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RESEARCH ARTICLE

Effect of walnut shell biochars on soil quality, crop yields, and weed dynamics in a 4-year field experiment

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Abstract

The introduction of biochar has been extensively tested under short-term greenhouse or field studies mainly in sandy or acidic soils, while its effects on soil properties, crop plants, and weed species especially in neutral or alkaline soils are still not well understood. Therefore, this study focused on relatively long effects of two walnut shell biochars (5 t ha^{-1}) on soil nutrient dynamics, two crop plants (wheat and lentil) growth and developments, and weed growth dynamics over 4 years (2014–2017). Applied biochar added once at the beginning of the experiment while planted crops were supplied with macro-nutrients and sprayed with pesticides according to conventional requirements of the region. Biochars improved soil properties by 10–23% during the first and second years while positive effects of biochars on weed growth were drastically higher (60–78% higher weed density) during the whole period of this study most likely due to increase in bioavailability of nutrient shortly after biochar amendment and indirect positive effects of biochars on soil physical properties as well. Consequently, biochar macro- and micro-nutrient will be utilized by weed plants with higher efficacy compared with crop plants.

Keywords Biochar · Plant productivity · Soil properties · Weed dynamics

Introduction

Soil in general sense and agricultural lands specifically have been under tremendous pressure mainly due to increasing demand for greater food production especially in West Asia where soil destruction is a main concern (Zabel et al. 2014; Khorram et al. 2015). Moreover, the total area of current fertile and suitable farming lands in this area has been rapidly decreasing during the last decade due to several reasons including destructive anthropologic activities (cities expansions) or natural disasters (unforeseen floods and heat waves) (Mulcahy et al. 2013). Furthermore, water deficiency as an additional major limiting factor for agricultural production, mainly in arid and semi-arid areas, is now being considered as a national security issue in Middle East because of higher consumption of available freshwater (Khorram et al. 2018). Therefore, the application of chemical fertilizers has become a necessary step in agricultural practice for crop growth and higher yield in these areas. To make matters worse, monoculture as the predominant method of cultivation in this region (Zuo and Zhang 2009), accompanied with the excessive use of chemicals, has led to some other new destructive issues like soil texture

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deformation and lower water holding capacity (WHC) (Ahmadi et al. 2016; Smider and Singh 2014), resulting in lower soil fertility, organism diversity, and pest resistance (Khorram et al. 2016a).

One of the proposed applicable methods for improving soil quality in line with sustainable agriculture is soil reinforcement through increasing the soil carbon using organic fertilizers such as compost, vermicompost, and biochars (Chan et al. 2008; Clough et al. 2013; Stewart et al. 2013). These organic compounds can accelerate the soil aggregation which most likely lead to higher WHC, nutrient availability, and consequently, improved microbial diversity (Baronti et al. 2014). Biochar as a by-product of biomass burning under limited oxygen regime has received more attention than other organic compounds due to its additional advantages like rich porous structure acting as a strong adsorption network to prevent the bioavailable soil nutrients from leaching into the deep soil profile (Khorram et al. 2015). Furthermore, high specific surface area (SSA) of biochar could be beneficial to provide suitable adsorption sites for different types of soil contaminants like heavy metals or pesticides resulting in lower bioavailability of xenobiotics for soil living organisms (Sopeña et al. 2012). It has been presented that biochar amendment could possibly lead to carbon sequestration (Beesley et al. 2011), enhanced nutrient uptake (Khorram et al. 2016a, b), and improved soil fertility, especially in acidic or tropical sandy soils (Harter et al. 2014). Moreover, it has been presented that fast pyrolysis biochars produced in higher temperature could be more beneficial than biochars produced in lower temperatures to the soil due to their greater porous structures which could facilitate the microbial growth and development (Sopeña et al. 2012). For instance, application of 96 mg ha^{-1} of hardwood biochar improved maize grain yield up to 55% over the control most likely due to the improvement of soil WHC and nutrient availability (Rogovska et al. 2014). Similarly, Sopeña et al. (2012) showed that the addition of 72 t ha^{-1} birch wood biochar increased barley yield by 10% a year after biochar amendment in the area which had been suffered from a prolonged drought period. The increase in the yield might be due to enhanced water availability and/or higher nutrient uptake by root plants.

However, the effect of biochar amendment on soil properties and crop yield may vary widely from positive to relatively negative depending on biochar physico-chemical properties, soil characteristics, plant growth dynamics, and also environmental conditions. For instance, although the application of 10 mg ha^{-1} wood biochar increased the water availability of agricultural soil by 17%, there were no meaningful positive effects on planted crops including wheat, turnip, and faba bean 3 months after biochar amendment. In this case, the increase of available water in soil resulted in higher and faster growth of wild species like weeds with more developed root systems (Khorram et al. 2018). Biochar amendment could also increase the risk of herbicide deficiency through higher adsorption of pesticide molecules by biochar particles (Lehmann and Joseph 2009). In our previous research, two hundred percent of higher weed growth rate compared with 32% higher growth rate of lentil, 4 months after the application of 15 t ha^{-1} two wheat straw biochars, was attributed to significant higher water holding capacity, greater nutrient availability, and lower bioavailability of herbicide molecules in soil pore water in biochar-amended soil (Khorram et al. 2018). In addition, as it has been previously mentioned, fast pyrolysis biochars could show stronger effects than slow pyrolysis biochars with respect to WHC and nutrient availability most likely due to higher SSA of fast pyrolysis biochars (Lehmann and Joseph 2009).

