2.96 b	2.76 c	37.5 a	28.8 a	26.8 a	1.03 g	2.11 g	2.72 d	0.86 d	1.06 d	1.59 cd	0.197 a	0.152 ab	0.158 ab
CP+0%RHB	17.5 ab	15.4 a-c	17.0 c	1.74 c	1.77 cd	1.77 d	18.1 e	9.2 g	9.1 e	3.02 b	5.15 b	5.42 ab	1.64 b	2.05 a	2.07 a	0.083 cd	0.064 d	0.109 bc
CP+2%RHB	17.2 ab	14.7 a-c	15.8 c	2.82 a	2.84 b	2.84 bc	21.9 de	14.9 de	10.2 de	2.13 c	3.65 de	4.19 c	1.17 c	1.83 bc	1.93 ab	0.103 c	0.071 d	0.094 c
CP+4%RHB	17.0 ab	13.3 c	15.0 c	3.11 a	3.53 a	3.62 a	29.3 bc	21.4 c	17.2 bc	1.84 d	3.26 e	3.67 c	1.12 c	1.64 c	1.76 bc	0.159 ab	0.105 b-d	0.11 bc
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
CV (%)	7.25	7.33	7.15	8.14	6.30	6.00	6.63	5.11	9.08	3.90	3.81	4.27	4.28	4.52	4.65	8.72	13.51	10.56

***$p \leq 0.001$
† Crop1, Crop2, Crop3 denote corn planting in the first, second, and third cropping cycles.
‡ Means within each column followed by the same letter indicate no statistically significant difference at $p \leq 0.05$ (Tukey's Studentized Range Test)

Table 6
The ratios of soil K/Ca and K/Mg concentrations, and corn shoot tissue K/Ca and K/Mg contents following the different application rates of rice husk biochar, either alone or in combination with cattle manure and compost, on the day of corn plant harvest in each successive cropping cycle.

Amendment	Soil K/Ca †			Soil K/Mg			Tissue K/Ca			Tissue K/Mg		
	Crop1‡	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	0.09 ef §	0.08 d	0.08 d	0.89 cd	1.08 ab	0.90 ab	3.1 g	1.92 f	1.68 d	6.6 h	5.7 ef	4.9 d
Un+2%RHB	0.12 de	0.08 d	0.09 d	0.87 cd	0.63 cd	0.72 c	13.2 ef	3.06 e	1.98 cd	22.7 ef	6.9 d-f	5.2 d
Un+4%RHB	0.20 c	0.11 c	0.12 bc	1.02 c	0.55 de	0.74 bc	21.0 bc	3.95 e	4.46 b	31.2 c	8.8 d	9.3 c
CM+0%RHB	0.33 ab	0.15 b	0.11 c	2.26 a	1.04 b	0.80 a-c	17.5 cd	5.4 d	5.02 b	27.2 cd	13.6 c	13.7 b
CM+2%RHB	0.30 b	0.15 b	0.13 ab	1.73 b	0.93 bc	0.72 c	24.2 b	8.71 b	4.60 b	36.0 b	19.4 b	10.1 c
CM+4%RHB	0.38 a	0.25 a	0.14 a	2.04 ab	1.38 a	0.93 a	36.6 a	13.7 a	9.86 a	43.6 a	27.3 a	16.9 a
CP+0%RHB	0.05 f	0.03 e	0.03 e	0.30 e	0.23 f	0.21 e	6.0 g	1.80 f	1.68 d	11.0 g	4.5 f	4.4 d
CP+2%RHB	0.08 ef	0.05 e	0.04 e	0.47 de	0.29 ef	0.27 e	10.3 f	4.09 e	2.43 c	18.7 f	8.2 de	5.3 d
CP+4%RHB	0.16 cd	0.09 cd	0.08 d	0.83 cd	0.45 d-f	0.46 d	15.9 de	6.56 c	4.67 b	26.1 de	13.1 c	9.7 c
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	***	***	***	***	***	***
CV (%)	9.11	7.93	6.40	14.73	15.09	9.37	8.70	6.96	6.02	5.78	8.68	9.66

