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Effects of biochar produced from different feedstocks and organic fertilizers on soil properties and maize (*Zea mays L.*) production in the northern part of Rwanda

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Abstract

This study applied biochar derived from different local feedstocks and organic fertilizers (OF) on contrasting acidic soils, Andosol and Nitisol, in order to investigate their effects on selected soil properties and maize growth and yield parameters. A split plot design was employed, with treatments being factorial combinations of OF (control without OF (OF0), cow manure (OF1), chicken manure (OF2), and compost (OF3)) as a main plot factor and biochar (no biochar applied (B0), maize straw biochar (B1), eucalyptus biochar (B2), pinus biochar (B3)) as a sub-plot factor. An amelioration in soil properties was observed in treated plots compared to the control, with a general increase in soil pH, organic carbon, total N, available P, K^+, Ca^{2+}, cation exchange capacity and porosity, and a decrease in Na^+, Al^{3+} and H^+, and bulk density. With both soils, biochar - OF combination resulted in better increase of the growth and yields of maize compared to the isolate use of biochar and OF. The highest maize yield (17.14% and 60.17% increase on Andosol and Nitisol, respectively) and above ground biomass (AGB) were achieved with OF2 + B2 treatment. Interactive effects of biochar and OF were significant with both soils, for K^+, stem girth, AGB and maize grain yield, emphasising a synergistic effect in the integrated use of biochar and OF. Thus, using biochar-OF combination, especially OF2 + B2, could be a good practice to be recommended for farmers in order to amend the Andosol and Nitisol and enhance maize production in the northern Rwanda.

Keywords Biochar, Organic fertilizers, Maize, Soil properties, Rwanda

1 Introduction

Conserving and enhancing soil fertility is an important strategy required for sustaining soil productivity. However, the low soil fertility is a current global problem encountered across several regions of our planet [1], and the decline in soil plant-available nutrients is particularly impacting the sub-Saharan Africa countries [2]. In the northern part of Rwanda, an area of great interest for the country's economy as a pivot for food

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production, the excessive soil nutrient mining and crop productivity decline remain problematic to farmers. This is mainly due to higher population density that is impacting limited arable lands through land use change and intensive soil cultivation and the vulnerability of this mountainous area to erosion [3].

In addition, the soils of this northern part of the country mainly consist of two types of soil, namely: Andosol and Nitisol. Andosol is a volcanic soil covering almost the entire area of Musanze district and a large adjacent part of Burera district. The rest part of Burera is predominated by Nitisol. These are important soils for crop production, but poor in some important soil-plant nutrients, with a particular higher P sorption capacity [4] resulting from higher concentrations in active Al and Fe. In Andosol, particularly, this P fixation can also be explained by higher amount of soil organic matter (SOM) and the presence of allophanes that readily bind P and limit its availability [5], a general characteristic for volcanic-derived soils [6, 7]. For improving such kind of soils, the use of organic amendments is recommended [4, 7]. Yet, the use of organic fertilizers (OF) is considered as a more effective long-term solution for sustaining soil productivity than a direct application of plant nutrients in the form of inorganic fertilizers [8].

However, despite the current growing and diversification in livestock production in Rwanda, there is still a gap of knowledge on the potential of different types of OF generated by local farmers, in improving diverse soils, especially Andosol and Nitisol, under local climatic conditions. A limited access of OF for their regular application on agricultural soils reported as a widespread problem impacting crop production in some regions of sub-Saharan Africa [9] is also a great concern in the northern part of Rwanda. Particularly in Musanze District, one of the districts of our study area, it is used by 13% of all farmers [10]. As a solution, biochar, a pyrolyzed biomass material that resides in the soil for longer time period than OF [11], could be used as a friendly tool for sustaining soil productivity while reducing the quantity and frequent use of expensive fertilizers. It could especially be beneficial for maize production, a major food crop in Rwanda, requiring huge amounts of fertilizers.

The agronomic and environmental benefits of the use of biochar is extensively studied and highlighted through different studies during the past 30 years [8, 12–16]. Recent studies had shown the ability of biochar in improving the growth and yield of maize [1, 17–20]. Particularly, some studies have already combined biochar and organic amendments and useful results were obtained regarding the impact of this integration on the soil and plant [17, 21–23], highlighting biochar potential for better and more efficient fertilizer utilization. However, there is still uncertainty in the knowledge about biochar application for its ability to maintain and improve the quality of varied soils, particularly those with different stages of degradation [24, 25], and the production of different crops. At present, field-based data evidencing the agricultural suitability of biochar applied on acidic soils such as Andosol and Nitisol, under temperate tropical highland conditions of Rwanda, are still scarce. In addition, previous biochar studies mostly ignored some critical plant parameters such as the belowground biomass (BGB) which is also an important part of the entire plant biomass, and reported biochar effect on maize growth focusing on the aboveground biomass (AGB) only. The root-to-shoot (R: S) ratio has been also ignored, although it could be helpful for estimating root biomass when shoot biomass is known.

Moreover, while previous studies indicate that the quality of biochar can vary with different factors, including feedstock materials used and the pyrolysis process [26–28], there is still limited data regarding the suitability of diverse local plant materials that are widely available in Rwanda though these materials could serve as feedstocks for biochar production [22]. Despite the lower level of industrialization reported to be a major reason of very low scalability of biochar production technologies in the region [29], it is worth to explore the agricultural suitability of biochar produced under local conditions, using earth kiln as a low-cost method that can allow the production of biochar with a wide range of local feedstocks. This could help in extending biochar field research, particularly under local conditions of a data-limited area such as Rwanda, in addition to the controlled settings under which biochar studies are mostly undertaken [11].

This study had therefore extended field research on biochar by combining biochar produced from different sources, under local conditions, with different local OFs, and considering soils of different levels of weathering on which maize is extensively grown in Rwanda. It had also taken into consideration the BGB, a component of maize plant that is not explored yet in biochar studies. To the best of our knowledge, this could be the first study of this kind conducted on the Andosol and Nitisol, under the Rwandan moderate tropical climate. We intended to (i) investigate the effect of biochar from different sources and OFs on selected soil physical and chemical properties, and (ii) evaluate the influence of these organic amendments on growth and yield parameters of maize in the Northern part of Rwanda. We hypothesised that the effect of biochar prepared from different feedstocks on soil properties, growth, and yield of maize could significantly be influenced by the type of OF with which it is used.

2 Materials and methods

2.1 Location and description of experimental sites

Experimental sites were established in Kinigi (2300 m altitude, 1° 25' S, 29° 35' E) and Rwerere (2107 m altitude, 01° 50' S, 29° 87' E) research stations of the Rwanda Agriculture and Animal Resources Development Board (RAB) that are respectively located in Musanze and Burera Districts. The two districts are predominated by contrasting soils, namely an Andosol in Musanze and adjacent part of Burera and a Nitisol in the eastern part of Burera. Prior to the start of the experiment, Kinigi site has been cropped with Irish potato (*Solanum tuberosum* L.) during the 2023B (2022/2023) season. Rwerere has been cropped with maize (*Zea mays L.*) during the 2023 A (2022/2023) season and kept as fallow until the starting of this experiment. Letters A and B stand for major crop growing seasons of Rwanda that usually start in September and March, respectively. During the study period, meteorological data recorded at the nearest stations of Kinigi (2267 m above sea level, 1° 44' S, 29° 59' E) and Ntaruka (1969 m above sea level, 01° 42' S, 29° 84' E) were accessed from the Rwanda Meteorological Agency. They were then used to draw a graph of precipitation and temperatures experienced at study sites during the study period (Fig. 1).

