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Using bio-based fertilizer derived from peri-urban wastes affects soil properties and lettuce yield and quality

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A R T I C L E I N F O

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A B S T R A C T

The use of waste-derived fertilizers, also known as bio-based fertilizers (BBFs), for the production of ready-to-eat vegetables can efficiently contribute to sustainability and circularity. However, studies on the efficiency and safety of these fertilizers are needed. Thus, this study aimed to examine and characterize the effects of combined application of BBFs on lettuce yield and quality and soil properties in a trial conducted under open field conditions. The eight experimental treatments included green- or food waste compost combined with either human urine, food waste digestate or synthetic fertilizer and compared to treatments with synthetic fertilizer alone or in combination with manure. The control treatment received no BBF or other type of fertilizer. The results showed statistically similar fresh lettuce yields after 48 days among the treatments, all of which were larger than the yield of the unfertilized control treatment. The highest fresh yield (73 t ha^{-1}) was observed with the combination of manure and synthetic fertilizer. Yield in treatments that received green waste or food waste composts tended to decrease slightly, more likely due to nitrogen immobilization after the application of incompletely stabilized composts and the low initial mineral N. Nitrate contents in fresh lettuce leaves were below the EU limits (3000 mg kg^{-1}) in all the treatments. Analysis of pathogens and trace elements present in aboveground lettuce showed no significant risk. The application of BBFs also appeared to maintain the soil pH compared to synthetic fertilizer treatments. The important nutrient and carbon contents of BBFs and their positive effect on lettuce yield associated with their non-harmful impact on lettuce quality suggest that BBFs can be used for vegetable production and to increase the soil carbon stocks and contribute to city sustainability.

1. Introduction

Large amounts of organic wastes are increasingly being generated in urban areas, especially in those that are densely populated (European Environment Agency, 2020). Furthermore, EU countries will be required to separately collect biowaste by early 2024 (European Commission, 2020), likely leading to a rise in organic waste volumes that can be efficiently recycled in agriculture, aligning with circular economy principles (Chojnacka et al., 2020). Recycling in agriculture has been used for centuries but concerns mainly agricultural wastes such as animal manure (Jarousseau et al., 2016; Stanhill, 1976). All organic wastes intended to be spread on agricultural fields can be referred to as bio-based fertilizers (BBFs). They can be divided into two main groups, amendments and fertilizers, related to their ability to contribute to soil organic matter stocks and improve soil structure or supply available nutrients to plants, respectively (Levavasseur et al., 2022).

Composts are stabilized and hygienized BBFs derived from composting, which is an aerobic biological decomposition process of organic wastes, including biowaste, green waste, and manure. Different composting processes exist. Windrow composting is a classic process characterized by large-scale production on an outdoor platform and the utilization of large machinery for regular compost row turning, which is needed to maintain aerobic conditions and accelerate microbial activities. This process can last approximately 6 months and may generate significant odors (Arvanitoyannis et al., 2008). Composting can also be carried out in semi-closed trays or closed tunnels under more controlled conditions than windrow composting. Recently, a new method, electromechanical composting, has been proposed for households, restaurants, and supermarkets to speed up biowaste processing in smaller volumes without generating significant odors (Canditelli et al., 2022). Briefly, during processing, the electromechanical apparatus automatically mixes the materials with blades every 2 h, which ensures oxygenation to optimize bacterial activity (Plana et al., 2016). Given the various feedstocks, processes, storage times and conditions before use,

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the produced composts may differ in their characteristics.

Digestates are BBFs defined as co-products of anaerobic digestion of various organic feedstocks (e.g. slurry, manure, crop residues, biowaste) to produce biogas. Anaerobic digestion has largely been used for agricultural waste processing, but recently, food waste is also increasingly being processed, producing digestates with potentially different characteristics (Xu et al., 2018). Additionally, the digestate pasteurization has been found to significantly decrease the pathogen risk when used for crop production (Nag, 2022).

In some peri-urban areas, separate collection of human urine and its use as a substitute for mineral nitrogen fertilizers has been explored by recent studies (Martin et al., 2022).

Farmlands in peri-urban areas represent an interesting outlet for all these BBFs. In these areas, market gardens produce major crops combined with more classical arable crops. Market gardening, particularly organic production, has emerged encouraged by a strong demand from the population of cities (Tedesco et al., 2017) and action plans to re-implement vegetable production in peri-urban areas (Pourias et al., 2015). Many studies have reported yield increases and quality improvements in vegetables such as lettuce or tomato after BBFs (composts, digestate, stored human urine) application either alone or in combination (Alromian, 2020; Hernández et al., 2016; Livonen and Tontti, 2010; Pradhan et al., 2009). In a combined application, the BBF is generally applied along with a reduced rate of synthetic fertilizer while maintaining the yield (Brunetti et al., 2019; De Rosa et al., 2016). Most combinations include amendments such as composts or manure with synthetic fertilizers applied directly or through fertigation. Studies on combinations of BBFs such as human urine and food waste digestate applied together at the planting period are lacking, although the practice is commonly observed in some market gardening areas.

In market gardening, the application of stable carbon-rich BBFs contributes to maintain soil organic carbon stocks, which are generally subjected to higher rates of degradation due to the intensive tillage required during soil preparation compared with other cropping systems. Additionally BBF application positively impacts related properties such as soil structure and soil water retention capacity (Diacono et al., 2019). Composts and manure were shown to increase carbon and nutrients in vegetable soils, but the effects were more noticeable over repeated applications (Morra, 2019; Hernández et al., 2016). The benefits of BBFs applications to soil recently converted from arable cropping (characterized by the absence or rare application of organic amendments) into vegetable production systems need to be investigated.

The use of BBFs generally falls under some regulations. In France, for instance, the use of organic amendments, including composts and manure, needs to meet the requirements of French standard NF U44–051 (AFNOR, 2006). Although some requirements also exist for digestates, their use for vegetable production is currently completely banned (Ministère de l'Agriculture et de l'Alimentation, 2019). In contrast, human urine is not specifically and clearly regulated. One main reason for the restriction on the use of some BBFs is to prevent the potential transfer of trace elements and pathogens to harvested products, especially leafy and ready-to-eat vegetables such as lettuce (Alromian, 2020; Murphy et al., 2016).

Literature analysis revealed a lack of insights into some new BBFs and the impact of their combined use on the productivity and quality of vegetables and on the properties of soil recently converted to market gardening. Therefore, the aim of this study was to assess the effects of combining diverse BBFs collected in the Paris area on lettuce yield, trace element, pathogen contents and soil properties under open field conditions. The BBFs included food waste compost from electromechanical composting, classic green waste compost, cow manure, stored human urine and pasteurized food waste digestate.

2. Materials and methods

2.1. Collection of BBFs

All BBFs were collected in peri-urban areas outside Paris, France. The green waste compost (GWC) was obtained from a local green waste composting plant that receives green wastes from neighboring communities, with a production capacity of 12,000 t of compost annually. The green waste included grass clippings, flower cuttings, and hedge and brush trimmings. The compost was produced on an open windrow composting platform over six months after being turned three times and screened at 25 mm. The food waste compost (FWC) was produced after 15 days of composting in an electromechanical apparatus followed by 8 weeks of maturation on an open platform and then screening at 20 mm. The feedstock mixture was a ratio of 5:1 (w/w) food waste (restaurant leftovers) and hardwood pellets. The cow manure (MAN) was collected from a cow breeding farm and kept on an open platform for more than a year. The food waste digestate (D) originated from microscale mesophilic anaerobic digestion of sorted food waste from households, restaurants and supermarkets. The digestion lasted for 1 month, and the digestate was pasteurized at 70 °C for 1 h. Human urine (HU) was collected from a university building using a waterless male urinal and stored for more than two years in an airtight tank.

2.2. Characterization of BBFs

2.2.1. Physico-chemical characteristics and pathogen contents

The BBF samples (three replicates) were collected after being thoroughly mixed on the day they were applied for physico-chemical characterization. Another sample was collected separately into a sterilized container for pathogen analysis. All samples were first stored at 4 °C, and depending on the analysis, they were used either in their fresh or dry form.