Nevertheless, since there is still lack of solid information about the effects of fast and slow pyrolysis biochars on plant growth and pesticide efficacy in agricultural fields of West Asian countries under rain-fed condition, a 4-year field experiment was conducted in an agricultural research mini-farm in northeast of Iran where more than 70% of croplands rely on rainfall for water supply (Khorram et al. 2018). The objectives of this study were as follows: (1) evaluation of the effects of biochars on macro- and micro-nutrients availability for crop plants over the growing seasons, (2) effectiveness of fast and slow pyrolysis biochars on wheat and lentil biomass, and (3) establishment of slow growth crops like lentil compared with the local weed species under rain-fed regime according to the conventional standard practices. Lentil and wheat were used in this study due to their strategic and key nutritional values in daily dietary of Iranian people. Wheat is the most important cereal in Iran and with the average production of 12 million tons, Iran is ranked as the 12th leading producer of wheat in the world (FAOSTAT 2015). Lentil is also another key crop product in Iran as the second vegetable-protein source after soybean with the average production rate of 270,000 tons per year (FAOSTAT 2015).

Materials and methods

Experiment location and soil properties

A field experiment for four successive years (2014–2017) was carried out at the agricultural research center of Technical and Vocational Trading Organization (TVTO) in northeast of Iran. The research area (59° 36′ E, 36° 16′ N) was 985 m above the sea level with annual precipitation and temperature range of 281–320 mm and −2.9 to 42.1 °C, respectively. Monthly weather data during the experimental period is presented in Fig. 1. The soil was clay loam with 16.8, 43.7, and 39.5% of sand, silt, and clay, respectively, with the following parameters: bulk density (BD), 1.62 mg m$^{3-1}$; pH, 7.23; total N,

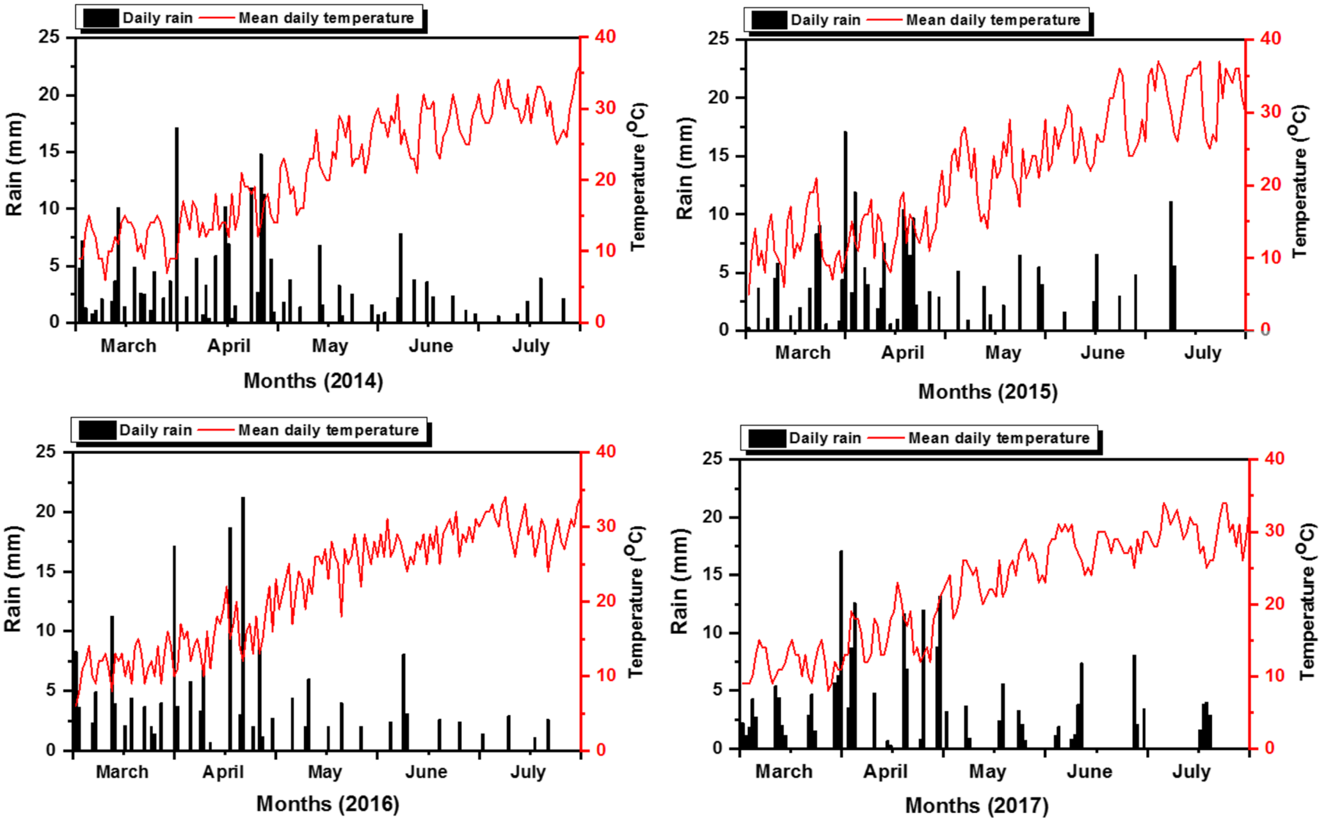

Fig. 1 Mean daily temperature and daily rain during growing season

0.84%; OC, 1.73%; total K, 210 mg kg^{-1}; available P, 2.95 mg kg^{-1}; and WHC, 21%.

Biochars

Two biochars produced from walnut shell (treated by slow and fast pyrolysis processes) provided by a local research start up incubator (Tehran, Iran). First biochar (B_1) was obtained through slow pyrolysis process (4 h, 450 °C) while the second biochar (B_2) was produced at 800 °C for 30 min (fast pyrolysis) (Table 1). The moisture content of tested biochars was measured after drying biochar at 105 °C for 24 h and pH was determined in a 1:5 (solid/water) solution. Chemical and physical properties of biochars were measured by methods described previously (Khorram et al. 2018).

