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ORIGINAL ARTICLE

Agronomic effects of biochar and wastewater irrigation in urban crop production of Tamale, northern Ghana

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Abstract Agricultural production needs to increase, particularly in sub-Saharan Africa, many rural people are undernourished, and the urban population is growing rapidly. It is worrisome that on many West African soils with low cation exchange capacity and soil organic carbon content, mineral fertilization is rather inefficient. Under these conditions, wherever available untreated wastewater is used for irrigation despite the potential health risks to producers and consumers. For intensively cultivated soils with high mineralization rates, biochar application has been advocated as a promising management option. However, the agronomic benefits of wastewater reuse in agriculture and its interaction with biochar have received only limited attention. This study therefore investigated the effects of mineral fertilizer application and biochar amendment at two water quality and quantity levels on soil moisture, plant nutrition and biomass production on a Petroplinthic Cambisol over 2 years. Rice husk biochar applied at 20 t ha^{-1} significantly increased fresh matter yields in the first five cropping cycles by 15%, and by 9% by the end of 2 years. Compared with clean water, wastewater irrigation increased yields 10–20-fold on unfertilized plots during the dry seasons, while a fourfold increment was observed in the wet seasons. This seasonal difference is likely a result of the high sequence of irrigation events during the dry season. In this study, fertigation with wastewater contributed significantly to plant nutrition and nutrient recovery while yield-increasing biochar effects disappeared over time. Soil moisture was enhanced by up to 9% due to biochar amendments under unfertilized conditions.

Keywords Fertigation · Soil moisture · Urban agriculture · Wastewater

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Introduction

The world's population is projected to grow to 8.5 billion by 2030, with more than half of this growth occurring in sub-Saharan Africa (SSA), a region where one-quarter of the population is currently undernourished (UN 2013). In most African countries, the population is growing faster than food production. Additionally, soil fertility is depleting as a result of nutrient removal without adequate replenishment (Sanchez 2002; Tully et al. 2015). In many regions of SSA, soils are already highly degraded and have a poor inherent soil fertility with low soil organic carbon (SOC) contents, low cation exchange capacity (CEC) and low water holding capacity (FAO and ITPS 2015; Tully et al. 2015).

Despite its possible health risk to irrigators and consumers (Hussain et al. 2002; Qadir et al. 2007; Amponsah et al. 2015), proper use of wastewater has been considered as an environmentally sound disposal practice which helps to replenish carbon (C) and nutrients lost during intensive, often year-round cultivation (Mohammad and Mazahreh 2003). Under these conditions wastewater irrigation can be an important source of plant nutrients (Singh et al. 2012; Lal 2013; Drechsel and Keraita 2014; Nyantakyi-Frimpong et al. 2016). However, Amponsah et al. (2015) also report that between half to one million Ghanaian city dwellers are at risk of infections from consuming vegetables that are irrigated with polluted water. Mineral fertilizer, however, can be expensive and water is often scarce, whilst wastewater treatment is non-existent in most African cities (Scott et al. 2004; FAO 2005).

On soils with low CEC and SOC, fertilization with mineral fertilizers alone is often inefficient, because of large nutrient losses from gaseous emissions and leaching (Graefe et al. 2008). Biochar is a C-rich product of pyrolysing biomass under oxygen deficiency (Lehmann and Joseph 2009) and its soil application has been advocated to enhance crop yields (Steiner et al. 2007; Jeffery et al. 2011; Cornelissen et al. 2013) as well as to improve nitrogen (N) use efficiency particularly on acid soils of low fertility (Chan et al. 2007; Steiner et al. 2008). Biochar also increases plant-water availability (Novak et al. 2012; Xiaoa et al. 2016) and is one option to increase SOC (Ma et al. 2016).

Notwithstanding, there are other field studies reporting contrary results (Lentz and Ippolito 2012; Schnell et al. 2012; Cornelissen et al. 2013; Bass et al. 2016). A review of 44 published biochar research articles shows that half of the studies did not find any yield increase or even reported negative yield responses to biochar application (Spokas et al. 2012). In a meta-analysis of 371 independent experiments, Biederman and Harpole (2013) found that, the average effect of biochar was neutral to positive, despite variability in soil type, climate, and production methods. Studies like ours, which was conducted over a 2-year period with 13 cropping cycles following one single biochar addition, are rare. Those published involve only two to five cropping cycles (Kulmatiski and Beard 2006; Steiner et al. 2007; Major et al. 2010; Haefele et al. 2011; Quilliam et al. 2013). Also, the agronomic effects of untreated wastewater reuse as well as its interaction with biochar are largely unknown.

This study therefore aimed at examining the effects of a single biochar application to an agricultural soil, mineral fertilizer addition, and different irrigation water qualities and quantities on biomass production, plant nutrition, and soil moisture over a 2-year period and multiple cropping cycles in northern Ghana. We hypothesized that biochar application, combined with fertilization and wastewater irrigation, increases yields beyond what either practice may generate alone.

Materials and methods

Study area

The study was part of a broader project aimed at testing improved management strategies to enhance nutrient and water use efficiency, maintain soil quality, and produce safer vegetables in urban agriculture of Tamale, Northern Region of Ghana (9°28′28.75″N latitude and 0°50′53.48″W longitude; Appendix i in Supplementary Material). The Tamale municipality is the largest in northern Ghana with an urban population of about 400,000 inhabitants (GSS 2012). The experimental site is governed by the Guinea savannah climate of West Africa and has a distinct rainy and dry season, characterized by a unimodal rainfall pattern with a mean annual rainfall of 1111 mm. The driest month is January with 2 mm average rainfall, whilst major rainfall occurs between August and September. The mean annual temperature is 29 °C (GMS 2002; CLIMATE-DATA.ORG 2016). During the field experiment, the precipitation during the rainy seasons (covering April to October) was 800 and 620 mm for the years 2014 and 2015, respectively (Appendix ii in Supplementary Material). The mean temperature during the experiment was 28.3 °C.

Experimental setup

Setup and management of the field experiment was the same as reported by a companion study of Manka'abusi et al. (see this Special Issue). It tested farmers' practice (FP_1) of fertilization in comparison to no fertilization (FP_0), biochar (BC) addition and FP_1 + biochar (FP_1 + BC). These four treatments were irrigated with either untreated wastewater (ww) or clean water (cw) and using farmers' usual "full" (f) or reduced (r, 2/3 of f) irrigation quantity. Clean water was sourced from Ghana Water Company Limited, while wastewater came from domestic sewage effluents from the Kamina Military Barracks. Irrigation water samples (clean and wastewater) were collected weekly for nutrient analysis while mineral fertilizer was collected at each application event for analysis (Table 1). The experiment was divided into four blocks (replicates) and each block was divided into four irrigation schemes (main-plots). The location of the main-plots (irrigation) within a block was randomized as well as the location of the sub-plots (treatments) within each main-plot (Haering et al. 2017; Appendices iii and iv in Supplementary Material).