The physico-chemical characterization of BBFs was performed using classical methods. The dry matter (DM) was analyzed by oven-drying at 105 °C for 24 h (AFNOR, 2007). The organic matter in all BBFs was estimated using the calcination method (480 °C for 6 h; AFNOR, 2011). The total carbon (TC) content was determined by the Dumas method (catalytic combustion at 900 °C), while the lime content was estimated using the Bernard calcimetry method. The organic carbon (OC) content was calculated by subtracting 12 % of the lime content from the total carbon content. Total N was determined according to the Dumas method for composts and manure (AFNOR, 2002a) and the Kjeldahl method for human urine and digestate (AFNOR, 2002b). Ammonium (NH_4^+) and nitrate (NO_3^-) contents were directly estimated in the liquid fraction of fresh samples based on the Berthelot and Griess methods, respectively (AFNOR, 2002c). The organic N content was calculated by subtracting the mineral N (sum of ammonium and nitrate contents) from the total N. Electrical conductivity (EC) and pH were analyzed on ground dry samples of manure and composts after extraction in water at a 1:10 ratio followed by filtration and measurements with a conductivity meter or a pH meter, respectively. The same method was used for human urine and digestate but on fresh samples (AFNOR, 2012a, 2012b). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S) and trace elements including cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb), cobalt (Co), copper (Cu), molybdenum (Mo) and zinc (Zn) were determined on ground dry samples of all BBFs by extraction with aqua regia (1/4 nitric acid–3/4 hydrochloric acid mixture) under reflux for 2 h followed by inductively coupled plasma atomic emission spectrometry (ICP-AES) analysis (AFNOR, 2009). The estimation of the other trace elements, namely, arsenic (As), mercury (Hg) and selenium (Se), was performed by similar extractions but followed by atomic absorption spectrophotometry with generation of hydrides.

Six pathogen indicators were assessed on the fresh samples: *E. coli* (NF EN ISO 16,649–2), *Clostridium perfringens*, fecal enterococci (NF EN ISO 7899–1), *Salmonella* (NF V 08–052 (05/97)), helminth eggs (XP X

33–017) and *Listeria monocytogenes* (NF V 08–055 (08/97)).

2.2.2. Laboratory incubation of BBFs

The BBFs, namely, FWC, GWC, MAN and D, were incubated under laboratory conditions by a partner laboratory (LDAR) following the protocol FD U44–163 to determine the kinetics of organic C and N mineralization in soil over 91 days (AFNOR, 2018). Human urine was not tested given its low organic matter content. The incubated mixtures were prepared with 25 g of 4-mm-sieved fresh soil alone or mixed with the different BBFs in four replicates. The quantity of BBFs added to the soil was calculated to provide approximately 2000 mg of organic C per kg of dry soil. The manure and composts added to the soil were first dried and ground, whereas fresh digestate was directly added. The soil used for the incubation was collected from the upper soil layer (0–30 cm) in the experimental field of the present study. The incubations were carried out at 28 °C in darkness. Carbon mineralization was measured by the dosage of carbon dioxide (CO_2) trapped in 10 ml of titrated 0.50 N sodium hydroxide after 1, 3, 7, 14, 21, 28, 49, 70 and 91 days of incubation. Mineral nitrogen measurements were executed after 0, 7, 14, 28, 49, 70 and 91 days of incubation by extraction with 100 ml of 1 M chloride potassium (KCl) followed by dosage using continuous-flow colorimetry (Griess and Berthelot methods for NO_3^- and NH_4^+, respectively; ISO 14,256–2:2005). The percentages of mineralized organic carbon (OCmin) and nitrogen (Nmin) were calculated as described in Eq. (1) and 2, respectively:

$$OCmin\ (\%\ Corg) = \frac{Cmin\ BBF\_soil - Cmin\_soil}{added\ OC} \times 100 \tag{1}$$

$$Nmin\ (\%\ Norg\ ) = \frac{Nmin\ BBF\_soil - Nmin\_soil}{added\ Norg} \times 100 \tag{2}$$

where Cmin BBF_soil is the mineralized carbon from the mixture of BBF and soil; Cmin_soil is the mineralized carbon from the soil alone; OC is the organic carbon in the added BBF; Nmin BBF_soil is the mineral nitrogen from the mixture of BBF and soil; Nmin_soil is the mineral N from the soil alone; and Norg is the organic nitrogen in the added BBF.

The N mineralized in the composts and manure under field conditions over 48 days (from lettuce planting to harvesting) was estimated from the laboratory incubation results by determining the equivalent incubation time using the correction factors described in the STICS model (Brisson et al., 2009) based on the temperature in the field compared to the constant temperature during incubation under controlled conditions (28 °C, field capacity). Thus, the percentage of organic N mineralized under field conditions was determined, and then, the total available N was determined considering the total organic nitrogen applied.

2.3. Field experiment

The field experiment was carried out at the experimental farm of the French National Research Institute for Agriculture, Food and Environment (INRAE), located in Thiverval-Grignon (Ile-de France Region, 48°50′21.7″N, 1°57′06.2″E) in a plot previously used for arable crop production (colza, wheat and barley successively). According to the Köppen–Geiger classification, the climate is a warm oceanic climate without a dry season (Cfb). The annual average temperature is 11.2 °C, and the average rainfall is 636 mm. The temperature, rainfall and evapotranspiration during the experiment were measured on a daily basis by a local weather station. The soil was a Luvisol (according to the French Soil Classification system) with a clay loam texture (20 % clay, 70 % silt, 10 % sand) in the 0–30 cm horizon and was slightly alkaline (pH 7.6) with organic carbon and nitrogen contents of 10.8 and 1.1 g kg^{-1}, respectively.

The experiment was set up in a randomized complete block design with three replicates per treatment (Figure S1 in the supplementary material). The trial included nine treatments: control (no fertilizer application), synthetic fertilizer (SF), manure + synthetic fertilizer (MAN_SF), green waste compost + synthetic fertilizer (GWC_SF), green waste compost + digestate (GWC_D), green waste compost + human urine (GWC_HU), food waste compost + synthetic fertilizer (FWC_SF), food waste compost + digestate (FWC_D) and food waste compost + human urine (FWC_HU). The synthetic fertilizer used was a granular NPK fertilizer (100 N, 35 P, 166 K g kg^{-1}) bought in the local market. The NPK fertilizer was employed as a positive control, reflecting a prevalent fertilization practice in market gardening of the study area. The unfertilized control was particularly necessary to calculate the nitrogen use efficiency (NUE) for SF and the different BBFs.

The soil was plowed at 30 cm depth in October 2020 and rotary-tilled at the same depth twice (04/07/2021, 04/21/2021). The elementary plots were 15-cm-high raised beds established manually on 06/04/2021. Each plot was 2 m long and 1 m wide with 0.7 m bands between the different plots. Since the analytical results were not available at the start of the experiment, the BBFs doses were first calculated based on previous knowledge about these BBFs. Then, the real doses applied were recalculated based on the analytical results of the BBFs. On the day prior to planting (06/07/2021), composts and manure were applied with the objective of supplying 3 t C ha^{-1}. Immediately after, food waste digestate, human urine or synthetic fertilizer were applied to supply 120 kg of available mineral N per ha, according to local practices. The available N provided by the BBFs was estimated by adding the mineral N provided by the BBFs and the proportion of organic N mineralized by the composts and manure over the lettuce growing period, estimated as 20 %, 11 % and 1 % of organic N (Norg) for food waste compost, manure and green waste compost, respectively (Levavasseur et al., 2022). All applied fertilizers were then mixed into the 0–15 cm soil layer. The doses of synthetic fertilizer and BBFs applied are reported in Table S1.