2.2 Experimental set-up and procedure

2.2.1 Biochar and compost preparation

The in-situ method of biochar production was adopted, and the slow pyrolysis was performed using the earth kiln method. This method was selected due to its suitability, as

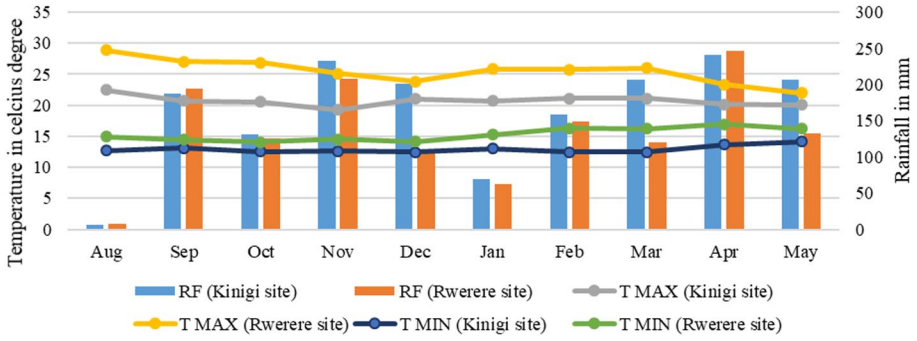


Fig. 1 Monthly total rainfall and mean temperatures recorded from August 2023 to May 2024 at Kinigi and Rwerere sites. RF: rainfall, T MAX: maximum temperature, and T MIN: minimum temperature

a low cost and small-scale biochar production technique, that is easily performed under local conditions. Biochar was produced from sun-dried maize straws, remains of eucalyptus (*Eucalyptus maidenii*) tree cutting (forest residues), and carpentry pinus (*Pinus patula*) residues. Earth kilns were established and each one received its particular feedstock type. After packing each kiln with respective feedstock, a soil layer of approximately 0.3 m of thickness was added and sealed over the biomass, and vertical walls were established with the same soil to avoid air entering in order to optimize biochar production. Only a small vent was left closer to the bottom and closed after firing. A chimney was established on the top of the kiln to allow slight escape of smoke. The pyrolysis process of the biomass was undertaken until no more smoke is produced. After pyrolysis, biochar was allowed to cool itself, and then the kiln was opened to remove dry and cooled biochar. Maize straw biochar was gently crushed by hand while eucalyptus and pinus-derived biochar were slightly crushed using mortar and pestle in order to ease their manually field application. The yield was estimated for each biochar type as a ratio of biochar weight with the weight of its original dry biomass.

Compost was prepared following the aerated static pile method. A sequence of dry materials consisting of crop residues, cow manure, green materials consisting of *Alnus acuminate* (locally known as alinus) and *Vernonia amygdalina* (locally known as umubirizi), chicken manure, wood ash, *Tithonia diversifolia* (locally known as kimbazi), and cow manure slurry was repeated for making layers until the composting pile reaches about 1.5 m high. Moistening was done at each layer. The whole pile was covered by dry grass, and kept on an open-roofed area. The first turning was performed at the end of the first two months, the following turnings were done at monthly basis, and we assumed that the compost was mature within 6.5 months. In this study, all composting activities were undertaken at the Bio Fertilizer Tech System (BFTS) Ltd, a company located in Gasabo district. Before being used, the compost was analysed at the Analytical laboratory for Soil, Plant and Water analysis of the RAB and the National Quality Testing Laboratories Division of the Rwanda Standards Board (RSB).

2.2.2 Experimental design, sowing and maize growing

Two similar experiments were undertaken in parallel at two different sites: Kinigi with Andosol and Rwerere with Nitisol. The trial was carried out in a split plot design, with treatments being factorial combinations of OF (control without OF (OF0), cow manure (OF1), chicken manure (OF2), and compost (OF3)) as a main plot factor and biochar (no

Table 1 Treatments of the field experiments with different types of organic fertilizers (OF) and biochar (B)

Treatment code	Fertilizer (OF) applied	Biochar (B) applied	Number of replications
OF0 + B0 (control)	OF0	B0	3
OF0 + B1	OF0	B1	3
OF0 + B2	OF0	B2	3
OF0 + B3	OF0	B3	3
OF1 + B0	OF1	B0	3
OF1 + B1	OF1	B1	3
OF1 + B2	OF1	B2	3
OF1 + B3	OF1	B3	3
OF2 + B0	OF2	B0	3
OF2 + B1	OF2	B1	3
OF2 + B2	OF2	B2	3
OF2 + B3	OF2	B3	3
OF3 + B0	OF3	B0	3
OF3 + B1	OF3	B1	3
OF3 + B2	OF3	B2	3
OF3 + B3	OF3	B3	3

OF0 + B0: control without OF and B, OF0: no OF applied, OF1: cow manure, OF2: chicken manure, OF3: compost, B0: no biochar applied, B1: maize straw biochar, B2: eucalyptus biochar, and B3: pinus biochar



Fig. 2 Application of biochar and OF on Kinigi Andosol (left) and Rwerere Nitisol (right)

biochar applied (B0), maize straw biochar (B1), eucalyptus biochar (B2), pinus biochar (B3)) as a sub-plot factor. A total of 16 treatments, with 3 replicates each, were considered. Forty-eight experimental plots were used, each plot with a size of 4.5 m^2 (3 m × 1.5 m) (Table 1). Each type of biochar was applied at a rate of 10 t/ha.

After measuring the amounts to be applied on respective experimental plots, different types of biochar were gently moistened, just before field application, to minimize possible loss, pollution between treatments and negative impacts on germination. OF were also applied at a rate of 10 t/ha, commonly used in Rwanda for maize production. On respective plots, these organic soil amendments were manually applied, seven days before planting, and thoroughly mixed in upper soil (approximately in 5 cm depth) for corresponding plots (Fig. 2). After levelling the soil surface, planting pits of 5–10 cm depth were established along each planting row. The 0.75 m inter-row and 0.50 m intra-row spacing were considered. To avoid border effects of treatments, a distance of 1.0 m was left between plots and between blocks.

The "RHMH1601" is a maize variety improved by the RAB for high altitudes that was grown as a test crop in this study. Its seeds were obtained from the Rwanda Agriculture and Animal Resources Development Board (RAB), the only one institution in charge of agricultural research in Rwanda. At sowing, the 3rd October 2023 (Rwerere) and 4th October 2023 (Kinigi), approximately 28 kg of seeds were sown per hectare, three seeds being sown per pit (at 5 cm depth) and covered with the soil. However, seedlings were thinned to two, two weeks after germination. Maize plants were grown under rain-fed conditions. Urea (100 kg/ha) was uniformly applied through the ring placement method, at the second weeding, just after eight weeks from the sowing day. Through weeding activities, the soil was gently tilled using hoes with wooden handle to ensure a deeper and evenly mixing of the applied biochar and/or OF with the soil while minimizing possible loss and pollution between treatments. The duration of this experiment was 7.5 months at Kinigi and 6.5 months at Rwerere, from the beginnings of the growing season of 2024 A (2023/2024) up to harvesting day, the 15th April 2024 at Rwerere and on the 14th May 2024 at Kinigi. The soil, cow manure, chicken manure and compost used in this study were analysed, prior to the start of this experiment, and their characteristics are presented in Table 2. The types of biochar prepared were also characterized and results are presented in Table 3, in the result section.

2.3 Data collection methods

The first soil sampling was performed three weeks before sowing, just after setting up the experiments, for the characterization of each experimental plot. For each experimental plot, a five-point sampling method was applied: soil samples were gathered from 0 to 30 cm depth and combined into one bulk sample. This depth was selected, even for the second soil sampling, because it usually contains high organic matter and major nutrient levels, and 30 cm is the deepest plough depth at which we assumed that a mixing of applied organic amendments or fertilizers and the soil might have occurred, given the method of weeding and cultivation used. Regarding soil-plant nutrients, we assumed that deeper mixing could also occur in this depth through rainfall and biological activities. To get the sample, a column of soil from the surface to 30 cm, was collected using a manual auger, and all the soil taken was used for ensuring the homogeneity of composite sample. At each plot, undisturbed sample was taken from 0 to 15 cm depth for measuring the bulk density (BD) and porosity. Soil samples were transported to the 'Analytical Laboratory for Soil, Plant and Water Analysis' of the RAB, where they were analysed. Soil chemical properties that were analysed included pH, CEC, soil organic carbon (SOC), total nitrogen (total N), available P, exchangeable cations (K, Ca, Mg and Na), micronutrients (Cu, Zn and Fe), and exchangeable acidity (Al^{3+} and H^{+}). The soil BD and porosity were measured as selected soil physical variables. Like biochar, compost, cow manure and chicken manure were subjected, in prior, to the analysis for their chemical properties (Table 2). The second soil sampling was done one day just after harvesting, following the procedure applied at the first sampling. At the laboratory, the same soil parameters considered for the first sampling were analysed following appropriate procedures for each parameter.

