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RESEARCH ARTICLE

Nitrogen budget and barley response to organic amendments in a sandy soil under simulated arid climate

Elie Le Guyader[1] | Mohamed El Mazlouzi[1] | Alexandra Guillaneuf[1] | Badji Tandina[1] | Maxime Gommeaux[1] | Julien Hubert[1] | Vincent Miconnet[1] | Béatrice Marin[1] | Samuel Abiven[2,3] | Diego S. Intrigliolo[4] | Maria José Delgado-Iniesta[5] | Pierre Girods[6] | Mahtali Sbih[7] | Kamel Guimeur[8] | Victor Kavvadias[9] | Rahma Inès Zoghlami[10] | Abdelfettah Abid[11] | Xavier Morvan[1]

[1]Université de Reims Champagne-Ardenne, Reims, France

[2]Laboratoire de Géologie, École Normale Supérieure, Paris, France

[3]CEREEP-Ecotron Ile-de-France, Saint-Pierre-lès-Nemours, France

[4]Centro de Investigaciones sobre Desertificación (CIDE) (CSIC-UV-GVA), Moncada, Spain

[5]Department of Agricultural Chemistry, Geology and Edaphology, University of Murcia, Campus Espinardo, Murcia, Spain

[6]Laboratoire d'Études et de Recherche Sur le Matériau Bois (LERMAB), INRAE, Université de Lorraine, Epinal, France

[7]Laboratory for Improving Agricultural Production and Protection of Resources in Dry Areas, University of Batna, Batna, Algeria

[8]Laboratoire de Diversité Des Ecosystèmes et Dynamiques Des Systèmes de Production Agricoles en Zones Arides (DEDSPAZA), Université Mohamed Khider, Biskra, Algeria

[9]Department of Soil Science of Athens, H.A.O. DEMETER—Institute of Soil and Water Resources, Attiki, Greece

[10]Institute of Arid Regions, Medenine, Eremology and Combating Desertification Lab (LR16IRA01), Medenine, Tunisia

[11]National Institute of Agronomic Research of Algeria, Touggourt, Algeria

Correspondence
Elie Le Guyader, Université de Reims Champagne-Ardenne, GEGENA UR3795, Reims 51100, France.
Email: elie.le-guyader@univ-reims.fr

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Abstract

Besides their potential for carbon sequestration, compost and biochar application in agriculture may constitute an alternative to mineral fertilizers by improving soil fertility and productivity in carbon-poor soils. This study focused on the impact of biochar and compost produced from date palm residues on nitrogen (N) leaching and plant uptake in a sandy soil cultivated with barley under arid climatic conditions. In addition to the unamended control soil (S), treatments with biochar (BC), urea (U), biochar+urea (BCU), compost (C) and biochar+compost (BCC) were tested. We followed soil fertility parameters, N leaching losses, N uptake and plant growth. Results showed a significant increase of barley yields with compost compared to urea (+66%) treatment (U), biochar amended (BC) and unamended soil (S). Biochar alone or co-applied with a nutrient source seems to reduce barley shoot biomass and grain yields at short term. Leachate N recovery and soil extractable inorganic N at the end of barley cultivation indicated that compost did not provide N in excess at barley maturation stage. Compost amended soils led to the highest N losses through leaching and thus environmental risk of N vertical transfer. However, compost had positive effects on soil nutrient status and barley yields. No synergistic effect was observed between biochar and compost. In conclusion, this paper highlights that date palm compost improved barley productivity in a coarse-textured soil, but with very short-term effects concerning available soil N.

KEYWORDS
biochar, carbon-poor soils, compost, N dynamics

1 | INTRODUCTION

In arid and semi-arid areas, soil organic matter (SOM) content is naturally low, generally <1.5% (Bernoux & Chevallier, 2013). These low SOM levels are associated with low nutrient inputs for crop production. SOM stocks are influenced by many factors such as pedoclimatic conditions and management practices (organic matter inputs, tillage, irrigation, vegetation and nitrogen fertilization; Chenu et al., 2019). At global scale, a growing number of studies focused on best management practices in agriculture to improve sustainable food production, including improving soil organic carbon (SOC) stocks (Constantin et al., 2010; Skadell et al., 2023; Zhuang et al., 2016).

Oasian agroecosystems in the MENA (Middle East and North Africa) region require copious irrigation due to extreme aridity index (e.g. AI ratio <0.5 for semi-arid areas and <0.2 for arid areas). Most of the cultivated soils in the Saharan region are sandy and therefore have low nutrient and soil water retention properties (Ibrahim et al., 2017; Le Guyader et al., 2024). The traditional irrigation method used by oasian farmers involves flooding the land. As a side effect, the use of poor quality irrigation water with moderate to high salt content can lead to soil secondary salinity (Rengasamy, 2006). Salts accumulate in the root zone due to insufficient leaching of salts and by upward movement of shallow saline water table (M. Khan & Prathapar, 2012). Artificial flushing of salts accumulated in the topsoil is often needed, combined with drainage systems to evacuate the excess water outside the oases and to reduce the risk of saltwater tables rising (Samy, 2010).

Most studies in arid areas focus on water challenges, but these specific conditions also lead to a depletion of available N. Efficiency in the use of mineral N for crops is low in the Saharan zone, with N-use efficiency (NUE) by maize <50 kg grain. kg^{-1}N (Chianu et al., 2012). Innovative solutions are needed to maintain soil fertility and facing complex challenges occurring in these areas, including desertification, climate change and salinization of soil and water (Bestelmeyer et al., 2015; Marlet et al., 2009). Most obvious nature-based solutions are related to organic waste management, and the different options it can offer (Cotrufo & Lavallee, 2022).

In an arid region of southern Morocco, El Janati et al. (2021) reported that 1 ha of palm grove produces around 2.4 t of dried date palm residues per year. This renewable resource is poorly recovered and mostly abandoned in fields, which can cause insect and disease infestation, or other environmental issues like accidental fires (El Janati, Robin, et al., 2022). Date palm residues co-composted with sheep manure showed promising results for increasing soil fertility and silage corn yields in an arid agroecosystem (El Janati, Akkal-Corfini, et al., 2022). Notably, soil available phosphorus, as well as nitrogen and phosphorus uptake by silage corn was enhanced over two growing seasons following a single compost application, suggesting a long-lasting effect of the compost.

Also biochar, obtained from the thermochemical conversion of biomass in an oxygen-reduced or inert atmosphere, offers promising potential to improve SOC sequestration (Azzi et al., 2024). This material is considered as one of the best soil conditioners due to its chemical stability and ability to retain nutrients (Lehmann & Joseph, 2015). However, the properties of biochars vary widely, depending on the feedstock and the conditions of production (Almutairi et al., 2022; Ippolito et al., 2020). These properties, for example, chemical composition, pH, porosity, specific surface area and cation exchange capacity (CEC), influence its interactions with soil and its fate within the ecosystem (Joseph et al., 2013; Liang et al., 2006). The persistent nature of biochars limits its use as a fertilizer because of insufficient release of nutrients in soil, particularly for biochars produced from low-nutrient biomass (Cross & Sohi, 2011; Igalavithana et al., 2016). Recently, several studies showed that biochars can be enriched with nutrient-rich sources to enhance its positive effects on soil fertility and crop productivity (Ndoung et al., 2021). For example, Kammann et al. (2015) showed that captured nitrate in co-composted biochar was largely protected against leaching and partly plant available. Another study combined urea with chemically and biologically oxidized biochars; they showed an improvement of NUE and rice yields (Antor et al., 2023).

Co-application of biochars and organic fertilizer may thus decrease fertilizer needs and reduce nutrient losses (Glaser et al., 2002; Yao et al., 2012). Nevertheless, there is a lack of knowledge regarding how biochar alters soil biology and crop productivity, particularly in arid and semi-arid areas (Arfaoui et al., 2019; Diatta et al., 2020).