Four-week-old lettuce seedlings were planted on 06/08/2021 at a density of 6 plants m^{-2} with 30 cm between both the rows and the plants as recommended by the variety developer. The variety “Batavia Marinski” was used given its wide production in the area and resistance to several diseases in open field conditions. A drip irrigation system was established a few days before planting and calibrated. Water was supplied based on daily plant requirements, which were calculated by multiplying the evapotranspiration value of the previous day by a culture coefficient (Kc) corresponding to the growth stage (0.5 for the first 3 weeks and 1 for the remaining period). No water was supplied following sufficient rainfall. A total amount of 63 mm of water was supplied over the 48 days in all treatments. The field trial lasted 48 days. The rainfall, irrigation and temperature data are presented on a daily basis in Figure S2. Weeds were removed manually twice during the experiment. No phytosanitary treatment was applied.

2.4. Lettuce analyses and related calculations

The lettuce aboveground biomass was harvested twice, after 23 days (4 harvested lettuce plants) and 48 days (6 lettuce plants) after planting. The fresh weight was measured. The dry weight was obtained after drying the fresh lettuce in an oven at 80 °C for 48 h. The physicochemical characteristics and pathogens were analyzed in lettuce harvested on day 48 only. Total nitrogen (TN) was analyzed using the Dumas method (ISO 16,634–2:2016), whereas P, K, Ca, Mg and trace elements (total Cu, Cd, Cr, Hg, Pb, Zn) were determined by extraction with aqua regia under reflux for 2 h followed by ICP–AES dosage. The nitrate content in the lettuce was measured using ion chromatography.

Four pathogens were measured on fresh lettuce: *Staphylococci* by colony count at 37 °C using Baird Parker’s gel medium (AFNOR, 1999), *Clostridium perfringens* by colony count at 37 °C in anaerobiosis (AFNOR, 2005), *Salmonella* by using the chromogenic medium SALMA One Day (Inovalys, 2021), and *Listeria monocytogenes* by using the chromogenic medium ALOA One Day at 37 °C (Inovalys, 2023).

Nitrogen use efficiency (NUE) is an indicator of nitrogen use from applied fertilizers and was calculated according to Eq. (3) (Benincasa et al., 2011; Greenwood et al., 1989). It was expressed as the percentage of total nitrogen (NUEtot) or mineral nitrogen (NUEmin) applied.

$$NUE(\%) = \frac{Ut - Uc}{Total\ N\ or\ Min\ N} \times 100 \tag{3}$$

where Ut is the nitrogen uptake (kg ha^{-1}) by lettuce in fertilized plots; Uc is the nitrogen uptake (kg ha^{-1}) by lettuce in unfertilized control plots; and Total N and Min N are the total and mineral nitrogen applied, respectively (kg N ha^{-1}).

The mineral fertilizer equivalent (MFE) was also calculated as presented in Eq. (4) (Shi et al., 2022). It represents the equivalent of SF, leading to the same N use as the BBFs.

$$MFE\ (\%) = \frac{NUE\ BBF}{NUE\ SF} \times 100 \tag{4}$$

where NUE SF and NUE BBF represent the nitrogen use efficiency based on total nitrogen applied from SF or from BBFs, respectively.

2.5. Soil analyses

2.5.1. Physico-chemical characterization

The soils were sampled in the 0–30 cm layer before applying the treatments and at 0–15 and 15–30 cm depths after the second harvest day (Day 48) in three replicates. The analyses were performed by an external laboratory (LDAR) on air-dried and 2-mm-sieved soil. Total N was measured by the Kjeldahl method (ISO 11,261:1995), and organic C was measured by the oxidation method. The pH was determined in a mixture of soil and water at 1:5 v/v. The Olsen method (ISO 11,263:1994) was used for available phosphorus determination. The cation exchange capacity (CEC) was analyzed using cobaltihexamine chloride extraction followed by spectrocolorimetry, while the exchangeable K, Ca, and Mg were determined by ICP–AES (ISO 23,470:2018)

2.5.2. Evolution of soil mineral N (SMN)

Soil mineral N was measured at two different depths, 0–15 cm and 15–30 cm, at the beginning of the experiment (before fertilizer application) and on the harvesting dates. After extraction of 50 g of fresh soil with 100 ml of a 1-M potassium chloride (KCl) solution for 1 h, the N—NH_4^+ and N—NO_3^- were measured using the Berthelot and Griess colorimetric methods, respectively (ISO 14,256–2:2005). The mineral N stocks in soil layers were calculated by multiplying the mineral N contents by the soil mass at the considered depth using its bulk density (1 g cm^{-3} for 0–15 and 15–30 cm).

2.6. Statistical analyses

The significance of differences in plant productivity and physico-chemical properties of lettuce and soil was subjected to one-way ANOVA, and afterward, Tukey's multiple range test was performed to compare the means using Rstudio software (version 2021.09.0 + 351). Prior to ANOVA, the normality of the data and the homogeneity of variances were checked using the Shapiro−Wilk test and Levene's test, respectively.

3. Results

3.1. Physico-chemical characteristics and pathogen contents of BBFs

The physico-chemical characteristics of the BBFs presented strong differences (Table 1). The dry matter (DM) content was higher in manure and composts compared to digestate and human urine. Composts and manure also showed high organic carbon (OC) contents and could be seen as amendments in contrast to human urine (HU) and digestate (D), which can be considered as N fertilizers given their

Table 1
Physico-chemical characteristics of bio-based fertilizers expressed on a fresh matter basis except for the trace elements (dry matter basis). Values represent the mean ± standard deviation of three measures. Row values with similar letters are not significantly different at $P \leq 0.05$ by Tukey's test. Values with the symbol "<" were not included in the comparisons. Moreover, no analysis was done when only one value was without "<". **NF U 44–051:** French standard for organic amendments (AFNOR, 2006).

Bio-based fertilizers	Green waste Compost	Food waste compost	Cow manure	Food waste digestate	Human Urine	Threshold defined by NF U 44–051
Form	Solid	Solid	Solid	Liquid	Liquid	–
Dry matter (g kg^{-1})	489±9 a	458±3 b	224±8 c	31±9 d	14±0 d	–
Organic matter (g kg^{-1})	269 ± 9 b	426±2 a	145±5 c	15±4 d	4 ± 0 d	–
Organic carbon (g kg^{-1})	151±7 b	217±1a	81±2 c	9 ± 2 d	0.3 ± 0.4 d	–
Total nitrogen (g kg^{-1})	7.5 ± 0.3 b	14.3 ± 0.6 a	5.9 ± 0.1 c	7.2 ± 0.2 b	7.2 ± 0.0 b	–
Organic nitrogen (g kg^{-1})	7.5 ± 0.3 b	13.3 ± 0.1 a	5.6 ± 0.1 c	1.3 ± 0.2 d	1.1 ± 0.1 d	–
C:Ntotal ratio	20.±0.5 a	15.±0.1 b	13.7 ± 0.5 c	1.1 ± 0.3 d	0.04±0 d	–
C:Norg ratio	20±0.5 a	16±0 b	14.5 ± 0.4 c	6.7 ± 0.8 d	0.3 ± 0 e	–
N-NH_4^+ (g kg^{-1})	<0.5 ± 0	1.2 ± 0.1 c	<0.2 ± 0	6 ± 0 b	6.2 ± 0.2 a	–
N—NO_3^- (g kg^{-1})	<0.09±0	<0.09±0	0.02±0	<0.16±0	<0.18±0	–
pH	8.7 ± 0.1 c	7 ± 0 e	9.3 ± 0.1 a	8.5 ± 0 d	9.1 ± 0 b	–
EC (mS cm^{-1})	1.1 ± 0.0 d	5.3 ± 0.1 c	5.5 ± 0.2 c	39±1 b	41±0 a	–
$CaCO_3$ (%)	2.5 ± 0.3 a	< 0.1 ± 0	0.8 ± 0.1 b	2.8 ± 0.3 a	2.4 ± 0.1 a	–
P (g kg^{-1})	1 ± 0 bc	1.4 ± 0.2 b	2 ± 0 a	0.8 ± 0.8 c	0.7 ± 0 d	–
K (g kg^{-1})	4 ± 0.2 c	5 ± 0.2 b	6 ± 0.2 a	2 ± 0 d	2 ± 0.1 d	–
Ca (g kg^{-1})	18±1 a	1.7 ± 0.1 c	5.4 ± 0.6 b	2.1 ± 2 c	<0.1 ± 0	–
Mg (g kg^{-1})	1.3 ± 0.1 b	0.4 ± 0.1 c	1.4 ± 0.1 a	0.1 ± 0.1 d	<0.02±0	–
Trace elements (expressed on a dry matter basis)						
As (mg kg^{-1})	3 ± 0	<1 ± 0	<1 ± 0	<2 ± 0	<5 ± 0	18
Cd (mg kg^{-1})	0.4 ± 0 b	<0.1 ± 0 b	0.3 ± 0 b	1 ± 0 a	<0.45±0	3
Cr (mg kg^{-1})	12±1 a	3 ± 0 b	8 ± 3 ab	11±3 a	<4 ± 0	120
Hg (mg kg^{-1})	<0.1 ± 0	<0.1 ± 0	<0.1 ± 0	<0.2 ± 0.1	<0.5 ± 0	2
Ni (mg kg^{-1})	6.7 ± 0.3 a	2.6 ± 0.2 c	3.8 ± 0.4 b	6.9 ± 0.1 a	<4.5 ± 0.2	60
Pb (mg kg^{-1})	37.3 ± 5.9 a	<3.6 ± 0.1	15.5 ± 10.6 b	<7.1 ± 1.3	<11.1 ± 0.4	180
Se (mg kg^{-1})	<0.6 ± 0	<0.6 ± 0.03	0.8 ± 0.02 b	1.4 ± 0.12 a	<1.8 ± 0.10	12
Co (mg kg^{-1})	2.9 ± 0.4 a	<0.7 ± 0	2.9 ± 0.1 a	<1.1 ± 0.3	<2.2 ± 0.1	/
Cu (mg kg^{-1})	37.5 ± 1.9 b	<14.6 ± 1.3	54.9 ± 0.7 b	173.2 ± 41.3 a	<43.5 ± 0.8	300
Mo (mg kg^{-1})	< 1.4 ± 0	<1.5 ± 0.1	2.6 ± 0 b	4 ± 0 a	4.4 ± 0.1	/
Zn (mg kg^{-1})	134±10 c	31±4 d	301±7 b	428±76 a	<22±0	600