Plant height and stem girth (cm) were measured for a sample of nine plants selected randomly from each plot. At silking, plant height measurements were taken from the soil surface to the point where tassel starts to branch. Stem diameter was measured, at

Table 2 The properties of cow manure (OF1), chicken manure (OF2), compost (OF3), and pre-planting soil (0–30 cm depth) at Rwerere and Kinigi experimental sites

Parameter	Unit	OF1	OF2	OF3	Soil/site	
					Andosol/Kinigi	Nitisol/Rwerere
Physical properties						
Moisture content	%	12.77	10.91	38.9		
Clay content	%				8.21	23.26
Silt content	%				34.04	18.68
Sand content	%				57.75	58.05
Soil bulk density	g/cm^3				0.967	1.326
Soil porosity	pu				58.82	46.69
Chemical properties						
pH (H_2O)		8.83	7.66	11.7	5.62	5.28
P	mg/kg	4708.8	13777.6	22061.6		
K	mg/kg	9379	21,082	26,560		
Ca	mg/kg	21,021	37,466	94,237		
Mg	mg/kg	4824	10371.6	17245.8		
Na	mg/kg	11278.4	21666.4	1187.2		
Electrical conductivity	ms/cm	4.45	10.27	12.58		
Organic carbon	g/kg	143.1	353.9	132	41.2	26.1
Organic matter	g/kg	246.7	610.1	227.6	71	45
CEC	cmol(+)/kg				24.68	19.85
Total N	g/kg	10.3	23.3	39.8	7.2	2.8
Available P	mg/kg				4.57	16.7
Exchangeable K	cmol(+)/kg				0.13	0.11
Exchangeable Ca	cmol(+)/kg				4.77	5.58
Exchangeable Mg	cmol(+)/kg				1.11	1.21
Exchangeable Na	cmol(+)/kg				0.15	0.23
Al^{3+}	cmol(+)/kg				0.28	0.54
H^+	cmol(+)/kg				0.29	0.36
Cu	mg/kg				2.76	2.81
Zn	mg/kg				11.76	11.83
Fe	mg/kg				33.66	79.07

pu: porosity units (100 pu is equivalent to 100%), CEC: cation exchange capacity

Table 3 The characteristics of maize straw biochar (B1), eucalyptus biochar (B2), and pinus biochar (B3) that were produced and used

Parameter	Unit	B1	B2	B3
Moisture content	%	0.93	6.77	20.23
pH (H_2O)		8.61	7.78	7.4
P	mg/kg	610.4	1613.2	1438.8
K	mg/kg	1660	3320	2241
Ca	mg/kg	1930.5	16,159	7722
Mg	mg/kg	301.5	2834.1	1507.5
Na	mg/kg	222.6	6900.6	4452
Electrical conductivity	ms/cm	2.38	0.79	0.32
Organic carbon	g/kg	27.5	426.5	450.4
Organic matter	g/kg	47.4	735.3	776.5
Total N	g/kg	1.1	4.1	3.2
C: N ratio	-	25	104.02	140.75

the plant base, using a pair of digital vernier caliper. The data on anthesis and silking were obtained through field observation by recording the date at 50% anthesis and 50% silking. This means that, for anthesis, these data consisted of the time (in days) between sowing date and when 50% of plants per plot shed pollen. For silking, they consisted of the time (in days) between sowing date and when 50% of plants per plot show silks.

To get data on the BGB, three representative maize plants were selected in each plot, at the R2 reproductive stage. After cutting each of these three plants at the level of soil surface, its root system was excavated to a depth of about 40 cm, from an area with 0.25 m radius. The sampling depth was considered as an approximate maximum length of rooting system for our test maize variety grown under our experimental conditions, on relatively shallow soils as was observed at both sites. This was confirmed, just before, through a careful checking, along the soil profile, regarding the vertical extent of the root for a sample of nine plants (three plants closer to each replication plots' position) from maize plants of the same variety that were grown paralleled and adjacent as buffer plants on the same experimental parcel. To separate the tissues of the excavated roots from soil, the soil was gently removed by washing the roots using water. Then, roots were kept enclosed in labelled bags and transported to the place where they were sun-dried (to a constant weight) for determination of their dry weight. The AGB of these selected three plants were also collected and sun-dried to a constant weight for measuring their dry weight. The R: S ratio was calculated by dividing the root dry weight by the dry weight of its respective aboveground biomass.

Being dry, all maize plants on each plot were harvested by cutting plants at the level of soil surface, and the field weighing method was applied to obtain the weight of the AGB that was converted to tonnes per hectare. The weight of the AGB and grains recorded for the three plants that were selected for the R: S ratio was added to the weight of the AGB and grains recorded at harvesting. The weights of the dry biomass (t/ha) for each harvest plot area were measured gravimetrically using an electronic balance. For each plot, maize were sun-dried and threshed to obtain grain yield (t/ha) at 15% grain moisture content. The 100-grain weight (100-GW) was measured for the seeds after being air-dried to a constant weight.

2.4 Procedures for laboratory analysis

Soil pH was measured following the pH(H_2O) method as described by [30]. For determination of CEC, the ammonium-saturation method described by [31] for CEC was applied, the pH being adjusted to 7.0 using a dilute ammonium hydroxide. The SOC content was determined using the wet oscillation method as described by [30], and the total N was estimated following the Kjeldahl method. For the available soil P, Bray's method No.1 was used by extracting 0.03 M ammonium fluoride in 0.025 M hydrochloric acid and quantify using the UV spectrophotometer. To determine the amounts of exchangeable cations, a soil sample was extracted with an excess of 1 M ammonium acetate ($NH_4C_2H_3O_2$) solution. K and Na content of the extract was then estimated with the help of a flame photometer, while the amounts of Ca and Mg were determined by using the atomic absorption spectrophotometer (AAS). Cu, Zn and Fe were extracted using the EDTA and estimated by using the AAS as described by [30]. Exchangeable acidity of the soil was determined following a titration method, as described by [30], using 1 M KCI as the extracting solution and titrating with 0.01 M NaOH, using phenolphthalein as

indicator. The particle size distribution was estimated following the hydrometer method. The soil BD was determined following the procedure described by [30] for non-stony soils, and particle density was determined following the laboratory protocol. Soil porosity was estimated from BD and particle density. Organic soil amendments were analysed following the laboratory protocol for OF analysis. The pH was measured following the pH(H_2O) method and estimated in a suspension of 1:10 OM: water ratio. The OC was determined following the wet oscillation method, while the total N was estimated by Kjeldahl method. The contents of P_2O_5, K_2O, CaO, MgO, and Na_2O were measured using a mixed acid method, and the estimation method was applied for respective element [32]. The EC was measured using a conductivity meter in a suspension of 1:10 OM: water ratio.

2.5 Statistical analysis of data

Statistical analyses of data were performed in RStudio Version 2025.05.1 + 513. The factorial ANOVA was performed to analyse the effects of different types of OF and biochar on selected soil and plant parameters at each of the two different experimental sites. The Least Significant Difference (LSD) test was further performed as a multiple comparison test for means. Different R packages were used, namely: readr to import excel sheets into RStudio [33], doebioresearch to perform the ANOVA [34], and ggplot2 to generate interaction plots [35].

3 Results

3.1 Biochar produced

The results of this study indicate higher yield and good characteristics of the biochar prepared using eucalyptus materials as feedstock, compared to other biochar types that were prepared from other local materials. The yields of biochar obtained were 0.1870 (g/g) for maize straw-derived biochar, 0.2984 (g/g) for pinus-derived biochar, and 0.3141 (g/g) for eucalyptus-derived biochar. Figure 3 shows different types of biochar that were produced and used in this study, and Table 3 below highlights their characteristics.

