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RESEARCH ARTICLE

Biochar and compost addition increases soil organic carbon content and substitutes P and K fertilizer in three French cropping systems

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Abstract

Biochar and compost are increasingly considered sustainable amendments to improve soil fertility, while reducing agrochemical use. However, the efficiency of biochar, compost, and especially their mixtures under field conditions in temperate regions is still poorly studied. The objective of this study was to evaluate the effects of biochar/compost mixtures on crop yield and soil properties in French temperate cropping systems and to compare the amendment effects to soils receiving mineral potassium and phosphorus fertilization. To this end, green waste compost alone (8 $t.ha^{-1}$) or in mixture with three contrasted biochars (8 $t.ha^{-1}$ compost and 4 $t.ha^{-1}$ biochar) were applied to maize-wheat cropping systems located in three major agricultural territories in France. Results showed that maize and wheat yields were predominantly site specific. Within each site, compost and biochar application led to similar yields and nutrient uptakes as compared to the mineral fertilization, suggesting that compost-biochar mixtures might be as efficient as mineral fertilizers to supply potassium and phosphorus, while biochar did not improve compost benefits to plant yield. Moreover, the effects of compost-biochar mixtures on soil organic carbon concentrations were site specific and led to no effect or increase by up to 53%. We conclude that compost-biochar mixtures may increase carbon content in soil and substitute phosphorus and potassium mineral fertilizers for crop production in temperate cropping systems, even though their effects are site specific.

Keywords Biochar · Compost · Crops · Mineral fertilization · Temperate cropping system · Yield

1 Introduction

The demand for food is increasing with a growing world population and it is forecasted that 60% higher yields will be needed by 2050 to meet food demands (Rahman et al. 2020). To produce more food on the same agricultural area, conventional agriculture usually relies on the application of chemical fertilizers, especially nitrogen (N), phosphorus (P), and potassium (K), and other agrochemical inputs (e.g., pesticides, irrigation). However, although all of the farmer practices (e.g., mechanization of the process, use of agrochemicals) highly improved yields in the past, new yields of most crops are stagnating (Brisson et al. 2010; Schauberger et al. 2018). The massive use of inorganic fertilizers not only impacts farmer's incomes due to the skyrocketing prices of these fossil-based products (Eisa et al. 2022) but also leads to environmental concerns. For instance, nutrients contained in chemical fertilizers, such as N and P, may be easily lost from agricultural systems through leaching or runoff and can contaminate waterways (Savci 2012; Adegbeye et al. 2020). In general, intensive agriculture causes soil degradation including loss of organic matter, erosion, and salinity (Kopittke et al. 2019). Consequently, there is a need to develop alternatives allowing to ensure high crop yield in a more environmentally friendly way.

It has been suggested that in the context of a circular economy, organic amendments should be used to improve

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the capacity of the soil to provide sufficient nutrients to plants for their growth and reproduction (Bünemann et al. 2018) and reduce the risk of nutrient leaching and loss through slower nutrient release (Calabi-Floody et al. 2018). In addition, organic amendments may improve soil organic carbon contents with positive effects on soil properties and functioning. The use of organic amendment has been recommended as one way to achieve the goals of the 4p1000 initiative, because contrary to chemical fertilizers, stable organic amendments have the advantage of leading to soil organic carbon storage in addition to providing benefits for soil fertility (Chabbi et al. 2017). Among the possible organic amendments, compost is already commonly used in cropping systems in France (about 4.4 Mt per year applied on average) (Houot et al. 2014). Compost is the product of microbial degradation of organic materials (Diacono and Montemurro 2010), mainly characterized by its high organic matter content and often elevated nutrient content, depending on the feedstock (Siedt et al. 2021). Compost was shown to improve soil fertility and crop yields (Doan et al. 2015; Kowaljow et al. 2017; Chehab et al. 2019). However, once applied to the soil, compost is easily degraded by microorganisms over time and therefore needs to be re-applied frequently. In contrast, biochar, the product of pyrolysis under low or absent oxygen conditions (Lehmann and Joseph 2009; Joseph et al. 2021), is a more stable amendment than compost (Das et al. 2020). Although socio-economic studies on biochar use are still scarce, manufacturing biochar from waste materials, such as crop straw, sludge, not only reduces the production price but also reduces the need to dispose of those materials, and thus the cost associated to it, while meeting the circular economy principles (Yrjälä et al. 2022). Biochar is characterized by a highly condensed carbon and aromatic structure, which is usually more stable against microbial decomposition and it can thus increase the soil organic matter content (Kuzyakov et al. 2014; Ayaz et al. 2021). Therefore, the utilization of biochar has recently been mentioned as a climate change mitigation strategy in the IPCC report of 2021 (Masson-Delmotte et al. 2021). In addition, even though it has usually a relatively low content in nutrients, its sorption capacity allows biochar to retain nutrients in soils, preventing their leaching (Hagemann et al. 2017a; Jeyasubramanian et al. 2021; Rasse et al. 2022). Moreover, the porous structure of biochar may provide new habitats for microorganisms, leading to increased microbial activity that promotes nutrient recycling (Gorovtsov et al. 2020). Therefore, combining biochar with compost could be beneficial, as it might allow for a better stability of compost due to a synergistic effect between the two amendments (Hagemann et al. 2017b; Naeem et al. 2018; Liang et al. 2021) and may improve compost efficiency by enhancing microbial functions and reducing nutrient loss (Al-Wabel et al. 2018).

It has been shown that such combinations could improve crop yield under tropical conditions (Doan et al., 2015) or soil fertility under temperate conditions (Liu et al. 2012), while reducing the negative impacts of agriculture on the environment. However, contrasting effects of compost-biochar mixtures have also been emphasized on crop yield and soil properties, with either positive (Abbas et al. 2020; Zahra et al. 2021), neutral (Trupiano et al. 2017; Seehausen et al. 2017; Abideen et al. 2020), or negative (Mensah and Frimpong 2018; Manolikaki and Diamadopoulos 2019) effects of their combination compared to their single application. In addition, only a few studies were carried out under field conditions, and most of those were performed in low-nutrient, acidic soils; arid (Rocci et al. 2019; Abd El-Mageed et al. 2021; Zahra et al. 2021); or tropical climates (Agegnehu et al. 2015, 2016; Hannet et al. 2021). Field studies with compost-biochar mixtures in temperate regions are still scarce (Glaser et al. 2015; Mierzwa-Hersztek 2016; Honvault et al. 2023) and biochars with contrasting properties have rarely been used as compost blends. Given the increasing need to find sustainable solutions for agricultural management in temperate regions, where soils have lost organic matter and agricultural practices often rely on heavy use of mineral fertilizer, blending compost with biochar could be a sustainable solution to enhance plant growth and soil quality. Therefore, there is an urgent need to study the effects of compost-biochar mixtures under temperate field conditions before recommending their use in cropping systems as a sustainable practice. As both biochar and compost have low available N contents and may not be able to replace mineral N fertilization, we investigated in this study their effect on K and P fertilizer requirements.