Soil properties

Soil samples were taken at the beginning of the study and at the end of each season at 0–0.2 m depth for analysis. Analysis of samples as described in Haering et al. (2017) included pH, total C, nitrogen (N), total and Bray-available phosphorus (P), potassium (K), magnesium (Mg), and CEC. The experimental site had a sandy loam texture with a sand content of 46% and a low clay content of 5–8%. It was classified as a Petroplinthic Cambisol according to the WRB classification (WRB, 2015) with a topsoil total C of 0.4%. Effective CEC was 38.8 mmol kg^{-1} and soil pH was moderately acidic (5.1; Haering et al. 2017). Soil volumetric water contents (VWC) of plots were measured weekly, in the evening before irrigation (four points per plot, averaged) by using a FieldScout TDR 100 Soil Moisture Meter (Spectrum Technologies Inc., Plainfield, IL, USA).

Crops

In all, 13 crops typically grown in the region were cultivated by the end of the experiment (Table 1). Nursing of seedlings, planting distance, weeding, tillage, loosening of soil and other production practices were carried out according to local farmers' practice. Crops were harvested when FP plots reached physiological maturity (according to the farmers' judgment), except for maize biomass which was harvested after the vegetative stage. A sampling area of 1.2×2.7 m (3.2 m^2) of each plot was harvested to measure crop biomass. Crops from a ≥ 0.4 m border around each plot were discarded at each harvest to minimize edge effects.

Nutrient inputs

Mineral fertilizer (NPK 15–15–15 and Urea 46–0–0, Springfield Agro, Singapore) and wastewater were the major sources of N, P, and K input. Fertilizer was applied by broadcasting at the farmers' recommended rates and frequency. Average mineral fertilizer input was 52 ± 18 kg N, 21 ± 8 kg P, and 30 ± 12 kg K ha^{-1} for all crops except for jute mallow (*Corchorus olitorius* L.) to which urea was applied at 117 ± 2 kg N. Mean wastewater input for crops cultivated in the rainy seasons was 42 ± 33 kg N, 7 ± 5 kg P, and 7 ± 3 kg K ha^{-1} whilst 111 ± 80 kg N, 43 ± 24 kg P, and 32 ± 25 kg K ha^{-1} was supplied during the dry seasons. The input from clean water was negligible compared with the other inputs (Table 1; Haering et al. 2017).

Biochar production and incorporation

Biochar was produced from rice husks by pyrolysis at 500 °C. The resulting biochar had 0.6% total N, 861 mg kg^{-1} P and 977 mg kg^{-1} K, an electrical conductivity (EC) of 900 µS cm^{-1}, volatile matter content of 23%, total C of 42% and an ash content of

Table 1 List of cultivated crops, irrigation quantities (mm) and nutrient inputs in (kg ha^{-1}) of a multi-factorial vegetable growing experiment conducted from May 2014 to April 2016 in Tamale (northern Ghana)

	Season 1 (2014 rainy season)			Season 2 (2014/15 dry season)			Season 3 (2015 rainy season)				Season 4 (2015/16 dry season)		
Crop number	1	2	3	4	5	6	7	8	9	10	11	12	13
Crop	Maize	Lettuce	Cabbage	Amaranth	Lettuce	Amaranth	Jute mallow	Jute mallow	Amaranth	Jute mallow	Roselle	Lettuce	Carrot
Planting date	May	Jun	Jul	Oct	Dec	Feb	Apr	Jun	Jul	Sep	Oct	Dec	Jan
Harvesting date	Jun	Jul	Oct	Nov	Jan	Mar	May	Jul	Aug	Oct	Nov	Jan	Apr
Crop duration (days)	31	28	72	30	48	30	31	30	34	35	36	35	91
Full irrigation	198.0	339.6	204.9	242.0	431.8	176.0	200.8	160.9	38.5	8.3	264.0	242.0	540.4
Reduce irrigation (mm)	126.5	228.3	145.8	170.5	298.4	118.3	148.5	115.5	27.5	8.3	180.1	166.4	391.8
Rainfall (mm)[a]	42.2	29.7	542.3	10.4	0.0	37.3	18.8	72.7	146.4	170.6	13.8	0.0	125.9
Fertilizer – N (kg ha^{-1})	84.4	85.5	58.8	31.9	54.1	31.9	115.1	119.5	30.6	45.4	45.2	46.1	57.2
Fertilizer − P (kg ha^{-1})	36.1	36.5	25.1	13.6	23.1	13.6	0.0	0.0	11.6	17.2	17.1	17.5	21.7
Fertilizer − K (kg ha^{-1})	52.3	53.0	36.5	19.8	33.6	19.8	0.0	0.0	15.0	22.3	22.2	22.6	28.1
ww – N (kg ha^{-1})	30.8	52.9	19.3	32.7	172.0	55.0	86.9	91.2	15.0	2.3	55.0	95.6	258.8
ww − P (kg ha^{-1})	4.6	7.9	3.5	12.5	53.8	28.5	14.7	13.8	1.4	0.1	33.4	44.8	87.3
ww - K (kg ha^{-1})	7.2	12.7	5.9	7.3	20.1	9.1	8.0	7.8	4.0	1.2	37.3	36.0	80.4
cw − N (kg ha^{-1})	0.5	0.9	0.5	1.7	3.0	1.2	1.1	0.5	0.1	0.0	1.3	1.2	2.6
cw - P (kg ha^{-1})	0.0	0.0	0.1	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.5	0.1	0.3
cw − K (kg ha^{-1})	2.3	3.9	1.5	2.7	4.8	2.0	2.1	1.4	0.7	0.2	5.8	5.3	11.8

Nutrient input estimates for cw and ww are based on full irrigation, values for reduced irrigation and other details can be found in Appendix ii in Supplementary Material

cw clean water, *ww* wastewater

[a] Rainfall quantities are same for full and reduced irrigated plots

45% (Appendix v in Supplementary Material). Biochar was incorporated into the soil (0–0.2 m) manually at a rate of 20 t ha^{-1}. After incorporation, soil of all plots was thoroughly tilled. The soil surface (0–0.2 m) was loosened before each cropping cycle to facilitate homogenous water infiltration and biochar distribution within the plots.

Tissue analysis

Fresh weight of aboveground biomass (stem and leaves) was measured, and for carrot, root biomass was additionally determined. After the first four cropping cycles, marketable yields were assessed in addition to the total aboveground biomass. After obtaining the fresh weight of crops on the sampling area, sub-samples were air dried for 3 days and further oven-dried to constant weight at 65 °C. Dried samples were ground to 1.5 mm to analyse nutrient concentrations. Total C and N were determined with an elemental analyser (Vario MAX CHN Elementar Analysensysteme GmbH, Hanau, Germany). Total P was measured with a spectrophotometer (Hitachi U-2000, Hitachi Ltd., Tokyo, Japan) at 460 nm following the P-yellow-method after extraction with HCl and colouration with an ammonium molybdate/ammonium vanadate reagent. Potassium (K) was determined by flame photometry (BWB-XP, BWB Technologies UK Ltd., Garforth, UK).