3.2 Soil chemical parameters

3.2.1 Soil pH and exchangeable acidity (Al^{3+} and H^+)

Soil pH had generally increased, with 0.11 units in Andosol (Kinigi) and with 0.12 units in Nitisol (Rwerere). In the Andosol, the highest pH (5.82 ± 0.01) was found in the plot treated with OF2 + B2, while the lowest pH (5.58 ± 0.03) was from the control plot (OF0 + B0). In the Nitisol, the pH ranged from 5.25 ± 0.08 (control) to 5.50 ± 0.08 (OF3 + B3). Additional data are given in Supplementary Information, Table S1. In both



Fig. 3 Maize straw biochar, crushed eucalyptus biochar, and crushed pinus biochar (left to right)

soils, soil pH was significantly affected by the use of OF ($p \leq 0.01$ and $p \leq 0.05$ in Andosol and Nitisol, respectively) and biochar ($p \leq 0.001$ and $p \leq 0.01$ in Andosol and Nitisol, respectively), though there was no interaction noticed in the effects of OF and biochar on the pH.

The exchangeable Al^{3+} ranged from 0.17 ± 0.01 cmol(+)/kg to 0.29 ± 0.02 cmol(+)/kg in Andosol and from 0.38 ± 0.04 cmol(+)/kg to 0.6 ± 0.02 cmol(+)/kg in Nitisol, with highest concentrations in control and lowest in OF2 + B2 treatments. Additional data are given in Supplementary Information, Table S1. The exchangeable Al^{3+} had generally decreased by 25.15% in Andosol and by 11.14% in Nitisol, relative to its respective initial concentrations. The use of OF and biochar had significantly ($p \leq 0.001$) influenced the variations in the exchangeable Al^{3+} in both soils, with interaction effect in Andosol ($p \leq 0.05$) only. The exchangeable H^+ had also decreased, from 0.29 ± 0.01 cmol(+)/kg (control) to 0.23 ± 0.02 cmol(+)/kg (OF3 + B1) in Andosol and from 0.38 ± 0.03 cmol(+)/kg (control) to 0.26 ± 0.03 cmol(+)/kg (OF3 + B2) in Nitisol. Additional data are given in Supplementary Information, Table S1. The exchangeable H^+ was significantly affected by OF ($p \leq 0.01$ and $p \leq 0.05$ in Andosol and Nitisol, respectively) and biochar ($p \leq 0.01$ and $p \leq 0.001$ in Andosol and Nitisol, respectively), though there was no significant interaction effect noticed.

3.2.2 SOC, Total N, Available P, and CEC

The results of this study show that SOC content varied from 41.33 ± 1.70 g/kg with OF0 + B1 to 42.43 ± 2.16 g/kg with OF1 + B2 in Andosol and from 26.10 ± 0.69 g/kg with OF1 + B1 to 27.60 ± 0.17 g/kg with OF2 + B3 in Nitisol. The total N content varied from 7.30 ± 0.30 with OF3 + B3 to 8.07 ± 0.85 with OF3 + B2 in Andosol and from 3.40 ± 0.20 g/kg with OF1 + B1 to 4.30 ± 0.20 g/kg with OF3 + B2 in Nitisol. At both sites, the available P was highest (7.27 ± 0.04 mg/kg in Andosol and 18.49 ± 0.46 mg/kg in Nitisol) with OF2 + B2 and lowest (4.68 ± 0.25 mg/kg in Andosol and 16.40 ± 0.53 mg/kg in Nitisol) in the control. Similarly, the CEC was highest (26.63 ± 0.72 cmol(+)/kg in Andosol and 21.39 ± 0.11 cmol(+)/kg in Nitisol) with OF2 + B2 and lowest (24.42 ± 0.17 cmol(+)/kg in Andosol and 19.65 ± 0.18 cmol(+)/kg in Nitisol) in the control. Additional data are given in Supplementary Information, Table S1.

The SOC was only significantly ($p \leq 0.05$) affected by the use of OF in Nitisol. The total N was significantly affected by both OF ($p \leq 0.01$) and biochar ($p \leq 0.05$) in Nitisol only. The available P was significantly affected by the use of OF and biochar, with p values ≤ 0.001 in Andosol and p values ≤ 0.01 in Nitisol. A significant ($p \leq 0.001$) interactive effect of OF and biochar on the available P was noticed in Andosol only. The CEC was significantly affected by the use of OF ($p \leq 0.05$ and $p \leq 0.001$ in Andosol and Nitisol, respectively) and biochar ($p \leq 0.01$ and $p \leq 0.001$ in Andosol and Nitisol, respectively). No interactive effect of the two factors on the CEC was observed in both soils.

Overall, resulting from the treatments applied, SOC, total N, available P and CEC had generally increased by 1.47%, 7.58%, 46.3% and 3.85% in Andosol, and by 2.26%, 35.11%, 6.1% and 4.7% in Nitisol, relative to their respective initial contents highlighted in the Table 2. Generally, as a response to the use of OF, the increase of the available P was in the order OF0 < OF1 < OF2 < OF3 in both soils, while the CEC had increased in the order OF0 < OF1 < OF3 < OF2 in Andosol and OF0 < OF1 < OF2 < OF3 in Nitisol. Additional data are given in Supplementary Information, Table S4.

3.2.3 Exchangeable base cations (K, Ca, Mg, and Na)

The use of OF and biochar led to general increase in the exchangeable K and Ca and decrease in the exchangeable Na in both soils. In Andosol, the highest exchangeable K (0.26 ± 0.01 cmol(+)/kg), Ca (5.75 ± 0.07 cmol(+)/kg) and Na (0.14 ± 0.01 cmol(+)/kg) contents were obtained with OF3 + B2, OF2 + B2 and OF2 + B2, respectively. The lowest values of the exchangeable K (0.12 ± 0.01 cmol(+)/kg), Ca (4.74 ± 0.04 cmol(+)/kg) and Na (0.11 ± 0.01 cmol(+)/kg) contents were recorded from the control. In Nitisol, the highest exchangeable K (0.19 ± 0.01 cmol(+)/kg), Ca (6.68 ± 0.18 cmol(+)/kg) and Na (0.18 ± 0.01 cmol(+)/kg) content values were obtained with OF2 + B2, OF3 + B3 and OF0 + B1, respectively. In this soil, the lowest exchangeable K (0.10 ± 0.02 cmol(+)/kg) and Ca (5.50 ± 0.12 cmol(+)/kg) contents were measured in the control, while the lowest exchangeable Na (0.07 ± 0.02 cmol(+)/kg) content was obtained with OF1 + B1. Exchangeable Mg varied from 0.85 ± 0.03 cmol(+)/kg) with OF0 + B3 to 0.94 ± 0.03 cmol(+)/kg) with OF2 + B0 in Andosol and from 1.15 ± 0.01 cmol(+)/kg) in the control to 1.25 ± 0.02 cmol(+)/kg) with OF1 + B0 in Nitisol. Additional data are given in Supplementary Information, Tables S1 and S2.

The exchangeable K was significantly affected by the use of OF in both soils (p values ≤ 0.001) and biochar in Andosol ($p \leq 0.001$) and in Nitisol ($p \leq 0.01$). The exchangeable Ca was significantly affected by the use of OF ($p \leq 0.05$ and $p \leq 0.001$ in Andosol and Nitisol, respectively) and biochar ($p \leq 0.001$ and $p \leq 0.01$ in Andosol and Nitisol, respectively). The exchangeable Mg was only significantly ($p \leq 0.05$) affected by the use of biochar in Andosol. The exchangeable Na was significantly affected by the use of OF ($p \leq 0.01$) in Nitisol only and biochar in Andosol ($p \leq 0.01$) and in Nitisol ($p \leq 0.001$). A significant ($p \leq 0.001$) interactive effect of OF and biochar on the exchangeable Na was observed in Nitisol. It was only on the exchangeable K that a significant ($p \leq 0.05$) interactive effect of OF and biochar was noticed in both soils.