Field-based pilot study

Experimental plots were established in August 2013 and the experiment was laid out in a complete randomized block

Table 1 Physical and chemical properties of walnut biochars

Biochar properties	B_1 (slow pyrolysis)	B2 (fast pyrolysis)
pH	7.9 ± 0.40	10.22 ± 0.49
Carbon content (g kg^{-1})	410.90 ± 11.55	540 ± 9.80
Nitrogen content (g kg^{-1})	9.47 ± 0.75	6.10 ± 0.23
Potassium (K) content (g kg^{-1})	7.14 ± 0.63	10.23 ± 0.28
Phosphorus (P) content (g kg^{-1})	6.10 ± 0.39	5.80 ± 0.21
Calcium (Ca) content (g kg^{-1})	51.20 ± 5.20	54.45 ± 3.75
Bulk density (g cm$^{3\ -1}$)	0.292 ± 0.25	0.266 ± 0.10
SSA (m^2 g^{-1})	108.21 ± 8.82	204.59 ± 7.30
Ash content (%)	22.74 ± 1.95	36.31 ± 2.92
Total pore volume (cm^3 g^{-1})	0.52 ± 0.11	1.04 ± 0.16
Micro pore volume (cm^3 g^{-1})	0.029 ± 0.03	0.215 ± 0.031

Data are the average of three replicates ± SD design (control, B_1, and B_2) with three replicates. Moisture rich biochars (200%) were manually applied once on 3rd of September 2013 (before starting the first year experiment) at 5 t ha^{-1} into the plots and were incorporated to a depth of 20 cm by moldboard plow. Each experimental plot (5.8 × 10 m) consisted of 12 rows, 0.40 m apart and 8 m in length. Experimental plots and replicated blocks were separated by 2-m wide pathway to avoid treatments effects. Two major crops planted in consecutive growing seasons from 2013 to 2017 were winter wheat (*Triticum aestivum* L) and lentil (*Lens culinaris* Medik.) (Table 2). Wheat seeds (Omid variety) were sown at a density of 150 seeds m^{2-1} by hand at depth of 1–2 cm on January 3rd (2014) and 8th (2016) while lentil (Mardom variety) seeds were planted at the depth of 2–3 cm on February 11th (2015) and 15th (2017) at the density of 200 seeds m^{2-1} (Table 2). Wheat was supplied two times with 60 and 85 kg N ha^{-1} on March 12th–14th and April 27th–30th and one time with phosphorous (super-phosphate) and potassium (potash, 75% K_2O) on April 15th at 30 and 75 kg ha^{-1}, respectively. However, lentil did not receive any fertilizer according to national practical guidance for lentil production (Khorram et al. 2018). Moreover, fluroxypyr (EC 25%) at 2.5 L ha^{-1} was applied once as the recommended post-emergence herbicide for wheat 4 weeks after wheat plantation while fomesafen (ReflexTM, SL 42.6%) at 1.5 L ha^{-1} applied once 2 weeks before lentil cultivation (Zand et al. 2007; Khorram et al. 2018).

Soil sampling and nutrient analysis

One or two days after harvest, five random soil samples (2 kg every time) were collected from every plot down to 30 cm depth and mixed and transported to the lab for nutrient analysis. Samples were taken from the center of plots to avoid cross contamination and treatment effects. Dry combustion elemental analyzer (Thermo Fisher Science, Beijing, China) was used for the measurement of TOC and TN after grinding the soil particles to < 0.5 mm with a method described previously (Vaccari et al. 2015). Briefly, The extraction with H_2SO_4 and $HClO_4$ using a flame photometer (TCVN 4053–81) was applied for total K content while extractable P was measured using the Olsen sodium bicarbonate ($NaHCO_3$) method (Olsen et al. 1954). Cation exchange capacity (CEC), pH, and bulk density (BD) were also measured according to the methods presented previously (Lehmann et al. 2011).

Crop and weed sampling and yield analysis

Assuming a full physiological maturity, wheat in 2 m^2 areas and lentil in 1 m^2 areas in central part of the plots were harvested by hand. Specific parameters such as plant height, underground biomass, grain number in spike (wheat), pod number per plant (lentil), and 1000-seed weight were measured randomly with 5 plants taken from each plot. N and P contents of the plants and seeds were determined using an elemental analyzer (Vario Max, Hanau, Germany) and ICP optical spectrometer (Varian Inc., Vista MPX), respectively. Plant materials were previously oven dried at 65% according to Vaccari et al. (2015). Mid-day leaf water potential of four fully developed and sun-exposed leaves in the middle part of the plants was measured between 11:30 A.M. and 2:30 P.M. on two sunny days using a pressure chamber (PMS, Instrumentation Co. Corvallis, OR, USA) (Padgett-Johnson et al. 2000).

Weed density inside each treatment was calculated based on the number of selected weed plants within three 1.5 m^2 quadrates in each biochar treatments divided by the corresponding values in control 12 and 6 weeks after pre- and post-emergence herbicides application (22th–29th of April for wheat; 27th of April–4th of May for lentil). Harvested weeds were immediately counted and oven dried at 65 °C for 36 h. Total weed biomass was measured using the same areas of treatments. Selected weeds for wheat plots were *Descurainia sophia* (L.) Webb. (flixweed), *Galium* sp. (bedstraw), *Sinapis arvensis* L. (wild mustard), *Cirsium arvense* (L.) Scop. (Canada thistle), *Convolvulus arvensis* L. (field bindweed), *Glycyrrhiza glabra* L. (licorice), *Alhagi persarum* Boiss. & Buhse. (camelthorn), and *Acroptilon repens* (L.) DC. (Russian knapweed) as the most troublesome weeds in wheat in northeast of Iran (Zand et al. 2007) while chosen major problematic weeds in rain-fed lentil production in that area were *Acroptilon repense* L. (Russian knapweed), *Carthamus oxyacantha* Bieb. (Wild safflower), *Cephalaria syriaca* L. (Syrian cephalaria), *Galium tricornutum* Dandy (Threehorn bedstraw), *Lithospermum*