***$p \leq 0.001$
† Units for K/Ca and K/Mg ratios: mg kg^{-1} in soil, g kg^{-1} in corn shoot tissue
‡ Crop1, Crop2, Crop3 denote corn planting in the first, second, and third cropping cycles.
§ Means within each column followed by the same letter indicate no statistically significant difference at $p \leq 0.05$ (Tukey's Studentized Range Test)

higher soil total N and better plant growth. However, the results showed similar total N (Table 3B) and mineral N levels (Table 4A) in soils treated with either cattle manure or compost, and plant growth was comparable. This suggests N loss from cattle manure treatments, likely due to NH_3 volatilization, supported by the high pH of cattle manure (9.02) compared to compost (5.50) (Table 1). NH_3 volatilization is commonly observed with cattle manure (Van der Stelt et al., 2007). Notably, soil pH at the corn harvest showed lower pH in cattle manure treatments than in compost treatments; however, it was possible that immediately after applying the amendments, cattle manure treatments might have a higher pH.

The soil used in this study exhibited an initial pH of 4.81 (Table 1), identified as a strong acidic nature (Slattery et al., 1999), a typical characteristic of tropical soils (Sanchez, 2019). Soil pH increased while exchangeable acidity decreased after the application of either rice husk biochar, cattle manure, or compost (Table 3A). This resulted in a decrease in the concentration of Al (Table 4A), which is known for its phytotoxicity in tropical sandy soils. Although compost and rice husk biochar lacked alkaline characteristics, their pH of 5.5 and 7.31 were classified as moderately acidic and neutral (Slattery et al., 1999). However, these amendments still possessed a pH higher than the initial soil (Table 1), contributing to the overall increase in soil pH. Moreover, the inherent properties of organic matter were recognized for their ability to mitigate soil acidity and lower Al concentration, which tend to intensify in more acidic conditions. Hue et al. (2001) demonstrated that a multitude of organic molecules had the capacity to engage in reduction reactions and chelation with soil Al, rendering an increase in soil pH and a decrease in Al concentration.

In the specified treatments where rice husk biochar was solely incorporated (Un+2%RHB and Un+4%RHB), as well as in those treatments that received only cattle manure (CM+0%RHB) or compost (CP+0%RHB), a comparison to soils devoid of any amendments (Un+0%RHB) revealed an increase in the concentrations of soil P, K, Ca, and Mg (Table 4A, B). However, an increase was observed solely in the shoot tissue P and K contents, without any corresponding increase in the tissue Ca and Mg (Table 5). This phenomenon was particularly pronounced in the first crop and indicative of K antagonism, which is to be explained in the subsequent section.

The utilization of un-combined organic amendments, *viz* cattle manure, compost, and rice husk biochar alone, not only led to immediate enhancements in soil properties and plant growth but also exerted a sustained influence on subsequent cropping cycles, even without additional amendments. The present study demonstrated that this enduring impact was visible for at least two additional growth cycles (the second and third cropping cycles). The effect was apparent through the increased dry weight of shoots, roots, and total biomass under Un+2%RHB, Un+4%RHB, CM+0%RHB, and CP+0%RHB when compared to the Un+0%RHB across the first to third cropping cycles (Table 7).

The decline in corn growth was observed with each successive cropping cycle across all treatments, which was likely due to the corn plant being limited in certain nutrients, particularly NO_3^--N, P, K, and Mg (Table 4), as only a one-time soil amendment application was made before the first crop. Additionally, the pot-based experimental design imposed a constraint on soil volume, leading to a progressive reduction in availability of those nutrients with each planting cycle.

Table 7
The shoot, root, and total shoot and root biomass of corn following the different application rates of rice husk biochar, either alone or in combination with cattle manure and compost, on the day of corn plant harvest in each successive cropping cycle.