The aims of this study were thus to evaluate the effects of different compost-biochar mixtures on soil chemical properties, plant growth, and plant nutritional status under field conditions representative of three major French agricultural regions (Fig. 1). To this end, three biochars with contrasting properties were applied in mixture with compost in a maize-wheat cropping system at low but realistic rates (4 $t.ha^{-1}$ biochar in mixture with 8 $t.ha^{-1}$ compost), and compared to compost alone (8 $t.ha^{-1}$ compost) and equivalent mineral P and K fertilization. Plant yields, nutritional status, and soil properties were monitored each year at harvest over 2 years. We hypothesized that there are positive effects of compost and biochar on crop growth (yield and nutrient contents), soil chemical fertility (pH, CEC, and nutrient availability), and soil organic matter content because of enhancement of soil quality due to amendment addition. We also hypothesized that compost-biochar mixtures will be a suitable substitute to P and K chemical fertilization. Moreover, we hypothesized that mixing biochar with compost would improve compost effects on soil fertility and crop growth because of additional effects, depending on its properties. To

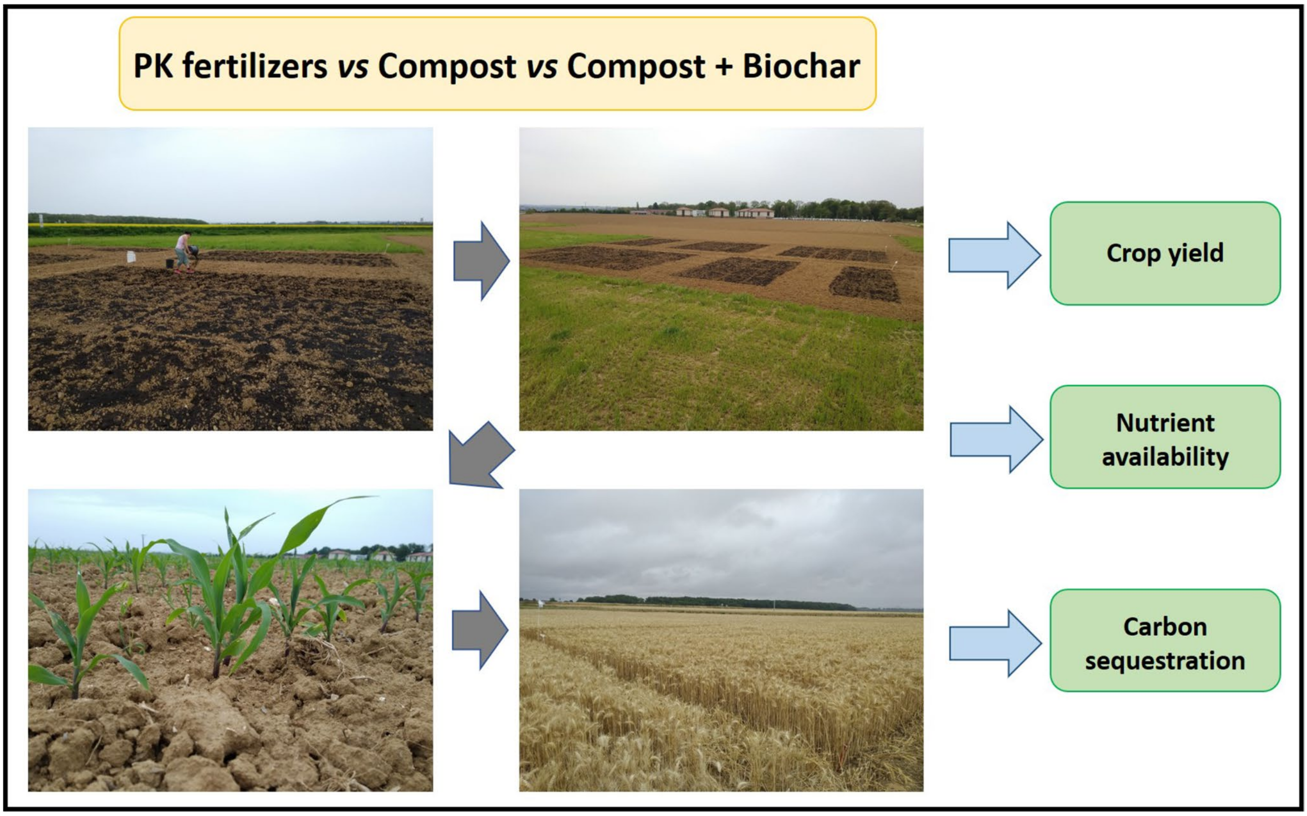

Fig. 1 Framework of the paper: applying organic amendments (compost and compost-biochar mixtures) to replace PK fertilizer and improve soil fertility and crop yield.

our knowledge, this study is one of the first, which evaluates the agronomic effect of different compost-biochar mixtures under temperate climate conditions in several regions over 2 years. It will help gain a better understanding of the response of soil and plants to organic amendments in temperate climates and the possibility to replace chemical fertilizer. In addition, as such combined biochar-compost application is of increasing interest to companies and farmers, especially in France, its results may help in decision-making.

2 Materials and methods

2.1 Study sites

Three sites were selected in three major agricultural regions (Hauts-de-France: 31,806 km^2, 68% of arable surface; Grand Est: 57,441 km^2, 53% of arable lands; and Centre-Val-de-Loire: 39,151 km^2, 61% of arable surface) in France. The first site was a Luvisol located in Beauvais (Oise, Haut-de-France region, 49°25′49″N, 2°04′51″E). The soil had a silty loam texture, precipitation was 669 mm per year on average and average monthly temperatures ranged between 6.5 and 14.9 °C (data of 2019 from MeteoFrance). The second site was a silty loam Fluvisol in Largitzen (Haut-Rhin, Grand Est region, 47°35′17″N, 7°15′08″E). At this site, annual precipitation was on average 773 mm and average monthly temperatures varied from 6.1 to 15.5 °C. The last site was a Cambisol located in Heugnes (Indre, Centre-Val-de-Loire region, 47°00′44″N, 1°24′30″E), with a loamy soil texture, annual precipitation of 737 mm per year and average monthly temperatures ranging from 7.3 to 16.3 °C.

Before starting the field trial, six soil samples per site were taken for soil characterization at 0–15 cm. The properties of the soils before the trial are presented in Table 1. Briefly, the sites in Haut-Rhin and Oise have a slightly basic pH (pH 7.4 to 7.9), while in Indre, the pH is slightly acidic (pH 6.5). The site in Haut-Rhin also has elevated C (2.3%), available P (0.11 g.kg^{-1}), and exchangeable cations (0.1 to 3 g.kg^{-1}) contents and the highest CEC (13.4 cmolc.kg^{-1}). From this analysis, the site in Haut-Rhin can be characterized as more fertile than the other two sites.

2.2 Compost and biochar amendments

Two amendment types were applied to the soil, a compost, and three compost-biochar mixtures. The compost was the result of 4 months of thermophilic phase and

Table 1 Properties of the soil (0–15 cm) before trial

	Units (dry weight)	Haut-Rhin	Oise	Indre
Texture		Silty-loam	Silty-loam	Loamy
Clay	%	17.8	20.5	21.5
Fine silt	%	36.2	26.4	20.6
Coarse silt	%	41.6	43.0	24.5
Fine sand	%	2.07	7.47	16.18
Coarse sand	%	2.2	2.6	17.22
pH (H_2O) [a]		7.4	7.93	6.48
Total carbonates [b]	%	0	0.8	0
Organic C [c]	g.kg^{-1}	22.57	10.22	13.57
Cation exchange capacity [d]	cmolc.kg^{-1}	13.47	10.92	10.32
Total N[e]	g.kg^{-1}	2.08	1.13	1.28
Total P	g.kg^{-1}	0.75	0.57	0.36
Total K	g.kg^{-1}	12.98	14.32	9.98
Total Mg	g.kg^{-1}	4.66	3.2	1.49
Total Ca	g.kg^{-1}	6.81	7.77	2.87
Total Na	g.kg^{-1}	8.69	5.85	2.14
Available P [f]	g.kg^{-1}	0.11	0.07	0.02
Exchangeable K [g]	g.kg^{-1}	0.24	0.12	0.14
Exchangeable Mg [g]	g.kg^{-1}	0.1	0.07	0.06
Exchangeable Ca [g]	g.kg^{-1}	3.12	3.94	1.94
Exchangeable Na [g]	g.kg^{-1}	0	0.01	0.01
DTPA-Fe[h]	mg.kg^{-1}	63.42	25.27	35.52
DTPA-Mn[h]	mg.kg^{-1}	16.02	10.17	15.83
DTPA-Cu[h]	mg.kg^{-1}	1.35	1.5	0.63
DTPA-Zn[h]	mg.kg^{-1}	2.43	1.95	1.4
Soluble B[i]	mg.kg^{-1}	0.58	0.32	0.6

[a]1:5 ratio NF ISO 10390; [b]NF ISO 10693; [c]dry combustion NF ISO 14235; [d]Metson method NFX 31-130; [e]Dumas method; [f]Joret Hebert method NFX 31-161; [g]NFX 31-108; [h]NFX 31-131; [i]NFX 31-122

2 months of maturation of green wastes, i.e., grass, poplar, and conifer branches. It was made and supplied by Fertivert (Seine-Maritime, France). Three feedstocks, coming from waste materials, were used to make the biochars: green waste compost residue biomass, Miscanthus (*Miscanthus* × *giganteus*), and rapeseed (*Brassica napus*) straws. Those specific raw materials were selected due to their availability, the contrasted properties of their resulting biochars, and positive results in a previous study (Honvault et al. 2022). The compost residues were made of the uncomposted biomass left after the process of the above-mentioned green waste compost. More details can be found in Nobile et al. (2020). The pyrolysis was performed in an industrial pyrolysis reactor (Biogreen®Pyrolysis Technology, ETIA, Oise, France) by VT Green (Allier, France). Pyrolysis temperature differed among the feedstocks, i.e., 450 °C for compost refusal biomass, 550 °C for Miscanthus, and 650 °C for rapeseed straw, but all biochars had the same residence time in the pyrolyzer (i.e., 10 min) (Table 2). Compost-biochar mixtures were manually prepared with a 70:30 weight ratio, on a dry matter basis. The characteristics of each mixture are presented in Table 3.