This study focused on the effects of organic amendment (compost and biochar) application on plant response, soil properties and the dynamics of soil nitrogen loss through leachate in the context of arid systems. The specific objectives of this study were to assess (i) the role of date palm biochar on nitrogen retention/transformation in the soil and (ii) the availability of nitrogen for the plant in the presence or absence of external nutrient inputs. For that, barley, widely cultivated in arid zones and tolerant to saline conditions and poor soils, was cultivated in controlled arid conditions with organic amendments.

2 | MATERIALS AND METHODS

2.1 | Soil sampling

The first 20 cm of a non-cultivated silty loamy soil from 'Saladares del Guadalentín', an endoreic floodplain, was sampled in the semi-arid region of Murcia (Spain) in March 2022 (GPS coordinates 37°50′23″N, 1°21′39″W). The soil was classified as a Fluvic Gypsic Sodic Solonchak (IUSS Working Group WRB, 2022), with typical xerophytic and halophytic vegetation. Soil was sieved to pass through a 2-mm sieve. The soil used in the current experiment, called initial soil, was obtained by adding quartz sand (grain size distribution in mass: 0.05–0.2 mm: 11%; 0.2–2.0 mm: 73%; >2.0 mm: 16%) to a final proportion of 1/4 original soil and 3/4 sand and coarse elements, in order to reproduce a similar texture to that found mainly in Saharan regions. The soil was considered representative of the dominant soils in this area, characterized by a sandy texture with poor OM, clay and oxydes contents. According to Dewitte et al. (2013), arenosols without horizon development and calcisols were the most represented soils in North Africa.

2.2 | Organic amendments

The compost was produced in winter 2022–2023 by Palm Compost company (Biskra, Algeria). Crushed date palm leaves (*Phoenix dactylifera* L.) were crushed to ≈2 cm length. Before making windrows, ca. 30% of sheep manure was added in volume, then mixed with the crushed leaves, as a source of nutrients and microflora to initialize the composting process. The windrows were soaked and turned regularly to ensure optimal water content, aerobic conditions and homogenization of the mixture. The mature product obtained after 3 months was sieved to <4 mm and stored at 4°C until the experiments.

Biochar from date palm residues (rachis) collected in Murcia region was obtained by slow pyrolysis under constant nitrogen flow at a temperature of 450 ± 5°C at LERMAB (Laboratory for Studies and Research on Wood Materials) in Épinal (France). Pyrolysis time was 2 h at 450°C after preheating to 150°C, with the temperature rising at a rate of 4.9°C·min^{-1} up to 450°C. The biochar was ground in an automatic mortar and then sieved through a mesh size of <1 mm.

Rock-Eval® 6 thermal method was used to quantify organic carbon in compost. Total nitrogen was measured with the Kjeldahl method in compost (NF ISO 11261). Biochar total carbon, nitrogen and hydrogen contents were measured by the SOCOR company (Dechy, France) by dry combustion using an elemental analyser (NF EN ISO 21663). Mineral content of biochar and compost was determined after 6 h heating at 550°C in a muffle furnace. Their calcium content was measured by inductively coupled plasma-optical emission spectroscopy (ICP-OES, iCAP 6300 Duo, Thermo Scientific) after mineralization of the ash with concentrated nitric acid in a DigiPrep digestion plate (SCP Science) and filtering <0.45 μm. Potential CEC of biochar was measured after pH adjustment to 7 and washing of samples until EC <0.2 mS. cm^{-1} (Munera-Echeverri et al., 2018). Biochar pH and EC were determined in a suspension of 5 g of soil to 50 mL of deionized water (ratio 1:10; Singh et al., 2017), while it was measured with a 1:5 ratio as for soil for compost.

Physical sorption of N_2 at 77 K was performed on the biochar with a Micromeritics ASAP2020 adsorption apparatus. The samples were outgassed during 12 h at 350°C before analysis. Specific surface area was calculated using the Brunauer–Emmett–Teller (BET) method completed with the Rouquerol correction. Physico-chemical properties of biochar and compost were summarized below (Table 1). Fraction of water-soluble salts of the compost was measured at 8.5% in dry weight, with a dominant part of undesirable elements such as Na, Cl and S (Table S2).

2.3 | Experimental design and organic amendments application

A mesocosm trial was conducted in an Ecolab climatic chamber at the CEREEP-Ecotron IdF research centre. For this purpose, cylindric PVC pots (19 cm diameter and 50 cm height; with 10.0 L of filled soil volume) were filled with air-dried soil as follows. Pozzolana (1 cm) was placed at the bottom of the pot to facilitate drainage, and a fine plastic filter mesh (<0.5 mm) was placed to prevent soil particles from reaching the leachate collection bags. The organic amendments were mixed thoroughly with soil

TABLE 1 Physico-chemical properties of organic amendments.

Parameters	Unit	Compost	Biochar
C_{org}	%	15.6 ± 1.8	62.0
H	%	ND	2.32
Total N	%	2.44	0.55
C/N	-	6.4	113
Calcium	% Ca	17.3 ± 2.8	2.0
Extractable inorganic nitrogen	% N-NH_4^+	0.45	ND
Mineral content	%	61.3 ± 3.5	15.2 ± 0.6
pH (water)	-	7.6 ± 0.1	9.7 ± 0.1
EC	mS. cm^{-1}	17.6 ± 0.3	7.6 ± 0.3
Potential CEC	cmol. kg^{-1}	ND	126 ± 5
Surface area	m^{-2}. g^{-1}	ND	13.5

Abbreviation: ND, not determined.

before the pots were packed. Two horizons were obtained by adding first unamended soil (17.5–35 cm depth) and then amended soil with the six following treatments (0–17.5 cm depth) in four replicates: (1) unamended control soil (S); (2) biochar (BC); (3) urea (U); (4) Biochar + urea (BCU); (5) compost (C); (6) Biochar + compost (BCC).

After setting the soil moisture to field capacity, urea (equivalent to 65 kgN. ha^{-1}) was applied in U and BCU treatments. Biochar was applied in BC, BCU and BCC at a dose of 4.2 g. kg^{-1} soil (i.e. 10.4 t. ha^{-1} assuming a soil depth of 0–17.5 cm and a bulk density of 1.41 g. cm^{-3}) and compost in C and BCC at 15 g. kg^{-1} soil (i.e. 37 t. ha^{-1}). The treatment combining biochar and compost (BCC) consisted in mixing the two products with corresponding doses for each pot, adjusting the water content to 100% by mass (biochar–compost mixture and distilled water with a 50:50 mass ratio), aerating regularly and maintaining constant humidity for 2 weeks at 20 ± 0.2°C before incorporating it into the soil. This biochar enrichment method was assessed to induce slow nutrient release behaviour with BCC.

An additional unamended soil and non-cultivated (NC) was added without replication to isolate the effect of plants on soil properties and leachate quality. The 25 pots (6 treatments × 4 replicates plus the non-cultivated soil) were placed randomly in the growth chamber. After soil re-humectation at field capacity, the pots were acclimatized for 8 days at a constant temperature of 15°C in the dark before sowing. Twenty-five seeds of spring barley (cv. RGT Planet) were sown in each pot on 14 June 2023 and then thinned to six plants per pot after 2 weeks of growth (equivalent to about 200 plants. m^{-2}).

The soil surface was kept moist during the barley emergence phase using a water sprayer. Irrigation was carried out manually by flooding with a 5-cm layer of water (i.e. 1.4 L), as the used method by farmers in the oases. Irrigation frequency with domestic water was once every 10 days after the plants have reached about 15 cm, then once a week from flowering stage. Cumulative water inputs during the crop (18.2 L/pot) represents around 0.075 gN-NO_3^-/pot, or 41% of the N supplied through urea addition (chemical composition of the water available in Table S1).

Optimal growth conditions were applied during the germination period (i.e. 1 week at 15.0°C in the dark). After that, climatic conditions varied every hour to reproduce daily fluctuations as well as seasonal trend (Figures S1 and S2). The air temperature, air-specific humidity and radiation were set to correspond to average hourly values determined over 5 years (2017–2021) during the period from January to April in the El Atilet oasis in Kebili, Tunisia.