Statistics

Data were analysed using a mixed model accounting for the effects fertilization, biochar amendment, quality and quantity of water using the procedure PROC MIXED in SAS (SAS Institute Inc 2009). As a multi-factorial design experiment, error terms for main-plot (water quality water quantity block) and sub-plot (nutrient management practices) were accounted for. To account for repeated measurement over time, an autoregressive model was used. Residuals were tested for normality (Shapiro-Wilks or Kolmogorov–Smirnov test) and homogeneity of variances in SAS statistical package version 9.2 (SAS Institute Inc 2009). Where necessary, data were $\log_{10}$ transformed prior to statistical analysis. All possible interactions up to the four-way interaction were included in conducting multiple least square mean comparisons using a Tukey's post hoc honest significant difference test at $p < 0.05$.

Results

Effects of fertilization and biochar on crop biomass production

Fertilizer application (irrespective of any other factors), compared with yields of unfertilized plots, significantly ($p < 0.01$) improved total biomass and marketable yields for all crops with the exception of carrot (crop 13) for which a 3% increase in total biomass and 15% increase in marketable yield was recorded. The highest increments were recorded for lettuce (crop 2) and amaranth (crop 9) with biomass and marketable yield increases of 263 and 1400% respectively (Tables 2, 3). Biochar amended plots (irrespective of any other factors), compared with unamended plots, on the other hand, significantly ($p < 0.05$) improved total biomass of the first four crops, on average by 15%. Marketable yield on biochar amended plots was on the other hand significantly improved for lettuce (crops 5 and 12) with a mean increment of 14% compared with unamended biochar plots. Biochar amendment on fertilized plots ($FP_1 + BC$) increased the total biomass yields of maize (crop 1) and amaranth (crop 4) compared with fertilized plots without biochar amendment (FP_1). A significant interaction between fertilization and biochar addition was observed for jute mallow (crop 8, $p = 0.01$) which led to a 15% decline in yield (Table 2; Appendix vii in Supplementary Material). Biochar amendment on unfertilized plots (BC) on the other hand, had a 82 and 42% increment, respectively, on the first two lettuce cropping cycles (crops 2 and 5; Table 2). The remaining crops were not significantly influenced by the addition of biochar, even though means of crop yields were numerically higher on both fertilized and unfertilized plots (Tables 2, 3), with the exception of amaranth (crop 6), jute mallow (crop 8), roselle (crop 11), and lettuce (crop 12).

From the sixth crop onwards, a significant interaction ($p < 0.05$) between fertilization and water quality was observed in amaranth (crop 6), jute mallow (crops 7 and 8), lettuce (crop 12) and carrot (crop 13). In these crops, wastewater irrigation led to significant higher yields in both fertilized (FP_1 + ww) and unfertilized

Table 2 Aboveground fresh matter biomass (t ha^{-1}) of selected treatments for the experimental crops in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016

Treatment	n	Biomass t ha^{-1}(FM)											
		Crop 1 Maize	Crop 2 Lettuce	Crop 4 Amaranth	Crop 5 Lettuce	Crop 6 Amaranth	Crop 7 Jute mallow	Crop 8 Jute mallow	Crop 9 Amaranth	Crop 10 Jute mallow	Crop 11 Roselle	Crop 12 Lettuce	Crop 13 Carrot
Fertilization													
Unfertilized	32	16.1 ± 1.0b	2.4 ± 0.4b	7.4 ± 0.7b	15.6 ± 2.5b	11.6 ± 1.7b	4.8 ± 0.7b	4.3 ± 0.5b	2.7 ± 0.5b	1.9 ± 0.1b	6.2 ± 0.6b	6.3 ± 0.9b	16.2 ± 2.4a
Fertilized	32	32.0 ± 1.7a	8.7 ± 0.6a	22.5 ± 1.1a	30.9 ± 2.7a	22.3 ± 1.8a	7.6 ± 0.6a	9.8 ± 0.6a	9.1 ± 0.9a	5.6 ± 0.5a	18.0 ± 0.7a	8.7 ± 1.2a	16.7 ± 2.2a
Biochar amendment													
No biochar	32	22.7 ± 1.8b	5.1 ± 0.7b	13.9 ± 1.6b	21.6 ± 3.0a	16.7 ± 2.0a	6.1 ± 0.7a	7.4 ± 1.0a	5.7 ± 0.9a	3.6 ± 0.5a	12.2 ± 1.2a	7.4 ± 1.1a	15.8 ± 2.3a
Biochar	32	25.4 ± 2.1a	6.0 ± 0.7a	16.1 ± 1.7a	24.9 ± 2.9a	17.2 ± 1.9a	6.3 ± 0.7a	6.9 ± 0.6a	6.1 ± 0.9a	4.0 ± 0.5a	12.1 ± 1.3a	7.6 ± 1.0a	17.1 ± 2.3a
Water quality													
cw	32	22.0 ± 1.9a	3.8 ± 0.6b	12.3 ± 1.7b	13.2 ± 1.9b	8.2 ± 1.1b	3.4 ± 0.4b	3.9 ± 0.5b	3.1 ± 0.7b	3.4 ± 0.5a	10.0 ± 1.2b	2.7 ± 0.3b	7.1 ± 1.1b
ww	32	26.1 ± 2.0a	7.3 ± 0.7a	17.7 ± 1.5a	33.3 ± 2.7a	25.7 ± 1.3a	9.0 ± 0.5a	10.1 ± 0.6a	8.7 ± 0.8a	4.2 ± 0.5a	14.2 ± 1.2a	12.2 ± 0.8a	25.9 ± 1.9a
Water quantity													
r	32	20.1 ± 1.7b	5.6 ± 0.7a	13.7 ± 1.4a	19.1 ± 2.4b	16.1 ± 1.8a	5.1 ± 0.5b	6.2 ± 0.6b	4.6 ± 0.7b	3.7 ± 0.5a	10.9 ± 1.1b	6.0 ± 0.8b	14.7 ± 2.5a
f	32	28.0 ± 2.0a	5.5 ± 0.7a	16.3 ± 1.8a	27.4 ± 3.2a	17.8 ± 2.1a	7.3 ± 0.8a	7.9 ± 0.7a	7.2 ± 1.0a	3.9 ± 0.5a	13.4 ± 1.3a	8.9 ± 1.2a	18.2 ± 2.0a
*Water quality*water quantity*													
cw + r	16	19.1 ± 2.5b	4.0 ± 0.9b	11.7 ± 2.1b	12.5 ± 2.5c	8.6 ± 1.6b	3.0 ± 0.4c	3.5 ± 0.5c	2.2 ± 0.7b	3.8 ± 0.7a	9.9 ± 1.7b	2.3 ± 0.4c	4.4 ± 1.1b
cw + f	16	24.9 ± 2.9ab	3.6 ± 0.9b	13.0 ± 2.6b	13.9 ± 3.0c	7.9 ± 1.7b	3.7 ± 0.6c	4.4 ± 0.7c	4.1 ± 1.1b	2.9 ± 0.7a	10.1 ± 1.7b	3.2 ± 0.5c	9.7 ± 1.7b
ww + r	16	21.1 ± 2.3b	7.1 ± 1.1a	15.7 ± 1.9ab	25.7 ± 3.5b	23.6 ± 1.9a	7.1 ± 0.4b	8.8 ± 0.8b	7.0 ± 1.0a	4.5 ± 0.7a	11.8 ± 1.4b	9.7 ± 0.8b	25.0 ± 3.2a
ww + f	16	31.0 ± 2.7a	7.4 ± 1.0a	19.6 ± 2.3a	40.9 ± 3.1a	27.8 ± 1.5a	11.0 ± 0.8a	11.4 ± 0.8a	10.4 ± 1.3a	3.9 ± 0.7a	16.6 ± 1.7a	14.7 ± 1.2a	26.7 ± 1.9a
*Fertilization*water quality*													
FP_0 + cw	16	14.0 ± 1.4b	1.0 ± 0.1d	4.1 ± 0.5c	3.6 ± 0.6c	2.6 ± 0.4d	1.6 ± 0.7d	1.3 ± 0.1c	0.6 ± 0.2c	1.6 ± 0.2b	3.6 ± 0.2d	2.1 ± 0.1d	4.6 ± 0.9c
FP_0 + ww	16	18.3 ± 1.3b	3.8 ± 0.5c	10.8 ± 0.7b	27.6 ± 2.5b	20.7 ± 0.9b	8.0 ± 0.2b	7.1 ± 0.5b	4.8 ± 0.5b	2.3 ± 0.2b	8.8 ± 0.7c	10.4 ± 0.9b	27.9 ± 2.1a
FP_1 + cw	16	30.1 ± 2.2a	6.6 ± 0.7b	20.6 ± 1.5a	22.7 ± 1.7b	13.9 ± 1.0c	5.2 ± 0.4c	6.4 ± 0.5b	5.7 ± 1.0b	5.3 ± 0.7a	16.4 ± 0.7b	3.3 ± 0.6c	9.6 ± 1.8b
FP_1 + ww	16	33.9 ± 2.4a	10.8 ± 0.5a	24.5 ± 1.5a	39.0 ± 4.3a	30.7 ± 1.5a	10.1 ± 0.8a	13.1 ± 0.7a	12.6 ± 0.8a	6.2 ± 0.6a	19.7 ± 1.2a	14.0 ± 1.3a	23.8 ± 3.1a
*Fertilization*biochar amendment*													
C	16	15.5 ± 1.5c	1.7 ± 0.5c	6.8 ± 1.1c	12.9 ± 3.5c	11.8 ± 2.6b	4.6 ± 1.0b	4.0 ± 0.9c	2.4 ± 0.6b	1.7 ± 0.2b	6.3 ± 0.8b	5.7 ± 1.2c	15.6 ± 3.4a
BC	16	16.7 ± 1.4c	3.1 ± 0.5b	8.1 ± 1.0c	18.3 ± 3.5b	11.5 ± 2.2b	4.9 ± 0.9b	4.4 ± 0.6c	2.9 ± 0.7b	2.2 ± 0.2b	6.1 ± 0.8b	6.8 ± 1.3bc	16.9 ± 3.4a
FP_1	16	29.8 ± 2.2b	8.4 ± 0.8a	21.0 ± 1.5b	30.3 ± 3.9a	21.6 ± 2.6a	7.5 ± 0.8a	10.8 ± 1.2a	9.0 ± 1.3a	5.5 ± 0.7a	18.0 ± 1.0a	9.0 ± 1.9a	16.1 ± 3.2a