2.3 Experimental design

At each site, twenty plots (10 × 3.2 m) were delimited in two rows of ten plots, separated by 3 m (Fig. S1). In total, five treatments were tested in four replicates arranged in a randomized complete block design: (i) a mineral fertilization ("MF"), where the same amount of P and K as in the compost was applied (calculated based on P and K contents in the compost and the application rate of the compost), i.e., 34 kg.ha^{-1} and 138 kg.ha^{-1}, respectively, in the form of triple superphosphate and KCl; (ii) compost alone ("Comp"); (iii) the mixture of compost with rapeseed straw biochar ("Comp + B-RS"); (iv) the mixture of compost with the *Miscanthus* biochar ("Comp + B-Misc"); and (v) the mixture of compost with the green waste compost residue biochar ("Comp + B-Ref"). The compost was applied at 19.6 t.ha^{-1} on a fresh weight basis, which equaled an application rate of 8 t.ha^{-1} on a dry weight

Table 2 Properties of biochars

	Units (dry weight)	Rapeseed biochar	Miscanthus biochar	Green waste compost residue biochar
pH (H_2O)[a]		11.2	10.4	11.4
Electrical conductivity[a]	$dS.cm^{-1}$	1.22	1.32	3.54
Cation exchange capacity[b]	$cmolc.kg^{-1}$	2.9	31	8.5
Porosity[c]	%	95.9	92.5	86.3
Density[d]	$g.L^{-1}$	73	112	291
Organic C[e]	%	62.27	74.04	55.53
Total N[f]	%	0.81	0.26	0.84
C:N		43.58	155.77	37.56
Ash content[g]	%	16.8	14	26.3
Total P[h]	$g.kg^{-1}$	3.75	3.06	3.71
Total K[h]	$g.kg^{-1}$	18.18	25.24	17.85
Total Mg[h]	$g.kg^{-1}$	4.16	0.6	5.07
Total Ca[h]	$g.kg^{-1}$	66.17	2.14	34.02

[a] 1:5 ratio NF ISO 10390; [b] Metson method NFX 31-130; [c] NF EN 13041; [d] NF EN 13041; [e] dry combustion NF ISO 14235; [f] Dumas method; [g] ISO 1171:2010; [h] total digestion followed by ICP measurement (NF EN 13560, ICP MS EN ISO 17294)

Table 3 Properties of the different amendment formulations applied to the field

	Organic C ($g.kg^{-1}$)	Total N ($g.kg^{-1}$)	C:N	Total P ($g.kg^{-1}$)	Total K ($g.kg^{-1}$)	Total Ca ($g.kg^{-1}$)	Total Mg ($g.kg^{-1}$)
Compost	292	27	10	4.2	17	29	2.8
Compost + rapeseed biochar	429	21	20	3.5	20	32	2.2
Compost + miscanthus biochar	337	18	18	3.4	16	24	2.3
Compost + green waste residue biochar	344	22	15	5.3	19	31	2.9

basis, while the mixtures were applied at 24.5 $t.ha^{-1}$ on a fresh weight basis, which corresponded to 12 $t.ha^{-1}$ on a dry weight basis, with 8 $t.ha^{-1}$ compost and 4 $t.ha^{-1}$ biochar. Following conservation agriculture principles, the soil was not tilled, but the amendments were incorporated at 5 cm depth using a rotary harrow. Amendments were applied on March 26, 2019 in Haut-Rhin, on April 8, 2019 in Indre, and on April 23, 2019 in Oise.

2.4 Crops

The trial lasted for 2 years and included two crops at each site. The first crop, maize, was sown with an 80 cm inter-row, which equaled to four maize rows per plot. The second crop included here was wheat. Table S1 summarizes the different steps on the field trial at the three sites. No additional irrigation was added. Nitrogen fertilization (50% urea + 50% NH_4NO_3) was applied during crop growth, depending on crop requirements and soil residual N content.

2.5 Soil and plant analyses

At the end of each growing season, both plant and soil samples were collected. For each plot, one composite soil sample was obtained from 10 sub-samples at 0–15 cm depth. The soil was analyzed for pH (NF ISO 10 390), organic C content (dry combustion, CHNS Flash 2000, Thermo Fisher Scientific), cation exchange capacity (NFX-31-130), available P (Joret-Hébert method NFX 31-161), and exchangeable K, magnesium (Mg), calcium (Ca), and sodium (Na) contents (NFX 31-108).

For maize, the total aboveground biomass of three plants was taken per plot, while for wheat, aerial biomass was sampled on an area of 0.5 m^2 in triplicates. The aerial biomass was dried at 60 °C for 48 h in order to determine the yield on a dry mass basis. Plant materials were then crushed to < 2 mm and analyzed for total N (Dumas method) and C (dry combustion, CHNS Flash 2000 Thermo Fisher Scientific) contents as well as macro- and micro-elemental concentrations, i.e., P, Ca, Mg, K, Na, Mn, Cu, Zn, and Fe, using dry combustion followed by ICP analysis (NF EN ISO

16634-1). Finally, the C/N ratio was calculated as well as the total element uptake per hectare (based on the dry weight production per hectare).

2.6 Statistical analysis

All soil and plant data were analyzed using R software version 3.5.1 (R Core Team 2013) using the same methodology. For each site, the normality assumption of the data was evaluated using the Shapiro test, then the data homoscedasticity was assessed with either Bartlett or Fligner tests, depending on the results of the Shapiro test. Means were compared using the ANOVA test for parametric data or Kruskal-Wallis test for non-parametric data, followed by post hoc comparison tests, TukeyHSD test, or Dunn test, respectively. In addition, on all of the data set (i.e., considering the three sites together), treatment, site, and their interaction effects were evaluated using a two-way ANOVA for parametric tests or Adonis test for non-parametric tests. Difference was considered significant at $p < 0.05$.

3 Results and discussion

3.1 Soil properties are modulated by organic amendments

In 2019, initial pH at the three sites was 6.5 (Indre), 7.5 (Haut-Rhin), and 8.1 (Oise). The C content ranged between 10.2 (Oise) and 22.6 g.kg^{-1} (Haut-Rhin) and the highest CEC was recorded at Haut-Rhin (13.5 cmolc.kg^{-1}), while Indre showed the lowest value (10.3 cmolc.kg^{-1}) (Table 4).

In 2019, compost alone only significantly increased SOC concentration in Oise (Fig. 2). Increased organic matter inputs, in the form of compost, usually lead to higher quantity and changes in the quality of soil organic matter (Magdoff and Weil 2004; Lima et al. 2009). Unlike in 2019, the effect of compost alone on SOC content was not significant in 2020, probably because of its fast biodegradation (Kimetu and Lehmann 2010; Agegnehu et al. 2017) and higher outputs of C than inputs, related to plant growth and previous harvest (2019).