Setpoint values were obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER) Project. Over the 4-month period, daily minimal air temperatures ranged between 3 and 15°C and maximal air temperatures between 15 and 30°C and relative humidity ranged between 36%–95% and 17%–48% (Figures S1 and S2). The delta between the hourly set values and the measured values in the growth chamber was ≤1°C for 97.5% of temperature timepoints and ≤5% for 75% of relative humidity timepoints.

2.4 | Soil analyses

For initial characterization, after 8 days of acclimatization, the upper soil layer (0–17.5 cm depth) was sampled in triplicate after homogenization, air-drying and sieving to 2 mm. The analyses were carried out at CAMA (Chaine d'Analyses Marne Ardennes, Reims). Soil granulometry was determined with Robinson's pipette method without decarbonation. SOC content was measured by sulphochromic oxidation (NF ISO 14235). Total nitrogen was measured with the Kjeldahl method (NF ISO 11261). Soil carbonate content was measured according to NF ISO 10693. Cation exchange capacity (CEC) and exchangeable cations were measured using the Metson method

(NF X31-130 and NF X31-108, respectively). Electrical conductivity (EC) and pH were measured at a ratio of 10 g of soil to 50 mL of deionized water (ISO 10390:2005). Soil available phosphorus was determined by Olsen method (NF X 31–161). Amorphous forms of Fe (Fe_{AO}) were extracted by ammonium oxalate (McKeague et al., 1971). Approximatively 100 g of fresh soil was stored immediately after sampling at −20°C for analysis of soil extractable inorganic nitrogen (ISO/TS 14256-1:2003).

The soils were also sampled at depths of 2–17.5 cm and 17.5–35 cm at the end of the experiment. We observed that root exploration was not limited by soil volume, whatever the treatment (Figure S3). The roots were sorted manually after air-drying of soils prior to subsequent physico-chemical analyses. The methods used were the same as described for initial soils.

After barley harvest, the volumetric mass was calculated in each pot by dividing the weight of soil added initially by the volume of soil in the cylinder (measured height × cylinder disc area). The stock of soil organic carbon ($t{\cdot}ha^{-1}$) and other elements (N, Olsen P and exchangeable K) in bulk soils were calculated according to the following equation:

$$\text{SOC stock} = H \times Vm \times SOC / 10 \quad (1)$$

where H is soil depth (0–17.5 cm); Vm, volumetric mass ($g{\cdot}cm^{-3}$); OC, soil organic carbon concentration in bulk soil ($g{\cdot}kg^{-1}$).

2.5 | Leachate sampling and analyses

The pots were equipped with 1.5 L bags (Conveen, Coloplast A/S, France) connected by a plastic tube under the pot. Leachate volumes were obtained by gravity flow and collected between 2 and 5 days after each irrigation event. The periods for watering and monitoring the crop were detailed in Figure 1. The number of replicates was a minimum of three samples per treatment over the whole barley cultivation, except for the first watering event where samples were collected in duplicate for S, U, BC and C treatments. Volumes smaller than 50 mL were considered insufficient, and therefore, their chemical composition was not considered.

Samples were filtered using cellulose acetate syringe filters with a pore size of 0.22 μm for analyses of NH_4^+ and dissolved organic carbon (DOC), and 0.45 μm for NO_3^-. Filtrates for NH_4^+ analyses were stored at −20°C, while filtrates for NO_3^- were stored at 4°C and analysed within 72 h. The NO_3^- concentrations were determined using a Dionex ICS2000 ion chromatograph system with membrane suppression and conductivity detection. The quantification limit of the system was ≈1.0 mg NO_3^-. L^{-1}. The NH_4^+ concentrations in the samples were determined using a Seal AA3 HR autoanalyser with a detection limit of 0.013 μmolN. L^{-1}. The DOC concentrations were determined using a Shimadzu TOC-L carbon analyser within 24 h from leachate collection; the detection limit of the system was 10 μgC. L^{-1}. We checked that the release of DOC in milli-Q water filtrated with acetate cellulose was negligible compared with DOC concentrations in all the samples.

2.6 | Plant sampling and analyses

Barley agro-morphological parameters (number of tillers, height and phenological stage) were measured or observed once a week. Aboveground biomass was measured

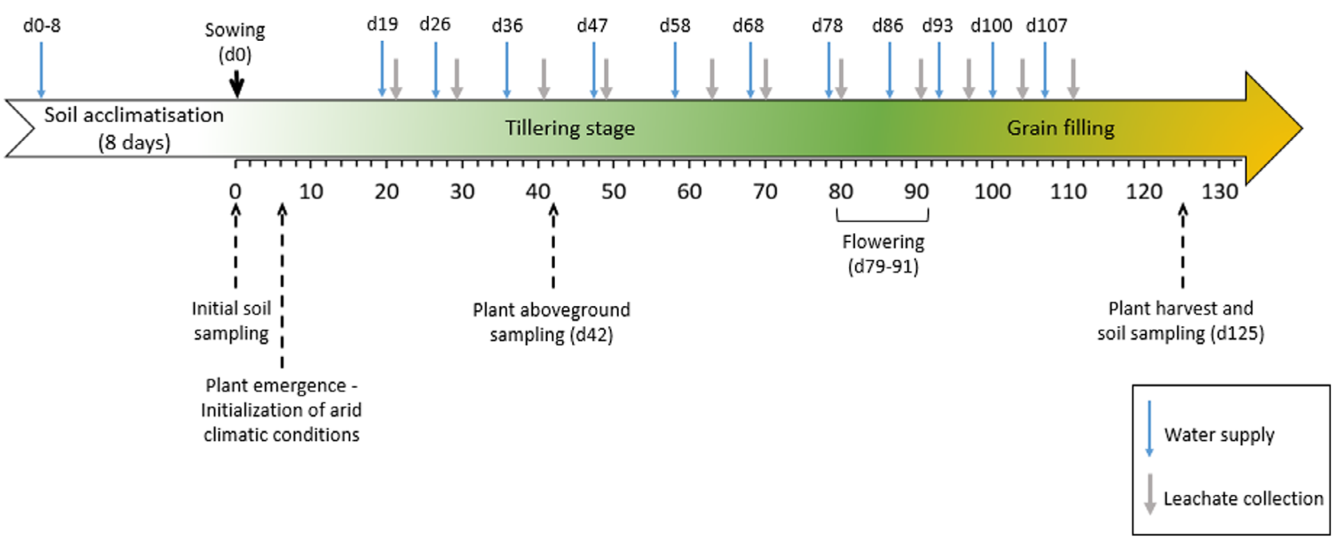

FIGURE 1 Calendar of the main cultivation operations and sampling strategy.

TABLE 2 Definitions and formulae used to describe nutrient use efficiency in barley.

Parameter	Unity	Calculation	Definition	References
NUEg (nitrogen use efficiency for grains)	kg grain. kg^{-1}N	GY/Na	GY, grain yield (kg. ha^{-1}); Na, initial soil available nitrogen (kgN. ha^{-1})	(Anbessa & Juskiw, 2012)
Agronomic efficiency (AE)	kg grain. kg^{-1}N	(GYa-GYu)/Ns	GYa, grain yield of the amended treatments for each replicate (kg. ha^{-1}); GYu, mean grain yield value of the unamended control soil; Ns, total nitrogen supply as organic amendment or urea (kgN. ha^{-1})	(Fageria & Baligar, 2005)
Harvest index (HI)	%	GY/(GY + SY)	GY, grain yield; SY, straw yield	(Donald & Hamblin, 1976)
Nitrogen nutrition index (NNI) at tillering and harvest stages	-	Grain N/Nc	Grain N, grain N concentration at tillering and harvest stages; Nc[a], critical N concentration (the minimum N concentration required to achieve maximum shoot growth)	(Ziadi et al., 2008)

[a]Nc was defined as a function of shoot biomass as proposed for barley by Justes et al. (1997): $Nc = 5.35 \times W^{-0.442}$. Where W is the total shoot biomass expressed in t. ha^{-1}. For AE calculation, the treatment with BC alone was not considered because we have made the assumption that this product does not provide available nitrogen.

at tillering stage (25th July, day 42) and harvest stage (17th October, day 125) after 72 h drying at 60°C. Aboveground biomass at tillering stage was determined by collecting one plant in each pot. Plants were then pooled by treatment ($n = 4$). At the final harvest, shoot and grain weight were determined for each plant (5 plants per pot). The root system was washed three times with distilled water and once with milli-Q water for biomass quantification in two soil depths (0–17.5 cm and 17.5–35 cm) after 72 h drying at 60°C.