Table 2 continued

Treatment	n	Biomass t ha^{-1} (FM)												
		Crop 1 Maize	Crop 2 Lettuce	Crop 4 Amaranth	Crop 5 Lettuce	Crop 6 Amaranth	Crop 7 Jute mallow	Crop 8 Jute mallow	Crop 9 Amaranth	Crop 10 Jute mallow	Crop 11 Roselle	Crop 12 Lettuce	Crop 13 Carrot
FP_1 + BC	16	34.2 ± 2.4a	9.0 ± 0.8a	24.1 ± 1.5a	31.4 ± 4.0a	23.0 ± 2.4a	7.8 ± 1.0a	9.2 ± 0.7b	9.3 ± 1.2a	6.0 ± 0.7a	18.1 ± 1.1a	8.3 ± 1.5ab	17.3 ± 3.1a

Data show means ± one standard error

Values followed by the same superscripts in a column are not significantly different using a Tukey multiple comparison test at $p < 0.05$

Values for carrot comprise below and aboveground yields

BC biochar, *C* control (no fertilizer, no biochar), *cw* clean water, *f* full irrigation, *FP_0* no fertilizer application, *FP_1* fertilization according to farmers' practice, *FP_1 + BC* farmers' practice + biochar, *r* reduced irrigation ($^2/_3$ f) and *ww* wastewater

(FP_0 + ww) plots compared with clean water irrigation (Fig. 1). Similarly, for marketable yields, crops irrigated with wastewater increased yields between 200 and 600% on unfertilized plots and between 20 and 80% on fertilized plots (Fig. 2). Interaction between fertilization and water quantity was significant ($p < 0.05$) in maize (crop 1), amaranth (crop 9) and lettuce (crop 12; Fig. 3; Appendix vii–viii in Supplementary Material). For these three crops, fully irrigated plots under FP_1 produced yields which were significantly higher than on the reduced irrigated plots. However, on the unfertilized plots (FP_0), water quantity did not influence yield. Our study did not show a significant interaction between all four factors (fertilization, biochar, water quality and quantity) in any of the crops apart from lettuce (crop 12). For this crop, the reduction in yield due to reduced irrigation was higher on wastewater irrigated plots than on clean water irrigated ones (Fig. 4).

Repeated measurement analysis of total fresh biomass including all cropping cycles, showed that fertilized plots compared with unfertilized plots doubled yields at the end of the 2 years ($p < 0.05$). Yield on biochar amended plots on the other hand increased by an average of 9% over the 13 cropping cycles ($p > 0.05$).

Effects of irrigation water quality and quantity on crop biomass production

Wastewater irrigation increased fresh biomass ($p < 0.05$) in all cropping cycles apart from maize (crop 1, $p = 0.10$) and jute mallow (crop 10, $p = 0.17$). The extent of the biomass increase varied across the cropping cycles with a mean annual increment of 142%. The greatest increase was recorded in lettuce (crop 12, + 352%) in the dry season and the lowest in maize (crop 1, + 19%) in the wet season. Reduced irrigation, on the other hand reduced yields, ranging from 5 to 57%. However, on lettuce (crop 2), reduced irrigated plots showed a marginal yield increase of 2% ($p = 0.90$) compared with fully irrigated plots. A significant increase ($p < 0.05$) was also observed in the marketable yield of jute mellow (crop 7) and roselle (crop 11; Tables 2, 3).