When applied in mixture, compost mixed with rape and Misc biochars increased SOC concentrations at the Indre site and all compost-biochar mixtures increased SOC at the Oise site, while no effect was observed at Haut-Rhin. In 2020, after a second cropping season, soil parameters were not affected by amendment addition except SOC (Table S2), but only at one site. More specifically, SOC increased at the Oise site with the application of rape, Misc, and Ref compost-biochar mixtures (Fig. 2 and Table 4).

The increase of SOC in the presence of biochar is consistent with most of studies and is related to the high content of stable C in biochar (Kuzyakov et al. 2014; Abbott et al. 2018). Combined, both amendments appeared to contribute to increase soil organic matter concentration. The Oise site had the lowest initial SOC content which could explain that it was more influenced by organic amendment application. The Oise site also contained carbonate calcium (Table 1), which might have contributed to stabilize the organic matter in soil, inducing a longer positive effect of the organic amendment application by promoting Ca^{2+} bridging with organic matter (Fernández-Ugalde et al. 2014; Martí-Roura et al. 2019). Moreover, the whole plant-soil system may have been affected differently by the amendments depending on the original soil properties, and thus C outputs and inputs differed between sites, which could explain the effects observed only at one site in the second year.

By contributing to soil CEC, biochars can also reduce nutrient loss and increase nutrient availability for plants (Agegnehu et al. 2017). However, such effects may be more pronounced after biochar aging (Aubertin et al. 2021). Although biochar may contribute to increase soil CEC (Liang et al. 2006), no change in CEC was observed in our study. This might be related to the low rate of amendment application (von Glisczynski et al. 2016; Singh et al. 2022). For instance, Liu et al. (2012) found that CEC was only elevated significantly when 32.5 t.ha^{-1} of compost was combined with the highest amount of biochar (20 t.ha^{-1}), which is far above the rate of application of our study. In addition, the initially high fertility status of our soils may explain that compost-biochar mixtures fail to increase CEC since its rise depends on soil properties (Singh et al. 2022) and nutrient-poor or infertile soils are usually more sensitive to biochar additions (Van Zwieten et al. 2010; Crane-Droesch et al. 2013). Moreover, according to Busch and Glaser (2015), compost-biochar mixtures have no impact on soil pH even at higher rate of application (25 t.ha^{-1}). In addition, the lack of changes of soil pH might be due to the initially high pH of our soils (Table 1) compared to other studies performed on acidic soils (Agegnehu et al. 2017).

In 2019, only exchangeable Na increased at the Oise site for mixtures containing biochars B-RS, B-Misc, and B-Ref, and exchangeable K increased at the Indre site with mixtures containing rape and Misc biochar (Table 4). Except for Na, compost-biochar mixtures did not affect soil properties in the second year. The soil exchangeable nutrient contents are usually increased by organic amendment addition (Liu et al. 2012; Agegnehu et al. 2016; Gao and DeLuca 2016; Safaei Khorram et al. 2019; Getahun et al., 2020). While compost application usually increases soil nutrient availability, the lack of effect of some composts on soil nutrient availability could result from both (1) a low application rate and (2) a high compost particle size limiting surface contact with soil (Duong et al. 2012). Our results are also in line with the study by von

Table 4 Soil chemical properties measured in 2019 and 2020 in the different treatments in the sites located in Indre, Oise, and Haut-Rhin

	2019			2020		
	Indre	Oise	Haut-Rhin	Indre	Oise	Haut-Rhin
pH						
MF	6.48 ± 0.10 a	8.13 ± 0.05 a	7.45 ± 0.17 a	7.23 ± 0.22 a	8.03 ± 0.15 a	7.53 ± 0.13 a
Comp	6.73 ± 0.25 a	8.20 ± 0.00 a	7.58 ± 0.10 a	7.20 ± 0.22 a	8.15 ± 0.06 a	7.53 ± 0.10 a
Comp + B-RS	6.83 ± 0.15 a	8.20 ± 0.00 a	7.58 ± 0.05 a	7.13 ± 0.06 a	8.10 ± 0.10 a	7.60 ± 0.08 a
Comp + B-Misc	6.70 ± 0.34 a	8.13 ± 0.05 a	7.55 ± 0.06 a	6.98 ± 0.38 a	8.10 ± 0.08 a	7.50 ± 0.22 a
Comp + B-Ref	6.77 ± 0.21 a	8.18 ± 0.05 a	7.48 ± 0.15 a	7.10 ± 0.24 a	8.08 ± 0.05 a	7.60 ± 0.08 a
Organic carbon (g.kg^{-1})						
MF	12.60 ± 0.57 a	10.08 ± 0.38 a	21.60 ± 2.27 a	10.48 ± 0.46 a	10.45 ± 0.53 a	22.63 ± 2.28 a
Comp	14.13 ± 0.65 ab	12.13 ± 0.56 b	23.40 ± 1.20 a	10.38 ± 0.36 a	12.30 ± 0.72 ab	23.83 ± 0.85 a
Comp + B-RS	16.00 ± 0.95 b	13.57 ± 0.47 b	24.90 ± 1.60 a	10.27 ± 1.31 a	15.63 ± 2.55 b	23.60 ± 1.21 a
Comp + B-Misc	15.73 ± 1.38 b	13.75 ± 1.30 b	23.83 ± 1.91 a	10.93 ± 1.31 a	14.80 ± 2.97 b	22.70 ± 0.96 a
Comp + B-Ref	14.87 ± 0.83 ab	13.70 ± 0.73 b	23.70 ± 1.67 a	11.65 ± 2.25 a	17.53 ± 5.31 b	23.18 ± 2.45 a
Cation exchange capacity (cmol$_{(+)}$.kg^{-1})						
MF	10.45 ± 0.92 a	10.98 ± 0.59 a	13.40 ± 0.74 a	9.28 ± 1.58 a	10.78 ± 0.60 a	12.80 ± 0.96 a
Comp	10.93 ± 0.49 a	11.60 ± 0.55 a	14.00 ± 0.66 a	9.40 ± 1.22 a	11.23 ± 0.68 a	13.38 ± 0.75 a
Comp + B-RS	10.80 ± 0.60 a	11.27 ± 0.72 a	13.75 ± 0.74 a	9.20 ± 1.21 a	11.33 ± 0.45 a	13.28 ± 0.82 a
Comp + B-Misc	11.15 ± 0.67 a	11.55 ± 0.76 a	13.65 ± 0.27 a	9.65 ± 1.04 a	11.48 ± 0.82 a	13.10 ± 0.46 a
Comp + B-Ref	10.90 ± 0.79 a	11.65 ± 0.68 a	13.88 ± 0.55 a	9.55 ± 1.09 a	12.08 ± 1.10 a	13.30 ± 0.78 a
Exchangeable phosphorus (g.kg^{-1})						
MF	0.030 ± 0.003 a	0.077 ± 0.004 a	0.122 ± 0.026 a	0.011 ± 0.003 a	0.076 ± 0.008 a	0.104 ± 0.026 a
Comp	0.030 ± 0.008 a	0.084 ± 0.010 a	0.129 ± 0.021 a	0.011 ± 0.003 a	0.081 ± 0.009 a	0.110 ± 0.015 a
Comp + B-RS	0.034 ± 0.002 a	0.080 ± 0.003 a	0.121 ± 0.021 a	0.011 ± 0.004 a	0.087 ± 0.017 a	0.104 ± 0.014 a
Comp + B-Misc	0.029 ± 0.004 a	0.086 ± 0.018 a	0.107 ± 0.021 a	0.012 ± 0.003 a	0.082 ± 0.020 a	0.105 ± 0.022 a
Comp + B-Ref	0.034 ± 0.008 a	0.084 ± 0.010 a	0.117 ± 0.017 a	0.014 ± 0.006 a	0.112 ± 0.046 a	0.097 ± 0.020 a
Exchangeable potassium (g.kg^{-1})						
MF	0.143 ± 0.008 a	0.160 ± 0.022 a	0.324 ± 0.088 a	0.091 ± 0.015 a	0.143 ± 0.016 a	0.239 ± 0.075 a
Comp	0.169 ± 0.019 ab	0.168 ± 0.024 a	0.276 ± 0.043 a	0.085 ± 0.007 a	0.143 ± 0.017 a	0.216 ± 0.067 a
Comp + B-RS	0.199 ± 0.000 b	0.180 ± 0.019 a	0.309 ± 0.040 a	0.105 ± 0.013 a	0.188 ± 0.021 a	0.234 ± 0.052 a
Comp + B-Misc	0.187 ± 0.039 b	0.168 ± 0.033 a	0.278 ± 0.014 a	0.100 ± 0.029 a	0.162 ± 0.054 a	0.241 ± 0.015 a
Comp + B-Ref	0.177 ± 0.010 ab	0.178 ± 0.014 a	0.324 ± 0.038 a	0.092 ± 0.020 a	0.189 ± 0.083 a	0.234 ± 0.018 a
Exchangeable magnesium (g.kg^{-1})						
MF	0.069 ± 0.014 a	0.072 ± 0.008 a	0.101 ± 0.014 a	0.067 ± 0.015 a	0.076 ± 0.009 a	0.096 ± 0.013 a
Comp	0.078 ± 0.010 a	0.083 ± 0.003 a	0.113 ± 0.010 a	0.064 ± 0.010 a	0.080 ± 0.008 a	0.106 ± 0.013 a
Comp + B-RS	0.080 ± 0.013 a	0.084 ± 0.007 a	0.109 ± 0.011 a	0.065 ± 0.014 a	0.092 ± 0.016 a	0.101 ± 0.009 a
Comp + B-Misc	0.079 ± 0.008 a	0.083 ± 0.006 a	0.113 ± 0.005 a	0.063 ± 0.005 a	0.090 ± 0.009 a	0.106 ± 0.006 a
Comp + B-Ref	0.078 ± 0.004 a	0.083 ± 0.008 a	0.117 ± 0.012 a	0.066 ± 0.007 a	0.099 ± 0.021 a	0.104 ± 0.004 a
Exchangeable calcium (g.kg^{-1})						
MF	1.88 ± 0.19 a	4.35 ± 0.50 a	2.98 ± 0.28 a	1.98 ± 0.32 a	4.76 ± 0.50 a	3.07 ± 0.21 a
Comp	2.09 ± 0.23 a	4.59 ± 0.55 a	3.24 ± 0.11 a	2.04 ± 0.09 a	4.53 ± 0.56 a	3.20 ± 0.10 a
Comp + B-RS	2.07 ± 0.13 a	4.44 ± 0.61 a	3.02 ± 0.09 a	1.87 ± 0.17 a	4.72 ± 0.42 a	3.08 ± 0.10 a
Comp + B-Misc	2.09 ± 0.24 a	4.27 ± 0.58 a	3.03 ± 0.25 a	1.98 ± 0.44 a	4.68 ± 0.50 a	3.02 ± 0.25 a
Comp + B-Ref	2.05 ± 0.29 a	4.51 ± 0.46 a	3.04 ± 0.20 a	1.97 ± 0.24 a	4.79 ± 0.64 a	3.15 ± 0.26 a
Exchangeable sodium (g.kg^{-1})						
MF	0.015 ± 0.014 a	0.014 ± 0.001 a	0.010 ± 0.006 a	0.009 ± 0.002 a	0.006 ± 0.001 a	0.004 ± 0.009 a
Comp	0.012 ± 0.003 a	0.017 ± 0.002 ab	0.009 ± 0.002 a	0.008 ± 0.001 a	0.007 ± 0.000 a	0.001 ± 0.002 a
Comp + B-RS	0.012 ± 0.001 a	0.019 ± 0.001 bc	0.010 ± 0.002 a	0.010 ± 0.004 a	0.007 ± 0.001 ab	0.000 ± 0.000 a
Comp + B-Misc	0.011 ± 0.001 a	0.017 ± 0.001 bc	0.010 ± 0.001 a	0.008 ± 0.001 a	0.007 ± 0.001 a	0.000 ± 0.000 a
Comp + B-Ref	0.018 ± 0.007 a	0.020 ± 0.002 c	0.012 ± 0.002 a	0.010 ± 0.003 a	0.009 ± 0.001 b	0.000 ± 0.000 a

