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ORIGINAL PAPER

Effects of Biochar and Biochar-Compost Mix as Soil Amendments on Soil Quality and Yield of Potatoes Irrigated with Wastewater

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Abstract

This study evaluated the impact of biochar, compost, and a biochar-compost mix on soil properties and yield of potatoes irrigated with wastewater. In each year of a 2-year (2017, 2018) field lysimeter study conducted under wastewater (WW) irrigation, a thrice-replicated completely randomized design (CRD) tested the effect of a factorial combination of 3 levels of barley (*Hordeum vulgare* L.) straw biochar amendment (none, 1%, and 3%) and 2 levels of mixed green and table waste compost amendment (none, 7.5%) on soil physicochemical properties, along with potato (*Solanum tuberosum* L.) plant growth, physiology, and yield components. Relative to the non-amended control, all amendment treatments had a significant positive effect ($p \leq 0.05$) on soil physicochemical properties and crop yield; however, amendments did not affect plant growth or plant physiological parameters. Higher temperatures in the second year led to significantly lower yields than in the first year. In 2017, compost alone increased potato yield under wastewater irrigation, whereas in 2018, yield was greater at the 3% biochar amendment rate than at the 1% amendment rate. We conclude that amending soils with biochar and biochar-compost mix is a feasible way to grow potatoes under wastewater irrigation, but application rate and biochar-compost mixing ratio should be properly selected to achieve a high potato yield. Biochar and biochar-compost amendments improved conditions for potato growth under wastewater irrigation, suggesting that wastewater irrigation of crops grown in amended soil may prove a feasible approach to reducing the need to treat wastewater destined for use as irrigation water, while increasing water and nutrient cycling to improve food security.

Keywords Crop productivity · Sandy soil · Soil amendment · *Solanum tuberosum* L · Wastewater irrigation

1 Introduction

Freshwater constitutes only about 0.8% of the total accessible water resources on Earth. Roughly, 80 countries in the world are facing water shortages (Dompka et al. 2002; Gleick 1993), and 2 billion people have no access to clean water (UN 2021). According to the WWF US (2016), two-thirds of the world's population face some type of water stress. Combined with an expected world population of 9.7 billion by 2050 (DESA 2015) and the concomitant rise in global food demand, the need for freshwater for irrigation will be intensified. Increased populations will also lead to increased wastewater discharge necessitating safe and sustainable methods of wastewater disposal, currently lacking in many cities around the world (DESA 2014).

According to UNFPA (2001), developing countries discharged 90–95% of all untreated sewage and 70% of industrial wastewater into surface waters, placing downstream populations and ecosystem functions at great risk. Globally,

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80% of wastewaters flows back into ecosystems, without being treated or reused (Baum et al. 2013; Corcoran et al. 2010). While irrigated agriculture currently occupies 20% of cultivated land, it represents an increasing proportion (40% at present) of global food production (IBRD-IDA 2020).

From an economic viewpoint, wastewater irrigation of crops under proper agronomic and water management practices may provide greater yields, additional water for irrigation, and fertilizer savings (Hussain et al. 2002). Accordingly, wastewater irrigation has the potential to increase agricultural food production, promote freshwater conservation, and limit the harmful practice of openly discharging untreated wastewater into bodies of water, then using the latter for irrigation, a common practice in developing countries, where it contributes to the contamination of agricultural soils (Qadir et al. 2010). Wastewater irrigation can also increase soil organic carbon (SOC) and nutrient availability, as well as provide better soil physicochemical and biological properties, including raising soils' available water content, thereby improving soil productivity (Marofi et al. 2015).

Various studies have recorded the positive effects of biochar and biochar-compost mixes on crop yields and soil properties (Kammann et al. 2015; Karami et al. 2011; Seehausen et al. 2017). Soil amendment with biochar and compost can improve crop yields by improving soil pH, increasing soil cation exchange capacity (CEC), supplying nutrients, promoting greater nutrient use efficiency (NUE), and improving water holding capacity (WHC) in sandy soils (Agegnehu et al. 2015; Jeffery et al. 2011). Compared to both wastewater and freshwater controls, soil amendment with either bamboo or bagasse biochar, in combination with wastewater irrigation, significantly increased the biomass yield of energy crops (Ramola et al. 2013). Despite that several studies have amended soils with biochar and compost, the effects of soil amendment with biochar and compost mix on soil and crop parameters are rare, especially in temperate regions (Cooper et al. 2020). Moreover, while few studies have investigated the effects of biochar and/or compost on the yield of agricultural crops under treated wastewater irrigation (Hameeda et al. 2019), to the best of our knowledge, even fewer studies have addressed the effects of using untreated wastewater to irrigate crops grown in coarse-textured soils amended with different rates of biochar, compost, and biochar-compost mix. Therefore, the objectives of this study were to evaluate the impacts of biochar, compost, and biochar-compost mix applied to sandy soils at different application rates on (1) soil physicochemical properties and (2) potato yield under untreated wastewater irrigation. We hypothesize that increasing application rates of biochar, compost, or biochar-compost mix would improve plant growth parameters and yield by improving soil physicochemical properties.

2 Materials and Methods

2.1 Field Setup

A 2-year study was conducted in the summers of 2017 and 2018 at the Macdonald Campus of McGill University, Sainte-Anne-de-Bellevue, QC, Canada (45° 24′ 48.6″ N latitude and 73° 56′ 28.1″ W longitude). In the spring of 2017, field lysimeters (1.0 m tall × 0.45 m inner diameter; Fig. 1) were filled with a local sandy soil (Table 1). After the first