A significant interaction ($p < 0.05$) between water quality and quantity was noted in lettuce (crop 5 and crop 12) and roselle (crop 11) where full irrigation increased yields only on wastewater irrigated plots by

Table 3 Marketable fresh matter yield (t ha^{-1}) of selected factor combinations for the experimental crops in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016

Treatment	n	Biomass t ha^{-1}(FM)								
		Crop 5 Lettuce	Crop 6 Amaranth	Crop 7 Jute mallow	Crop 8 Jute mallow	Crop 9 Amaranth	Crop 10 Jute mallow	Crop 11 Roselle	Crop 12 Lettuce	Crop 13 Carrot
Fertilization										
Unfertilized	32	14.4 ± 2.3b	6.2 ± 1.4	1.8 ± 0.3b	1.3 ± 0.2b	0.2 ± 0.1	0.6 ± 0.1b	4.6 ± 0.5b	4.7 ± 0.9b	2.0 ± 0.5
Fertilized	32	29.0 ± 2.5a	8.6 ± 1.7	3.1 ± 0.2a	4.7 ± 0.3a	3.0 ± 0.4	1.8 ± 0.2a	14.5 ± 0.6a	6.5 ± 1.1a	2.3 ± 0.5
Biochar amendment										
No biochar	32	20.0 ± 2.8b	8.0 ± 1.6	2.4 ± 0.3a	2.9 ± 0.4a	1.4 ± 0.4	1.2 ± 0.2a	9.6 ± 1.0a	5.3 ± 1.1b	1.9 ± 0.4
Biochar	32	23.4 ± 2.6a	6.9 ± 1.5	2.5 ± 0.3a	3.0 ± 0.4a	1.7 ± 0.4	1.3 ± 0.2a	9.5 ± 1.1a	5.9 ± 1.0a	2.4 ± 0.5
Water quality										
cw	32	12.1 ± 1.8b	0.1 ± 0.1	1.5 ± 0.2b	2.0 ± 0.4b	0.8 ± 0.3	1.0 ± 0.2b	7.7 ± 1.0b	1.0 ± 0.3b	0.5 ± 0.2
ww	32	31.3 ± 2.4a	15.6 ± 0.9	3.5 ± 0.2a	4.0 ± 0.3a	2.3 ± 0.4	1.4 ± 0.2a	11.5 ± 1.0a	10.2 ± 0.8a	3.8 ± 0.5
Water quantity										
r	32	18.0 ± 2.2a	6.7 ± 1.6	2.0 ± 0.2b	2.7 ± 0.4a	1.4 ± 0.4	1.1 ± 0.2a	8.6 ± 1.0b	4.4 ± 0.8a	1.3 ± 0.3
f	32	25.4 ± 3.0a	8.1 ± 1.5	2.9 ± 0.3a	3.2 ± 0.4a	1.6 ± 0.4	1.3 ± 0.2a	10.5 ± 1.1a	6.8 ± 1.2a	3.0 ± 0.6
*Water quality*water quantity*										
cw + r	16	11.3 ± 2.3c	0.0 ± 0.0	1.3 ± 0.2c	1.6 ± 0.4b	0.5 ± 0.4	0.8 ± 0.2b	7.7 ± 1.5b	1.0 ± 0.4c	0.4 ± 0.2
cw + f	16	12.8 ± 2.8c	0.1 ± 0.1	1.6 ± 0.3c	2.3 ± 0.6b	1.0 ± 0.4	1.3 ± 0.2ab	7.6 ± 1.4b	1.1 ± 0.4c	0.6 ± 0.3
ww + r	16	24.6 ± 3.0b	15.0 ± 1.6	2.8 ± 0.1b	3.8 ± 0.5a	2.3 ± 0.6	1.5 ± 0.2a	9.4 ± 1.2b	7.9 ± 0.8b	2.1 ± 0.5
ww + f	16	38.0 ± 2.9a	16.1 ± 0.9	4.1 ± 0.2a	4.1 ± 0.5a	2.3 ± 0.6	1.3 ± 0.2a	13.5 ± 1.4a	12.5 ± 1.1a	5.5 ± 0.6
*Fertilization*water quality*										
FP_0 + cw	16	3.3 ± 0.6c	0.0 ± 0.0	0.5 ± 0.1d	0.3 ± 0.0d	0.0 ± 0.0	0.5 ± 0.1c	2.2 ± 0.1d	0.6 ± 0.1c	0.0 ± 0.0
FP_0 + ww	16	25.5 ± 2.3b	13.3 ± 1.2	3.2 ± 0.2b	2.2 ± 0.2c	0.3 ± 0.1	0.8 ± 0.1b	7.0 ± 0.6c	8.8 ± 0.9b	4.0 ± 0.7
FP_1 + cw	16	20.9 ± 1.6b	0.1 ± 0.1	2.4 ± 0.2c	3.7 ± 0.4b	1.6 ± 0.5	1.6 ± 0.2a	13.1 ± 0.5b	1.5 ± 0.5c	1.0 ± 0.3
FP_1 + ww	16	37.2 ± 3.7a	17.6 ± 1.0	3.8 ± 0.3a	5.7 ± 0.2a	4.3 ± 0.5	2.1 ± 0.2a	15.9 ± 0.9a	11.6 ± 1.2a	3.6 ± 0.7
*Fertilization*biochar amendment*										
C	16	11.9 ± 3.3c	7.3 ± 2.2	1.8 ± 0.4b	1.2 ± 0.3b	0.1 ± 0.1	0.5 ± 0.1c	4.7 ± 0.8b	4.1 ± 1.1b	1.8 ± 0.6
BC	16	16.8 ± 3.3b	4.9 ± 1.7	1.9 ± 0.4b	1.3 ± 0.3b	0.2 ± 0.1	0.7 ± 0.1b	4.5 ± 0.8b	5.3 ± 1.3a	2.2 ± 0.8
FP_1	16	28.1 ± 3.6a	8.7 ± 2.5	3.0 ± 0.3a	4.6 ± 0.4a	2.8 ± 0.6	1.8 ± 0.2a	14.5 ± 0.7a	6.6 ± 1.8a	2.0 ± 0.5
FP_1 + BC	16	30.0 ± 3.5a	8.5 ± 2.3	3.1 ± 0.3a	4.7 ± 0.4a	3.1 ± 0.5	1.9 ± 0.2a	14.5 ± 0.9a	6.5 ± 1.5a	2.7 ± 0.8

Data show means ± one standard error

Values followed by the same letters in a column are not significantly different (Tukey multiple comparison test, $p < 0.05$). Those without values were not analysed due to incomplete data

Marketable yields for crops 1–4 were not determined

Values for carrot are both below and aboveground yields

BC biochar, *C* control (no fertilizer, no biochar), *cw* clean water, *f* full irrigation, FP_0 no fertilizer application, FP_1 fertilization according to farmers' practice, $FP_1 + BC$ farmers' practice + biochar, *r* reduced irrigation and *ww* wastewater