MF, mineral fertilizer; *Comp*, green waste compost; *Comp + B-RS*, green waste compost + rapeseed biochar; *Comp + B-Misc*, green waste compost + *Miscanthus* biochar; *Comp + B-Ref*, green waste compost + green waste compost residue biochar. Letters indicate significant difference between treatments for each site

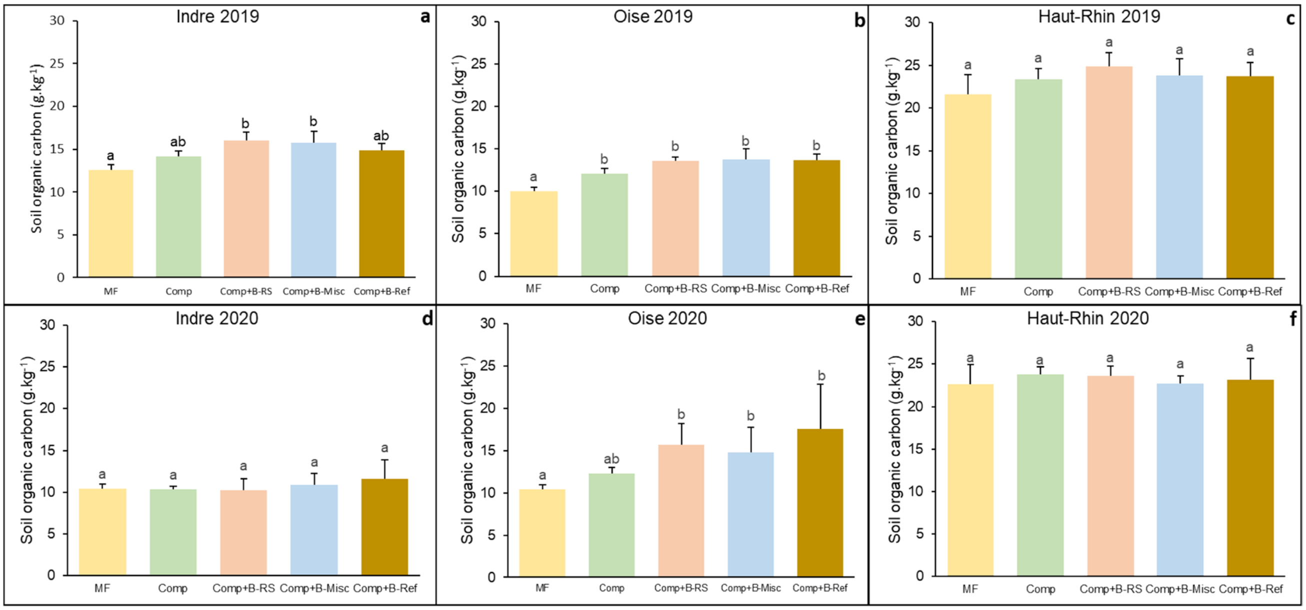

Fig. 2 Soil organic carbon content (g.kg^{-1}) measured in 2019 (**a–c**) and 2020 (**d–f**) in the different treatments in the sites located in Indre (**a**,**d**), Oise (**b**,**e**), and Haut-Rhin (**c**,**f**). MF, mineral fertilizer; Comp, green waste compost; Comp + B-RS, green waste compost + rapeseed biochar; Comp + B-Misc, green waste compost + *Miscanthus* biochar; Comp + B-Ref, green waste compost + green waste compost refusal biochar biochar. Letters indicate significant difference between treatments for each site.

Glisczynski et al. (2016), finding few and short-time effects of compost-biochar mixtures on soil nutrient stocks after application to a German agricultural soil. However, they differ from most studies showing that biochar often increases soil pH and available nutrients few weeks after its application (Chan et al. 2007; Agegnehu et al. 2016, 2017; Getahun et al. 2020). The lack of effect of compost-biochar mixtures on available nutrient concentrations has been attributed by von Glisczynski et al. (2016) to the fact that nutrient availability depends on both the source of biochar and its rate of application. In our study, none of the three diverse compost-biochar mixtures led to significant changes in soil nutrient availability neither compared to the mineral treatment nor to compost alone. Therefore, the lack of effect of compost-biochar mixtures on nutrient availability is likely due to two different factors, i.e., the low biochar application (4 t.ha^{-1}) compared to most studies, which use at least 10 t.ha^{-1} (Jeffery et al. 2011; Schulz et al. 2014; Agegnehu et al. 2017) and the initial high fertility of the investigated soils.