important content of readily available nitrogen, particularly ammonium ($N—NH_4^+$, 6 g kg^{-1}). In contrast, composts and manure presented mainly organic N and low mineral N contents. Composts and manure had higher C:Ntotal ratios than D and HU. Because of the high proportion of $N—NH_4^+$ content in these last two BBFs, they had a larger C:Norg than C:Ntotal, while the composts and manure had quite similar C:Norg and C:Ntotal.

Regarding the other nutrients, composts and manure had higher contents of potassium than HU and D. MAN had the highest phosphorus content, and green waste compost (GWC) had the highest calcium (Ca) and magnesium (Mg) contents. FWC, D and HU had much lower Mg contents than GWC and MAN. All BBFs had alkaline pH values except for food waste compost (FWC), which was neutral. The electrical conductivity of HU and D was approximately eight times higher than that of the composts and manure. The GWC, HU and D had carbonates ($CaCO_3$) contents between 2.4 and 2.8 %, while the two other BBFs had very low $CaCO_3$ contents.

All trace elements in the BBFs (Table 1) were below the threshold values of the French standard NF U 44–051 defined for organic amendments such as composts and manure. The GWC met the requirements set by the French standard NF U 44–051 regarding the six pathogens analyzed (Table 2). Likewise, the pathogen levels in HU were satisfactory except for those of fecal enterococci; however, they were acceptable according to the French fertilizing material approval criteria. FWC and MAN did not fully comply with the French standard because of a fecal enterococci level above the threshold and the presence of viable helminth eggs, respectively. Moreover, D did not meet the requirement for fecal enterococci.

3.2. Stability of organic matter and availability of N in BBFs

The biodegradability of organic carbon (OC) in BBFs has been approached through the measurement of C mineralization during incubation in soil under controlled conditions (Fig. 1A). D presented very high biodegradability with almost 100 % C mineralization during incubation. FWC was also rather biodegradable, with 33 % of mineralized C. GWC and MAN presented the most stable organic matter, with only 9 and 7 % of organic C mineralized, respectively.

The organic nitrogen mineralization of BBFs in soil was also assessed under controlled conditions in the laboratory (Fig. 1B). A strong mineralization of organic N was observed with the digestate, which was much lower in the case of the manure. The application of the two composts resulted in N immobilization. However, the N immobilized in soil with GWC (equivalent to 2.5 % of applied Norg) was rather low compared with FWC (equivalent to 19 % of applied Norg).

Based on the equivalence calculations, the percentage of mineralized organic nitrogen over 48 days in the field corresponded to the values obtained after 23 days of incubation, i.e., - 4.2 %, −17.0 % and 2.6 % for GWC, FWC and manure, respectively (Fig. 1B). Digestate was not included given the negligible added organic N. The N mineralized by these BBFs was then calculated according to the organic nitrogen applied, and by adding it to the mineral nitrogen already present in the BBFs, the actual available nitrogen for lettuce was obtained (Table 3). These results differed from expected, as observed from the variations in the available nitrogen, and the majority of treatments resulted in less than the 120 kg ha^{-1} initially envisaged. Instead of mineralization, GWC and FWC led to nitrogen immobilization in soil estimated at 6 and 32 kg ha^{-1}, respectively. Mineralization occurred with manure but was lower than expected, producing only 7.4 kg ha^{-1}. The applied nutrients other than nitrogen are also presented in Table 3.

3.3. Lettuce yield

Lettuce harvested after 23 and 48 days of growth showed significant differences in fresh yield (Fig. 2). On day 23, all fertilized treatments significantly increased the yield compared to the unfertilized treatment (control), except for FWC_HU and FWC_D. On the last harvest day (day 48), only the manure and synthetic fertilizer combination (MAN_SF) showed a significant increase on yield compared to the control, reaching 73 t ha^{-1}. However, this value did not differ significantly from those of the other fertilized treatments. Lettuce dry yield was also affected by the treatments at day 23 with a similar trend as the fresh yield, whereas no significant difference was observed at day 48 (Figure S3). A strong positive correlation was observed between dry yield and total available nitrogen over 48 days (R^2=0.78) and initial mineral nitrogen applied (R^2=0.91). The fresh yield was less correlated with these two factors (R^2=0.5 and 0.43, respectively) (Figure S4).

3.4. Nitrogen use efficiency and mineral fertilizer equivalent

The nitrogen use efficiencies based on the applied mineral N (NUEmin) were not significantly different among the treatments, although there was a strong variation, ranging from 22 % in the GWC_HU treatment to 44 % in the MAN_SF treatment (Table S2). In contrast, significant differences were found among treatments regarding the nitrogen use efficiency calculated based on total N (NUEtot), with SF presenting the highest value (35 %), while the values of the other treatments varied from 6 to 17 %. Similar to NUEmin, mineral fertilizer equivalent (MFE) did not differ significantly among treatments (Table S2) but showed considerable variation among them (from 17 % in FWC_HU to 49 % in GWC_SF).

3.5. Nutrient contents of lettuce

The N and K contents in aboveground lettuce at the end of the experiment were significantly affected by the treatments (Fig. 3), whereas the P, Ca and Mg contents did not differ (Figure S5). Compared to the control treatment, all the fertilized treatments significantly increased the N content of lettuce, except the treatments with FWC (FWC_SF, FWC_HU, FWC_D) and urine (GWC_HU and FWC_HU). Most treatments fertilized with SF (SF, MAN_SF and GWC_SF) increased the N content of lettuce compared to the other fertilized treatments, although

Table 2
Pathogen contents of the fresh bio-based fertilizers applied. NF U 44–051: French standard for organic amendments. Values with "+" mean that the standard judges the products as "acceptable", although their content exceeds the threshold. NA: Not analyzed. ND: Not defined in the standard.