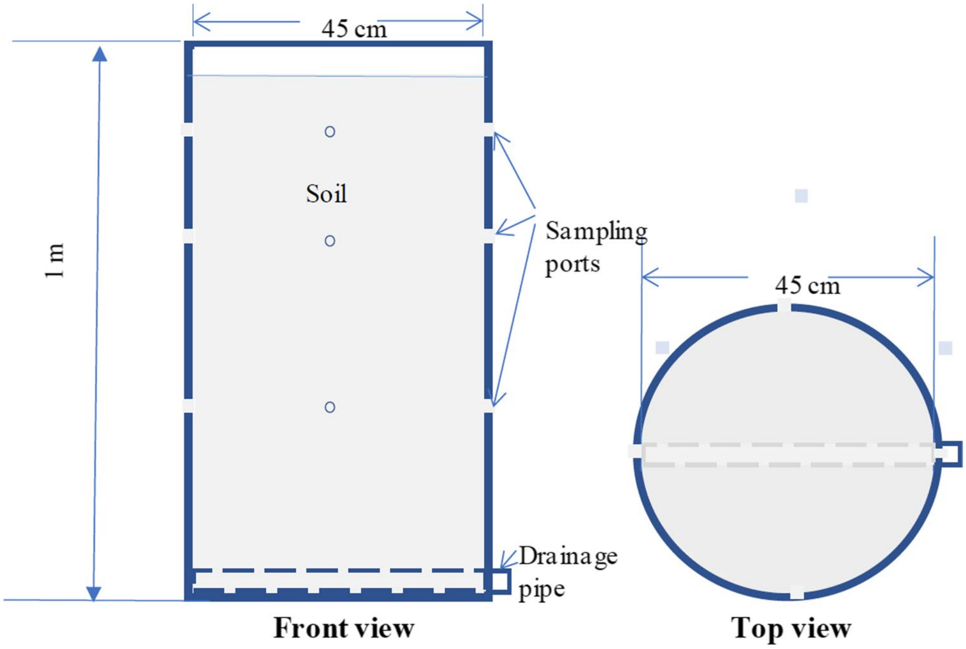

Fig. 1 Schematic diagram of lysimeter

Table 1 Soil physiochemical properties prior to soil amendments

Mineral components	mg kg^{-1}	Soil properties	
N	3.67 ± 0.21	Sand (%)	92.2
P	74.7 ± 3.52	Silt (%)	4.3
K	54.7 ± 6.03	Clay (%)	3.5
Mg	50.0 ± 2.93	pH	5.61 ± 0.19
Ca	754 ± 48.15	SOM (%)	1.82 ± 0.05
Al	1689.2 ± 96.85	EC (mS cm^{-1})	66.43 ± 11.13
Mn	1.9 ± 0.22	ZPC	3.40
Cd	< LOD	CEC (cmol(+) kg^{-1})	3.35 ± 0.33
Cr	21.1 ± 2.81	C (%)	0.82 ± 0.14
Cu	6.8 ± 1.24	N (%)	0.085
Fe	8822 ± 352.14	C:N ratio	9.61 ± 0.72
Pb	< LOD	DOC (mg kg^{-1})	29.52 ± 2.15
Zn	22 ± 5.14	Bulk density (Mg m^{-3})	1.35

SOM, soil organic matter; *EC*, electrical conductivity; *ZPC*, zero point of charge; *CEC*, cation exchange capacity; *DOC*, dissolved organic carbon; *LOD*, limit of detection. N, P, K, Mg, Ca, Mn, and Al were determined using Mehlich III extraction (Mehlich 1984); the heavy metals Cd, Cr, Cu, Fe, Pb, and Zn were determined using hot acid extraction (Kargar et al. 2015) and quantified by inductively coupled plasma optical emission spectrometry (ICP-OES). Other soil properties were adapted from a previous study conducted with soil from the same field (ElSayed et al. 2013)

season and harvest sampling efforts, the experimental units were protected with plastic bags over the winter until the next season.

The treatment combinations were as follows: (i) non-amended soil (WW control) (BC_0CP_0); (ii) 1% biochar alone (BC_1CP_0); (iii) 3% biochar alone (BC_3CP_0); (iv) 7.5% compost alone ($BC_0CP_{7.5}$); (v) 1% biochar and 7.5% compost ($BC_1CP_{7.5}$); and (vi) 3% biochar and 7.5% compost ($BC_3CP_{7.5}$). According to the treatment, biochar and/or compost was thoroughly mixed into the soil, ensuring homogeneity in the upper 0.10 m layer of the lysimeter soil at the onset of the experiments (2017). Compost was added to the soil at a rate of 7.5% (w/w), while biochar was added at rates of 1% or 3% (w/w). The compost and biochar remained in the lysimeters after the first year of harvest and were present at the onset of the second year of experiment.

To determine initial nitrogen (N), phosphorus (P), and potassium (K) levels in the soil, soil samples were taken prior to planting in 2017. In both 2017 and 2018, three fertilizers, i.e., urea, triple super phosphate (TSP), and potassium chloride (KCl), were applied according to locally recommended rates for potato (cv. Russet Burbank). Specifically, N was applied at a rate of 180 kg N ha^{-1} (Parent and Gagné 2010); 30% of N fertilizer was applied on day 0, 30% on day 31 after planting, and the remaining 40% in four equal parts on days 46, 53, 60, and 67 post-planting (Stark et al. 2004). Each season, at planting, all treatments received 280 kg K ha^{-1} and 44 kg P ha^{-1} (Parent and Gagné 2010).

In both years, prior to planting, SENCOR® 75 F (active ingredient: metribuzin, 4-amino-6-*tert*-butyl-3-methylsulfanyl-1,2,4-triazin-5-one), a common herbicide approved for use in Canada, was applied to the soil at the rate of 2.25 L ha^{-1} following local guidelines (OMAFRA 2019). Seed potatoes were purchased from Global Agri. Services Inc. (New Maryland, NB, Canada). Potato tubers were stored at 8–10 °C on receipt, then warmed to room temperature 2 weeks prior to planting to promote sprouting. On the day of planting, one tuber was planted 0.10 m deep in the center of each lysimeter.

A canvas tent was set up over the lysimeters to prevent precipitation from entering them. To supplement the natural light, 10 LED bulbs (60 W) were installed in an equally spaced array above the lysimeters, and operated 4 h per day. An Apogee MQ-200 Quantum Flux sensor (Apogee Instruments Inc., Logan, UT) was used to determine the quantum flux under the tent. Daily weather data for both 2017 and 2018 was collected for the field location (45° 25′ 38.000″ N, 73° 55′ 45.000″ W) from Environment Canada and averaged for each month of interest (Environment-Canada 2021).

2.2 Physicochemical Characterization of Biochar, Compost, and Soil

Barley straw biochar was purchased from Alberta Innovates–Technology Futures (AI-TF) at Vegreville, AB, Canada. Prior to carbonization, the barley straw feedstock was chopped into pieces less than 0.05 m in length. Pyrolysis was performed in a batch rotary drum (203 × 61 cm) at ~ 535 °C for 28 min (total retention time 83 min). The final product was cooled by purging the drum with CO_2 gas for 2–3 h. The compost used was derived from mixed green and table waste supplied by the West Island region of Montreal, QC (City of Baie-D'Urfé).