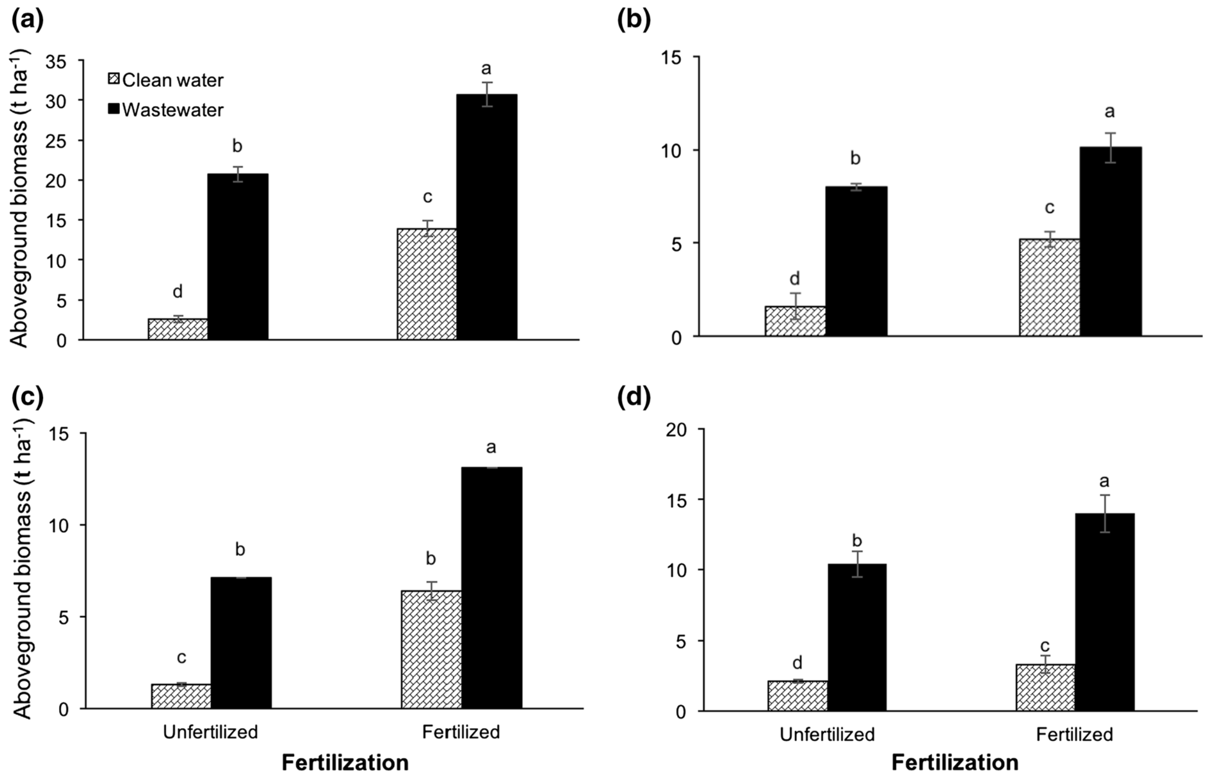

Fig. 1 Aboveground biomass (FM) of **a** amaranth (crop 6), **b** jute mallow (crop 8), **c** lettuce (crop 12) and **d** carrot (crop 13), affected by wastewater irrigation on fertilized and unfertilized plots in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016. Data show means (n = 16) ± one standard error; columns with the same letter are not significantly different (Tukey multiple comparison test, $p < 0.05$). *FM* fresh matter. Values for carrot comprise below- and aboveground yields

40–60% (Fig. 5). A 50% increment was recorded in marketable yields of lettuce (crop 5), jute mallow (crop 7) and roselle (crop 11) on wastewater irrigated plots (Appendix vii–viii in Supplementary Material).

At the end of the 2 years, wastewater compared with clean water irrigation had doubled yields ($p < 0.05$). Full irrigation on the other hand led to a 23% higher cumulative yields (data not shown).

Plant nutrition

Fertilizer application, as well as wastewater irrigation, significantly increased N concentration in plant tissue of all crops except for amaranth (crop 9) and jute mallow (crop 10). The effect of biochar amendment on plant tissue N was particularly high ($p < 0.05$) in maize (crop 1) and amaranth (crops 6). In both crops, biochar amendment resulted in a 10% decrease in plant N nutrient concentration. Irrigation water reduction did not influence plant N concentration in any of the cropping cycles (Table 4).

With the exception of amaranth (crop 9), jute mallow (crop 10), and lettuce (crop 12), all wastewater irrigated plants had significantly higher P and K concentrations in their shoot tissue compared with those of clean water irrigated plants. Most plants fertilized according to farmers' practice had significantly higher P than unfertilized plants. Exceptions were amaranth (crop 6) and jute mallow (crops 7, 8 and 10). Plant tissue K was higher in plants on fertilized plots, except for that in lettuce (crop 5), jute mallow (crop 8), and amaranth (crop 9). Plants grown on biochar amended soils recorded higher P concentrations in plant tissue in the first year, while K concentrations were different in maize (crop 1) and lettuce (crops 5 and 12) (Table 4, Appendix xi–xv in