Bio-based fertilizers	Green waste compost	Food waste compost	Cow manure	Food waste Digestate	Human urine	Fertilizing material approval criteria*	Threshold defined by NF U 44–051
Escherichia coli (MPN/g)	<100	<100	< 400	< 100	< 100	1000/g	1000/g
Clostridium perfringens (MPN/g)	<40	<10	> 15,000	50^+	<10	10/g	ND
Fecal enterococci (MPN/g)	2862	94,489	2567	965	129^+	100/g	10,000/g
Salmonella	Absent	Absent	Absent	Absent	Absent	Absent/25 g	Absent/25 g
Listeria monocytogenes	Absent	Absent	Absent	Absent	NA	Absent/25 g	Absent/25 g
Viable Helminth Eggs	Absent	Absent	Present	Absent	Absent	Absent/1.5 g	Absent/1.5 g

*criteria for the approval of fertilizing materials and growing media used in agriculture in France. They are used for human urine and food waste digestate.

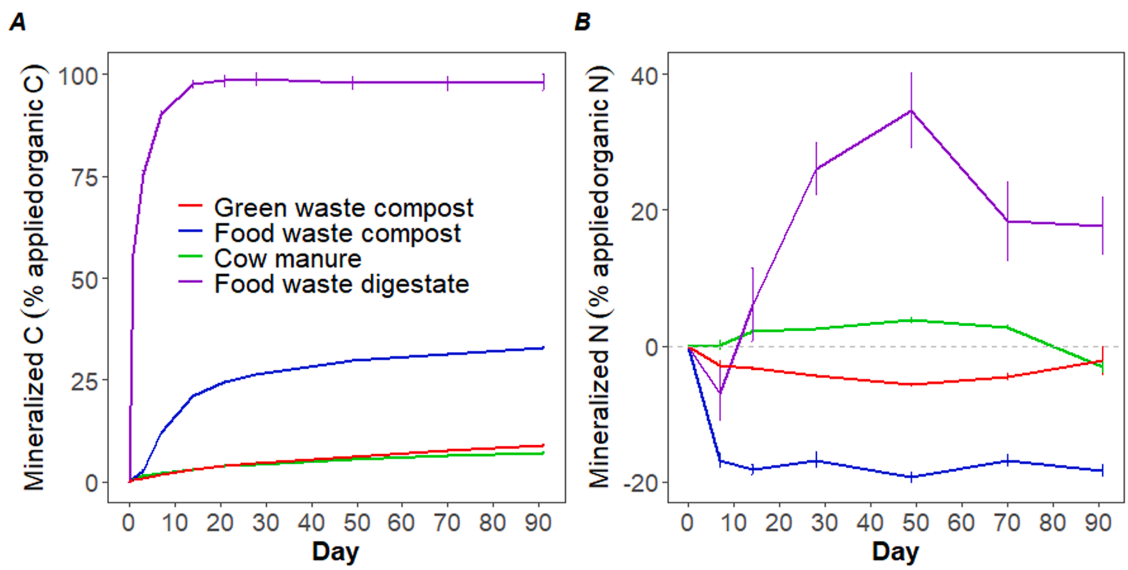

Fig. 1. Organic carbon (A) and nitrogen (B) mineralization of the bio-based fertilizers. Each error bar represents the standard deviation of four replicates at a given measurement point.

Table 3
Actual total available N over the growing period (48 days) based on mineral N and measured organic N mineralization after 23 days during incubation, applied carbon and other nutrients added by bio-based fertilizers in the different treatments. Control: unfertilized treatment, SF: synthetic fertilizer, MAN_SF: manure + synthetic fertilizer, GWC_SF: green waste compost + synthetic fertilizer, FWC_SF: food waste compost + synthetic fertilizer, GWC_D: green waste compost + digestate, GWC_HU: green waste compost + human urine, FWC_D: food waste compost + digestate, FWC_HU: food waste compost + human urine.

Treatments	Mineral N from the treatments (kg ha^{-1})	Organic N from composts or manure (kg ha^{-1})	N mineralized by composts or manure (kg ha^{-1})	Total available mineral N over 48 days (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	C (t ha^{-1})
Control	0	0	0	0	0	0	0	0	0
SF	120	0	0	120	42	199	0	0	0
MAN-SF	79	288	7	86	125	428	279	76	4
GWC-SF	118	136	−6	112	60	264	327	24	3
GWC-HU	106	136	−6	100	23	92	328	24	3
GWC-D	117	136	−6	111	34	104	370	25	3
FWC-SF	68	188	−32	37	38	156	25	5	3
FWC-HU	63	188	−32	31	22	80	26	5	3
FWC-D	68	188	−32	36	26	85	44	6	3

not significantly. The highest K content in lettuce was recorded with the combination of manure and SF (MAN_SF). Statistically similar K contents were observed with all treatments, including in the synthetic fertilizer and control plots. Lettuce P, K, and Ca contents showed a positive and strong correlation with the amount of the respective nutrient applied (p<0.01, R^2=0.71 to 0.75, Table S3). Likewise, the available N applied was positively correlated with the lettuce N content (p<0.05, R^2=0.53).

In all the treatments, the nitrate contents in lettuce ranged from 160 to 240 mg kg^{-1} fresh lettuce and were below 3000 mg kg^{-1} (Figure S6), the maximum EU fixed value for fresh lettuce produced in open fields and harvested between 1 April and 30 September (European Commission, 2011). However, the highest values were found in lettuces that received synthetic fertilizer.

The N, P, K, Ca and Mg uptake by lettuce (expressed in kg dry matter ha^{-1}) was not different among the treatments, except for N, where GWC_SF and SF differed from the control but were not different from the other treatments (Figure S7).

3.6. Trace elements and pathogens in aboveground lettuce

The trace element contents in fresh lettuce were below the maximum limits set by the EU (European Commission, 2006) (Table 4). The highest Pb, Ni and Cr contents were measured in the unfertilized control plots. No significant difference was found among treatments in regard to Zn and Cu contents. The Cd content in dry matter was higher in plots fertilized with SF compared to other fertilization treatments (Table S4). In all treatments, the pathogens were not detected or were below the detection limits (Table S5).

3.7. Effect of BBFs application on soil properties

3.7.1. General soil characteristics

Significant differences were observed with treatments compared to the initial soil (Table 5). Overall, the treatments with SF led to a decrease in soil pH and increases in available P, exchangeable K, and Mg. The CEC also varied among treatments but remained statistically similar to the initial status. No effect of treatments was found on organic C, total N or exchangeable Ca content. Furthermore, none of the characteristics of the soil sampled from 15 to 30 cm depth differ significantly either among treatments or compared to the initial soil (Table S6).