Figure 4 highlights the interactions between biochar and OF on the exchangeable Al^{3+}, available P, and the exchangeable K and Na in Andosol and Nitisol.

3.2.4 Micronutrients (Cu, Zn and Fe)

In Andosol, the highest Cu (2.81 ± 0.10 mg/kg), Zn (11.94 ± 0.46 mg/kg) and Fe (34.41 ± 0.43 mg/kg) contents were obtained with OF1 + B2, OF3 + B0 and OF1 + B2, respectively. The lowest values of Cu (2.71 ± 0.04 mg/kg), Zn (11.50 ± 0.29 mg/kg) and Fe (31.24 ± 0.61 mg/kg) contents were recorded from OF2 + B2, OF3 + B3 and OF1 + B1. In Nitisol, the highest Cu (2.86 ± 0.05 mg/kg), Zn (12.09 ± 0.02 mg/kg) and Fe (78.79 ± 3.73 mg/kg) contents were measured in the control. The lowest values of Cu (2.74 ± 0.04 mg/kg), Zn (11.39 ± 0.77 mg/kg) and Fe (72.68 ± 2.66 mg/kg) contents were recorded from OF2 + B2, OF3 + B2 and OF2 + B2, respectively. Additional data are given in Supplementary Information, Table S2. In general, the results of this study indicate that they was no significant influence of the use of OF and biochar or their interaction effect on micronutrients (Cu, Zn and Fe) content of both soil observed, except with biochar on Cu ($p \leq 0.05$) in Nitisol.

3.3 Soil physical parameters

The analysis of the experimental soils indicates that Andosol was sandy loam, while Nitisol was sandy clay loam (Table 1). BD was significantly affected by biochar in Andosol

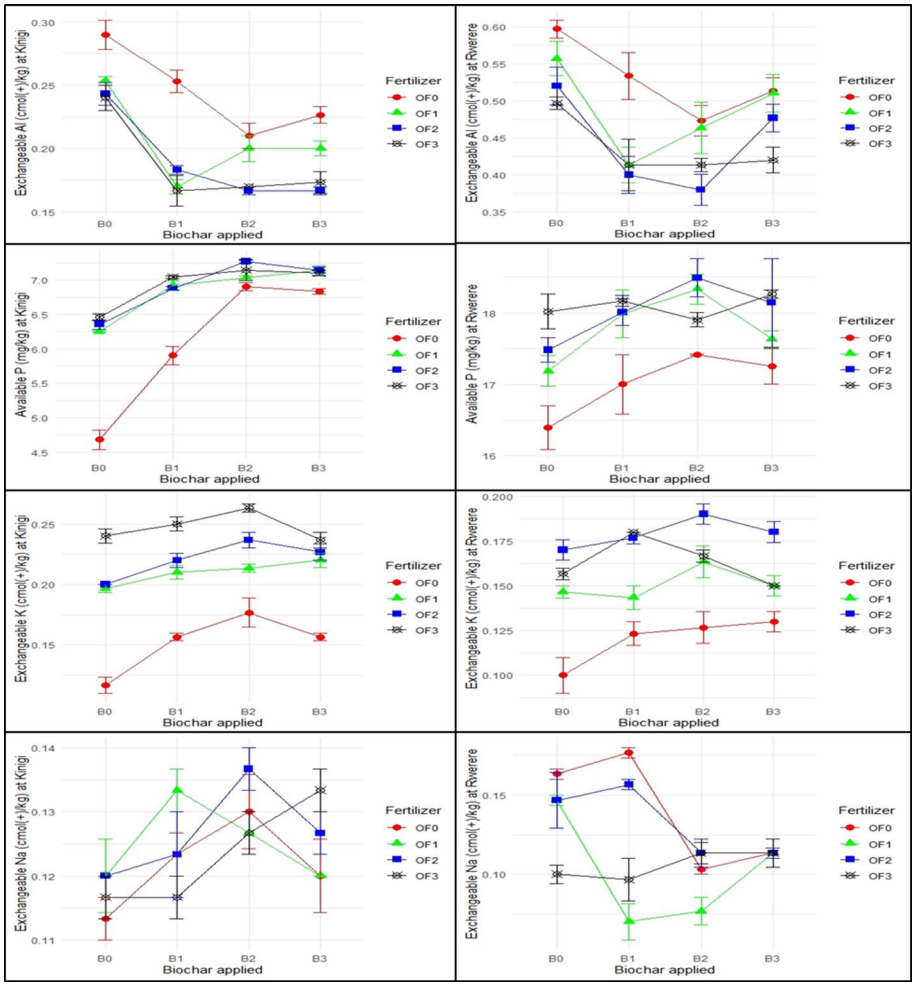


Fig. 4 Interaction effect of biochar and OF on the exchangeable Al^{3+}, available P, and the exchangeable K and Na in Andosol and Nitisol. OF0: control without OF, OF1: cow manure, OF2: chicken manure, OF3: compost, B0: no biochar applied, B1: maize straw biochar, B2: eucalyptus biochar, and B3: pinus biochar

($p \leq 0.05$) and by OF ($p \leq 0.01$) in Nitisol. A significant interaction effect between OF and biochar on BD ($p \leq 0.01$) was noticed in Nitisol only. In general, referring to the initial values (Table 1), the BD had decreased at both sites, varying from 0.967 g/cm^3 to 0.961 g/cm^3 for Andosol and from 1.326 g/cm^3 to 1.279 g/cm^3 for Nitisol. In contrast, soil porosity had generally increased, from 58.82 pu (Table 1) to 58.87 pu for Andosol and from 46.69 pu to 47.74 pu for Nitisol. Regarding the response of our study soils to specific treatments applied, the BD recorded was highest in the control for both Andosol (0.98 ± 0.02 g/cm^3) and Nitisol (1.35 ± 0.01 g/cm^3), while it was lowest with OF1 + B0 (0.95 ± 0.02 g/cm^3) for Andosol and OF2 + B1 (1.20 ± 0.03 g/cm^3) for Nitisol. In Andosol, the porosity was highest with OF1 + B0 (61.61 ± 0.81 pu) and lowest with OF1 + B3 (56.01 ± 1.85 pu). In Nitisol, the porosity was highest with OF2 + B0 (50.12 ± 6.24 pu) and lowest with OF1 + B3 (46.30 ± 1.18 pu). Additional data are given in Supplementary Information, Table S2.

3.4 Maize growth and yield parameters

3.4.1 Plant height

At Kinigi site, the highest plant height (179.67 ± 1.53 cm) was obtained with OF2 + B2 treatment, while the lowest (144.67 ± 2.08 cm) was obtained with OF1 + B1. At Rwerere site, the highest height (177.10 ± 1.77 cm) was obtained with OF2 + B0, while the lowest (110.13 ± 1.21 cm) was obtained with OF0 + B1. Additional data are given in Supplementary Information, Table S3. The results of this study indicate that plant height was significantly (p values ≤ 0.001) affected by OF at both sites and by biochar at Rwerere only. A significant interaction effect between OF and biochar on plant height was observed at Kinigi ($p \leq 0.05$) and Rwerere ($p \leq 0.001$).

3.4.2 Stem girth

Maize plants grown in Andosol (Kinigi site) have shown a better vigour than those grown in Nitisol (Rwerere site). In general, the average stem girth was 3.22 ± 0.23 cm at Kinigi and 2.98 ± 0.38 cm at Rwerere. At Kinigi, stem girth varied from 2.83 ± 0.06 cm with OF0 + B0 to 3.50 ± 0.00 cm with OF2 + B3. At Rwerere, stem girth varied from 2.50 ± 0.10 cm with OF0 + B0 to 3.80 ± 0.26 cm with OF2 + B2. Additional data are given in Supplementary Information, Table S3. With respect to the OF applied, maize stem girth was detected in the order OF0 < OF1 < OF2 = OF3 on Andosol and OF0 < OF1 < OF3 < OF2 on Nitisol (Additional data are given in Supplementary Information, Table S6). Maize stem girth was significantly affected by the use of OF at both sites (p values ≤ 0.001) and by the use of biochar with $p \leq 0.001$ at Kinigi and $p \leq 0.01$ at Rwerere. A significant interaction effect between these two factors on stem girth was observed at both sites with $p \leq 0.001$ and $p \leq 0.01$ at Kinigi and Rwerere, respectively.