Amendment	Shoot dry weight (g)			Root dry weight (g)			Total dry weight (g)		
	Crop1†	Crop2	Crop3	Crop1	Crop2	Crop3	Crop1	Crop2	Crop3
Un+0%RHB	0.88 f ‡	0.40 e	0.11 f	0.43 f	0.25 d	0.07 d	1.31 g	0.65 e	0.180 f
Un+2%RHB	1.96 cd	1.04 cd	0.32 e	0.77 b-d	0.44 c	0.18 b-d	2.72 de	1.48 cd	0.490 e
Un+4%RHB	1.77 d	1.29 ab	0.47 d	0.50 f	0.66 ab	0.27 a-c	2.27 f	1.95 ab	0.730 d
CM+0%RHB	2.46 b	0.89 d	0.51 cd	0.87 bc	0.48 bc	0.26 a-c	3.33 c	1.36 d	0.767 cd
CM+2%RHB	2.80 a	1.29 ab	0.79 a	1.14 a	0.64 ab	0.29 a	3.94 a	1.93 ab	1.083 a
CM+4%RHB	1.89 cd	1.50 a	0.56 bc	0.65 de	0.66 a	0.26 a-c	2.53 e	2.16 a	0.810 b-d
CP+0%RHB	2.69 ab	0.88 d	0.25 e	0.91 b	0.48 a-c	0.17 cd	3.60 b	1.36 d	0.420 e
CP+2%RHB	2.07 c	1.03 cd	0.64 b	0.75 cd	0.54 a-c	0.28 ab	2.82 d	1.56 cd	0.920 b
CP+4%RHB	1.52 e	1.17 bc	0.57 bc	0.55 ef	0.54 a-c	0.31 a	2.07 f	1.71 bc	0.877 bc
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	***	***	***
CV (%)	4.32	6.8	6.23	6.89	12.04	16.63	3.22	6.58	6.26

***$p \leq 0.001$
† Crop1, Crop2, Crop3 denote corn planting in the first, second, and third cropping cycles.
‡ Means within each column followed by the same letter indicate no statistically significant difference at $p \leq 0.05$ (Tukey's Studentized Range Test)

3.2. The proper balancing combination uses of rice husk biochar with cattle manure and compost

Even though the use of rice husk biochar alone was observed to have improved the growth of corn (Un+2% RHB and Un+4% RHB vs. Un+0%RHB) (Table 7), the co-application of rice husk biochar, however, with cattle manure and compost resulted in a more significant enhancement in corn growth. This indicated that combining these organic amendments can be more advantageous than when used individually.

The use of rice husk biochar combined with cattle manure positively impacted corn growth even in the first crop. The effect continued to be sustained to subsequent cropping cycles. However, the extent of the enhancement depended on the optimal application rates. The results indicated an increase in corn growth in both CM+2%RHB and CM+4%RHB during the second cropping cycle and CM+2%RHB during the first and third cycles, relative to CM+0%RHB (Table 7). These findings were consistent with the PCA outputs (Fig. 1), which showed that the dry weight of shoots, roots, and total biomass positively correlated with rice husk biochar rates throughout the three successive cropping cycles (Fig. 1A, D, and G). Moreover, the application of 2% rice husk biochar with cattle manure (CM+2%RHB) was observed to be located in the same quadrant of the PCA as the shoot, root, and total dry weight of corn for all three cropping cycles (Fig. 1B, E, and H). However, a higher rate of rice husk biochar with cattle manure (CM+4%RHB) resulted in decreased corn growth during the first and third cropping cycles compared to the lower rate (CM+2%RHB) (Table 7). This trend aligned with the PCA, where CM+4%RHB was situated in the quadrant antithetical to corn biomass across the three cropping cycles (Fig. 1B, E, and H).

Combined-using rice husk biochar with compost had a negative effect on corn growth in the first cropping cycle, shown by lower growth in treatments CP+2%RHB and CP+4%RHB compared to CP+0%RHB (Table 7). The PCA corroborated this adverse relationship for the first cropping cycle (Fig. 1C), which indicated that an increased rate of rice husk biochar in conjunction with compost intensified the negative association with corn biomass. However, these detrimental effects subsided over time and yielded solely advantageous outcomes in the later corn crops. This was evident in the enhanced corn growth in subsequent crops, notably CP+4%RHB in the second cropping cycle, and both CP+2%RHB and CP+4%RHB in the third cropping cycle, when juxtaposed with CP+0%RHB for each respective cycle. The PCA conducted for the second (Fig. 1F) and third cropping cycles (Fig. 1I) affirmed this positive correlation, where the combined use of compost and rice husk biochar was positively linked to corn biomass.