3.7.2. Soil mineral nitrogen (SMN) stocks

Prior to the application of BBFs, the mineral nitrogen content was

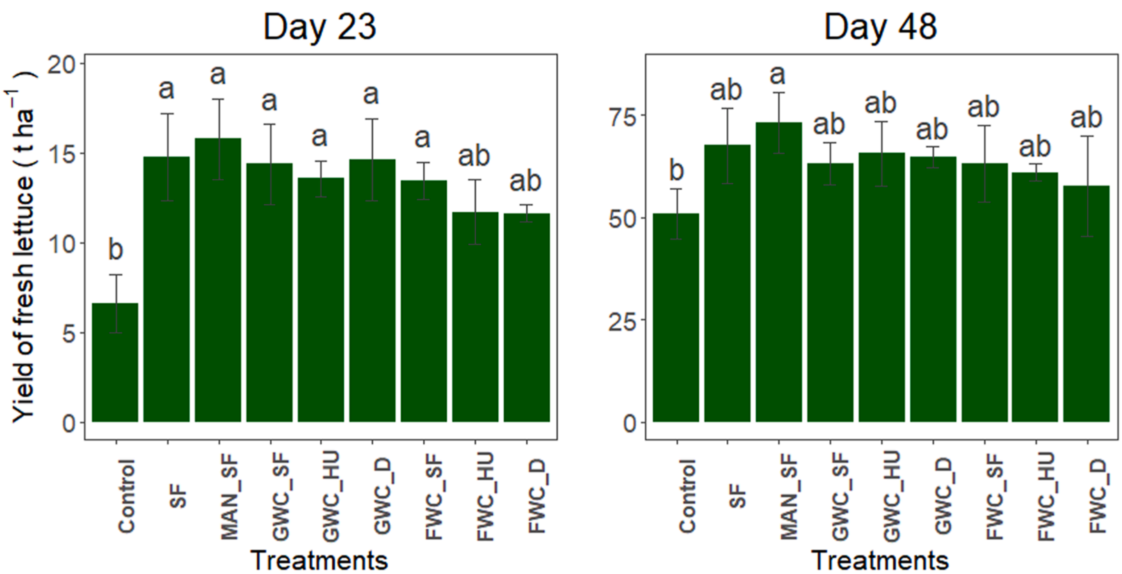

Fig. 2. Fresh yields of lettuce at days 23 and 48. The bars represent the means of three replicates, while the error bars indicate the standard deviations. Bars with similar letters are not significantly different at $P \leq 0.05$ by Tukey's test. Control: unfertilized treatment, SF: synthetic fertilizer, MAN_SF: manure + synthetic fertilizer, GWC_SF: green waste compost + synthetic fertilizer, FWC_SF: food waste compost + synthetic fertilizer, GWC_D: green waste compost + digestate, GWC_HU: green waste compost + human urine, FWC_D: food waste compost + digestate, FWC_HU: food waste compost + human urine.

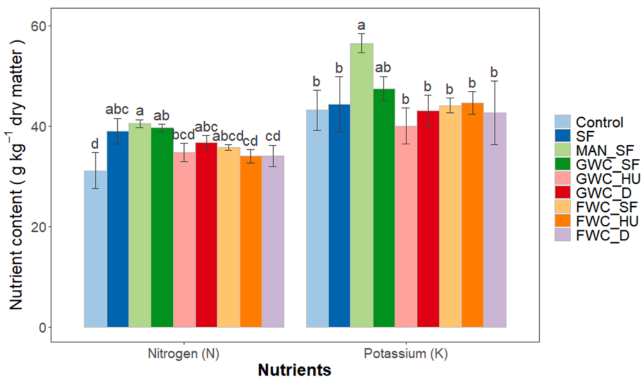

Fig. 3. Physico-chemical characteristics of lettuce: N, and K contents. The results are expressed on a dry matter basis. The bars represent the means of three replicates, while the error bars indicate the standard deviations. Bars with similar letters or without letters are not significantly different at $P \leq 0.05$ by Tukey's test. Control: unfertilized treatment, SF: synthetic fertilizer, MAN_SF: manure + synthetic fertilizer, GWC_SF: green waste compost + synthetic fertilizer, FWC_SF: food waste compost + synthetic fertilizer, GWC_D: green waste compost + digestate, GWC_HU: green waste compost + human urine, FWC_D: food waste compost + digestate, FWC_HU: food waste compost + human urine.

approximately 29 kg ha^{-1} in the 0–15 and 15–30 cm soil layers (red dotted lines, Fig. 4); thus, there was a total Nmin content of 58 kg ha^{-1} in the 0–30 cm layer. After the application of the BBFs, a significant increase was observed on day 23 compared to the initial soil stock in the 0–15 cm layer. The contributions of the treatments to the 0–15 cm SMN stocks (differences between stocks in treated and control plots) were 80, 51, 82, 97, 108, 65, 41, and 30 kg ha^{-1} for SF, MAN_SF, GWC_SF, GWC_HU, GWC_D, FWC_SF, FWC_HU, and FWC_D, respectively, and were globally consistent with the initial mineral nitrogen applied with the treatments as listed in Table 3 ($R2=0.67$, $p<0.01$, Figure S8). The 0–15 cm SMN stocks were significantly higher in the SF, GWC_SF, GWC_HU, GWC_D and FWC_SF plots than in the control plots. No significant difference in the SMN stocks was identified among the treatments in the 15–30 cm layer after 23 days. At the last harvest day (day 48), the SMN stocks decreased in various treatments in the 0–15 cm (CONTROL, GWC_D, FWC_HU, FWC_D) and 15–30 cm (all treatments except MAN_SF and GWC_SF) layers compared to the initial stocks. The 0–15 cm SMN stocks in the fertilized plots were not significantly different than the stocks in the control plot except in the GWC_HU treatment after 48 days. Similar trends were observed in the 15–30 cm layers, with MAN_SF and GWC_SF displaying significantly higher stocks than the control treatment.

4. Discussion

4.1. Characteristics of BBFs

The composts and manure presented high carbon contents associated with a biodegradability below 30 % of applied OC and thus the ability to increase soil organic matter when applied. However, although food waste compost contained higher organic carbon than green waste compost and manure, its organic carbon was characterized by a high biodegradability, making this compost potentially less efficient at contributing to soil carbon stocks compared to the two other organic amendments. The very large mineralization of organic C after FWC addition to soil indicated the lack of stabilization during composting. The electromechanical composting process for food waste is quite fast and based on a mixture of woody pellets that are probably not completely degraded. Some adjustments may be needed regarding either the type or proportion of feedstocks or the duration of processing for stable compost production. Houot et al. (2003) indicated that the C biodegradability of a FWC decreased from 15 % to 3 % by extending the compost maturation period from two to four months in windrow composting.

The N immobilization observed after compost addition to soil (large for FWC, much lower for GWC) may be again related to incomplete stabilization during the composting process and to their rather high C:N ratio (Lazicki et al., 2020). Our study showed different kinetics of nitrogen mineralization compared to the literature for the same type of BBFs (Levavasseur et al., 2022), particularly for the FWC obtained by electromechanical processing, for which specific information was absent. This indicates that additional knowledge on the BBFs are necessary to provide useful advice for BBF application.

The food waste digestate (D) had a very low dry matter content, which could be advantageous because it eliminates the need for the

Table 4
Trace element contents in fresh lettuce. Values represent the means±standard deviations of three replicates. Different letters denote significant differences among treatments at $P < 0.05$ by Tukey's test. Control: unfertilized treatment, SF: synthetic fertilizer, MAN_SF: manure + synthetic fertilizer, GWC_SF: green waste compost + synthetic fertilizer, FWC_SF: food waste compost + synthetic fertilizer, GWC_D: green waste compost + digestate, GWC_HU: green waste compost + human urine, FWC_D: food waste compost + digestate, FWC_HU: food waste compost + human urine.

Treatments	Biomass (t ha^{-1})	Dry matter (%)	Cd (mg kg^{-1})	Pb (mg kg^{-1})	Ni (mg kg^{-1})	Cr (mg kg^{-1})	Hg (mg kg-^{1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})
Control	51±6 b	5.03±0.06 a	0.05±0 b	0.18±0.01 a	0.17±0.04 a	0.27±0.07 a	<0.05	0.48±0.01	16±0
SF	68±9 ab	4.63±0.15 ab	0.06±0 ab	0.09±0.01 bc	0.11±0.02 ab	0.17±0.03 ab	<0.05	0.44±0.01	16±0
MAN_SF	73±7 a	3.87±0.40 b	0.05±0 ab	0.05±0.01 c	0.07±0.02 b	0.09±0.02 b	<0.05	0.42±0.05	14±0
GWC_SF	63±5ab	4.93±0.76 a	0.07±0.01 a	0.09±0.02 bc	0.12±0.02 ab	0.18±0.04 ab	<0.05	0.5 ± 0.08	18±0
GWC_HU	66±8 ab	4.53±0.21 ab	0.05±0 b	0.11±0.03 abc	0.13±0.03 ab	0.2 ± 0.06 ab	<0.05	0.47±0.04	15±0
GWC_D	65±3 ab	4.73±0.21 ab	0.05±0 ab	0.09±0.04 bc	0.11±0.02 ab	0.15±0.04 ab	<0.05	0.47±0.04	17±0
FWC_SF	63±9 ab	4.53±0.35 ab	0.06±0 ab	0.11±0.03 abc	0.13±0.03 ab	0.2 ± 0.05 ab	<0.05	0.46±0.07	15±0
FWC_HU	61±2 ab	4.60±0.12 ab	0.05±0 ab	0.12±0.02 abc	0.14±0.02 ab	0.21±0.02 ab	<0.05	0.51±0.03	16±0
FWC_D	58±12 ab	4.93±0.49 a	0.06±0 ab	0.17±0.04 ab	0.16±0.04 a	0.25±0.06 a	<0.05	0.5 ± 0.07	17±0
EU Threshold	–	–	0.2	0.3	*ND*	*ND*	*ND*	*ND*	*ND*

ND: Not defined for lettuce.