Consistently with Jeffery et al. (2011) and Lévesque et al. (2021), we conclude that even though biochar is frequently considered to improve soil fertility (Abbott et al. 2018), its application in combination with compost has a limited effects on physico-chemical properties of soils in temperate regions when using “realistic” application rates. Applied doses in this field experimental trial are nevertheless relevant in regard to realistic agricultural practices and particularly when considering the current price of biochar (between \$600 and \$1200 per ton) (Yrjälä et al. 2022).

Nevertheless, amendments can increase soil C sequestration without decreasing crop yields (Oldfield et al. 2018). Our observations support the fact that the application of compost-biochar mixtures leads to higher C concentrations in soils, especially when applied to low-carbon soils. Indeed, the Haut-Rhin site had a higher initial C content than the Indre and Oise sites and amendment effects on SOC content are thus less important under these conditions. Both, compost alone and compost-biochar mixtures, increased SOC contents. The presence of biochar in the mixture allowed the effect to be maintained over time because of its inherent higher stability and possible interactions between both materials (Aubertin et al. 2021), while compost alone showed a temporary increase only, which makes it less suitable for enhancing carbon storage in soil.

3.2 Maize and wheat yields are not affected by organic amendments

Maize yields ranged between 4.6 and 23 t.ha^{-1}, while wheat yields ranged between 5.4 and 8.8 t.ha^{-1} at the three sites (Fig. 3). Both maize and wheat yields decreased in the order Haut-Rhin > Oise > Indre. At all the three sites, maize biomass production and wheat yields were not affected by the application of the organic amendments (Fig. 3). The interaction between treatment × site was not significant (Tables

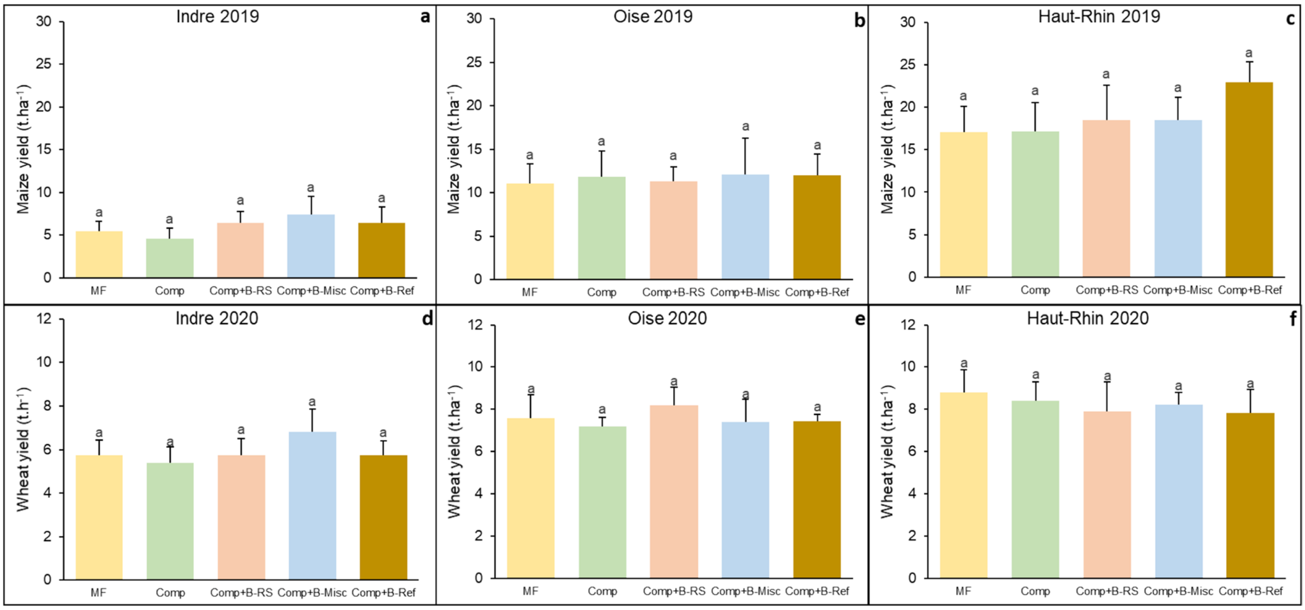

Fig. 3 Yield (t.ha^{-1}) of maize (**a**–**c**) and wheat (**d**–**f**) grown under the different treatments in the sites located in Indre (**a**,**d**), Oise (**b**,**e**), and Haut-Rhin (**c**,**f**). MF, mineral fertilizer; Comp, green waste compost; Comp + B-RS, green waste compost + rapeseed biochar; Comp + B-Misc, green waste compost + *Miscanthus* biochar; Comp + B-Ref, green waste compost + green waste compost refusal biochar biochar. Letters indicate significant difference between treatments for each site.

S3 and S4). Our data are in contrast to studies from tropical low fertile agricultural systems, where biochar and compost have been shown to improve plant biomass and yield, both separately and in combination (Doan et al. 2015; Liu et al. 2017; Chehab et al. 2019). This was related to improvements of the initial poor soil conditions, i.e., lower bulk density and higher organic matter content, nutrient availability, and pH (El-Naggar et al. 2019; Libutti and Rivelli 2021; Agbede 2021), while our tested soils were already highly fertile.

Several studies demonstrated that combining compost with biochar could improve yields compared to single amendments (Cao et al. 2017; Agegnehu et al. 2017; Manolikaki and Diamadopoulos 2019; Abideen et al. 2020; Abbas et al. 2020). In contrast, other studies observed that, compared to single biochar or compost amendment, their combination had a negative (Trupiano et al. 2017) or neutral effect (Seehausen et al. 2017) on plant growth. This field study showed no effect of amendment application (alone or combined) on maize and wheat yield, irrespective of the site, which is related to the site climate region of the studied sites and the application rate. Indeed, several meta-analyses attempted to unravel the effects of amendment application, alone or combined, on crop yields. These studies revealed that growth improvements were higher in tropical regions than in temperate zones, at higher application rates of amendments and in acidic to neutral soils with a coarse to medium texture (Jeffery et al. 2011; Biederman and Harpole 2013; Wortman et al. 2017; Farhangi-Abriz et al. 2021; Xu et al. 2021; Bai et al. 2022). Thus, it could be hypothesized that amendments had no effects because of a low application rate and an optimal N fertilization.

In addition, the lack of treatment effects also reflects the potential of compost and compost-biochar mixtures to replace mineral nutrients. Even though mineral N fertilizer was applied in all treatments to sustain plant growth and avoid possible N deficit in crops induced by biochar and compost application (Gao et al. 2019), treatments with biochar/compost mixtures did not receive mineral P and K fertilization but showed yields as high as in the mineral treatment.