Table 2 Important days for field experiments

Year	Crop	Planting date	Harvesting date	Soil sampling date
First	Winter wheat	3 January 2014	14 August 2014	15 August 2014
Second	Lentil	15 February 2015	12 July 2015	14 July 2015
Third	Winter wheat	8 January 2016	2 August 2016	5 August 2016
Fourth	Lentil	11 February 2017	7 July 2017	10 July 2017

Table 3 Soil property changes after biochar amendment in 4 years

Year/plant	Treatment	pH	TOC (g/kg)	TN (g kg^{-1})	AK (mg kg^{-1})	AP (mg kg^{-1})	CEC (cmol kg^{-1})	WHC (%)	BD (mg m $^{3-1}$)
First (wheat)	Control	7.32 ± 0.10 a	1.73 ± 0.12 a	0.85 ± 0.10	210 ± 15 a	2.95 ± 0.42 a	15.60 ± 0.74 a	21.66 ± 1.80 a	1.65 ± 0.11 a
	B1 (5 t ha^{-1})	7.59 ± 0.22 b	2.36 ± 0.27 b	0.99 ± 0.08	257 ± 24 b	9.10 ± 0.34 b	17.14 ± 0.36 b	26.33 ± 2.25 b	1.37 ± 0.00 b
	B2 (5 t ha^{-1})	7.73 ± 0.35 b	2.64 ± 0.35 b	1.02 ± 0.14	261 ± 19 b	8.88 ± 0.71 b	17.63 ± 0.85 b	27.00 ± 2.12 b	1.35 ± 0.17 b
	P value	*	**	ns	**	***	*	**	*
Second (lentil)	Control	7.28 ± 0.49	1.75 ± 0.23 a	0.84 ± 0.12 a	212 ± 8 a	2.99 ± 0.73 a	15.69 ± 0.59 a	21.33 ± 1.04 a	1.65 ± 0.08 a
	B1 (5 t ha^{-1})	7.40 ± 0.31	2.20 ± 0.14 b	1.17 ± 0.13 b	243 ± 16 b	6.19 ± 1.14 b	16.98 ± 0.33 b	24.66 ± 1.33 b	1.42 ± 0.10 ab
	B2 (5 t ha^{-1})	7.48 ± 0.40	2.29 ± 0.26 b	1.21 ± 0.18 b	247 ± 9 b	6.10 ± 0.60 b	17.02 ± 0.61 b	25.33 ± 1.69 b	1.41 ± 0.16 b
	P value	ns	*	*	**	**	*	*	*
Third (wheat)	Control	7.33 ± 0.44	1.72 ± 0.20	0.86 ± 0.06	211 ± 10	2.91 ± 0.59 a	15.62 ± 0.46	21.00 ± 2.13	1.64 ± 0.15
	B1 (5 t ha^{-1})	7.42 ± 0.59	1.95 ± 0.42	0.89 ± 0.17	221 ± 6	4.16 ± 0.39 b	16.01 ± 0.23	23.33 ± 1.22	1.55 ± 0.09
	B2 (5 t ha^{-1})	7.40 ± 0.28	2.01 ± 0.24	0.88 ± 0.12	222 ± 5	3.94 ± 0.29 b	16.10 ± 0.65	24.00 ± 2.18	1.55 ± 0.14
	P value	ns	ns	ns	ns	*	ns	ns	ns
Fourth (lentil)	Control	7.30 ± 0.51	1.74 ± 0.15	0.84 ± 0.14	210 ± 14	2.94 ± 0.67	15.64 ± 0.39	21.66 ± 0.99	1.65 ± 0.12
	B1 (5 t ha^{-1})	7.37 ± 0.26	1.83 ± 0.18	0.86 ± 0.09	216 ± 18	3.18 ± 0.55	15.91 ± 0.41	22.66 ± 1.33	1.57 ± 0.07
	B2 (5 t ha^{-1})	7.41 ± 0.43	1.92 ± 0.29	0.88 ± 0.07	218 ± 8	3.14 ± 0.29	16.00 ± 1.10	23.00 ± 1.56	1.56 ± 0.18
	P value	ns	ns	ns	ns	ns	ns	ns	ns

TOC total organic carbon, *TN* total nitrogen, *AK* available potassium, *AP* available phosphorus, *CEC* cation exchange capacity, *WHC* water holding capacity, *BD* bulk density. "ns" showed there was no significance between data according to Tukey's test at $P < 0.05$. Data are the average of three replicates ± SD

arvense L. (Corn gromwell), *Salsola kali* L. (Common saltwort), *Goldbachia laevigata* (M.Bieb.) DC, *Chenopodium album* L. (Common lambsquarters), and *Convolvulus arvensis* L. (field bindweed) (Ahmadi et al. 2016).

Statistical analysis

All data was subjected to analysis of variance (one-way ANOVA) at a significance level of $p < 0.05$ using SPSS version 16.0 statistical software (SPSS, Inc., Chicago, IL). The normality of data and homogenecity of variances were tested by Kolmogorov-Smirnov and Levene median tests and means were separated using Duncan multiple range test (DMRT) set at 0.05. Data were analyzed separately by year because the weather conditions, including temperature and precipitation, and planted species were different.

Results

Biochar effects on physical and chemical properties of soil

The effects of biochar addition on soil properties during the experiment period are presented in Table 3. Biochars amendment (B_1 and B_2) significantly improved the majority of measured soil characteristics through decreasing bulk density (BD) and increasing total organic carbon (TOC), WHC, and available potassium (AK) and phosphorus (AP) during the first 2 years of experiment (Table 3) with no significant difference between two biochars. BD of tested soil decreased from 1.65 mg m$^{3-1}$ in control to 1.35–1.37 mg m$^{3-1}$ during the first year of biochar amendment and remained significantly lower during the second year (1.41–1.42 mg m$^{3-1}$). Similarly, WHC and CEC increased 25.00–28.00% and 12.00–14.00%, respectively, after the first year of biochar amendment and kept significantly higher than the corresponding values of control until the end of the second year. Moreover, the amount of AK which was 210.00 mg kg^{-1} in control increased to 257.00–261.00 after biochar amendment. Nevertheless, soil pH increased only during the first year of experiment from 7.32 in control to 7.56–7.73 in biochar-amended treatments.