For nitrogen determination in barley shoot and grains, 0.5 g dry biomass was mineralized with 9 mL concentrated H_2SO_4 at 400°C during 30 min. Nitrogen concentrations were measured by micro Kjeldahl's distilling unit. Grain nitrogen content was used to calculate the protein content in barley grain following this calculation:

$$\text{Protein content in grain} = \%\text{N (grain)} \times 5.4 \quad (2)$$

where nitrogen-to-protein conversion factor (5.4) was selected for cereals (Mariotti et al., 2008).

2.7 | Calculation of nitrogen balance and nitrogen use efficiency

Cumulated inorganic N leaching ($CumN_{leach}$) loss was calculated by multiplying the N-NO_3^- concentrations and volumes leached for each event of the four replicates. Then, N amounts (gN/pot) were converted to stocks as follows:

$$CumN_{leach}\ (kgN.\ ha^{-1}) = N/\text{soil weight}/1000 \times H \times BD \times (1\ \text{ha}/\text{pot area})$$

where N is inorganic N amount loss per pot (gN/pot); soil weight expressed in kg/pot; H is soil depth (cm); BD, volumetric mass ($g.cm^{-3}$); pot area (283.53 cm^2).

Inorganic loss fraction over the total applied N was calculated following this equation:

$$\text{Inorganic N loss (\%of applied N)} = \frac{\text{CumulatedNloss} \in \text{eachtreatment} - \text{cumulatedNloss} \in \text{control}}{Ns} \quad (3)$$

where control is unamended cultivated soil; Ns is the total nitrogen supply as compost or urea ($kgN.ha^{-1}$). Nutrient exports in grain and straw as $kgN.ha^{-1}$ were calculated by multiplying the yield by grain N and straw N concentration, respectively.

Definitions and calculation of agronomic indices are summarized in Table 2.

2.8 | Data analyses

Analysis of variance (ANOVA) were carried out using R 4.3.0 statistical software to test for effects of the treatments (organic amendments or urea addition) on soil properties, leached elements and plant response with field replicates of 4. Data from analytical replicates of 3 were used for the initial soil. The treatments were compared to the control (unamended) soil. Tukey's honest significant difference test was applied to separate the means. The level of significance was set at $p = .05$ for a 'significant' difference and 'highly significant' if $p < .01$.

3 | RESULTS

3.1 | Physico-chemical properties of the initial unamended and amended soils

The major N and P elements are deficient in this soil, which also has a neutral pH (Table 3). Compared to the control, a significant increase of pH was observed for all treatments and of EC only for compost. After harvest, there was no effect of compost on soil EC (data not shown). Compost addition led to a significant increase in total soil N (+133%), available P (+721%) and exchangeable K (+790%) concentrations. The addition of biochar alone enhanced exchangeable K (+220%).

Treatments S and BC at the sowing stage showed very low soil extractable inorganic nitrogen concentrations (Table 3). The amount of extractable inorganic nitrogen, estimated at 11 and 12 kgN. ha^{-1} in the control S and BC, respectively (given an initial bulk density of 1.41 g. cm^{-3}), was low and below the recommendations for barley crops. In semiarid conditions in Spain, barley yields range between 1 and 5 t. ha^{-1} with 60–150 kg of N applied per hectare (Cantero-Martınez et al., 2003). The low levels of total and extractable N in the initial soil justify the application of N.

Urea addition increased extractable inorganic nitrogen by a factor of around 5 (Figure 2 and Table 4). The form of nitrogen in the U treatment was predominantly NH_4^+, whereas it was mainly NO_3^- in the treatments S and BC (Figure S4). The compost addition led to the highest concentrations of soil extractable inorganic nitrogen (Figure 2 and Table 4) mainly in NH_4^+ form. The biochar addition did not affect significantly the extractable inorganic N ($NH_4^+ + NO_3^-$) concentrations of the initial soil in any treatment (Table 3).

After the barley harvest, the extractable inorganic N concentration in the upper layer of the non-cultivated soil (NC) seems similar to that of the initial control soil (Figure 2). However, concentrations of inorganic nitrogen drastically decreased in cultivated pots, whatever the treatments. After harvest, soil extractable inorganic nitrogen in C and BCC treatments was, respectively, 1.60 and 1.52 mgN. kg^{-1} soil in the upper layer, which is significantly higher than concentrations measured in treatments BC and BCU.

Applying compost to the soil increased the average SOC content by 72% and more than doubled total N at the initial date. Compost also enriched Olsen P content in the soil by a factor of 7.2. SOC stocks with compost and/or biochar addition were not different and significantly higher than the control at the sowing stage (Table 4). At the end of the experiment, SOC stocks in the upper layer increased significantly in BC, BCU, C and BCC treatments. BCC treatment showed the highest value (+59% SOC compared with the control). Also SOC stocks in BC and C treatments showed

TABLE 3 Physico-chemical properties of initial soils (0–17.5 cm depth).

Parameters	Unit	S	BC	U	BCU	C	BCC
Particle size distribution	% >2 mm	9.4 ± 1.6					
	% Sand	71.0 ± 1.3					
	% Silt	14.0 ± 1.7					
	% Clay	5.0 ± 2.0					
pH (water)	-	7.03 ± 0.1^{c}	7.50 ± 0.1^{b}	7.86 ± 0.1^{a}	7.83 ± 0.1^{a}	7.86 ± 0.1^{a}	7.95 ± 0.1^{a}
EC	mS. cm^{-1}	1.89 ± 0.1^{c}	2.08 ± 0.1^{b}	1.94 ± 0.1^{bc}	1.97 ± 0.1^{bc}	2.26 ± 0.1^{a}	2.30 ± 0.1^{a}
C_{org}	%	0.53 ± 0.03^{c}	0.84 ± 0.02^{ab}	0.57 ± 0.02^{c}	0.90 ± 0.05^{a}	0.91 ± 0.07^{a}	0.78 ± 0.03^{b}
Total N	%	0.03 ± 0.001^{e}	0.04 ± 0.001^{d}	0.04 ± 0.001^{d}	0.04 ± 0.001^{c}	0.07 ± 0.001^{a}	0.05 ± 0.002^{b}
Extractable inorganic N	mg N. kg^{-1}	4.4 ± 1.4^{a}	4.9 ± 0.6^{a}	25.9 ± 2.8^{b}	21.2 ± 2.2^{b}	57.5 ± 11.7^{a}	50.1 ± 12.7^{a}
Olsen P	mg P. kg^{-1}	19 ± 2^{c}	23 ± 3^{c}	25 ± 1^{c}	28 ± 2^{c}	156 ± 8^{a}	86 ± 18^{b}
K exch.	mg K. kg^{-1}	60 ± 4^{c}	192 ± 6^{b}	99 ± 64^{bc}	139 ± 66^{bc}	534 ± 44^{a}	570 ± 59^{a}
Fe_{Ao}	mg. kg^{-1}	29 ± 7	ND	ND	ND	ND	ND
CEC	cmol. kg^{-1}	3.1 ± 0.2^{a}	3.0 ± 0.3^{a}	2.8 ± 0.2^{a}	2.8 ± 0.3^{a}	3.1 ± 0.2^{a}	2.8 ± 2^{a}
Total $CaCO_3$	%	2.8 ± 0.1	ND	ND	ND	ND	ND

Note: Values for NC treatment correspond to the control soil S. The letters represent the significant differences from a one-way ANOVA analysis ($n = 3$). Numbers followed by the same letter are not significantly different at the 5% level.