Regarding the results of the PCA conducted over various cropping cycles (Fig. 1A-I), it was observed that the application of rice husk biochar, especially at high rates (4% RHB) in conjunction with cattle manure or compost, caused a reduction in corn growth. The tissue K content was located within the same quadrant in the PCA results or one that indicated an inverse trend relative to these treatments. In all cropping cycles, tissue K generally displayed an antithetical or inverse relationship with tissue Ca and Mg content (Fig. 1A-I), paralleling the decrease in corn biomass (Table 7). Upon examining the nutrient concentrations in the soil (Table 4B), it was established that the levels of

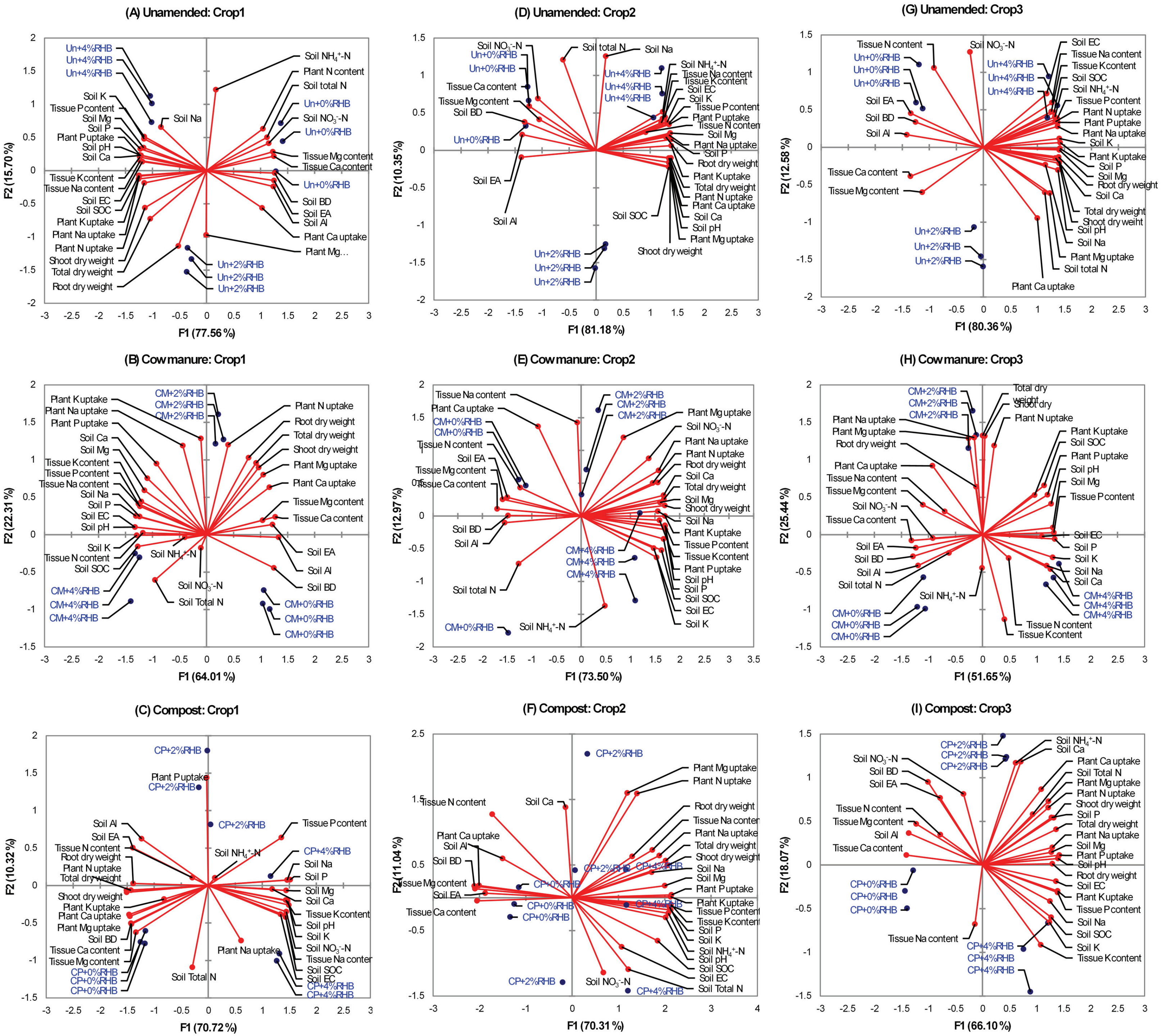

Fig. 1. The eigenvalues of soil-plant responses and factor scores of different soil amendments obtained through the principal component analysis, demonstrate the relationships between soil amendments: unamended (A, D, G), cattle manure (B, E, H), and compost (C, F, I)—in combined uses with varying dose rates of rice husk biochar (0%, 2%, and 4% w w^{-1}). The combinations were observed to influence corn growth across three successive cropping cycles: Crop1 (A, B, C), Crop2 (D, E, F), and Crop3 (G, H, I)

K, Ca, and Mg were suboptimal across all treatments and cropping cycles, except for the Ca concentration in the second cropping cycle under CP+2%RHB, where the required concentrations were 290 mg K kg^{-1} for K, 401 mg Ca kg^{-1} for Ca, and 243 mg Mg kg^{-1} for Mg (Peverill et al., 1999). Despite this, the soil concentrations of these nutrients experienced an upsurge following the introduction of rice husk biochar, escalating in tandem with the biochar application rates (Table 4B).

Deficiencies in tissue Ca and Mg were observed during the first cropping cycle (Table 5). According to Reuter et al. (1997), the optimal nutrient values for corn are 3–7 g kg^{-1} for Ca and 1.5–4.5 g kg^{-1} for Mg. In the first cropping cycle, using 4% rice husk biochar in concert with cattle manure, which adversely affected corn growth, resulted in corn shoot tissue Ca content measuring 1.03 g kg^{-1} and Mg content measuring 0.86 