The effects of biochar on crop growth and yields

Biochar amendment led to a significant increase in vegetative growth (Table 4) and yield (Fig. 2) ($P > 0.05$) during the first 2 years of experiments. For instance, biochar addition increased the root length and underground biomass of wheat and lentil by 22.10–25.60% and 34.40–38.70%, respectively, during the first 2 years. Similarly, plant potassium and

Table 4 Biochar effects on vegetative growth of crops in 4-year period

Year/plant	Treatment	AH (cm)	RL (cm)	UB (g 4 plants^{-1})	MLW (MPa)	P (mg plant^{-1})	N (mg plant^{-1})	K (mg plant^{-1})
First (wheat)	Control	69.5 ± 3.3 a	30.1 ± 2.5 a	1.98 ± 0.22 a	− 1.71 ± 0.30 a	90.66 ± 7.12 a	1826.00 ± 240.00 a	112.66 ± 11.80 a
	B1 (5 t ha^{-1})	77.4 ± 2.7 b	36.2 ± 2.0 b	2.68 ± 0.29 b	− 1.16 ± 0.25 b	116.33 ± 5.82 b	2606.00 ± 380.00 b	144.20 ± 12.25 b
	B2 (5 t ha^{-1})	77.8 ± 1.9 b	37.3 ± 2.8 b	2.71 ± 0.31 b	− 1.10 ± 0.2 b	117.46 ± 6.87 b	2624.00 ± 410.00 b	151.10 ± 9.12 b
	P value	*	**	**	**	**	***	***
Second (lentil)	Control	32.2 ± 1.1 a	12.6 ± 0.8 a	1.08 ± 0.12 a	− 1.93 ± 0.17 a	75.11 ± 4.75 a	4726.00 ± 450.00 a	97.83 ± 10.29 a
	B1 (5 t ha^{-1})	38.9 ± 2.3 b	15.4 ± 1.6 b	1.45 ± 0.19 b	− 1.5 ± 0.21 b	97.18 ± 6.14 b	5920.00 ± 560.00 b	127.13 ± 16.4 b
	B2 (5t ha^{-1})	39.0 ± 2.6 b	15.6 ± 1.1 b	1.49 ± 0.27 b	− 1.56 ± 0.27 ab	100.33 ± 0.60 b	6103.00 ± 530.00 b	130.86 ± 22.4 b
	P value	*	*	*	*	**	***	***
Third (wheat)	Control	70.3 ± 2.4 a	29.4 ± 1.9	2.04 ± 0.30	− 1.56 ± 0.14	88.13 ± 5.62 a	1886.00 ± 410.00	115.00 ± 15.33
	B1 (5 t ha^{-1})	74.3 ± 1.5 ab	32.2 ± 2.2	2.11 ± 0.17	− 1.43 ± 0.22	96.66 ± 7.23 ab	1940.00 ± 220.00	123.80 ± 16.42
	B2 (5 t ha^{-1})	75.1 ± 2.2 b	31.7 ± 1.3	2.08 ± 0.23	− 1.40 ± 0.28	96.66 ± 4.45 ab	1988.00 ± 360.00	123.76 ± 11.87
	P value	*	ns	ns	ns	*	ns	ns
Fourth (lentil)	Control	33.0 ± 0.8	12.8 ± 1.2	1.02 ± 0.19	− 1.92 ± 0.24	77.33 ± 5.59	4616.00 ± 390.00	99.09 ± 21.08
	B1 (5 t ha^{-1})	36.1 ± 2.7	13.2 ± 1.5	1.08 ± 0.21	− 1.95 ± 0.38	81.66 ± 5.55	4760.00 ± 440.00	102.66 ± 12.74
	B2 (5 t ha^{-1})	35.2 ± 2.2	12.9 ± 0.9	1.03 ± 0.17	− 1.86 ± 0.31	78.66 ± 6.17	4703.00 ± 280.00	103.33 ± 14.33
	P value	ns	ns	ns	ns	ns	ns	ns

AH aboveground plant height, *RL* root length, *UB* underground biomass, *MLW* mid-day leaf potential water, *P* plant P content, *N* plant N content, *K* plant K content. "ns" showed there was no significance between data according to Tukey's test at $P < 0.05$. Data are the average of three replicates ± SD

nitrogen contents enhanced 34.00–36.00% and 30.00–44.00% during the same time period. Moreover, mid-day leaf potential water of wheat and lentil dropped by 20.00% and 35.00% after 1 and 2 years of biochar addition. Moreover, aboveground height of wheat during the first year of experiment increased from 69.50 cm in control to 77.40–77.80 cm and this positive effect remained significant until the third year when aboveground height was 11.00%. However, it is noteworthy that biochar types had no significant effects on measured plant properties during the whole period of study ($P > 0.05$).

Similar results were observed for dry matter yield of the tested crops as biochar amendment resulted in 22.00% and 40.00% higher grain number (in wheat) and number of pods (in lentil) per plant, respectively (Fig. 2). In addition, the weight of 1000 seeds had also increased by 28.00% and 26.00% in the first and second years of this study, respectively. Moreover, nitrogen content of seeds as an important factor for nutritional values of grains and beans raised 26.00–30.00% during the first growing season of wheat and lentil (2014–2015).