Barley straw biochar and compost samples were characterized through an ultimate and proximate analysis. As shown in Table 2, moisture content, ash content, volatile matter, and fixed carbon content (ASTM D7582 and ISO 562 for volatile) were determined by proximate analysis, while carbon, hydrogen, oxygen, N, and sulfur contents were determined by ultimate analysis (ASTM D5373 and ASTM D4239 for S). The analyses of biochar and compost were performed at the CanmetENERGY (NRC) Characterization Laboratory, Ottawa, ON, Canada. The heavy metal content was determined by hot acid extraction (USEPA 1996; Kargar et al. 2015). The P, K, calcium (Ca), magnesium (Mg), and manganese (Mn) concentrations were determined following Mehlich III extraction (Mehlich 1984), while N was determined following the method of Carter and Gregorich (2008).

Table 2 Properties of barley straw biochar (BC), and mixed green and table waste compost (CP)

Parameter	Observed value (%, w/w)		*Heavy metal and mineral concentrations (mg kg^{-1})*			*Allowable thresholds (mg kg^{-1})**	
	BC	*CP*		*BC*	*CP*	*BC*	*CP*
Moisture TGA	3.88	4.38	Cd	< LOD	< LOD	1.40	20.00
Ash TGA	19.29	64.43	Cr	29.80	19.91	64	1060
Volatile	18.19	29.09	Cu	< LOD	44.22	63	757
Fixed carbon	62.53	6.47	Fe	706.71	8205.25	NA	NA
Carbon	70.40	18.80	Pb	< LOD	< LOD	70	505
Hydrogen	2.20	1.83	Zn	33.11	90.01	200	1850
Nitrogen	1.07	1.28	N	5.12	36.81	NA	NA
Total sulfur	0.53	0.16	P	244.02	763.72	NA	NA
Oxygen	6.47	13.47	K	18,201.05	4324.15	NA	NA
SSA (m^2 g^{-1})	8.5	2.05	Mg	520.23	1008.01	NA	NA
pH	9.61	7.87	Ca	750.09	4991.21	NA	NA
EC (mS cm^{-1})	4302.02	1226.61	Mn	40.02	40.15	NA	NA

TGA, thermogravimetric analysis; *SSA*, specific surface area; *EC*, electrical conductivity; *NA*, not available. **Based on* International Biochar Initiative allowable thresholds of heavy metals in biochar, and Guidelines for Compost Quality (Canadian Council of Ministers of the Environment-2005) (mg kg^{-1})

The CEC was measured using the $BaCl_2$ method (Hendershot et al. 2008). The soil pH was measured following the method of Rayment and Higginson (1992) using a pH electrode (Accumet pH meter model AB15, Fisher, Scientific, USA). Soil organic matter (SOM) was quantified by loss-on-ignition (Schulte et al. 1991). The soil moisture content (θ) was determined by the gravimetric method (ASTM 1988).

2.3 Irrigation

The day before planting, each lysimeter was watered to field capacity using freshwater. After planting (day 0), each lysimeter was irrigated with wastewater every 10 days: eight times per season. Each wastewater irrigation consisted of 11.5 L of synthetic wastewater applied per lysimeter. The irrigation volume was determined based on the water requirements (500–700 mm) and growing season (120 days) of the potato crop. The make-up of the synthetic wastewater is given in Table 3. The organic contaminants and heavy metals concentrations were representative of a worst-case scenario wastewater.

2.4 Plant Physiological Parameters

Relative chlorophyll content (SPAD) was estimated 2 days before each irrigation and 5 days after each irrigation, using a chlorophyll meter (SPAD-502 Plus; Konica Minolta). Plant photosynthetic activity, stomatal conductance, and transpiration rate were measured 5 days after each irrigation, using Li-Cor 6400 (LI-COR, Nebraska, USA). Crop vigor, quantified by reflectance (normalized difference vegetation index (NDVI)), was measured, 5 days after irrigation, using an active crop canopy sensor (Crop Circle ACS-470; Holland Scientific Inc., NE, USA).

2.5 Plant Harvest

In both years, potatoes in each lysimeter were harvested 120 days after planting, as per local growing season recommendations for 'Russet Burbank' potatoes. Above-ground biomass was cut off at ground level with a knife, then separated into stems and leaves. The weight of the above-ground biomass, number of branches, shoot weight, and the height of the shoot were measured. The underground biomass was harvested, roots and tubers separated and weighed, and the yield components counted and graded (number of tubers, weight of tubers, and graded tuber (50 mm) weight and numbers (Shiri-e-Janagard et al. 2009; USDA 1983).

2.6 Data Analysis

Physiological parameters were analyzed by considering the treatment and measurement time as factors. For soil properties, plant growth, and yield components, treatment was considered as the only factor; therefore, the analyses were one-way analysis of variance. Each year was analyzed separately. Least significant difference test was used for a pairwise comparison, and differences were considered significant when $p \le 0.05$. All analyses were performed using IBM SPSS® V.24 (Copyright © IBM Corp 2016 Armonk, NY).

Table 3 Components and concentrations in synthetic wastewater

Category	Substance/compounds	Country	Concentration (mg L^{-1})	Reference
Basic synthetic wastewater constituents				
C source	Na acetate	NA	79.37	Nopens et al. (2001)
	Milk powder	NA	116.19	
	Soy oil	NA	29.02	
	Starch	NA	122	
	Yeast extract	NA	52.24	
N source	NH_4Cl	NA	12.75	
	Peptone	NA	17.41	
	Urea	NA	91.74	
P source	$Mg_3O_8P_2$	NA	29.02	
Minerals	$CaCl_2$	NA	60	LaPara et al. (2006)
	$NaHCO_3$	NA	100	
Surfactant	*Triton X-100*	NA	30*	Aboulhassan et al. (2006)
Wastewater contaminants				
Heavy metals	Chromium (Cr)	India	2	Ahmad et al. (2011)
	Cadmium (Cd)	India	5	
	Lead (Pb)	India	16	
	Iron (Fe)(II)	India	120	
	Zinc (Zn)	India	3	
	Copper (Cu)(II)	India	8	
Hormones	Estrone: E1	S. Korea	8.15 (20)*	Sim et al. (2011)
	Estradiol: E2	S. Korea	0.634 (20)*	
	Estriol: E3	S. Korea	2.28 (20)*	
	Ethinylestradiol: EE2	China	0.33 (20)*	Zhou et al. (2012)
	Progesterone	China	0.90 (20)*	Huang et al. (2009)
PPCPs	Ibuprofen	Canada	45*	Guerra et al. (2014)
	DEET	USA	6.5*	Lietz and Meyer (2006)
	Caffeine	China	6.6*	Sui et al. (2010)
	Carbamazepine	S. Korea	21.6*	Sim et al. (2011)
	Diclofenac	India	25.68*	Singh et al. (2014)
	Triclosan	UK	21.9*	Sabaliunas et al. (2003)
	Oxytetracycline	China	19.5*	Li et al. (2008)

*Concentrations in μg L^{-1}. *NA*, not applicable; *PPCPs*, pharmaceutical and personal care products. Numbers in () indicate the concentration used in this work

3 Results

3.1 Soil Physiochemical Properties

Our results indicated that the application of single or combined compost and biochar amendments (BC_1CP_0, BC_3CP_0, $BC_0CP_{7.5}$, $BC_1CP_{7.5}$, $BC_3CP_{7.5}$) altered soil physicochemical properties, as compared with the non-amended control (BC_0CP_0). The soil CEC, SOM, and pH were significantly increased by soil amendment with compost (Table 4).