Abbreviations: BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; ND, not determined; S, control soil; U, urea.

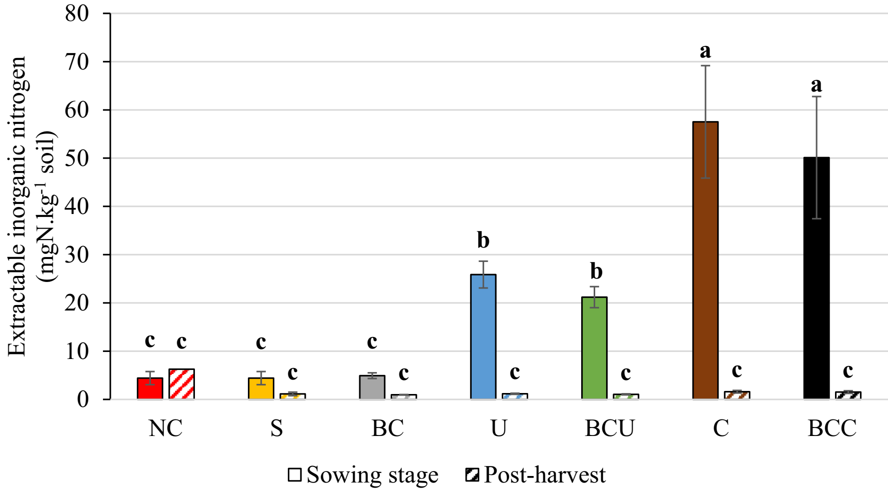

FIGURE 2 Total extractable inorganic nitrogen concentrations in the upper soil layer (0–17.5 cm) at sowing and post-harvest stages ($n = 3$ for all treatments at sowing stage; $n = 4$ for all treatments except NC after harvest). Numbers followed by the same letter are not significantly different at the 5% level. The values measured in triplicate in the unamended soil were copied out for both NC and S at sowing stage. BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; NC, non-cultivated soil; S, control soil; U, urea.

TABLE 4 Evolution of soil stocks during barley growth (upper layer).

		OC (tC. Ha^{-1})	Total N (tN. Ha^{-1})	Extractable inorganic N (kgN. Ha^{-1})	Olsen P (kgP. Ha^{-1})	Exch. K (kgK. Ha^{-1})
NC	PH	11	0.7	15.5	12	88
S	I	13 ± 1^{b}	0.7 ± 0.03^{ef}	11 ± 3^{c}	21 ± 2^{defg}	122 ± 10^{defg}
	PH	10 ± 1^{c}	0.6 ± 0.1^{f}	3.4 ± 1.4^{ab}	8 ± 1^{fg}	71 ± 13^{g}
BC	I	21 ± 1^{a}	0.9 ± 0.01^{cde}	12 ± 2^{c}	24 ± 3^{def}	394 ± 10^{b}
	PH	13 ± 1^{b}	0.7 ± 0.1^{ef}	2.4 ± 0.1^{b}	9 ± 2^{fg}	120 ± 28^{defg}
U	I	14 ± 1^{b}	0.9 ± 0.01^{cde}	64 ± 7^{c}	27 ± 0^{de}	203 ± 130^{cdefg}
	PH	9 ± 1^{c}	0.6 ± 0.1^{f}	2.9 ± 0.3^{ab}	8 ± 1^{fg}	99 ± 64^{g}
BCU	I	22 ± 1^{a}	1.0 ± 0.03^{bc}	52 ± 5^{c}	30 ± 2^{d}	284 ± 140^{bc}
	PH	13 ± 2^{b}	0.7 ± 0.1^{f}	2.6 ± 0.3^{b}	13 ± 2^{efg}	100 ± 27^{efg}
C	I	22 ± 2^{a}	1.6 ± 0.03^{a}	142 ± 29^{c}	168 ± 8^{a}	1093 ± 90^{a}
	PH	13 ± 1^{b}	0.9 ± 0.1^{cde}	3.9 ± 0.7^{a}	118 ± 8^{b}	222 ± 56^{cdef}
BCC	I	19 ± 1^{a}	1.1 ± 0.04^{b}	124 ± 31^{c}	93 ± 19^{c}	1167 ± 120^{a}
	PH	15 ± 1^{b}	0.9 ± 0.1^{cd}	3.8 ± 0.7^{a}	122 ± 13^{b}	259 ± 25^{bcd}

Note: Data are presented as means ±SEs ($n = 3$ for initial soils; $n = 4$ for post-harvest soils, except for NC with no replicate). Numbers followed by the same letter are not significantly different at the 5% level.

Abbreviations: BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; I, initial; NC, non-cultivated soil; PH, post-harvest; S, control soil; U, urea.

very similar values after harvest. The estimated amount of belowground residues in the upper layer ranged between 0.10 and 0.22 tC. ha^{-1}, assuming the carbon concentration of roots was 0.45 g. g^{-1} (Bolinder et al., 2007). This component can thus be considered negligible and has not been accounted for in the SOC stocks.

Total nitrogen in the soil was higher than the control in C and BCC treatments after the barley harvest. Extractable inorganic N was similar in all treatments after harvest, but there was a significant enrichment in the upper layer of BCC and C compared to the bottom layer. BC alone did not affect available phosphorus, while C and BCC treatments had significantly higher available P content even after harvest. Both compost and biochar increased exchangeable K in upper and bottom layers (Table 4; Table S3).

The sum of the stocks of organic carbon, Olsen P and exchangeable K in soil from the individual treatments BC and C, referred to as expected values for BCC, was compared with the actually measured values for BCC. Measured SOC stocks were slightly lower than the expected values in BCC considering individual values measured with biochar and compost inputs (Figure S5). Measured stocks of available P and exchangeable K at the end of the experiment were similar to the expected values.

3.2 | Leaching of inorganic nitrogen during the experiments

Mean volume leachate collected was 544 mL/pot and per watering event over 11 events. The mean cumulated leached volumes were lower in the compost treatments (4.2 and 4.9 L for C and BCC, respectively) compared with the other treatments (ranged between 5.1 and 6.6 L; Figure S6), even though the difference was not significant. The proportion of leached volume ranged between 23% and 36% of water supply by irrigation.

Concentrations of NH_4^+ in leachates were low (<0.23 mg N-NH_4^+. L^{-1}) compared to NO_3^- at all watering events and for all treatments (Figure S7). Nevertheless, fluctuation in NH_4^+ and NO_3^- concentrations followed the same pattern depending on the treatment. There was a peak in NO_3^- concentrations at the second watering event for C and BCC treatments (Figure 3). Compost addition led to greater nitrate losses than the control and all other treatments. Nitrate concentrations in leachates in BCC were similar to the C treatment, except at the second event where we observed a significant 25% reduction of N-NO_3 losses. The nitrification peak was observed at day 26 for treatments C and BCC. Inorganic nitrogen losses in treatments with urea showed no significant difference compared with the control soil, but the concentrations for each pot were higher at the third event (day 36). Between days 36 and 47, NO_3^- concentrations decreased in all the treatments and seems lower than the non-cultivated soil (NC; ≈5 mgN. L^{-1}). Nitrate concentrations were randomly below the quantification limit (<1.0 mg. L^{-1}) for all treatments after watering at d58, d86 and d107.

The leaching release balance for the entire experiments shows an increase in nitrate losses around 403% in C treatment compared with the control (Table 5).