Weed growth under biochar amendment regime

Although positive effects of biochar application on soil properties and planted crops remained significant for a year or two, biochar stimulation effects on weed growth and development lasted for the whole period of experiment with no significant difference between biochar types (Fig. 3) ($P < 0.05$). For instance, weed density increased 25.00% in biochar-amended treatments compared with control during the first year (2014), followed by additional 25.00% during 2015 to 2017. Similar trend observed in total weed biomass where biochar addition resulted in 22.00%, 49.00%, 28.00%, and 32.00% higher values during four growing seasons (Table 4). Since lentil is considered as a slow growth crop with long establishment period compared with wheat as a fast growing legume (Zhang et al. 2016), the risk of biochar was greater for lentil treatments. Therefore, although biochar amendment led to 61.00–78.00% higher underground biomass of weeds in wheat treatments, the underground biomass of weeds in lentil treatments increased by 98.00–105.00%.

Discussion

Biochar effects on physical and chemical properties of soil

Introduction of biochar into the soil has led to significant changes of soil chemical properties with no significant differences between fast and slow pyrolysis biochars. Biochars increased the soil pH significantly during the first year. The

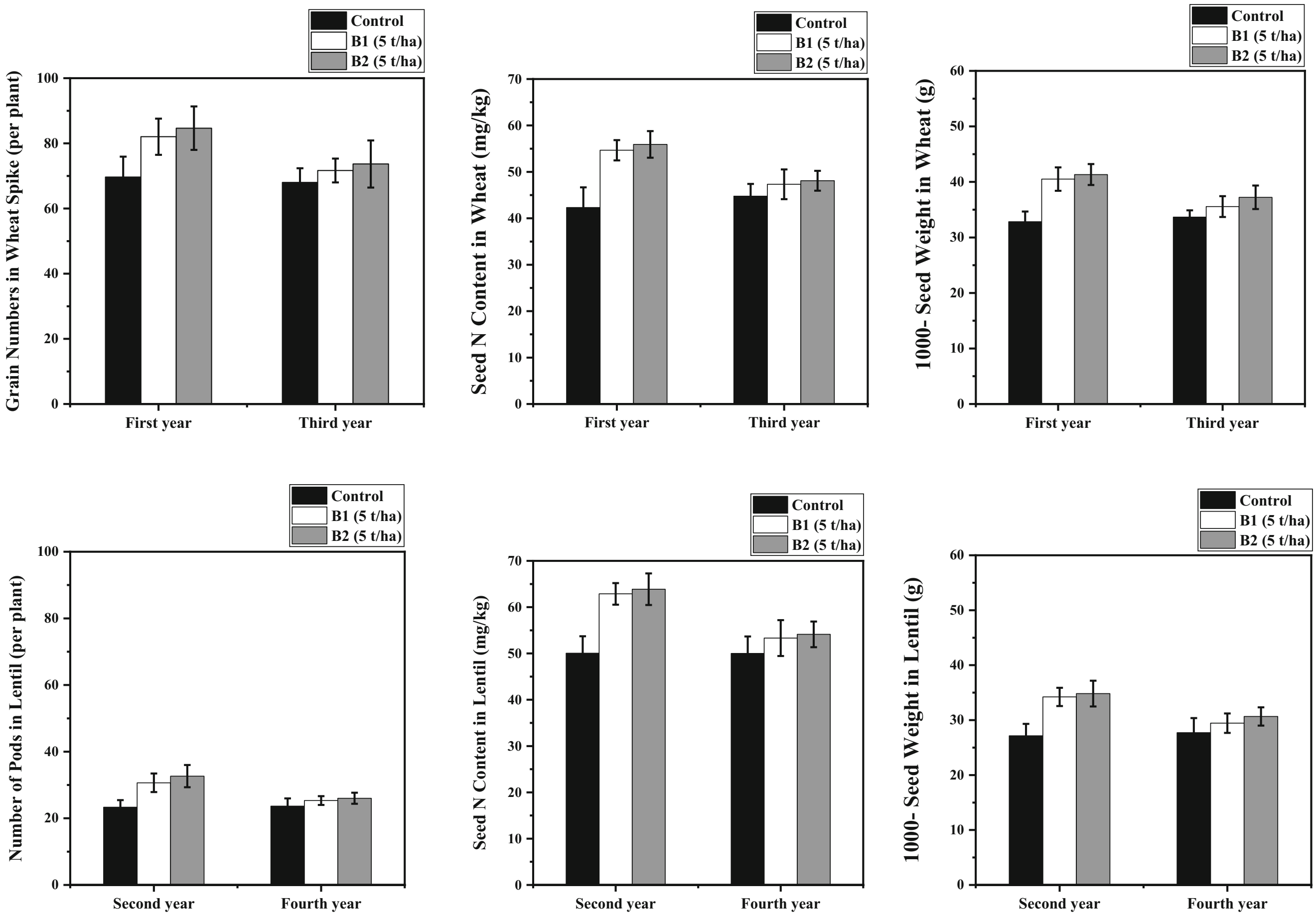

Fig. 2 Wheat and lentil yields after biochar amendment

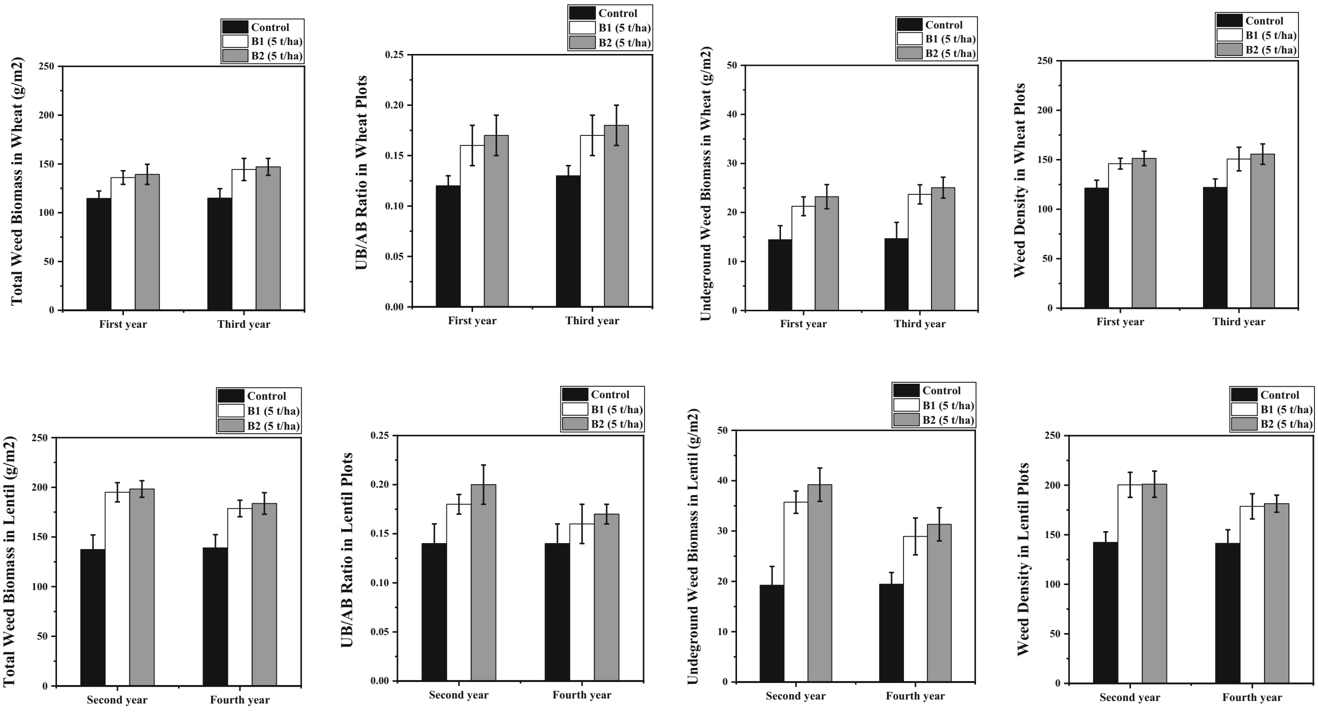

Fig. 3 Weed growth under biochar treatment regimes

increase of soil pH after biochar amendment could be explained by liming effects of biochar ash content (Doan et al. 2015; Vaccari et al. 2015). However, this effect was most likely depressed by the production of acidic compounds on biochar surface through the oxidation of biochar particles inside the soil shortly after biochar amendment (Cheng et al. 2006; Laghari et al. 2015; Griffin et al. 2017). There was no delay in biochar effects on soil in our study as it has been reported frequently before (Griffin et al. 2017; Haider et al. 2017). This could be due to relatively high precipitation in autumn accelerating the biodegradation of rich wet biochar which had been added 4 months before the first crop plantation (September 3rd, 2013) resulting in active interaction between soil particles, biochar particles, and their microbial communities (Jones et al. 2012; Solaiman et al. 2010; Tammeorg et al. 2014). It has been presented that higher bioavailability of essential nutrients in biochar-amended acidic soils would be mainly due to the increase of CEC after biochar amendment (Hossain et al. 2010). Higher CEC in biochar-amended soils could be related to the higher surface area and charge density of the biochars as usually there are higher available negative charges on biochar particle surface with higher tendency to retain positively charged ions like calcium (Ca^{2+}), potassium (K^{+}), phosphorus (P), and nitrogen (N) (Jones et al. 2012). Moreover, significant biochar effects including higher soil pH and greater retention of cations could last for 4 or 5 years in acidic or sandy soils (Lazcano et al. 2011; Griffin et al. 2017). For instance, Major et al. (2010) demonstrated that the bioavailability of K^{+}, Ca^{2+}, and Mg^{2+} was higher in biochar-amended soils a year