Figure 5 below highlights the interactions between biochar and OF on plant height and stem girth of maize at Kinigi and Rwerere sites.

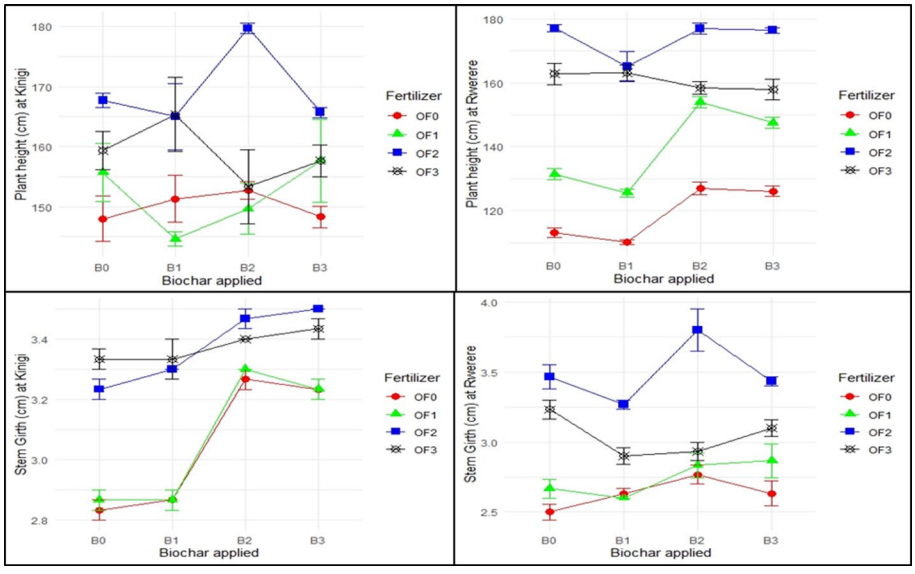


Fig. 5 Interaction effect of biochar and OF on plant height and stem girth of maize at Kinigi and Rwerere. OF0: control without OF, OF1: cow manure, OF2: chicken manure, OF3: compost, B0: no biochar applied, B1: maize straw biochar, B2: eucalyptus biochar, and B3: pinus biochar

3.4.3 Anthesis, silking, and anthesis- silking interval (ASI)

Overall, anthesis and silking periods were short for maize grown at Rwerere than those grown at Kinigi. The shortest durations of anthesis (107.33 ± 1.53 days, with OF2 + B0) and silking (109.00 ± 0.00 days, with OF2 + B2) were observed at Rwerere, while the longest anthesis (127.33 ± 0.58 days, with OF0 + B1) and silking (131.00 days, with OF0 + B1 and OF3 + B0) were observed at Kinigi. The ASI ranged from two to five days at Kinigi and from one to five days at Rwerere. Yet, the shortest (one day) ASI was recorded at Rwerere. Additional data are given in Supplementary Information, Table S3).

The anthesis was significantly affected by OF at Rwerere ($p \leq 0.001$) and by biochar at Kinigi ($p \leq 0.05$). The silking was significantly affected by OF at both sites ($p \leq 0.05$ and $p \leq 0.001$ at Kinigi and Rwerere, respectively), while a significant ($p \leq 0.01$) interactive effect of OF and biochar was noticed at Kinigi. The ASI was significantly affected by OF at both sites ($p \leq 0.01$ and $p \leq 0.001$ at Kinigi and Rwerere, respectively) and by biochar ($p \leq 0.05$) at Rwerere only. A significant ($p \leq 0.01$) interactive effect of OF and biochar on the ASI was noticed at Kinigi only.

3.4.4 Belowground biomass (BGB), aboveground biomass (AGB) and root-to-shoot (R: S) ratio

At Kinigi, the averaged BGB per plant ranged from 0.009 to 0.017 kg. The highest value (0.015 ± 0.001 kg) of the BGB was obtained with OF3 + B2, while the lowest (0.0100 ± 0.0010 kg) value was obtained with OF1 + B1. At Rwerere, the averaged BGB per plant ranged from 0.0126 to 0.0140 kg. The highest value (0.0139 ± 0.0001 kg) was obtained with OF2 + B3, while the lowest value (0.0127 ± 0.0002 kg) was recorded from the control. Additional data are given in Supplementary Information, Table S3. The application of OF caused differences in the AGB in the order OF0 < OF1 < OF3 < OF2 at both sites (additional data are given in Supplementary Information, Tables S6). At Kinigi, the highest value (5.30 ± 0.03 t/ha) of the AGB was obtained with OF2 + B2, while the lowest value (4.98 ± 0.03 t/ha) was obtained with OF1 + B0. At Rwerere, the highest value (5.37 ± 0.15 t/ha) of the AGB was also obtained with OF2 + B2, while the lowest (3.96 ± 0.05 t/ha) was from the control. The R: S ratio ranged from 0.046 to 0.071 at Kinigi and from 0.024 to 0.067 at Rwerere. Additional data are given in Supplementary Information (Table S3).

At both sites, there were significant differences in the BGB, AGB and R: S ratio as response to the use of OF and biochar. The BGB was significantly affected by OF ($p \leq 0.01$ and $p \leq 0.05$ at Kinigi and Rwerere, respectively) and biochar ($p \leq 0.01$ and $p \leq 0.001$ at Kinigi and Rwerere, respectively), and a significant ($p \leq 0.01$) interactive effect of these two factors on BGB was noticed at Rwerere only. Both OF and biochar significantly (p values ≤ 0.001) affected the AGB at the two sites, with a significant interactive effect ($p \leq 0.05$ and $p \leq 0.01$ at Kinigi and Rwerere, respectively). The R: S ratio was significantly affected by the use of OF and biochar at Kinigi ($p \leq 0.05$) and at Rwerere ($p \leq 0.001$). A significant ($p \leq 0.001$) interactive effect of OF and biochar on the R: S ratio was noticed at Rwerere only.

3.4.5 Maize grain yield

In general, higher grain yields were from maize grown in Andosol than those grown in Nitisol. Grain yield responded to the use of OF in the order OF1 < OF0 < OF2 < OF3 at Kinigi and OF0 < OF1 < OF3 < OF2 at Rwerere (additional data are given in

Supplementary Information, Table S6). At Kinigi, the highest grain yield (12.25 ± 0.55 t/ha) was recorded from the plot treated with OF2 + B2, while the lowest yield (10.04 ± 0.34 t/ha) was recorded from the plot treated with OF1 + B0. At Rwerere, the highest grain yield (12.11 ± 0.41 t/ha) was recorded from the plot treated with OF2 + B2, while the lowest grain yield (7.56 ± 0.13 t/ha) was from the control plot. Additional data are given in Supplementary Information, Table S3. Considering the highest maize grain yields recorded, grain yield increased by 17.14% at Kinigi and by 60.17% at Rwerere, relative to the yield obtained from control plots.

Maize grain yield significantly differed among the treatments resulting from the use of OF ($p \leq 0.01$ and $p \leq 0.001$ at Kinigi and Rwerere, respectively) and biochar ($p \leq 0.001$ at both sites). A significant interaction effect between OF and biochar on grain yield was noticed for at both sites ($p \leq 0.05$ and $p \leq 0.01$ at Kinigi and Rwerere, respectively). The 100-grain weight was only significantly affected by the use of OF ($p \leq 0.05$) and biochar ($p \leq 0.01$) at Rwerere, with no significant interactive effect.

Figure 6 highlights the interactions between biochar and OF on maize BGB, AGB, R:S ratio, and grain yield at Kinigi and Rwerere sites.