The CEC at the soil surface was higher ($p \leq 0.05$) in the $BC_3CP_{7.5}$, $BC_1CP_{7.5}$, and $BC_0CP_{7.5}$ treatments than in the BC_3CP_0, BC_1CP_0, and BC_0CP_0 treatments. However, at the 0.10-m soil depth, the CEC was only significantly higher ($p \leq 0.05$) in the $BC_3CP_{7.5}$ treatment than under other treatments, except for $BC_0CP_{7.5}$. No significant differences were observed between the soil CEC under the BC_0CP_0, BC_1CP_0, and BC_3CP_0 treatments. At both soil depths (surface and 0.10 m), SOM was greater ($p \leq 0.05$) under $BC_3CP_{7.5}$ than under BC_0CP_0, BC_1CP_0, or BC_3CP_0. There was no significant ($p > 0.05$) difference between BC_1CP_0 and BC_3CP_0 relative to the BC_0CP_0 control at either depth. Similarly, at both depths, soil under the $BC_0CP_{7.5}$ and $BC_3CP_{7.5}$ treatments showed a higher ($p \leq 0.05$) pH than soils treated with BC_1CP_0 or receiving no amendment (BC_0CP_0). Also, $BC_3CP_{7.5}$ and $BC_1CP_{7.5}$ showed higher ($p \leq 0.05$) pH values than their compost-free counterparts BC_3CP_0 and BC_1CP_0, at either depth.

Table 4 Effects of biochar, compost, and biochar-compost mix on soil cation exchange capacity (CEC), soil organic matter (SOM), and pH

Treatments	CEC (cmol(+) kg^{-1})		SOM (%)		pH	
	Surface	0.10 m	Surface	0.10 m	Surface	0.10 m
BC_0CP_0	1.78 ± 0.29^{b}	2.62 ± 1.24^{c}	2.79 ± 0.64^{c}	2.72 ± 0.18^{b}	5 ± 0.10^{d}	5.26 ± 0.14^{d}
BC_1CP_0	1.69 ± 0.31^{b}	1.88 ± 0.33^{c}	2.89 ± 0.37^{c}	3.07 ± 0.56^{b}	5.18 ± 0.15^{cd}	5 ± 0.21^{d}
BC_3CP_0	1.94 ± 0.44^{b}	4.12 ± 1.34^{bc}	2.84 ± 0.67^{c}	2.90 ± 0.31^{b}	5.33 ± 0.14^{bc}	6.11 ± 0.03^{c}
$BC_0CP_{7.5}$	4.58 ± 0.94^{a}	7.39 ± 0.93^{ab}	3.19 ± 0.70^{bc}	3.87 ± 0.89^{ab}	5.6 ± 0.11^{a}	6.43 ± 0.32^{bc}
$BC_1CP_{7.5}$	4.60 ± 1.46^{a}	5.54 ± 0.29^{b}	4.76 ± 0.10^{b}	3.62 ± 0.17^{ab}	5.43 ± 0.17^{ab}	6.5 ± 0.14^{b}
$BC_3CP_{7.5}$	5.73 ± 2.74^{a}	7.57 ± 1.60^{a}	6.77 ± 1.91^{a}	4.89 ± 1.49^{a}	5.66 ± 0.11^{a}	7.13 ± 0.15^{a}

The different superscript lowercase letters in each column represent a significant difference at $p \leq 0.05$; values are mean ± standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

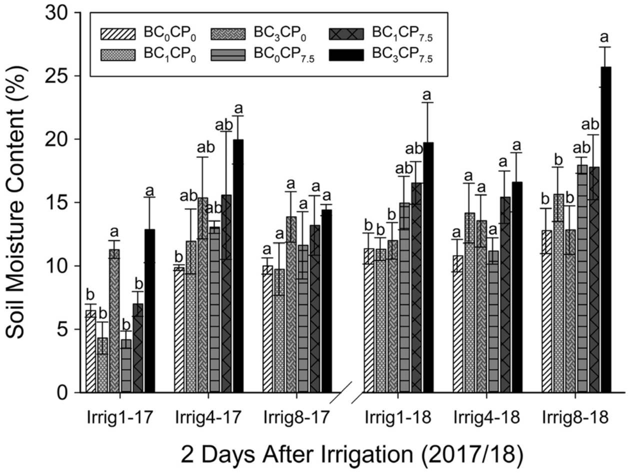

Fig. 2 Moisture content of soil collected 2 days after irrigations 1 (Irrig1), 4 (Irrig4), and 8 (Irrig8) in 2017 and 2018. The different letters on the bars in each column represent significant difference at $p \leq 0.05$; error bars are standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

No significant difference was observed between BC_0CP_0 and BC_1CP_0 at either depth.

In 2017, on 2 days after the first irrigation, the θ was higher ($p \leq 0.05$) under $BC_3CP_{7.5}$ and BC_3CP_0 than under all other treatments (Fig. 2; 2 days after irrigation 4), the θ for the $BC_3CP_{7.5}$ was higher ($p \leq 0.05$) than that under the control (BC_0CP_0). However, neither amendment influenced θ on 2 days after irrigation 8. No amendment effects on θ were observed in 2018 for 2 days after irrigation 4, and for 2 days after irrigation 8, when θ under $BC_3CP_{7.5}$ was higher than under BC_3CP_0, BC_1CP_0, or BC_0CP_0. A similar increase was also observed on 2 days after the first irrigation, where θ was higher under $BC_3CP_{7.5}$ than under BC_1CP_0, BC_3CP_0, or BC_0CP_0.