after one-time application of biochar and it stayed still significantly higher than unamended soils until the end of fourth year. However, it could not be the main reason of higher nutrient availability in this study due to the fact that the soil pH at the beginning of the experiment was 7.23 (within the ideal range for nutrient solubility (Hossain et al. 2010; Lehmann et al. 2011)) and there was no significant difference between CEC and pH of biochar-amended and unamended treatments. Therefore, higher concentration of bioavailable nutrients ions could be principally due to direct addition of biochars through enhancement of nutrient supply (Jones et al. 2012) and increasing nutrient use efficiency (Zhang et al. 2016).

Water holding capacity (WHC) of agricultural soil especially in arid areas is another key factor highly influenced by biochar amendment. Positive effect of biochars on WHC and water retention capacity (WRC) is probably due to direct and indirect mechanisms. On one hand, direct mechanism includes the binding of water molecules with available cations/anions on the surface of biochar particles and also the accumulation of water molecules inside the porous structures of biochars (Lehmann and Joseph 2009; Larney and Angers 2012). Generally, strong H-bonds between water molecules and biochar aromatic compounds lead to lower downward flux of water with dissolved nutrients (Clough et al. 2013). Indirect mechanism on the other hand involves the capture of water droplets inside the newly created network made by microorganisms like fungi between soil and biochar particles (Gul et al. 2015).

The effects of biochar on crop growth and yields

Biochar positively affects plant growth most likely through the enhancement of physical ("initiator process") and chemical ("continuing process") properties of the soil (Lehmann et al. 2011; Khorram et al. 2016a, b). BD and WHC are among the most important soil physical properties which are influenced by biochar during the initial process. Lower BD in biochar-amended soil probably helps the root systems of plants for facilitated development of their root systems through greater aeration in upper layer of the soil (0–20 cm) resulting in prompted establishment and shorter vegetative growth stage (Lehmann et al. 2011). Furthermore, higher WHC increases the bioavailability of soil nutrients in soil pore water where they can be utilized faster through well-developed radicles. In addition, higher WHC most likely lead to longer retaining of water molecules in growing layer of the soil between rain cycles (Genesio et al. 2015). The addition of 15 $t\ ha^{-1}$ wood biochar increased the efficiency of plant water relation as the total biomass per water unit in vineyard field increased by 24% (Baronti et al. 2014). Similarly, Genesio et al. (2015) presented that the addition of commercial biochar increased the crop yield only through the improvement of soil physical properties like WHC and CEC especially during the long period of drought stress. Moreover, Baronti et al. (2010) demonstrated that 16% higher grain yield in biochar-amended plots was attributed to improved soil water retention capacity and reduced nutrient leaching rather than nutrient availability through biochar amendment because there was no significant difference between N content of the wheat grains in biochar-treated and untreated plots.