4 Discussion

4.1 Effect of biochar and organic fertilizers on selected soil properties

Although the northern part of Rwanda is considered as a pivot for food production in the country, the excessive soil nutrient mining and crop productivity decline remain problematic to farmers mainly due to higher population density that is impacting limited arable lands through land use change and intensive soil cultivation [3]. The two districts of our study area are the most populated in the northern province, with the population density of 1157 inhabitants/km^2 and 682 inhabitants/km^2 for Musanze and Burera respectively [36]. In this area, soil fertility decline is also accelerated by erosion, a worldwide challenge for soil management and crop production, which is globally causing an annual loss of about 20–30 Gt of the most fertile and agriculturally important soil [37]. In fact, the soil of the northern part of Rwanda is much susceptible to erosion and degradation due to the hilly topography characterized by steep slopes and the prevailing heavy rainfall, leading to substantial soil and nutrient loss [10, 38].

As response to the fertility depletion and the ever-growing food demand, the use of inorganic fertilizers had increased, supported by the Government will, although it is unbalanced with the use of organic soil amendments. Conversely, this practice is reported among major factors that pose the reduced ability of the soil to support crop production in Rwanda [39]. Yet, inefficient use of fertilizers causes the unbalance in soil plant nutrients, lower food production and harm the environment, and may lead to potential abandonment of agricultural lands [40]. Given the traditional (mixed crop-livestock) farming system predominating in the study area, the production and accessibility of OF is still low, explaining the unbalance in the use of fertilizers. However, the appropriate use of OF is also essential for increasing crop yields, while minimizing potential economic and environmental-associated costs [41]. In this study, the use of biochar and OF had shown an ameliorative effect for the two contrasting acidic soils, Andosol and Nitisol, predominantly found in the northern part of Rwanda.

Soil pH, a critical factor influencing the availability of soil-plant nutrients, had increased in both soils. The positive change of soil pH generally noticed with biochar

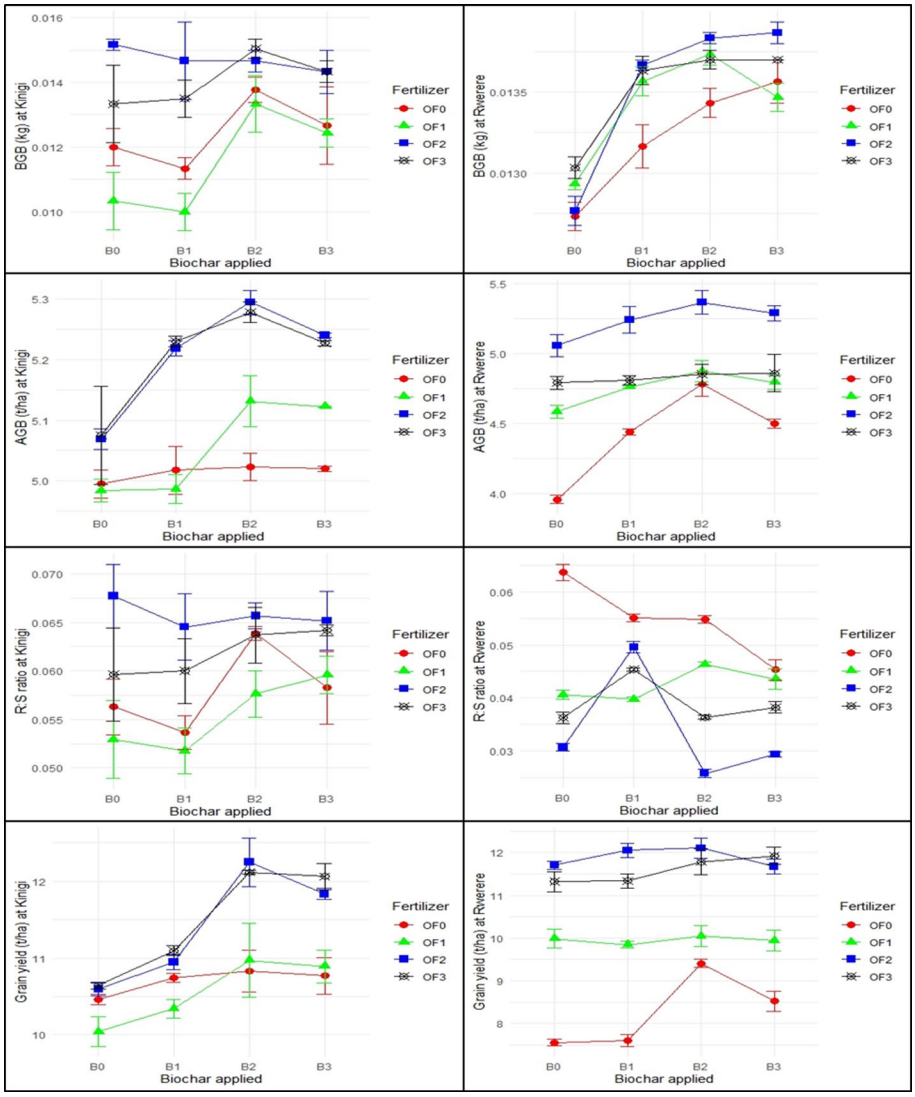


Fig. 6 Interaction effect of biochar and OF on maize belowground biomass (BGB), aboveground biomass (AGB), root-to-shoot (R: S) ratio, and grain yield at Kinigi and Rwerere. OF0: control without OF, OF1: cow manure, OF2: chicken manure, OF3: compost, B0: no biochar applied, B1: maize straw biochar, B2: eucalyptus biochar, and B3: pinus biochar

and OF combined could be attributed to the synergy in the effects of biochar used together with OF. This might have resulted from the intrinsic biochar potential to rise soil pH alongside with the complexation of free Al^{3+} and H^{+} ions with organic anions in the soil [22, 42]. Yet, the concentration in soil exchangeable Al^{3+} and H^{+} had notably reduced and significantly affected by the use of biochar and OF in both soils. The rise in soil pH could also result from the increased saturation of the soil CEC by basic exchangeable cations that are supplied from organic amendments to the exchangeable surfaces of the soil [42, 43]. This process can particularly explain the better performance of B2 as indicated by the results of this study. The higher basic cations content of this biochar deriving from eucalyptus, compared to other types of biochar also used, could mirror the highest CEC and better results generally noticed with OF2 + B2 treatments. Even though the porosity of biochar was not measured in this study, the potential of B2 in rising soil pH can also reflect from its likely better porous structure that might have

allowed a better retaining of basic exchangeable cations in its internal pores against possible losses through leaching. In addition, the alkaline characteristic of the ash that is generated during pyrolysis process could also contribute to the increase in soil pH [17, 42]. Different biochar types used in this study might have contained an amount of ash, although the ash content was not quantified, particularly due to local conditions under which they were produced. Interestingly, despite the higher pH of B1 probably resulting from its ash content, the pH increase was lower in the soil where B1 was used compared to the soil treated with B2 and B3. This could be related to the lower content in organic matter and basic cations observed in this biochar deriving from maize straw. Moreover, the higher pH increase noticed in Nitisol compared to that observed in Andosol could be attributed to the initial lower pH level of Nitisol compared to the Andosol. Referring to the standardized soil pH ranges [32], Nitisol was strongly acidic while Andosol was moderately acidic. Previous studies [44–46] also highlight the importance of the initial soil pH and a better ameliorative effect of biochar in more acidic or degraded soils. Thus, using organic amendments such as B2 could be a good strategy for rising the pH of our study soils, particularly Nitisol.

The analysis had shown that the soil of the northern part of Rwanda is poor in some critical soil-plant nutrients, especially phosphorus. A very low initial content in the available P was noticed in both soils. In fact, Andosol is a potential fertile soil for crop production, but strong phosphate fixating soil due to the presence of active Al and Fe [4, 7]. Likewise, Nitisol, being an acidic soil, is characterized by a high P sorption capacity due to its higher content in Fe and Al oxides [47]. Overall, these soils were acidic and their Fe concentration was very high. Such soils can be improved through better practices of nutrient management, such as the use of organic amendments [4, 7]. Consistently, a general increase in the available P following the use of biochar and OF, particularly with OF3 and B2, could be attributed to the reduction in Fe and Al^{3+} concentrations as noticed in both soils, confirming the results from previous studies [17, 22, 48]. Therefore, applying biochar and OF could bring a solution to the problem of high P sorption in Andosol and Nitisol.