3.2 Plant Growth Parameters

No amendment treatment affected plant growth parameters (plant height, no. of branches, shoot fresh weight, or root fresh weight; Fig. 3), relative to the BC_0CP_0 control in either year. Plant height and shoot fresh weight were greater in 2018 compared with 2017. For example, the mean shoot weight for BC_0CP_0 was 0.9 kg in 2017 and 1.45 kg in 2018, while for $BC_3CP_{7.5}$, shoot weight was 0.9 kg in 2017 and 1.31 kg in 2018. Similarly, mean shoot height for BC_0CP_0 was 997 mm in 2017 and 1,212 mm in 2018, while for $BC_3CP_{7.5}$, it was 943 mm in 2017 and 1061 mm in 2018. The increase in plant growth parameters during the second season can be attributed to a greater mean temperature in the summer of 2018 than in the summer of 2017. Increased temperatures, up to a point, can facilitate plant uptake of nutrients to the above-ground biomass as a result of enhanced photosynthesis and faster evolving plant phenology.

3.3 Plant Physiological Parameters

The plant physiological parameters of SPAD, NDVI, transpiration rate, stomatal conductance, and photosynthesis showed no significant treatment effect ($p > 0.05$); however, there was a significant time effect ($p \leq 0.05$) in both years (Fig. 4), i.e., SPAD readings declined with plant age.

Another indicator for plant canopy health or vigor measured over the 2 years, the NDVI also showed no significant difference ($p > 0.05$) across treatments (Fig. 5), indicating that the treatments did not impact above-ground plant growth, in comparison to the control (BC_0CP_0). In 2017, NDVI ranged from 0.87 (day 51) to 0.78 (day 91), while in 2018, NDVI ranged from 0.79 (day 55) to 0.85 (day 95).

LICOR measurements of photosynthesis and transpiration rates, as well as stomatal conductance, were only taken in 2018 (Fig. 6). None of these parameters showed any significant single treatment or treatment interaction (treatment × time) effect. However, time had a significant effect

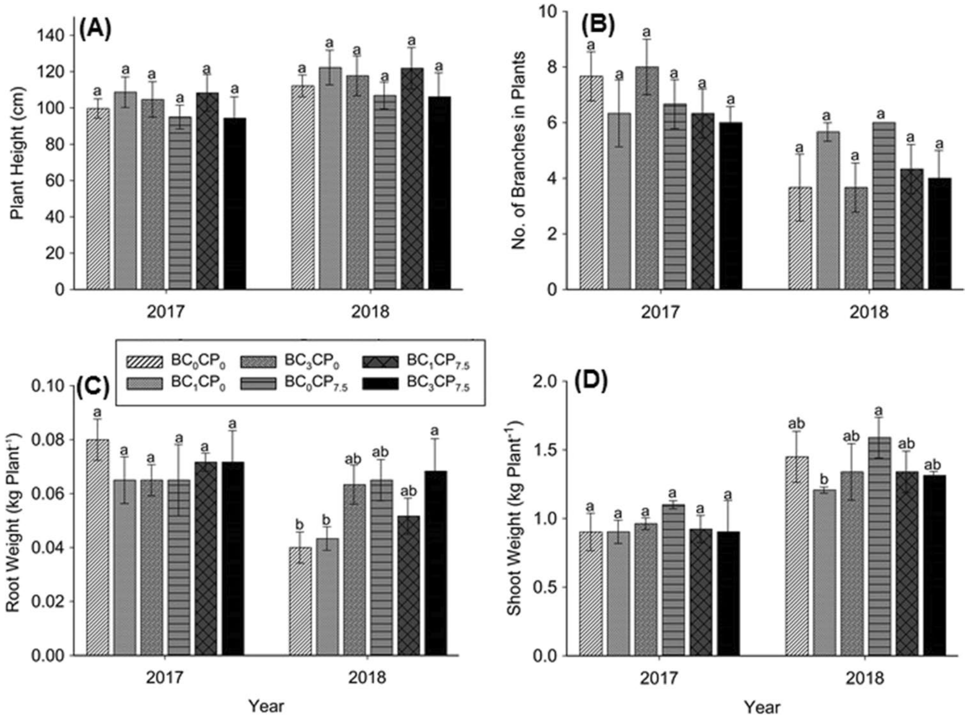

Fig. 3 Effect of biochar and/or compost amendments on potato (A) plant height, (B) number of branches, (C) root weight, and (D) shoot weight in 2017 and 2018. The different letters on the bars in each column represent significant difference at $p \leq 0.05$; error bars are standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

($p \leq 0.05$) on response. The photosynthetic rate ranged from a maximum of 11.7 µmol CO_2 m^{-2} s^{-1} (day 65) to a minimum of 5.4 µmol CO_2 m^{-2} s^{-1} (day 95). Transpiration rate ranged from a minimum of 0.59 mmol H_2O m^{-2} s^{-1} (day 45) to a maximum of 3.9 mmol H_2O m^{-2} s^{-1} (day 65). Stomatal conductance ranged from a maximum of 0.48 mol H_2O m^{-2} s^{-1} (day 65) to a minimum of 0.074 mol H_2O m^{-2} s^{-1} (day 95).

3.4 Yield Components

Yield components for each treatment were compared to the BC_0CP_0 control group (Fig. 7). The greatest mean tuber weight observed in both years was for $BC_3CP_{7.5}$ at 1.58 kg in 2017 and 0.88 kg in 2018. Compared to the BC_0CP_0 non-amended treatment, no significant differences ($p > 0.05$) were observed in either year for the compost treatments alone or in combination with biochar. Compared to 2017, mean potato tuber weight per plant in 2018 decreased by 28.3% in the BC_0CP_0 treatment (0.88 kg in 2017 to 0.64 kg in 2018). The corresponding reductions under BC_1CP_0, $BC_1CP_{7.5}$, $BC_0CP_{7.5}$, and $BC_3CP_{7.5}$ were 66, 61, 50, and 44%, respectively. Potato tuber weight did not reduce in the BC_3 (BC_3CP_0 and $BC_3CP_{7.5}$) treatments in either year. No significant difference ($p > 0.05$) in the number of tubers per plant was observed between the amended treatments and the BC_0CP_0 control in either year. The number of tubers that were not damaged and over 50 mm in size (i.e., marketable potatoes) was not significantly affected ($p > 0.05$) by amendment treatments (compared with control BC_0CP_0 or between treatments) in either year.

4 Discussion

Biochar and biochar-compost mixes have previously been shown to improve soil properties (Agegnehu et al. 2017). This was also observed in the present study: amendment with compost and biochar-compost mixes significantly increased ($p \leq 0.05$) soil CEC, pH, and SOM (Table 4).