Furthermore, positive effects of biochar on plants could also take place through the improvement of soil chemical properties like nutrient availability during continuing process. Biochars usually release several macro- and micro-nutrients into the soil few months after their introduction (Lehmann et al. 2011). In addition, a portion of soil nutrients which is prevented from being leached from upper layer of the soil through the adsorption to biochar particles will be released gradually during the aging process partially due to greater activity of microbial communities (Laghari et al. 2015; Khorram et al. 2016a, b). In addition, a small increase of soil pH and CEC can provide a suitable equilibrated environment for cations/anions exchange (Lehmann and Joseph 2009). It is shown that the increase of soil CEC and pH after biochar application resulted in higher bioavailability of Ca^{2+} and K^{+}, and P and N uptake by grapevine during 2 years after the introduction of 22 t ha^{-1} wood biochar (Baronti et al. 2014). Similarly, 16% higher plant length and root biomass in corn was attributed to higher bioavailability of K^+ and N 2 years after the addition of 15 t ha^{-1} wood chips biochars (Haider et al. 2017). Similarly, in our previous study, 24% higher aboveground height and root length of lentil was also ascribed to higher availability of P, N, and Ca^{2+} during the lentil-growing period (Khorram et al. 2018).

Positive effects of biochars in this study lasts mainly for 2 years which was in agreement with other field studies especially rain-fed cultivations (Major et al. 2010; Khorram et al. 2016a, b). Zhang et al. (2016) who studied on the effects of wheat straw biochar on maize yield presented that slow pyrolysis wheat straw biochar improved the crop yield during the first and second years after biochar amendment by 11.9% and 35.4%, respectively, mainly through higher availability of P during the reproductive growth stage of maize.

Weed growth under biochar amendment regime

There are some reports regarding the effects of biochar amendment on weed outbreak risk through lower herbicide efficacy and nutrient availability in short time (Nag et al. 2011; Doan et al. 2015; Khorram et al. 2018). However, still there is no solid evidence about the relatively long-term effects of biochar amendment on weed growth and development under national local herbicide application regime in the field.

Reduced herbicide efficacy could be initially due to higher adsorption capacity of biochar compared with soil organic matter resulting in deactivation of herbicide molecules short time after herbicide applications which result in lower bioavailability of free herbicide ions in soil pore water (Khorram et al. 2015). In our previous study, the application of 5–15 t ha^{-1} wheat straw biochars significantly decreased the fomesafen residue in soil pore water leading to 60–122% higher weed density 4 months after the addition of fresh biochar, respectively (Khorram et al. 2018). However, since fomesafen (water solubility in pH = 7, 50 mg L^{-1}) and fluroxypyr (water solubility in pH = 7, 6500 mg L^{-1}) are among the highly soluble pesticides and biochars are highly water adsorbent compounds (Nag et al. 2011), herbicide deactivation by biochar particles could not fully explain significant higher growth of weeds. Nag et al. (2011) who studied the efficacy of atrazine and trifluralin in 1% wheat straw biochar-amended soil reported that deactivation of atrazine as a relative water-soluble herbicide (35 mg L^{-1}) was almost half of that in trifluralin (water solubility in pH = 7, 0.2 mg L^{-1}) as water insoluble herbicide. In addition, as the specific surface area of added biochar usually decreases during the time due to “aging process,” higher continuous growth and developments of weed in this study could be probably due to complex mechanisms including facilitated nutrient availability and improved soil physico-chemical properties resulting in higher compatibility of weeds compared with crop plants. It has also been presented that 60% and 85% higher weed biomass 2 and 3 years, respectively, after the introduction of 2% bamboo biochar was attributed to the higher availability of nutrients (Doan et al. 2015). In addition, since the growth of underground part of plants is considered as an index for faster establishment of plants and earlier start of reproductive growth phase, the increase of U/A value in biochar-amended soils could possibly be a sign for greater weed outbreaks in the following years due to (1) the production of higher numbers of weed seeds during growing season and (2) earlier maturity of weed seeds which will be spread out earlier. However, this phenomenon needs to be investigated in future studies.

Conclusion

Our study explored 4-year effects of two walnut shell biochars produced at different pyrolysis temperature on soil physico-chemical properties, crop productivity, and weed growth and development. One-time addition of 5 t ha^{-1} biochars into an agricultural soil with clay loam structure, poor nutrients, and low fertility increased wheat and lentil yields during the first and second years. These positive effects could be partially attributed to higher bioavailability of nutrient ions like K^+ and Ca^{2+} and partially due to improved soil chemical properties like higher CEC which did not persist after the second year. However, native weed species continuously grew during the whole period of the experiment. Although the direct effects of biochar can explain the higher weed density and weed biomass during the first 2 years of the study, the successive higher growth of weeds during the last 2 years could be the result of indirect mechanisms like improved physical properties of the biochar-amended soil including lower bulk density and consequently greater aeration. These physical properties possibly provide better environment for prompt growth and establishment of weeds which are generally more successful than crop plants to expand their developed root system to the deeper depth of the soil. Since there are some absolute positive effects of biochar on soil quality and plant growth and development, we suggest the use of a lower rate of biochar addition in specific application way like root zone application of crop plants. This could affect the soil near the root systems of crop plants positively without or with minimum negative impacts on weed growth. Nevertheless, since usually the soils in agricultural fields are being partially plowed annually, the addition of low rate of biochar can improve the soil physical and chemical properties gradually. Nonetheless, long-term field experiments are needed to understand the complex effects of biochars on soil-plant-weed nutrient correlation especially under rain-fed conditions.

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