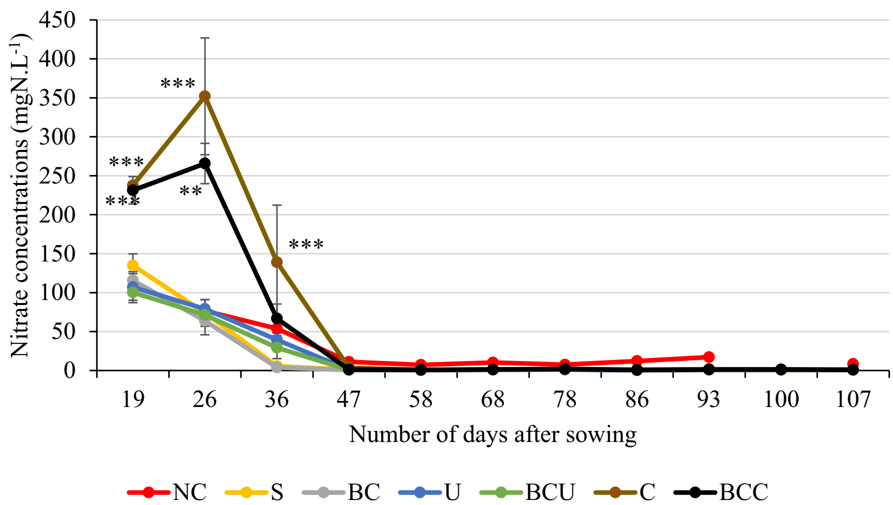

FIGURE 3 Dynamic of nitrate losses in leachate. Data are averaged over treatments, vertical bars represent SEs of the means, asterisks indicate significant differences from the control within times at 5% level (*), 1% level (**), and 0.1% level (***). BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; NC, non-cultivated soil; S, control soil; U, urea.

TABLE 5 Cumulated carbon and nitrogen release amounts in leachate.

Parameters	Unit	NC	S	BC	U	BCU	C	BCC
NO_3^--N losss	kgN. ha^{-1}	41	31 ± 5^b	23 ± 6^b	48 ± 8^b	45 ± 6^b	156 ± 33^a	126 ± 20^a
N losses fraction over N input	% of applied N	-	-	-	32 ± 15^a	25 ± 12^{ab}	11 ± 3^b	8 ± 2^b
DOC losses	kgC. ha^{-1}	94	283 ± 30^a	219 ± 100^a	258 ± 54^a	291 ± 54^a	301 ± 17^a	280 ± 48^a
C losses fraction over initial SOC	% of total SOC	0.36	1.08 ± 0.12	0.53 ± 0.24	0.92 ± 0.19	0.65 ± 0.12	0.66 ± 0.04	0.72 ± 0.12

Note: NH_4^+ concentrations were negligible. Data are averaged over treatments, vertical bars represent SEs of the means ($n = 4$, except for NC with no replicate). Numbers followed by the same letter are not significantly different at the 5% level.

Abbreviations: BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; NC, non-cultivated soil; S, control soil; U, urea.

3.3 | Leaching of dissolved organic carbon

Dissolved organic carbon (DOC) concentrations were measured in leachates for 10 of the 11 events collected (Figure 4). In the non-cultivated soil, DOC losses were lower than all the treatments during the whole period. The dynamics of DOC leaching was different between the treatments with or without compost. DOC concentrations in leachate between days 19 and 36 were significantly higher in treatments with compost compared to the cultivated control soil. No significant difference was detected between BCC and C treatments. When urea was applied, DOC concentrations increased in leachate between days 26 and 58 after sowing (p-value<0.01 and p-value<0.05 for U and BCU treatments, respectively). Then, after day 58, DOC losses gradually decreased in all cultivated treatments to reach a plateau around 0.13 gC. L^{-1} at the end of the experiment.

Cumulated amounts of DOC exported were similar between the cultivated treatments, ranging between 219 and 301 kgC. ha^{-1} (Table 5). The proportion of leached DOC attributed to the compost at day 36 (delta between cumulated DOC losses in C treatment and control S) was estimated at 1.3% of the exogenous organic carbon input. After barley harvest, DOC losses fraction over initial SOC ranged between 0.36% and 1.08% (Table 5).

3.4 | Barley growth response to organic amendments and urea

Grain yield was highly significantly higher in BCC and C treatments than in all the other treatments (Table 6). Compost addition in C treatment increased grain yield by 141% compared to the control and 66% compared to the urea treatment. Treatments with urea (BCU and U) showed significantly higher grain yield than the control and BC treatment. An opposite trend in average grain yield was measured with the addition of biochar alone and with external nutrient inputs. Similar trends for shoot biomass were observed, but it was significantly lower in BCC compared with C treatment.

The nitrogen content of grains at harvest was not significantly different between treatments (Table 6). Mean grain protein content was low, varying between 6.2 ± 0.5% and 7.2 ± 0.3%.

A gain in precocity at the tillering stage of about 1 week was observed when compost was added (data not shown). The number of primary tillers was highly significantly higher when compost was used alone or combined with biochar (Table 6). Secondary tillers appeared in the BC treatment while it was very limited for the C treatment. At the tillering stage, shoot biomass at day 36 was higher in BCC and C compared to all the other treatments. At the same stage, with urea addition, shoot biomass in the BCU was significantly higher than in the BC treatment.

3.5 | N use efficiency of barley

Combining the results for barley yields and nitrogen content, calculated nitrogen exports for grain ranged from 29.6 kgN. ha^{-1} (BC treatment) to 64.5 kgN. ha^{-1} (C treatment) (Figure S8). For shoot biomass, they ranged from 5.6 kgN. ha^{-1} in BC treatment to 14.8 kgN. ha^{-1} in C treatment.

Nitrogen use efficiency (NUEg) was highly significantly lower in treatments with compost or urea, as well as BC treatments compared with control soil (Table 7).

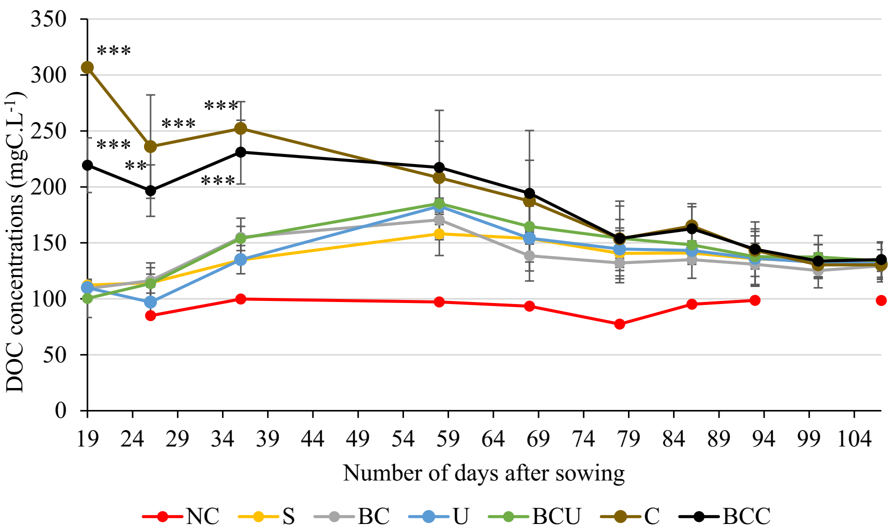

FIGURE 4 Dynamic of dissolved organic carbon (DOC) losses in leachate. Data are averaged over soils, vertical bars represent SEs of the means, asterisks indicate significant differences from the control (S) within times at 5% level (*), 1% level (**), and 0.1% level (***). BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; NC, non-cultivated soil; S, control soil; U, urea.

TABLE 6 Plant agromorphological parameters at tillering and harvesting stages and nitrogen concentrations in grains.