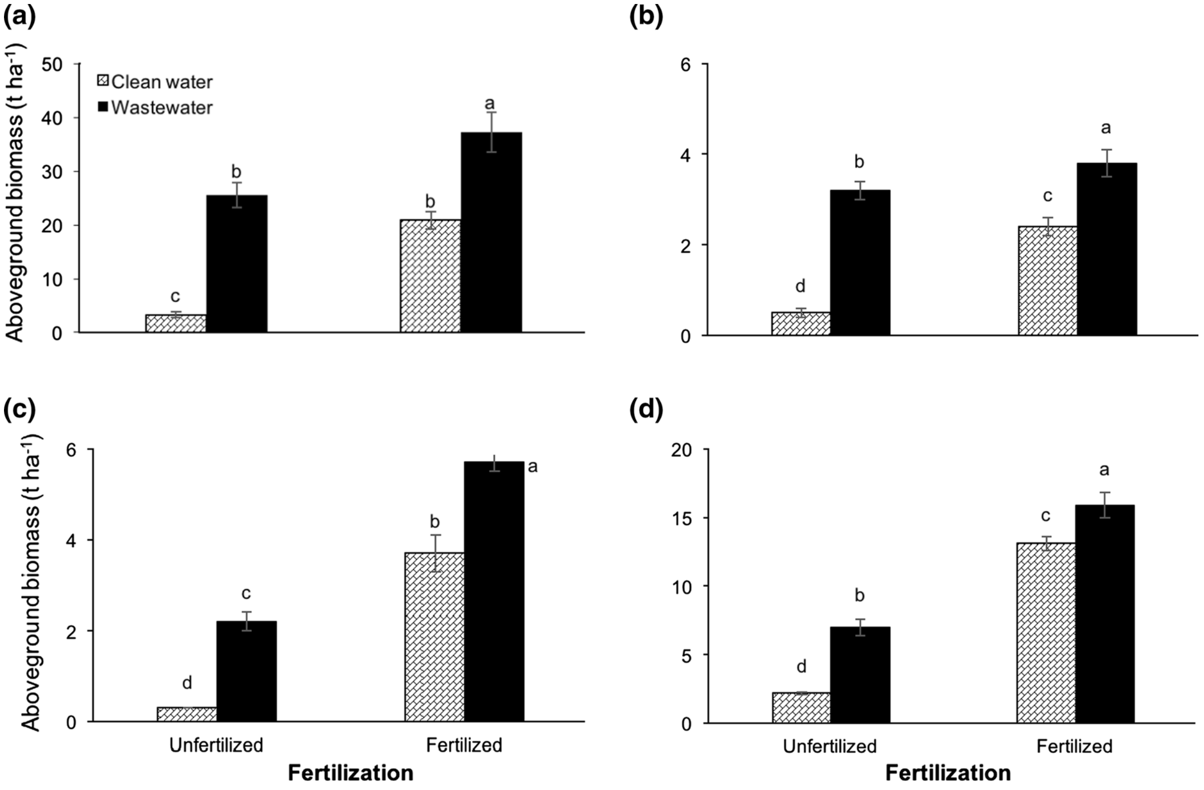

Fig. 2 Marketable yield (FM) of **a** lettuce (crop 5), **b** jute mallow (crop 7), **c** jute mallow (crops 8) and **d** roselle (crop 11) influenced by fertilization and water quality in a multi-factorial vegetable growing experiment in Tamale (northern Ghana). Data show means (n = 16) ± one standard error; columns with the same letter are not significantly different using a Tukey multiple comparison test at $p < 0.05$. *FM* fresh matter

Supplementary Material). Calcium and Mg concentrations in plant tissue were inconsistent. Apart from fertilizer application that resulted in differences in the Mg content, biochar amendment, water quality and quantity rarely influenced Mg and Ca concentrations (Appendix xi–xv in Supplementary Material).

Soil volumetric moisture content

Compared with unfertilized plots, application of mineral fertilizers (irrespective of other factors) led to a marginal change in mean soil volumetric moisture content (VMC) between $-$ 10 and 13%. In four cropping cycles, specifically, lettuce (crop 2 and 5; 8%), cabbage (crop 3; 6%), and carrot (crop 13; 13%), a significant higher VMC were recorded on fertilized soils. The mean VMC of biochar amended soils, compared with soils without biochar were higher, but these differences were not significant in any cropping cycle. While biochar amended plots under fertilized conditions ($FP_1 + BC$) did not show an increase in the mean soil volumetric moisture content, a significant increment of 4 and 7% was observed in cabbage (crop 3) and amaranth (crop 6), respectively, on unfertilized biochar amended plots (BC). The mean soil moisture content of the wastewater-irrigated plots was similar to that of clean water-irrigated plots, with the exception of lettuce (crop 5) where it showed a 15% increment. Full irrigated plots, on the other hand, showed a significantly higher mean soil moisture content in maize (crop 1), lettuce (crops 5 and 12), amaranth (crop 6), jute mallow (crop 8), and carrot (crop 13) with increments ranging from 22 to 85%.

Discussion

Many studies have shown yield increases with rice husk biochar, particularly on low fertility soils under both greenhouse and field conditions (Carter et al.

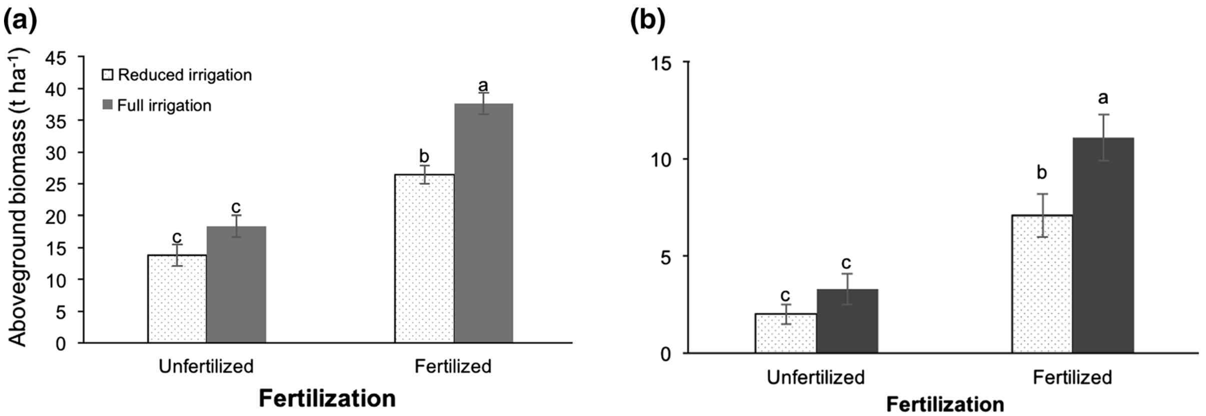

Fig. 3 Aboveground biomass (FM) of **a** maize (crop 1), and **b** amaranth (crop 9) influenced by fertilization and water quantity in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016. Data show means (n = 16) ± one standard error; columns with the same letter are not significantly different using a Tukey multiple comparison test at $p < 0.05$. *FM* fresh matter

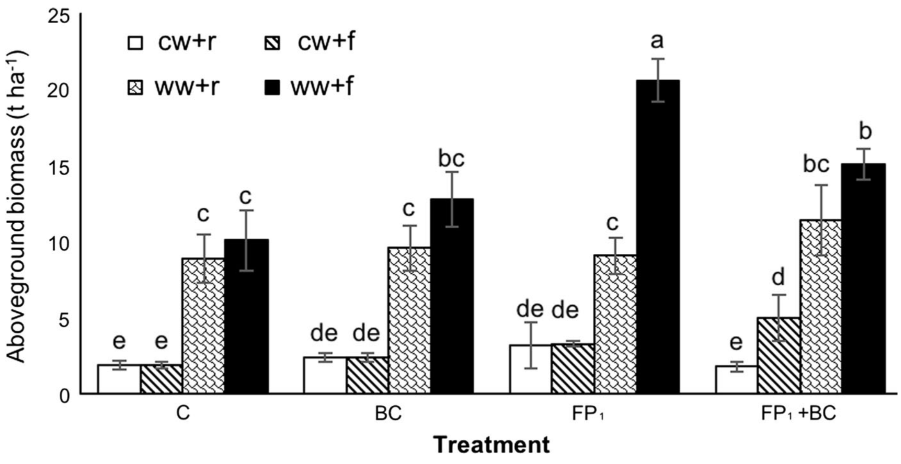

Fig. 4 Aboveground biomass (FM) of lettuce (crop 12) influenced by water quality and quantity in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016. Data show means (n = 4) ± one standard error; columns with the same letter are not significantly different using a Tukey multiple comparison test at $p < 0.05$. *BC* biochar, *C* control (no fertilizer, no biochar), *cw* clean water, *f* full irrigation, *FM* fresh matter, FP_0 no fertilizer application, FP_1 fertilization according to farmers' practice, $FP_1 + BC$ farmer's practice + biochar, *r* reduced irrigation ($^2/_3$ f) and *ww* wastewater