The lower quality and poor productivity of soils are mainly associated with a decline in soil-plant available nutrients and SOC deriving from the decomposition of SOM [3, 8, 11]. Interestingly, biochar is reported to improve soil quality and maintain the level of soil-plant available nutrients [25]. In this study, biochar did not only maintain the level of nutrients in the soil; it had also caused the change in their availability. Differences observed in their change could be attributed to varied quality of different OFs and biochar sources that were used. Given the general increase noticed for nutrients such as the exchangeable K and Ca and CEC in both soils, in consistence with previous study [28], this experiment evidences the effect of biochar feedstock type on soil properties.

Overall, the Andosol had lower BD compared to the Nitisol. This could be attributed to higher SOM, higher content in fine particles (silt + clay) and lower proportion in sand particles as were observed in the Andosol. A low BD is among important characteristics of volcanic-originated soils such as Andosol [49] and a good attribute for plant roots development [7]. At harvesting, soil BD was generally lower in the soil treated with B3, probably resulting from the higher organic carbon content noticed in this pinus-derived biochar. In both soils, the BD had generally decreased, while the porosity had increased. This is consistent with a recent meta-analysis conducted on 59 studies on biochar

influence on physical and chemical soil properties [28]. The higher diminution of BD observed in Nitisol compared to that observed in Andosol could be related to the higher increase in SOC stock that had occurred in Nitisol. Therefore, adding carbon-rich materials, such as biochar, to these soils could reduce their BD, and could be more effective and beneficial for Nitisol than for Andosol.

4.2 Effect of biochar and organic fertilizers on the growth and yield of maize

The northern part of the country is suitable for maize production, one of the six priority crops identified for the crop intensification program (CIP). By initiating the CIP in 2007, the Government of Rwanda envisaged the promotion of monoculture and commercialization of maize, rice, wheat, white potato, beans, and cassava [50, 51]. However, there is still a gap in maize yield across the country which is attributed to the inadequate soil amendments and management practices [52]. The results of this study highlight a significant benefit in the use of biochar and OF for improving the investigated growth and yield parameters of maize.

Maize grown in Andosol have shown higher plant height and a better vigour than those grown in Nitisol. In fact, Andosol was initially richer in some nutrients that are important for plant growth than Nitisol. In addition, the application of nitrogen (N) fertilizer was done during rainy period, closer to the end of the V8-V11 stage. The efficient use of N by plants through its retention against leaching and volatilization might have been higher in Andosol than in Nitisol. Previous study revealed that biochar potential in reducing N_2O emissions tend to be higher in soils having high silt content than in others [53]. This is supporting our results, since the silt content was higher in Andosol than in Nitisol. Moreover, due to higher SOM content observed in Andosol, the loss of other nutrients through leaching might have been lower in this soil than in Nitisol. The higher values of plant height and stem girth generally obtained with B2 could be related to better characteristics of this eucalyptus-derived biochar, including higher N content, compared to other types of biochar also used. Further, significant interaction effects between OF and biochar on plant height and stem girth observed for both soils could be linked to the synergistic effect noticed between biochar and OF on soil parameters such as pH, exchangeable K and available P.

The BGB was measured at the R2 reproductive stage. According to [54], this stage is critical for capturing the maximum root biomass per plant while minimizing the decomposition and loss of root dry matter. Although the highest value of BGB recorded was greater in Andosol, the average amount of BGB per plant was generally lower in Andosol than in Nitisol. This was unexpected, given a reported good characteristic of Andosol for easing root penetration [7]. The higher value of BGB generally obtained with OF2 could be attributed to its nutrient and organic carbon contents, similarly for the AGB. In this study, the amount of the AGB recorded at Kinigi was generally higher than that recorded at Rwerere. This was evident since stem girth and height of maize plants were also higher on Andosol. Greater amounts of the AGB obtained with OF2 + B2 could have resulted from higher nutrient and organic carbon contents of OF2 and B2, and reflect to a synergy noticed between these two organic amendments in their positive effects on the properties of Andosol and Nitisol.

Given the simplicity of collecting data related to the AGB, the R: S ratio could effectively serve as an important parameter to estimate plant root biomass. However, it is

often ignored, and most of field studies investigating plant biomass report the AGB only, probably due to the ease of measuring the shoot biomass. In this study, the R: S ratio was determined. Its ranges at both sites were consistent with previous study that found the R: S ratio varying from 0.04 to 0.13 for maize grown under field conditions [54]. However, significant differences observed in R: S ratio could be related to the differences also noticed in the effects of OF and biochar on BGB and AGB.

Overall, maize grain yield was higher at Kinigi than at Rwerere. The higher grain yields particularly obtained with OF2 + B2 treatment for both soils, like the case of the AGB, could be attributed to the positive and synergistic effect between these two organic soil amendments noticed in both soils. Previous studies have also shown the ability of biochar in improving the growth and yield of maize [1, 17–20] and the synergistic effect between biochar and organic amendments in improving soil properties and crop production [21, 22]. Furthermore, our results indicating a better increase in grain yield observed at Rwerere compared to that observed at Kinigi, with OF2 + B2, are also consistent with previous studies [45, 46] that reported a better ameliorative potential of biochar in more acidic or degraded soils compared to others. Given the increased yields of maize grains generally obtained from treated plots compared to control plots, the use of biochar and OF could be a better strategy for bridging the existing gap in maize production across the country and meeting the national demand while reducing a significant importation of maize. In Birunga and Central Bugesera agro-ecological zones of Rwanda, particularly, this gap is estimated to be 4.6 t/ha and 5.1 t/ha [52].

5 Conclusion

This study shows an ameliorative potential of biochar and OF on Andosol and Nitisol. An improvement in soil parameters was noticed in treated plots at the two sites. Although the response in soil parameters varied among the treatments, an overall increase was observed in soil pH, SOC, total N, available P, exchangeable K and Ca, CEC and soil porosity, while an overall decrease was observed in the exchangeable Na, Al^{3+} and H^{+} and soil BD. Among plant parameters, this study had considered the BGB as an important component of plant biomass that had been overlooked in previous biochar studies. Overall, the mixed use of biochar and OF had better increased the growth and yield of maize compared to isolate use of biochar or OF. Highest values of the BGB were obtained with OF3 + B2 combination for Andosol and with OF2 + B3 for Nitisol. The AGB and grain yield were higher with OF2 + B2 at both sites, an increase in grain yield being higher on Nitisol. Significant interaction effects between biochar and OF were observed at both sites for the exchangeable K, maize stem girth, AGB and maize grain yield, besides those noticed at each of the sites, highlighting a synergistic effect in the combined use of biochar and other organic soil amendments. Therefore, a strategy of using the combination of OF and biochar, especially OF2 + B2, is recommended in order to improve the fertility of Rwandan acidic soils, Andosol and Nitisol, and enhance maize production especially on the Nitisol. It could be an efficient option, environmentally and economically viable, for responding to the substantial need of smallholder farmers regarding the access and use of organic soil amendments that are hugely required for maize production. Further studies should explore the agricultural suitability of biochar through long-term field experiments, and should be extended to other soil types on

which maize is grown, considering different agro-ecological conditions and a variety of fertilizers that are ordinarily used in Rwanda.

Supplementary Information

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Supplementary Material 1

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Author contributions
All the authors contributed to the conception and design of the study. Charles Lwanga Twagiramungu prepared materials, conducted field and laboratory works and wrote manuscript drafts. Bobe Bedadi, Claver Ngaboyisonga, Concorde Nsengumuremyi and David Fangueiro commented on drafts. All authors read and approved the final manuscript.

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Data availability
The data supporting the findings of this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate
This study did not involve human participants or animals. No endangered, protected, or restricted plant species were used. Therefore, no specific ethical approval was required for this type of agronomic research in Rwanda. This study was conducted under the permission (N°: NCST/482/426/2023) obtained from the National Council for Science and Technology (NCST) of Rwanda.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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