Table 5
Soil (0–15 cm depth) characteristics before bio-based fertilizers application (initial soil) and on the harvest day (day 48). All results are expressed on a dry soil basis. Values represent the means ± standard deviations of three replicates. Column values with no letter in common differ significantly at $P \leq 0.01$ (Tukey's HSD test). Control: unfertilized treatment, SF: synthetic fertilizer, MAN_SF: manure + synthetic fertilizer, GWC_SF: green waste compost + synthetic fertilizer, FWC_SF: food waste compost + synthetic fertilizer, GWC_D: green waste compost + digestate, GWC_HU: green waste compost + human urine, FWC_D: food waste compost + digestate, FWC_HU: food waste compost + human urine.

Initial soil and at d48	pH	CEC (cmol^{+} kg^{-1})	Organic C (g kg^{-1})	Total N (g kg^{-1})	Available P (g kg^{-1})	Exchangeable K (g kg^{-1})	Exchangeable Ca (g kg^{-1})	Exchangeable Mg (g kg^{-1})
Initial soil	7.6 ± 0.1 a	16.4 ± 0.5 ab	10.8 ± 0.5	1.1 ± 0.01	0.04±0 c	0.14±0.01 b	3 ± 0	0.15±0 c
Control	7.8 ± 0.1 a	15.8 ± 0.6 ab	11.3 ± 0.5	1.1 ± 0.01	0.04±0.01 c	0.13±0.01 b	3 ± 0	0.15±0.02 c
SF	6.4 ± 0.1 c	15.2 ± 0.4 b	11.2 ± 0.5	1.3 ± 0.1	0.08±0.02 a	0.3 ± 0.1 a	3 ± 0	0.2 ± 0.03 a
MAN_SF	7.3 ± 0.2 ab	16.6 ± 0.1 a	12.2 ± 0.4	1.2 ± 0.1	0.05±0.01 bc	0.2 ± 0.1 ab	3 ± 0	0.17±0.01 abc
GWC_SF	6.9 ± 0.4 b	15.6 ± 0.7 ab	11.6 ± 0.3	1.3 ± 0.1	0.06±0.01 ab	0.23±0.05 ab	3 ± 0	0.2 ± 0.02 ab
GWC_HU	7.5 ± 0.3 a	16.7 ± 0.4 a	12.2 ± 0.5	1.3 ± 0.1	0.04±0 bc	0.14±0.01 b	3 ± 0	0.16±0.03 bc
GWC_D	7.7 ± 0.1 a	16.7 ± 0.4 a	11±0.5	1.2 ± 0	0.04±0 c	0.14±0.01 b	3 ± 0	0.16±0.01 bc
FWC_SF	7.3 ± 0.1 ab	16.2 ± 0.3 ab	12 ± 0.1	1.2 ± 0	0.05±0bc	0.16±0.01 ab	3 ± 0	0.16±0.01 bc
FWC_HU	7.7 ± 0.1 a	16.6 ± 0.4 a	12±1	1.2 ± 0.1	0.04±0 c	0.14±0.01 b	3 ± 0	0.16±0.01 bc
FWC_D	7.5 ± 0.2 a	16.4 ± 0.4 ab	12.1 ± 0.9	1.2 ± 0.1	0.4 ± 0 c	0.14±0.02 b	3 ± 0	0.15±0 bc

additional phase separation typically required for other types of digestates with higher dry matter content to increase their value as a fertilizer (Czekała, 2022). The considerable potassium content in manure and composts has the potential to benefit vegetables that typically have a strong requirement for this element to support their growth, especially in soils with low contents. (Chen et al., 2017). The alkalinity of all BBFs except FWC can be interesting for soil pH increase. However, the high electrical conductivity in HU and D should be taken into consideration to avoid soil salinization, as highlighted by Martin et al. (2022). HU and D presented trace elements contents below the standards of composts and manure, which constitute a positive aspect for their use as BBFs. Conversely, the unsatisfactory pathogen levels found in FWC and D but also in the commonly used manure need to be further examined. Composting has been shown to lower pathogens contents but not sufficiently in some cases (Gurtler et al., 2018). Pasteurization decreases pathogens in biowaste digestate, but Bagge et al. (2005) indicated a risk of recontamination depending on future handling. It is generally difficult to clearly identify the source of contamination given that our BBFs underwent different phases, such as collection on farms, transportation and storage (more than a month). To minimize contamination risks, it is advisable to implement a comprehensive set of practices, including proper collection and transportation procedures that involve using clean, dedicated equipment and minimizing contact with potential contaminants (Gurtler et al., 2018). Additionally, BBFs should be stored in a controlled, clean environment to reduce exposure to external contaminants and adverse weather conditions. Whenever possible, BBFs should be applied immediately after collection to minimize storage duration.

4.2. Yield and physico-chemical characteristics of lettuce

Plant yield is generally related to the available nitrogen provided when no other nutrients are limiting (Kamireddy et al., 2023). The combination of BBFs with N fertilizing potential such as human urine and digestate, along with BBFs with amendment properties such as composts and manure was expected to provide immediately available N from the fertilizing BBFs, along with additional N released through the mineralization of BBFs with amendment characteristics. However, it is difficult to precisely estimate nitrogen release because it depends on the nature of the amendments as well as on other parameters such as soil type and climatic conditions (Geisseler et al., 2021).

At day 23, the comparable fresh yield obtained in some FWC treatments, when compared to the unfertilized control plot could be attributed to two main factors. These include the lower initial mineral nitrogen added to the FWC treatments (63–68 kg ha^{-1}) compared to the other fertilizer treatments (79–120 kg ha^{-1}), in addition to the nitrogen immobilization shown during the laboratory incubation. These assumptions are consistent with the low SMN stocks within the top 15 cm of soil. At day 48, the higher fresh yield obtained with MAN_SF may have resulted from the progressive N release that allowed better nitrogen uptake by lettuce over the growing period (Mounirou et al., 2023). In contrast, the N immobilization by FWC and GWC could explain the lower yields with these related treatments. This finding was corroborated by the positive correlation between dry yield and available or initial mineral nitrogen. In the present work, during the application period, we did not take into account the immaturity of either food waste compost or green waste compost, as it could not be assessed prior to the field trial. However, it has been suggested that immature composts