As the compost amendment's mineral content exceeded that of biochar (Table 2), a significant ($p \leq 0.05$) and greater increase in soil CEC, relative to non-amended soil, was found for the singly applied compost treatment than either singly applied biochar treatments. Epstein et al. (1976) found that upon a soil's amendment with compost, the minerals it bears are released to the soil, thereby increasing exchangeable cations in the soil exchange complex. Under combined compost-biochar amendments, one would therefore expect that a greater rate of biochar application would result in a greater retention of compost-borne minerals within the compost, thereby increasing the soil CEC.

At corresponding levels of biochar amendment (BC_0, BC_1, BC_3), wastewater-irrigated soils amended with compost ($CP_{7.5}$) showed greater SOM levels than those receiving no compost amendment (CP_0). These observations that, under wastewater irrigation, a compost amendment enhances SOM closely concur with the results of Marofi et al. (2015). This effect is likely tied to the compost's high organic matter

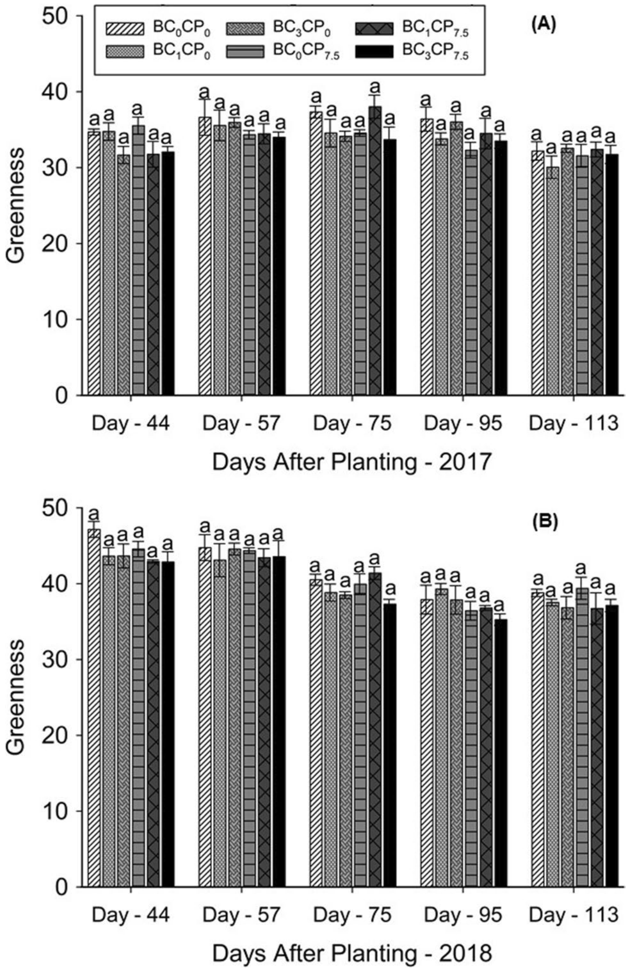

Fig. 4 Effect of biochar, compost, and biochar-compost mix on potato plant greenness readings (SPAD) in (A) 2017 and (B) 2018. The same letters on the bars in each column represent no significant difference at $p \leq 0.05$; error bars are standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

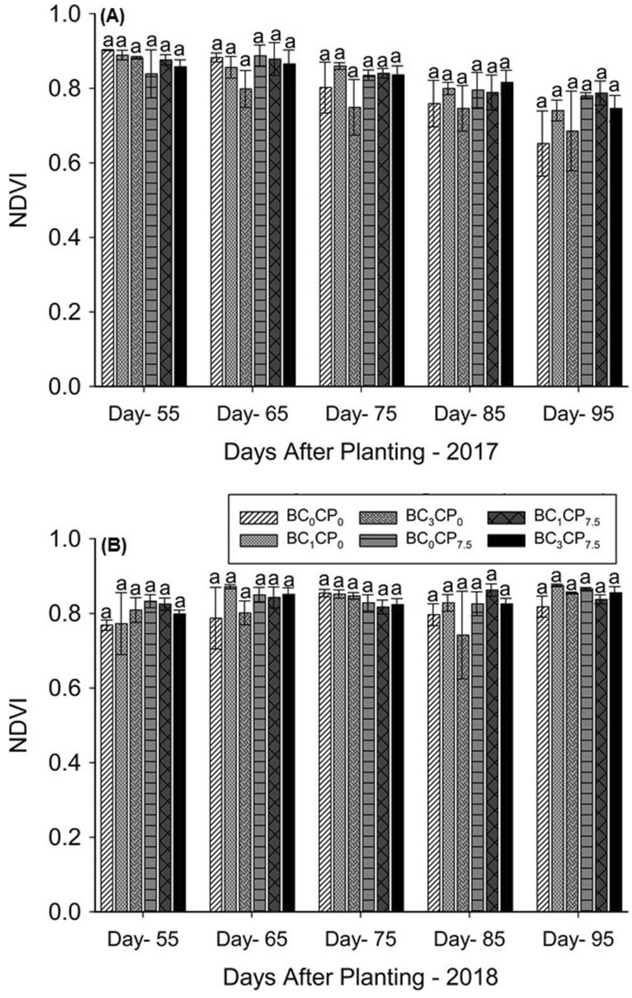

Fig. 5 Effect of biochar, compost, and biochar-compost mix on normalized difference vegetation index (NDVI) readings on potato plants in (A) 2017 and (B) 2018. The same letters on the bars in each column represent no significant difference at $p \leq 0.05$; error bars are standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

content (Table 4). However, an increased SOM can also be associated with soil amendments' rate of mineralization. As compost bears less fixed C (Table 2) and exhibits a lesser C/N ratio than biochar, compost would mineralize faster in soil (Bolan et al., 2012). Although soil amendment with biochar alone did not increase SOM, raising its application rate from 1 to 3% in compost treatments ($CP_{7.5}$) did improve mineralization of organic matter, thereby increasing SOM levels (Table 4). Therefore, when co-amending soils with biochar and compost, an increase in the rate of biochar amendment may increase SOM.

Overall, our results suggest that soil amendment with a combination of the higher percentage of biochar (3%) along with compost may help stabilize and retain the organic matter contributed by the compost. In contrast, Agegnehu et al. (2015) found that a mixed amendment of compost and biochar had no more effect on SOC as an indicator of SOM than compost or biochar amendments alone. This disparity may reflect the different sources, rates and ratios of amendments used in the two studies.