Site location had a high influence on both maize and wheat yields. Among the three sites, Haut-Rhin was the one with the highest yields, which could be related to its higher initial CEC, C, and available P, K, and Mg concentrations as well as more favorable climate conditions (Table 1). This was particularly the case in 2019, during which a drought event occurred, which was particularly intense in Oise (250-mm rainfall between April and September) and Indre (260-mm rainfall between April and September), but less in Haut-Rhin (350-mm rainfall between April and September). Moreover, available P concentration and CEC followed the same trend as biomass production, i.e., Haut-Rhin > Oise > Indre, and thus could be the main parameters controlling crop yields, especially in case of P, which is known to be a key driver of the productivity of agro-ecosystems (Faucon et al. 2015), especially in temperate areas (Houben

Table 5 Maize and wheat elemental concentrations measured in 2019 (maize) and 2020 (maize) in plants grown on the different treatments in the sites located in Indre, Oise, and Haut-Rhin

	Maize			Wheat		
	Indre	Oise	Haut-Rhin	Indre	Oise	Haut-Rhin
Total carbon content (%)						
MF	45.9 ± 0.2 a	46.1 ± 0.2 a	46.2 ± 0.2 a	44.5 ± 0.4 a	44.7 ± 0.2 a	44.2 ± 0.4 a
Comp	46.0 ± 0.6 a	45.9 ± 0.6 a	46.5 ± 0.4 a	44.8 ± 0.8 a	44.8 ± 0.5 a	44.2 ± 0.2 a
Comp + B-RS	45.7 ± 0.3 a	46.4 ± 0.0 a	46.3 ± 0.2 a	44.8 ± 0.4 a	44.8 ± 0.1 a	44.3 ± 0.1 a
Comp + B-Misc	45.7 ± 0.3 a	46.1 ± 0.5 a	46.4 ± 0.2 a	45.2 ± 0.7 a	44.7 ± 0.1 a	44.2 ± 0.3 a
Comp + B-Ref	45.8 ± 0.7 a	46.1 ± 0.6 a	46.3 ± 0.2 a	44.8 ± 0.5 a	44.7 ± 0.3 a	44.4 ± 0.3 a
Total nitrogen content (%)						
MF	1.2 ± 0.1 a	1.0 ± 0.2 a	1.2 ± 0.1 a	1.3 ± 0.0 a	1.4 ± 0.4 a	1.2 ± 0.1 a
Comp	1.3 ± 0.2 a	1.1 ± 0.2 a	1.2 ± 0.1 a	1.3 ± 0.1 a	1.0 ± 0.1 a	1.3 ± 0.2 a
Comp + B-RS	1.3 ± 0.1 a	1.1 ± 0.2 a	1.1 ± 0.0 a	1.1 ± 0.2	1.2 ± 0.2 a	1.1 ± 0.1 a
Comp + B-Misc	1.2 ± 0.2 a	1.0 ± 0.2 a	1.2 ± 0.0 a	1.2 ± 0.2 a	1.1 ± 0.1 a	1.2 ± 0.2 a
Comp + B-Ref	1.2 ± 0.1 a	1.0 ± 0.1 a	1.3 ± 0.1 a	1.3 ± 0.1 a	1.1 ± 0.1 a	1.2 ± 0.1 a
Phosphorus concentration (g.kg^{-1})						
MF	1.0 ± 0.2 a	2.2 ± 0.4 a	2.3 ± 0.1 a	1.9 ± 0.1 a	2.1 ± 0.4 a	2.6 ± 0.5 a
Comp	1.1 ± 0.3 a	2.3 ± 0.6 a	2.3 ± 0.2 a	1.8 ± 0.2 a	1.8 ± 0.2 a	2.7 ± 0.3 a
Comp + B-RS	1.2 ± 0.2 a	2.3 ± 0.6 a	2.0 ± 0.2 a	1.9 ± 0.2 a	1.9 ± 0.2 a	2.7 ± 0.3 a
Comp + B-Misc	1.3 ± 0.3 a	2.3 ± 0.3 a	2.1 ± 0.1 a	1.8 ± 0.2 a	1.9 ± 0.2 a	2.7 ± 0.1 a
Comp + B-Ref	1.1 ± 0.1 a	2.3 ± 0.5 a	2.3 ± 0.3 a	1.9 ± 0.2 a	1.9 ± 0.1 a	2.8 ± 0.2 a
Potassium concentration (g.kg^{-1})						
MF	9.0 ± 0.4 a	10.5 ± 0.5 a	10.3 ± 0.5 a	6.9 ± 0.7 a	6.9 ± 1.0 a	10.0 ± 0.8 a
Comp	9.6 ± 1.3 a	10.2 ± 0.7 a	9.4 ± 0.5 a	6.9 ± 1.0 a	5.7 ± 0.1 a	10.4 ± 0.5 a
Comp + B-RS	10.5 ± 0.8 a	11.1 ± 0.5 a	10.7 ± 0.7 a	6.3 ± 0.9 a	7.0 ± 1.4 a	9.8 ± 0.5 a
Comp + B-Misc	9.6 ± 0.8 a	10.5 ± 0.1 a	10.2 ± 0.5 a	7.6 ± 1.5 a	6.3 ± 1.1 a	7.8 ± 4.4 a
Comp + B-Ref	9.4 ± 0.5 a	10.3 ± 0.4 a	10.0 ± 0.6 a	7.8 ± 0.4 a	6.8 ± 0.9 a	10.0 ± 0.9 a
Calcium concentration (g.kg^{-1})						
MF	3.9 ± 0.2 a	4.8 ± 0.3 a	2.8 ± 0.7 a	1.6 ± 0.1 a	2.1 ± 0.5 a	1.6 ± 0.7 a
Comp	4.1 ± 0.4 a	4.5 ± 0.4 a	2.5 ± 0.3 a	1.8 ± 0.2 a	1.8 ± 0.2 a	1.7 ± 0.4 a
Comp + B-RS	3.6 ± 0.6 a	4.7 ± 0.7 a	2.9 ± 0.3 a	1.5 ± 0.1 a	2.1 ± 0.7 a	1.4 ± 0.1 a
Comp + B-Misc	3.5 ± 0.2 a	4.4 ± 0.3 a	2.8 ± 0.4 a	1.9 ± 0.5 a	1.8 ± 0.1 a	1.6 ± 0.2 a
Comp + B-Ref	3.8 ± 0.3 a	4.8 ± 0.7 a	3.0 ± 0.2 a	1.8 ± 0.3 a	2.0 ± 0.3 a	1.6 ± 0.2 a
Magnesium concentration (mg.kg^{-1})						
MF	1842 ± 138 a	1753 ± 95 a	1163 ± 92 a	796 ± 93 a	787 ± 36 a	832 ± 60 a
Comp	1949 ± 227 a	1719 ± 93 a	1113 ± 78 a	784 ± 71 a	727 ± 31 a	841 ± 63 a
Comp + B-RS	1787 ± 244 a	1843 ± 122 a	1076 ± 102 a	811 ± 108 a	781 ± 40 a	826 ± 59 a
Comp + B-Misc	1840 ± 197 a	1724 ± 100 a	1116 ± 67 a	742 ± 51 a	770 ± 21 a	814 ± 25 a
Comp + B-Ref	2005 ± 103 a	1743 ± 121 a	1134 ± 66 a	778 ± 68 a	775 ± 46 a	821 ± 32 a
Sodium concentration (mg.kg^{-1})						
MF	8 ± 3 a	12 ± 3 a	4 ± 2 a	6 ± 2 a	5 ± 1 a	4 ± 0 a
Comp	6 ± 2 a	11 ± 2 a	5 ± 1 a	5 ±1 a	5 ± 1 a	4 ± 1 a
Comp + B-RS	8 ± 4 a	13 ± 2 a	5 ± 1 a	5 ± 1 a	6 ± 2 a	13 ± 17 a
Comp + B-Misc	8 ± 5 a	9 ± 3 a	6 ± 2 a	7 ± 4 a	5 ± 1 a	4 ± 1 a
Comp + B-Ref	8 ± 5 a	12 ± 1 a	4 ± 1 a	5 ± 1 a	5 ± 0 a	4 ± 1 a
Manganese concentration (mg.kg^{-1})						
MF	31 ± 4 a	42 ± 6 a	26 ± 6 a	20 ± 5 a	43 ± 7 a	32 ± 9 a
Comp	33 ± 5 a	43 ± 3 a	26 ± 4 a	20 ± 3 a	46 ± 5 a	29 ± 7 a
Comp + B-RS	27 ± 6 a	45 ± 2 a	27 ± 5 a	20 ± 2 a	46 ± 6 a	32 ± 5 a
Comp + B-Misc	26 ± 4 a	41 ± 6 a	28 ± 2 a	20 ± 6 a	46 ± 3 a	29 ± 5 a
Comp + B-Ref	28 ± 9 a	43 ± 4 a	30 ± 3 a	17 ± 2 a	45 ± 7 a	28 ± 2 a

Table 5 (continued)