g kg^{-1}. Similarly, applying 2% and 4% rice husk biochar, which impeded corn growth when combined with compost, yielded corn shoot tissue Ca content of 2.13 and 1.84 g kg^{-1} and Mg content of 1.17 and 1.12 g kg^{-1}, respectively. This pattern is indicative of a K antagonistic effect on Ca and Mg. This phenomenon arises due to the shared protein transporter utilized by K, Ca, and Mg for cellular uptake, with the transporter's active sites exhibiting a preferential affinity for K over Mg and Ca (Xie et al., 2021), thus favoring K absorption. Elevated soil K levels consequently inhibited the uptake of Ca and Mg, culminating in deficiencies of the latter two cations (Mengel and Kirkby, 2001; Xie et al., 2021). Moreover, Xie et al. (2021) have expounded that the K antagonistic effect extends to the xylem loading and translocation processes from root to shoot. The transport of Ca and Mg is further encumbered due to their higher valency, which enables their adherence to the xylem surface, thereby erecting a barrier that further retards the uptake of Ca and Mg from the soil media into the root cells.

The use of high-ash biochar, leading to its high cation content, has raised concerns about the potential for one nutrient to affect another negatively. These concerns are particularly relevant in tropical and subtropical soils with limited nutrient retention capacity. Butnan et al. (2015) found that applying eucalyptus biochar with 3.9% ash at a 4% w w^{-1} rate to loamy sandy soil resulted in antagonistic interactions of K to Ca and Mg in corn. It is worth noting that nutrient antagonism is not limited to coarse-textured soils, as it also occurs in fine-textured soils. This was demonstrated by the recent discovery of Butnan and Vityakon (2023) that the application of rice husk biochar with 30.3% ash at a 2% w w^{-1} rate in loam soil induced Mg antagonism towards Ca and Si towards Fe in rice. These findings underscore the importance of prudence in using biochar to avert potential harm to plants. Factors such as the biochar ash content, the biochar dose rate, and the soil texture can help ensure the safe and effective use of biochar in agriculture.