The 2017 potato tuber yield stood within the range (0.90 to 2.12 kg per plant) reported by Bethke et al. (2014) for cv. 'Russet Burbank', cultivated in Canada, over three growing seasons. In 2018, the tuber yield declined for all treatments, except those amended with 3% biochar alone or in combination with compost (0.89 kg per plant). The differences in temperature between the growing seasons of 2017 (6 days with temperatures above 30 °C) and 2018 (18 days with temperatures above 30 °C) could have been the reason for

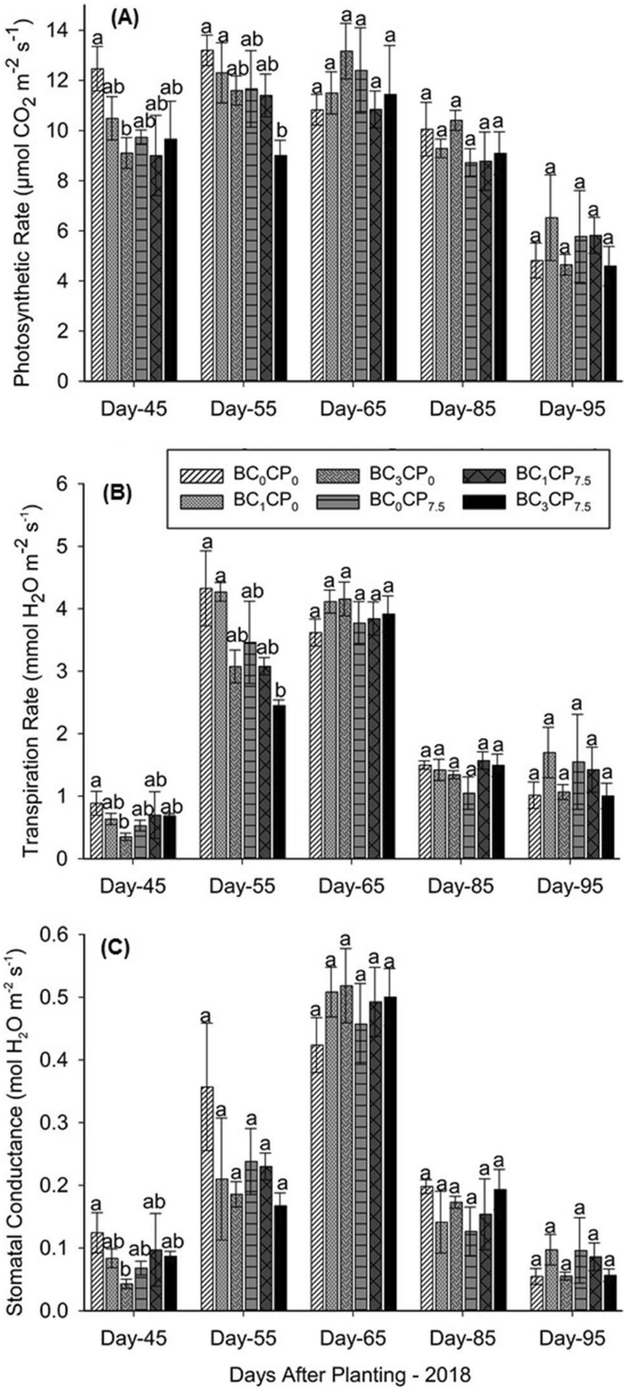

Fig. 6 Effect of biochar, compost, and biochar-compost mix on (A) photosynthetic rate, (B) transpiration rate, and (C) stomatal conductance of potato plants in 2018. The different letters on the bars in each column represent significant difference at $p \leq 0.05$; error bars are standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

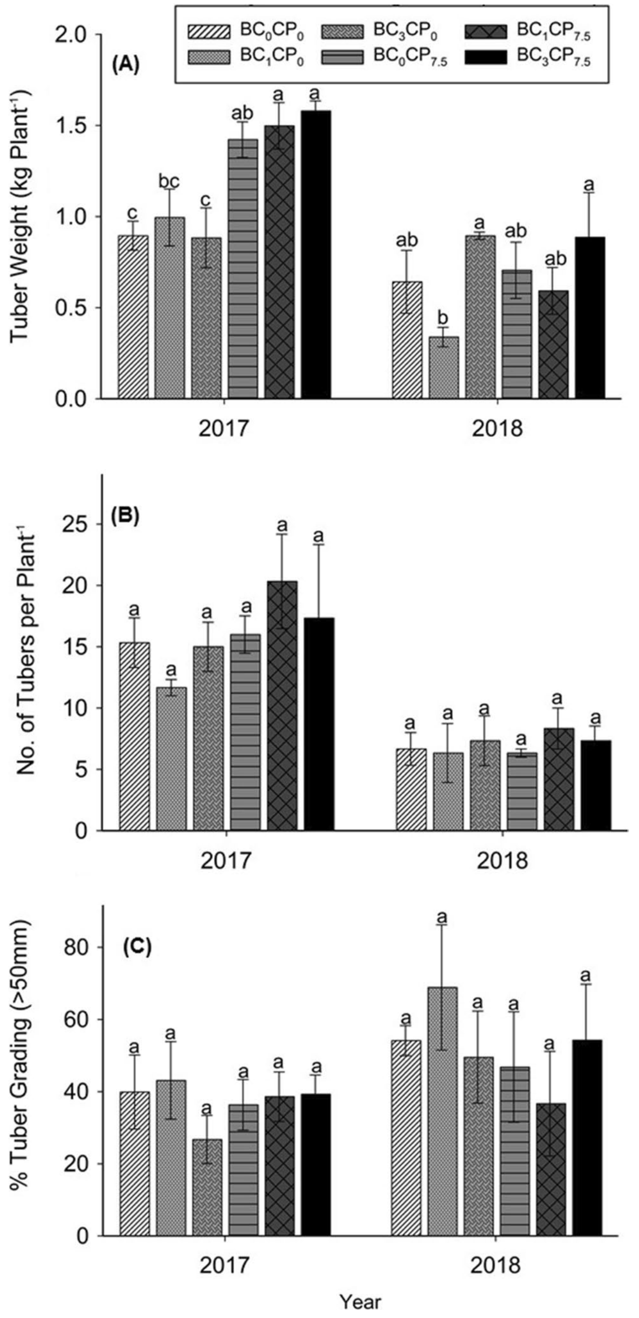

Fig. 7 Effects of biochar, compost, and biochar-compost mix on potato (A) tuber weight, (B) number of tubers, and (C) tuber grading in 2017 and 2018. The different letters on the bars in each column represent significant difference at $p \leq 0.05$; error bars are standard error of three replicates. BC_0CP_0: non-amended soil; BC_1CP_0: 1% biochar alone; BC_3CP_0: 3% biochar alone; $BC_0CP_{7.5}$: 7.5% compost alone; $BC_1CP_{7.5}$: 1% biochar and 7.5% compost; and $BC_3CP_{7.5}$: 3% biochar and 7.5% compost

lower yield in 2018 (Table 5). Indeed, high temperatures can affect both tuber initiation and growth by reducing the potato plant's CO_2 assimilation rate (Ku et al. 1977). At temperatures above 25 °C, a greater portion of mass is partitioned