Parameters	Number of primary tillers	Number of secondary tillers	Shoot biomass at tillering stage (g/plant)	Final shoot biomass (g/plant)	Grain yield (g/plant)	Nitrogen concentrations in grains (%)
S	0.8 ± 0.2^{c}	0.4 ± 0.3^{ab}	0.20 ± 0.03^{bc}	1.25 ± 0.16^{d}	1.38 ± 0.38^{c}	1.33 ± 0.05^{a}
BC	0.5 ± 0.1^{c}	0.6 ± 0.1^{a}	0.17 ± 0.04^{c}	1.22 ± 0.22^{d}	1.28 ± 0.31^{c}	1.31 ± 0.07^{a}
U	1.3 ± 0.3^{bc}	0.2 ± 0.1^{ab}	0.22 ± 0.06^{bc}	1.73 ± 0.34^{c}	2.00 ± 0.49^{b}	1.16 ± 0.11^{a}
BCU	1.1 ± 0.4^{c}	0.2 ± 0.2^{ab}	0.37 ± 0.10^{b}	1.71 ± 0.31^{c}	1.91 ± 0.41^{b}	1.16 ± 0.11^{a}
C	2.6 ± 0.1^{a}	0.1 ± 0.1^{b}	0.69 ± 0.13^{a}	2.78 ± 0.77^{a}	3.32 ± 0.91^{a}	1.17 ± 0.08^{a}
BCC	2.0 ± 0.3^{ab}	0.2 ± 0.2^{ab}	0.64 ± 0.08^{a}	2.36 ± 0.49^{b}	3.01 ± 0.66^{a}	1.21 ± 0.07^{a}

Note: Data are averaged over treatments ($n = 20$, except grain N concentrations where $n = 4$). Numbers followed by the same letter are not significantly different at the 5% level.

Abbreviations: BC, biochar; BCC, biochar + compost; BCU, biochar + urea; C, compost; S, control soil; U, urea.

TABLE 7 Nitrogen use efficiency traits/agronomic indices of spring barley.

Treatment	Initial soil-extractable N (kgN. ha^{-1})	NUEg (kg grain. kg^{-1} N)	AE (kg. kg^{-1} N)	HI (%)	NNI (tillering stage)	NNI (post-harvest)
S	11^{c}	223^{a}	-	52.3^{a}	0.31^{c}	0.30^{b}
BC	12^{c}	186^{b}	-	51.2^{a}	0.31^{c}	0.29^{b}
U	64^{b}	55^{c}	16.9^{a}	53.7^{a}	0.44^{b}	0.32^{b}
BCU	52^{b}	61^{c}	12.0^{ab}	51.3^{a}	0.42^{b}	0.30^{b}
C	142^{a}	39^{c}	3.5^{b}	52.8^{a}	0.54^{a}	0.40^{a}
BCC	124^{a}	43^{c}	3.2^{b}	56.0^{a}	0.50^{ab}	0.41^{a}

Note: Where NUEg, nitrogen use efficiency, is grain yield per unit of available N (soil N + applied N). Numbers followed by the same letter are not significantly different at the 5% level.

Abbreviations: AE, agronomic efficiency; HI, Harvest index; NNI, nitrogen nutrition index.

Agronomic efficiency (AE) was significantly lower in compost amended soils compared with treatments with urea. Harvest index (HI) values were similar in all treatments. Nitrogen nutrition index (NNI) was higher with urea and compost addition at tillering stage, while only C and BCC treatments showed a significant increase at barley harvest (Table 7).

4 | DISCUSSION

4.1 | Influence of organic amendments on soil physico-chemical properties

Both organic amendments improved SOC stocks at the end of barley cultivation, without differentiation between compost and/or biochar amended soils. In the treatment BCC, measured SOC stocks were slightly lower than expected from the sum of the individual BC and C treatments. We suggest that a small part of organic carbon was mineralized during mixing of biochar and compost before incorporation to soil. The significant decrease in SOC stocks between day 0 and harvest in all treatments reflects favourable conditions for carbon mineralization, such as weak OM protection (Chassé et al., 2021), the absence of limiting water and the high soil temperatures that occurred.

Available P decrease in C treatment was significant, but the stocks remain high compared with treatments without compost, suggesting long-lasting effects for the availability of this nutrient.

The mineral composition of the compost used (i.e. high soluble salt content) increased the EC of the initial soil. Previous studies have highlighted the potential risk of soil and water salinization with the application of organic amendments as the compost used (Gondek et al., 2020; Ullah et al., 2018). Hence, particular care must be taken with the doses and frequencies of application of organic amendments, as well as with long-term monitoring of the potential accumulation of salts in cultivated soils.

The lack of compost effect on soil EC after harvest could be explained by the salt release in leachate, aligning with a significant reduction in soil EC in the upper layer in all treatments during cultivation (data not shown). The risk of salinization would therefore be more related to the enrichment of drainage water.

4.2 | Impact of N organic sources on the dynamic of N and DOC

The present study showed that cultivated soil with a coarse-texture leads to N leaching mostly during the first month of barley growth (about 96% and 99% of cumulated inorganic N loss for control S and C treatments, respectively). NO_3^- was the predominant form of leached N, but the dominant extractable form was NH_4^+ in the soil enriched with compost or urea at the sowing stage (Figure S2). Thus, the period between sowing and day 36 corresponds to intense nitrification activity (i.e. more than 99% N-NO_3^- form in leachates), especially when nitrogen was supplied with compost or urea. Nitrate export through leaching was significantly higher in C and BCC treatments than in all other treatments, even though leachate volumes were lower (Table 5). Leachate volumes collected in compost amended soils were lower due to the higher plant productivity and water uptake. Higher content of organic matter provided by compost could also improve water retention in the soil (de Jesus Duarte et al., 2022). After barley harvest, the low amounts of soil extractable inorganic nitrogen in the upper layer of all treatments (mean values ranging from 2.4 to 3.9 kgN. ha^{-1}) compared to the initial mean values (ranging from 11 to 142 kgN. ha^{-1}) reinforces the idea of fast depletion of nitrogen with both urea or compost additions.

Based on NO_3^- concentrations in the leachate, compost addition did not improve the duration of available N supply compared to urea treatments. We observed a trend towards increasing NO_3^- concentrations in the NC leachate compared with the cultivated treatments from day 47 (Figure 3). This suggests that N limitation likely affects barley growth from the tillering stage. Flood irrigation, traditionally used by oasian farmers to irrigate crops, may have favoured inorganic N leaching (Pool et al., 2022). Nevertheless, the contribution of N supplied by the irrigation water used to the cumulated inorganic nitrogen was not negligible (i.e. 41% of the N supplied through urea addition). The N provided by irrigation probably partially compensated for the low soil supply. This also illustrates the importance of measuring inorganic N in irrigation water to optimize N inputs in relation to crop needs.

The N losses fraction over N inputs (ranging around 8%–32%, Table 5) was in line with those reported by Hussain et al. (2020), ranging between 14% and 38% of N added with mineral fertilizers lost through leaching annually over 7 years in different cropping systems. Interestingly, although the difference was not significant, the proportion of N-NO_3^- losses over the total applied N seems higher in the U and BCU treatments (around 32% and 25%, respectively) than in the compost treatments, suggesting higher leaching fraction of the total N supplied with urea.

NH_4^+ and NO_3^- extractable from the soil were similar after harvest between the treatments BC, BCU, BCC and their respective treatments without biochar addition. Although the nitrate concentrations tended to be smaller in leachates with BC treatments (Figure 3), the non-significant effect reinforces the hypothesis that date palm BC had limited effect on soil inorganic nitrogen retention. This observation is in line with a review on biochar–N interactions conducted by Clough et al. (2013), which showed that pyrolysis <600°C has very limited NO_3^- adsorption potential. A meta-analysis reported an overall reduction (≈10%) of extractable soil inorganic nitrogen at short term (1 month) in biochar amended soils (Nguyen et al., 2017). The same authors also found that high-dose biochar applications (2%–10%) caused higher reduction of extractable soil inorganic nitrogen. In the present study, the relatively low pyrolysis temperature and the moderate dose of biochar (0.42% in weight) may explain the non-significant effect on soil N retention.