The study observed that combining rice husk biochar with cattle manure and compost resulted in K antagonism during the first cropping cycle. This observation was made due to the high K contents present in the organic amendments (Table 1). Specifically, the cattle manure and compost showed 17,365 and 3,506 mg K kg^{-1}, respectively. The rice husk biochar was also found to have a significant K content of 1,062 mg K kg^{-1}.

In the second and third cropping cycles, the combination of cattle manure and compost with rice husk biochar showed a lower harmful effect relative to the first cycle, as evidenced by the corn biomass responses (Table 7). Mitigation of the deficiencies of Ca and Mg (Table 5) indicated that the passage of time contributed to diminished toxicity associated with organic amendments containing excessive K. This improvement was observed because soil K concentrations in all treatments exhibited a gradual decline in the second and third cropping cycles (Table 4), while soil Ca and Mg concentrations remained constant throughout all cropping cycles. Simultaneously, shoot tissue nutrient content revealed a general trend of decreasing tissue K content over time. In contrast, tissue Ca and Mg contents showed an opposite trend, increasing in the second and third cropping cycles (Table 5). These results suggested that Ca and Mg had a stronger competitive ability for plant uptake against K in the later cropping cycles than the first. Xie et al. (2021) demonstrated that the antagonistic interaction between these nutrients was bidirectional, where K not only hindered the absorption of Ca and Mg, but the opposite was also possible, albeit to a lesser extent. This study supports this claim by indicating that Ca and Mg could compete with K and mitigate the intensity of K antagonism. This conclusion is reinforced by the data showing decreased K/Ca and K/Mg ratios in both soil and plant tissues (Table 6).

Tissue Na content was found to have increased when rice husk biochar, cattle manure, or compost was administered individually, compared to soil without organic amendments (Table 5). The Na content increase was generally proportional to the quantity of rice husk biochar applied, regardless of whether the biochar was used alone or in combination with cattle manure or compost. Despite these increases, the tissue Na concentration in each treatment did not exceed the threshold known to cause Na toxicity in corn, which is 5 g kg^{-1} (Reuter et al., 1997). This indicated that the organic amendments used in this study did not cause salt toxicity in corn. Additionally, the soil electrical conductivity readings for all treatments remained below the salinity classification threshold of 2 mS cm^{-1} (Peverill et al., 1999), which further supports the non-saline nature of the soil after treatment.

Another interesting aspect is C and N dynamics. In general, C decreased over time from the first to third cropping cycles (Table 3A). This result was expected since soil amending materials were added only before the first cycle, and soil organic C naturally declined due to mineralization (Wu et al., 1998). However, it is surprising that total N concentrations increased, especially in treatments combining cattle manure or compost with rice husk biochar. Logically, total N should have decreased due to ongoing N mineralization. This issue warrants further in-depth study.

4. Conclusions

The results of this study clearly established that applying rice husk biochar, cattle manure, or compost alone enhanced key soil properties and stimulated plant growth. These effects were noticeable right from the initial cropping cycle and persisted through the second and third cycles, even though the organic amendments were applied only once. It firmly indicated that for improving sandy textured soil, there was no need for recurrent application of these organic amendments with every cropping cycle to maintain enhanced fertility.

Using cattle manure or compost alone was effective in improving soil and plant growth, but their combined use with rice husk biochar yielded even better results. Although this combination initially caused a deleterious effect during the first cropping cycle, especially when using the high application rates of cattle manure and compost with rice husk biochar, this effect was only temporary due to K antagonism towards Ca and Mg. Subsequent crops experienced only the beneficial effects, as the negative effect was conclusively mitigated. This highlighted the implication of selecting the appropriate combinations and rates of these organic amendments to optimize longer-term soil productivity and plant growth in sandy soils.

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