Table 5 Monthly mean daily minimum, maximum, and mean temperature for Sainte-Anne-de-Bellevue, Quebec, for 2017 and 2018 (Environment Canada, 2021)

Temperature (°C)	May	June	July	August	September	October
2017						
Max	17.5	23.2	24.8	24.2	23.2	18.4
Min	8.2	13.6	15.3	14.0	12.4	7.1
Mean	12.9	18.4	20.1	20.1	17.8	12.8
2018						
Max	21.4	23.7	29.2	27.4	22.5	10.2
Min	8.7	12.8	17.6	17.3	11.9	3.1
Mean	15.1	18.4	23.4	22.3	17.2	6.6

towards above-ground biomass than towards tubers (Van Dam et al. 1996), while above 30 °C, tuber growth rates decline substantially (Burton 1972), leaving tubers unformed or severely delayed in development (Mendoza and Estrada 1979). Accordingly, the hypothesis that high temperatures impeded potato tuber development in 2018 is strongly supported. Although not applicable in the present study, disease and low seed quality may also affect potato yield (Kooman and Haverkort 1995; Kooman 1995).

In both years, the improved soil CEC and SOM could explain the improved tuber yield observed in the soils amended with compost and biochar-compost mixes. Increased CEC and SOM are known to increase nutrient availability to plants, including potatoes (Porter et al. 1999). In 2017, the greater soil CEC and SOM under the compost and biochar mix ($BC_1CP_{7.5}$ and $BC_3CP_{7.5}$) treatments led to significantly improved tuber yields, compared to the BC_0CP_0, BC_1CP_0, and BC_3CP_0 treatments. In 2018, tuber yields under $BC_3CP_{7.5}$ were greater than those under the BC_1CP_0 treatment, with the only other significant difference being between BC_1CP_0 and BC_3CP_0 treatments. On the basis of both years' results, the treatment combination of $BC_3CP_{7.5}$ improved yield the most. Our results are consistent with several other studies, where crop yield increased with biochar amendment (Barrow 2012; Blackwell et al. 2015; Chan et al. 2008) but was in contrast with the decrease in yield observed by Deenik et al. (2010).

The improvement of soil properties by biochar and biochar-compost amendment explains, to a large extent, the improved plant growth conditions observed in both years for the biochar treatments. Biochar amendment in 2017 had a significant positive effect on potato tuber yield, compared to the non-amended control (BC_0CP_0), while in 2018, the tuber yield was significantly greater in the BC_3CP_0 treatment than in either the BC_1CP_0 or BC_0CP_0 treatment. Therefore, we interpret this as showing that the impact of biochar amendment on plant yield may increase over time as the biochar gets conditioned (Wang et al. 2016).

Both SPAD and NDVI values were consistent with those in the literature (Shamal and Weatherhead 2014), although they showed no significant response to amendment treatments. This lack of amendment treatment effect parallels the results of Nzediegwu et al. (2019) and may be associated with several factors, including the quality of irrigation water (Chartzoulakis and Klapaki 2000; Savvas et al. 2007) and/or water deficit (Dorji et al. 2005; Katerji et al. 1993), which adversely impact NDVI. As plant tolerance to water deficits in the root zone is limited, such deficits can negatively affect canopy biomass, thereby lowering the NDVI value, which in such a case is representative of lower crop production and health (De Pascale et al. 2003). Patil et al. (2014) reported a similar impact of wastewater vs. freshwater on NDVI when used for irrigation.

While significant differences in growth parameters were noted when cannabis (*Cannabis sativa* L.) plants were grown in a biochar-amended (vs. non-amended) soil (Chandra et al. 2008; Hussain et al. 2017), the same treatments applied to potato plants in the present study did not result in any significant difference in growth parameters, likely because of the difference in crops. Potatoes, being a tuber crop, may respond differently to changes in soil conditions imposed by soil amendments.

Overall, potato tuber yield reflected changes in soil properties, but the crop's above-ground growth parameters (e.g., SPAD) did not. The decline in SPAD parameter values during the potato plant's growth and development (Fig. 4) reflects potato plants' different nutrient requirements at different physiological stages. Higher SPAD values between days 44 and 57, compared to those recorded at the end of growing season (Fig. 4), were likely representative of the greater nutrient accumulation into biomass during the vegetative phase than during the maturation stages (Nzediegwu et al. 2019).

The similarity of potato yields achieved with wastewater irrigation in the present study and under freshwater irrigation (e.g., Bethke et al. 2014) indicates that wastewater had little or any negative impacts on potato yield, thus highlighting the viability of using wastewater for crop production. Under the present study's wastewater irrigation regime, detectable levels of heavy metals were found in both the skin and flesh of potato tubers, as well as in potato roots and above-ground biomass, and this across all amendment combinations and in the non-amended control. However, heavy metal concentrations were significantly lower ($p \leq 0.05$) in the compost and biochar-amended treatments as compared to the control. The potatoes produced under the present treatment combinations would likely be safe for consumption based on their having hazard quotients (Sharma et al., 2016) inferior to 1.0 for heavy metals such as Cu, Fe, and Pb.

5 Conclusions

A 2-year field lysimeter study was carried out to investigate the use of biochar and compost soil amendments in potatoes grown under wastewater irrigation. Amending a sandy soil with biochar, compost, or biochar-compost mix significantly improved soil physicochemical properties (e.g., cation exchange capacity, soil organic matter, and pH), and potato yield depending on biochar application rate and biochar-compost mixing ratio. The change in soil physicochemical properties apparently led to improved nutrient uptake and greater yield. In two consecutive years, potato yield was greater under mixed biochar-compost soil amendments than under biochar or compost amendments applied singly. However, it is recommended to conduct such studies for longer periods to draw more concrete conclusions as to the potential benefits or constraints accruing from such amendments.

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Author Contribution Ali Mawof: investigation, methodology, data curation, formal analysis, writing—original draft.

Shiv Prasher: funding acquisition, conceptualization, project administration, methodology, resources, supervision, writing—review and editing.

Stephane Bayen: supervision, validation, writing—review and editing.

Christopher Nzediegwu: methodology, writing—review and editing.

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Declarations

Conflict of Interest The authors declare no competing interests.

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