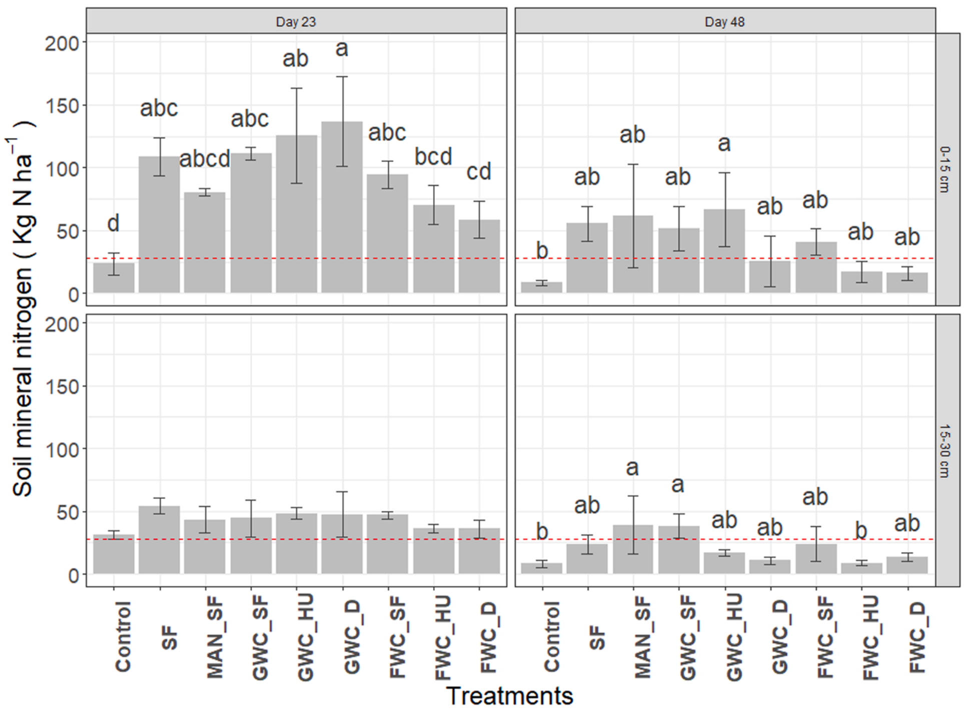

Fig. 4. Soil mineral nitrogen stocks in the different treatments at days 23 and 48 and for the 0–15 cm and 15–30 cm soil layers. The red dashed line represents the initial mineral nitrogen stock prior to bio-based fertilizers application. Values represented by bars with similar letters are not significantly different within the same date and depth at $P \leq 0.05$ by Tukey's test. Control: unfertilized treatment, SF: synthetic fertilizer, MAN_SF: manure + synthetic fertilizer, GWC_SF: green waste compost + synthetic fertilizer, FWC_SF: food waste compost + synthetic fertilizer, GWC_D: green waste compost + digestate, GWC_HU: green waste compost + human urine, FWC_D: food waste compost + digestate, FWC_HU: food waste compost + human urine.

should be applied some weeks before planting to avoid N immobilization, particularly for short-cycle crops such as lettuce (30–60 days) (Madrid et al., 2011). Accurate estimation of BBF N mineralization enabled compost, combined with reduced rate of mineral nitrogen, to produce comparable vegetable yields than full-rate of mineral nitrogen (De Rosa et al., 2016; Hernández et al., 2016). In the study of De Rosa et al. (2016), the reduced rates varied between 18 and 20% less urea being applied. Other limiting nutrients could have led to the differences observed in our study, but, soil nutrients seemed sufficient, as shown by the statistically similar P, K, Ca, and Mg uptake, including in the control plots. In addition, the nutrient contents in the soil were estimated to be 119, 423, 8605, 450 kg ha^{-1} for available P and exchangeable K, Ca, Mg, respectively, which were much higher than those required by lettuce.

The mineral nitrogen use efficiency (NUEmin) values obtained in our experiment were higher than those of Nicoletto et al. (2014), whose findings ranged from 9 to 10 % for Batavia lettuce grown under a combination of digestate with mineral fertilizer through fertigation. Moreover, they found no significant variation between treatments, including BBFs and SF alone.

BBFs application did not alter the nutrient concentrations of lettuce (Hernández et al., 2016). The nitrate content range of fresh lettuce was at least 10 times lower than the EU limits. This was in concordance with Nicoletto et al. (2014), who found that nitrate contents were lower than the EU limits, approximately 200 mg kg^{-1} for Batavia fresh lettuce fertilized with different rates of fruits and distillery by-product digestate combined with synthetic fertilizer. As observed by Pavlou et al. (2007), treatments with SF showed higher nitrate accumulation in plant tissues compared to those with BBF fertilizers.

4.3. Trace elements and pathogens in lettuce

In the present study, the trace elements were below the thresholds both in the applied BBFs and the harvested plants, which was consistent with several studies on composts (Paradelo et al., 2020; Zubillaga and Lavado, 2002). Paradelo et al. (2020) also identified that a one-time application of composts in lettuce production did not significantly increase trace element uptake above the EU limits, even when the composts contained trace elements above the EU limits. However, some studies found that lettuce presented higher contents of Zn, Pb, Cd, and Ni than the national standards (Alromian, 2020), depending on the rate of BBFs application (Intawongse and Dean, 2006). The higher cadmium uptake in the treatments with synthetic fertilizer (SF) could be attributed to the cadmium contained in the phosphate fertilizer (Roberts, 2014). It could also be explained by the decrease in pH due to the application of SF either separately or in combination with GWC, which increased the bioavailability of this element (Intawongse and Dean, 2006; Rieuwerts et al., 1998).

The absence of pathogen risk observed with the application of different BBF combinations (although some pathogens exceeded the standard threshold) is in line with previous studies (Livonen and Tontti, 2010; Nag, 2022; Wießner et al., 2009), which reported no significant contamination of lettuce after the application of fresh and composted farmyard manure and manure biogas digestate. However, the results of Livonen and Tontti (2010) were obtained when BBFs were applied 2 weeks before planting. In our study, even when BBFs were applied one day before planting, no impact was observed on lettuce quality. In contrast, Murphy et al. (2016) revealed that both *Salmonella senftenberg* and *E. coli* could be transferred to lettuce after low levels of inoculation in food waste compost and digestate, depending on climatic conditions. Our observed outcomes might be attributed to the interplay between the lower contamination levels of BBFs and the high temperatures during the trial (Figure S2).

4.4. Effect of BBFs application on soil properties

The application of composts and manure did not significantly affect the soil organic carbon and nitrogen contents, although increases in these values were observed. This result is consistent with Baiano &

Morra (2017), who highlighted that the effects of organic amendment generally may not be apparent after one application. Hernández et al. (2016) observed a significant increase in soil organic C and N contents only after two successive compost applications of 17 or 26 t ha^{-1}. The effects of the organic amendments may be more visible in the longer term after repeated applications. The significant decrease in soil pH induced by SF application tended to be related to the amount that was added. This was in line with Tkaczyk et al. (2020), who found that the reduction in soil pH increased with the amount of SF applied. Furthermore, continuous application of NPK fertilizer could lead to a reduction in pH, as indicated by Ge et al. (2018). Conversely, the absence of an effect with BBFs that were not combined with SF highlighted the ability of BBFs to maintain soil pH. This aspect could be beneficial in preventing additional expenses for soil liming, particularly for farmers facing soil acidification (Wang et al., 2019). In addition, increasing pH limits the transfer of trace elements. The exchangeable nutrients tended to be higher in the SF treatments; however, the nutrients present in the organic part of the applied amendments constituted a stock for future crops. Moreover, repeated use of these BBFs can increase soil organic matter stocks under vegetable crops, promote beneficial microbial activity, maintain nutrient balance, and reduce the need for synthetic fertilizers, which prices are increasingly rising (Alexander et al., 2022; Hernández et al., 2016; Yadav et al., 2020). Nevertheless, careful monitoring is necessary to prevent potential risks like nutrient loss or heavy metal accumulation (Yadav et al., 2020).

5. Conclusion

In the present study, BBFs collected in peri-urban areas of Paris were characterized and their effects on lettuce yield and quality were explored. Green waste compost and cow manure showed a better potential to increase soil carbon stocks than food waste compost. The influence of the composting process in addition to the feedstock type was also highlighted. Food waste digestate and human urine are interesting providers of readily available nutrients, particularly nitrogen. Overall, the combined application of BBFs with amendment and fertilizing value showed an important impact on lettuce yield and nutrient content and did not pose any risk of nitrate, trace element or pathogen contamination after one application. The highest increase in yield was observed with the combination of manure and synthetic fertilizer. The impact of one-time BBF application on soil was less apparent overall, except for pH, which was decreased in the synthetic fertilizer treatments, unlike in the treatments with BBFs only. It can be concluded that combining BBFs with amendment and fertilizing properties can sustain lettuce yield and quality while improving soil properties. However, it is relevant to accurately define BBF typologies to provide the most appropriate advice to market gardeners and avoid the risks of nitrogen immobilization and negative impacts on vegetables such as lettuce. In the future, the addition of BBFs in market gardening should be studied under other conditions with the presence of mulch or in other climates and soil types. The benefits of repeated BBF applications should also be explored.

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CRediT authorship contribution statement

Lelenda Florent Kebalo: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Writing – original draft. **Patricia Garnier:** Conceptualization, Investigation, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Laure Vieublé Gonod:** Conceptualization, Investigation, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Sabine Houot:** Conceptualization, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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