	Maize			Wheat		
	Indre	Oise	Haut-Rhin	Indre	Oise	Haut-Rhin
Copper concentration (mg.kg^{-1})						
MF	4.2 ± 0.6 a	4.3 ± 0.9 a	5.2 ± 1.3 a	3.2 ± 0.2 a	3.6 ± 0.4 a	3.4 ± 0.4 a
Comp	4.6 ± 0.8 a	4.6 ± 1.3 a	4.9 ± 0.3 a	3.2 ± 0.3 a	3.0 ± 0.1 b	3.8 ± 0.4 a
Comp + B-RS	4.6 ± 0.5 a	4.7 ± 1.0 a	4.8 ± 0.7 a	3.1 ± 0.4 a	3.4 ± 0.5 ab	3.3 ± 0.3 a
Comp + B-Misc	4.6 ± 0.7 a	4.6 ± 1.1 a	5.1 ± 0.2 a	3.3 ± 0.5 a	3.3 ± 0.3 ab	3.6 ± 0.2 a
Comp + B-Ref	4.5 ± 0.5 a	4.4 ± 0.5 a	5.7 ± 0.6 a	3.5 ± 0.2 a	3.5 ± 0.1 a	11.2 ± 15.2 a
Zinc concentration (mg.kg^{-1})						
MF	26 ± 5 a	39 ± 9 a	20 ± 2 a	17 ± 2 a	17 ± 5 a	16 ± 4 a
Comp	29 ± 5 a	39 ± 10 a	20 ± 2 a	16 ± 3 a	13 ± 2 a	18 ± 2 a
Comp + B-RS	28 ± 5 a	41 ± 11 a	17 ± 2 a	17 ± 5 a	16 ± 4 a	17 ± 2 a
Comp + B-Misc	35 ± 8 a	39 ± 6 a	19 ± 1 a	16 ± 3 a	14 ± 3 a	17 ± 2 a
Comp + B-Ref	32 ± 8 a	40 ± 11 a	21 ± 2 a	18 ± 2 a	15 ± 2 a	17 ± 1 a
Iron concentration (mg.kg^{-1})						
MF	92 ± 5 a	115 ± 13 a	100 ± 18 a	39 ± 3 a	45 ± 6 a	47 ± 10 a
Comp	118 ± 26 a	107 ± 11 a	118 ± 4 a	47 ± 14 a	51 ± 8 a	67 ± 23 a
Comp + B-RS	124 ± 20 a	126 ± 12 a	111 ± 32 a	39 ± 2 a	57 ± 5 a	76 ± 41 a
Comp + B-Misc	125 ± 39 a	139 ± 15 a	132 ± 56 a	41 ± 13 a	52 ± 7 a	55 ± 8 a
Comp + B-Ref	107 ± 13 a	116 ± 12 a	118 ± 5 a	42 ± 10 a	53 ± 5 a	55 ± 11 a
C/N						
MF	40 ± 4 a	46 ± 7 a	38 ± 3 ab	34 ± 1 a	34 ± 10 a	38 ± 2 a
Comp	37 ± 5 a	44 ± 9 a	38 ± 3 ab	34 ± 2 a	45 ± 3 a	34 ± 5 a
Comp + B-RS	36 ± 2 a	44 ± 9 a	42 ± 1 b	42 ± 8 a	38 ± 7 a	42 ± 3 a
Comp + B-Misc	38 ± 5 a	45 ± 8 a	38 ± 1 ab	38 ± 8 a	40 ± 5 a	39 ± 7 a
Comp + B-Ref	38 ± 3 a	47 ± 4 a	35 ± 3 a	34 ± 2 a	39 ± 2 a	39 ± 5 a

MF, mineral fertilizer; *Comp*, green waste compost; *Comp + B-RS*, green waste compost + rapeseed biochar; *Comp + B-Misc*, green waste compost + *Miscanthus* biochar; *Comp + B-Ref*, green waste compost + green waste compost residue biochar biochar. Letters indicate significant difference between treatments for each site

et al. 2019). Globally, although no benefit of amendment application on crop yields was measured, no negative effect was observed either, showing that these organic amendments could replace chemical P and K fertilization without negatively impacting growth in the three pedoclimatic conditions included in this study. Other studies confirmed the potential of biochar and compost applied together to replace chemical fertilizers (Alvarez et al. 2017; Sánchez-Monedero et al. 2019; Zulfiqar et al. 2019). In addition to reducing chemical fertilizer requirements, which is economically and environmentally beneficial, biochar and compost provide other ecosystem services such as the maintenance of the earthworm population (Honvault et al. 2023), the reduction of nutrient leaching, increase in soil microbial activity, improvement of water retention (Paetsch et al. 2018), carbon storage, and reduction in CO_2 and N_2O emissions, mitigating climate change (Song et al. 2019; Semida et al. 2019). However, compost quality must be monitored, as some studies reported addition of contaminants, such as heavy metals and/or plastics (Ng et al. 2018).

3.3 Nutrient uptake is similar across organic amendment treatments

Overall, nutrient concentrations in maize and wheat were highly affected by the site location (Tables S3 and S4). In general, maize grown at Oise presented a higher nutritional status (higher N, P, K, Ca, Na, Mn, and Zn concentrations) than at Indre and Haut-Rhin, while no differences in plant nutritional status could be found for wheat at the different sites (Table 5). However, total element uptake was significantly higher in maize and wheat grown at Haut-Rhin (Table S5). This can be related to the higher biomass production at this site. The differences between sites in terms of plant nutrient uptakes are directly related to the properties of the soils. Indeed, the Haut-Rhin site had the highest exchangeable nutrients, thus more nutrients available for plant uptake.

Contrary to the site location, organic amendment application did not affect nutrient uptake (concentration and total assimilation) (Tables S3, S4, S5, and 5). The only effect was found for the C/N ratio of maize, which showed a higher value on rape plots than Comp + B-Ref plots, but with no differences with the MF control. This contradicts previous studies showing that biochar and compost amendments can increase nutrient uptake by plants, such as N, P, K, Ca, Mg, Fe, Zn, due to their ability to increase soil pH and thus modify nutrient availability and increasing soil CEC, preventing nutrients from leaching and ultimately improving their uptake by plants (Agegnehu et al. 2016, 2017; Naeem et al. 2018; Elshony et al. 2019; Abideen et al. 2020; Libutti and Rivelli 2021). Although biochar and compost amendments are known to improve plant nutritious status, some studies also demonstrated that applying biochar and compost, single or in mixture, could decrease nutrient uptake by plants (Zulfiqar et al. 2019), or have no effect (Schmidt et al. 2014; Sánchez-Monedero et al. 2019). In other studies, depending on the element, plant species, and soil type considered, the effects of organic amendment differed, which was related to the effect that the amendments had on soil chemical properties, especially nutrient availability (Manolikaki and Diamadopoulos 2019; Sorrenti et al. 2019; Tesfaye et al. 2021). The lack of effects in this study could be related to the fact that none of the amendments affected available nutrient contents in soil. Indeed, the soils studied are located in temperate climatic region and have a high fertility, while the improvement of nutrient uptake by plants are usually observed in tropical regions, and with acidic nutrient poor soils (Tesfaye et al. 2021).

4 Conclusion

In agricultural soils under temperate climate, the application of compost, alone or combined with three types of biochar, showed similar effects on soil fertility parameters, on maize and wheat yields and their nutritional status over 2 years under field conditions. Therefore, we reject our hypotheses that application of biochar along with compost improves the effect of compost on soil fertility and plant growth, when applied at realistic dosages and on fertile soils. Nevertheless, compost-biochar mixtures were as efficient as mineral fertilizer to supply nutrients (P and K) and sustain crop yields and, in some instances, increased soil organic C concentration. We conclude that the combination of compost with biochar, under fertile and temperate climatic conditions, might substitute mineral PK fertilizers to grow crops while improving soil C content. However, economic analyses are needed to assess whether substituting P and K in mineral fertilizer with compost-biochar mixtures is an economically viable option. Increased carbon concentration in soil by 30% at the Oise site showed that in specific pedoclimatic contexts, application of biochar compost mixtures may be useful to achieve the goals of the 4 p1000 initiative.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due to the project still ongoing but are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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