DOC concentrations in leachate ranged from 77 to 307 mg. L^{-1} (Figure 4), which is higher than values reported in agricultural soils from different regions (North America, central Europe and an Andisol from Chile), varying between 3 and 70 mg. L^{-1} (Zsolnay, 1996). In the present study, high desorption of DOM may be due to the coarse texture and low ferrous oxides content in the initial soil (Table 3). Compost addition increased DOC concentrations in leachate during the first three events (days 19–36), but the cumulated DOC losses did not differ between the treatments. DOC release from non-cultivated soil seems lower than from cultivated soil, meaning that the rhizosphere probably induced DOC production in the leachates. Based on the difference between the control (S) and non-cultivated soil (NC) leachates, plant cultivation increased DOC concentrations by 54% on average (weighted value for leachate volume).

4.3 | Effects of N organic sources on plant growth and N uptake

Date palm compost highly promoted barley development in the present study, which is in line with silage corn yield obtained in field experiments with a similar compost mixture (El Janati, Akkal-Corfini, et al., 2022). Nitrogen supply with compost or urea did not improve barley grain N concentration, but total aboveground N uptake increased with compost (+108%) or urea (+30%), due to the increase in biomass production. Based on the initial soil extractable inorganic nitrogen concentrations, urea was considered as a moderate N supply (+53 kgN. ha^{-1}), whereas compost addition led to a high N supply (+131 kgN. ha^{-1}). The total mean N uptake values obtained in C treatment, ranging from 66 to 98 kgN. ha^{-1}, are comparable with the results of field studies, which reported values ranging from 45 to 90 kgN. ha^{-1} (Agegnehu et al., 2016) and 54 to 109 kgN. ha^{-1} (Shejbalová et al., 2014) for barley under organic and inorganic fertilization.

In the present study, biochar seems to reduce barley yields. This observation, although not significant, supports those of Alotaibi and Schoenau (2019), who showed a significant decrease in aboveground biomass of wheat grown for 5 weeks with the application of 8 t. ha^{-1} of date palm biochar produced at 400 and 500°C in an alkaline sandy soil in Saudi Arabia. The authors also showed that the application of date palm BC produced at a temperature higher than 500°C reduced plant N and P uptake when applied alone or in combination with NPK fertilizers.

The nitrogen use efficiency (NUEg) assesses the efficiency of converting applied N to produce grain yield (Anbessa & Juskiw, 2012). The highest NUEg values resulted from S and BC treatments (Table 7). NUEg was lower in soils amended with compost or urea, which reflects a lower efficiency in the use of N compared with the unamended soil and BC treatment. We suggest that N translocation in the grain was more efficient in the treatments without N addition, due to soil available N deficiency. Urea and compost provided nitrogen in a highly soluble and rapidly available form. However, in sandy soils with low nutrient and water retention capacities, this rapid availability led to significant nitrogen losses through leaching, especially during early stage where root uptake is low. These losses reduce the efficiency of nitrogen utilization by the plants, resulting in lower NUEg. Also the decrease in NUEg may have been due to the increased soil N supply. Gaseous emissions (NH_3 and/or N_2O) may have reduced N supply benefits for plants, as they can represent a significant loss in sandy soils following N application (Awale & Chatterjee, 2017; Siegfried et al., 2011). It is worth noting that the potential gain in NUEg decreases with the N application dose (Anbessa & Juskiw, 2012). Without organic fertilizer source, more than half of the nitrogen taken up by aboveground biomass would come from SOM mineralization and irrigation water. Indeed, initial soil extractable nitrogen for S and BC treatments amounted to 11 and 12 kgN. ha^{-1}, respectively, whereas estimated total N exports from barley were 35 and 38 kgN. ha^{-1}.

Grain harvest index (HI) did not differ significantly among the treatments (Table 7). Mean values were slightly higher than 50%, which is in line with values reported under field experiments for modern spring barley cultivars (Peltonen-Sainio et al., 2008). It means that partitioning of biomass has been maintained even though the biomass was higher with compost addition. Indeed, high aboveground biomass measured in C and BCC treatments were associated with more developed root systems (Figure S9). Barley grain protein content was low for the cultivar used (Wiśniewska, 2022). Nitrogen nutrition index (NNI) was less than 1 at tillering and harvest stages. NNI values were very low in all treatments, confirming that there was a severe N limitation for plants at both stages. The higher tillering capacity observed in BCC and C treatments was associated with higher barley yields but no improvement in grain N concentrations. Since soil N was limiting after the tillering stage, it is likely that N supplied via irrigation water was able to partially counter the plant N deficiency and grain filling.

The proportion of the N supplied from the compost and taken up by the aboveground biomass was estimated at 4.5 ± 1.7% in the C treatment (difference between N uptake by plants in the control and in treatment C). Nitrogen recovery was therefore quite low compared to the leached fraction of N attributed to the compost (13.8% ± 3.7%). Apparent compost N mineralization rate was estimated at 18.3% over barley cultivation and under the conditions applied. Inorganic N release from the compost was equivalent to 4.5 kgN. t^{-1} of compost dry matter, which can be considered as a medium N mineralization rate for the 4 months of barley cropping period (Lashermes et al., 2010). However, we observed a fast depletion of inorganic N in leachate in C and BCC treatments. The lack of a standardized method for compost production can lead to batch heterogeneity. With a similar initial mixture, other studies mentioned higher C:N ratios ranging between 15.4 and 16.9 in mature composts (El Janati, Akkal-Corfini, et al., 2022; Ghouili et al., 2023). Thus, considering this type of product, organic C:N ratio measured in the compost was low and its extractable inorganic nitrogen fraction was high. Improving the composting process is therefore required to increase the duration of available nitrogen supply with compost, since there is a correlation between net N mineralized and organic C:N ratio of organic amendments (Jensen, 1929; Parnaudeau et al., 2004).

Shi et al. (2012) found that high N mineralization rate via urea resulted in low N utilization efficiency and high loss of NO_3^- through leaching. In the present study, the sandy texture of the soil resulted in poor N recovery by the plants, regardless of the organic fertilizer source. Moreover, biochar applied alone or co-applied with N-rich source (urea or compost) did not affect grain yield or NUEg of barley. In the tested conditions, date palm biochar application seems to reduce barley development at short term. Previous studies did not find any benefit of the addition of biochar compared to application of compost alone on soil and crops (D'Hose et al., 2020; Fornes et al., 2024).

The enrichment method of mixing BC with compost did not enhance the longevity of the effects of compost in terms of providing nitrogen to plants and soil. This could be explained by a low modification of biochar surface properties due to the very short-term ageing of the mixture. Our study focused on nitrogen dynamics, but it cannot be ruled out that biochar and organic amendments mixture may have beneficial effects on water retention properties and biological functioning of the soil under other conditions such as water stress (Khan et al., 2021; Védère et al., 2023).

5 | CONCLUSION

This study aimed to test the potential of date palm-based biochar and compost or their mixture on the spring barley productivity and nitrogen losses through leaching under controlled climatic conditions. Plant development was significantly affected by compost and urea addition (+141% and +66% grain yield, respectively). In contrast, BC alone or co-applied with a source of nutrients tended to reduce the barley shoot biomass and grain yields. Our results pointed out that biochar did not reduce significantly NO_3^- and NH_4^+ leaching from soils.

Analyses of the leachates and plant N uptake revealed the fast N depletion in soil through leaching and a poor recovery by the plants. In addition, at harvest, soil extractable inorganic nitrogen in all treatments was lower than the initial level of un-amended soil, showing that the compost provided nitrogen only at the earliest phenological stages of barley under the applied conditions. Even though compost addition markedly increased barley grain yield, N losses in this treatment were higher than expected considering this type of product. More accurate timing of N mineralization is needed to synchronize N availability and the crop demand. A fractionation of N supply targeting peak demand of barley would be recommended to improve agronomic efficiency.

In general, these results show that date palm compost contributes to improve the barley productivity in a coarse-textured soil, but with very short-term effects concerning soil N status. Further studies should focus on the role of organic amendments on the availability of other macro- (P, K) and micronutrients in deficient soils, as well as their potential effects on soil salinization.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

ORCID

Elie Le Guyader https://orcid.org/0000-0001-6271-3661
Maria José Delgado-Iniesta https://orcid.org/0000-0002-9940-2936

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