2013; Gandahi et al. 2015; Kamara et al. 2015; Manickam et al. 2015; Munda et al. 2015). In our study in northern Ghana, the significant effects of biochar amendments on crop yields were restricted to the first six months or five cropping cycles comprising maize, amaranth, and lettuce. Biochar increased yields of the first and fourth cropping cycles on fertilized plots (FP_1 + BC). Lettuce (crops 2 and 5), on the other hand, showed a substantial increase in yield on unfertilized plots (BC) compared with control plots in the third and fifth cropping cycles (Table 2). These crop performances are consistent with other research results (Yamato et al. 2006; Cornelissen et al. 2013; Zhang et al. 2016; Agegnehu et al. 2016). Agegnehu et al. (2016) reported that biochar addition of 10 t ha^{-1} to fertilized plots resulted in an 18% total biomass increment, which is higher than the yield increases in our study. Carter et al. (2013) observed a

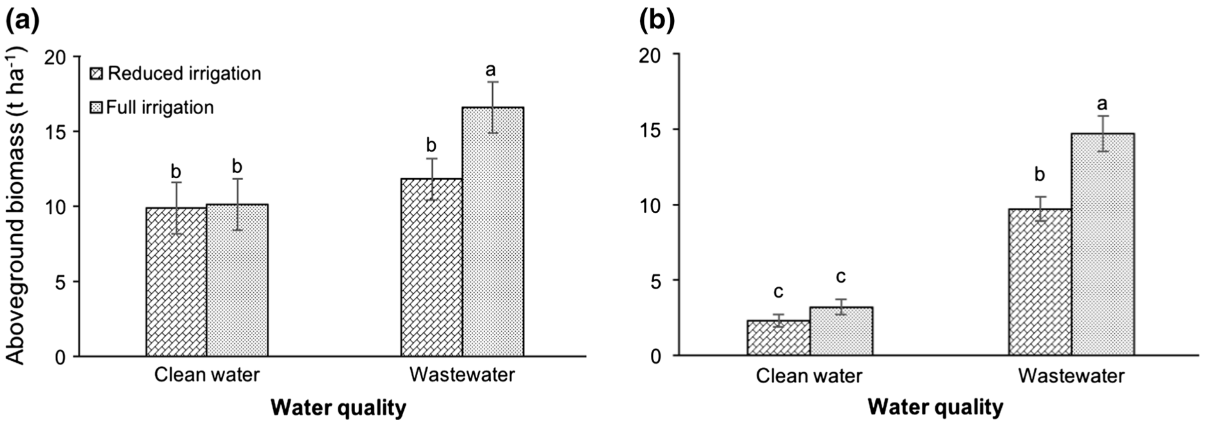

Fig. 5 Aboveground biomass (FM) of **a** roselle (crop 11), and **b** lettuce (crop 12) influenced by water quality and quantity in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016. Data show means (n = 16) ± one standard error, columns with the same letter are not significantly different using a Tukey multiple comparison test at $p < 0.05$). *cw* clean water, *f* full irrigation, *r* reduced irrigation ($^2/_3$ f), *FM* fresh matter and *ww* wastewater

pronounced effect of biochar on fertilized and unfertilized plots in their first two cropping cycles of lettuce and cabbage, but a decline in the third cropping cycle when lettuce was cultivated.

Results from this study on the other hand are contrary to those of Major et al. (2010), who recorded no change in maize yields in their first experimental year but significant increases in the second year following a 20 t ha^{-1} soil amendment with wood biochar. One of the factors that may contribute to the short-term biomass increment is the nutrient input from the rice husk biochar, especially P and K which would be in line with results reported in other studies (Lehmann et al. 2003; Enders et al. 2012). The significantly higher plant P concentration in the tissues of plants grown on biochar plots in the first year is likely a result of the additional P input from the applied biochar. Considering that, the addition of nutrients from the rice husk biochar was relatively low compared with inputs from wastewater and fertilizer, the high P concentration in plant tissue could also be a result of an increase of soil P availability by the biochar addition (Gao and DeLuca 2016). Likely, not all of the applied biochar N was plant available since biochar N is usually tied up in heterocyclic compounds (Knicker 2010). The reduction of plant tissue N in maize and amaranth (crop 6) could be attributed to N immobilization as observed by Bargmann et al. (2014).

Lettuce yields were significantly higher in biochar amended unfertilized plots (crop 2 and 5) than in fertilized plots. The reported optimal pH range for lettuce is between 6.0 and 7.0 with a minimum pH of 4.2 (FAO). The use of mineral fertilizers resulted in a significant decline in soil pH from 5.1 at the onset of the study to a pH of 4.5 after 1.5 years (Haering et al. 2017). The decline in soil pH could have contributed to the decrease in yields of lettuce under fertilized conditions. After reviewing 371 independent biochar studies, Biederman and Harpole (2013) concluded that biochar can provide nutrients and promote plant growth by increasing pH and reducing leaching losses. In contrast to Biederman and Harpole (2013) and Gwenzi et al. (2015), in this study biochar stabilized the pH (Haering et al. 2017).

It has been shown that fertigation with nutrient-rich wastewater irrigation in daily small dosages instead of large single fertilizer applications can improve nutrient use efficiency by up to 40% without affecting crop yield (Sathya et al. 2008; Mikkelsen et al. 2015). Wastewater irrigation has been reported to raise the concentration of N, P, and K in cauliflower and red cabbage significantly (Kiziloglu et al. 2008) and it also raised soil available N, P, and K (Singh and Agrawal 2012; Singh et al. 2012). During our 2-year field study, wastewater irrigation supplied N, P and K at 950, 300 and 230 kg ha^{-1}, respectively, while a similar amount was added with NPK and urea (800, 230 and 320 kg ha^{-1}). The effect of wastewater on crop yields

Table 4 Effects of selected treatments on nutrient tissue concentration (mg g^{-1}DM) in different crops

No.	Crop	Nutrient concentrateion (mg N g^{-1} DM)											
		(mg N g^{-1} DM)		(mg N g^{-1} DM)		(mg P g^{-1} DM)		(mg P g^{-1} DM)		(mg K g^{-1} DM)		(mg K g^{-1} DM)	
		Unfertilized	Fertilized	No biochar	Biochar	Unfertilized	Fertilized	No biochar	Biochar	Unfertilized	Fertilized	cw	ww
1	Maize	24.9 ± 0.6b	30.1 ± 0.5a	28.3 ± 0.7a	26.8 ± 0.7b	3.3 ± 0.1b	4.5 ± 0.1a	3.7 ± 0.1b	4.1 ± 0.1a	30.6 ± 1.5b	39.0 ± 1.3a	33.4 ± 1.6a	36.3 ± 1.4a
2	Lettuce	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
3	Cabbage	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
4	Amaranth	22.0 ± 0.6b	31.3 ± 0.7a	26.7 ± 1.0a	26.6 ± 1.1a	2.6 ± 0.1b	4.9 ± 0.1a	3.6 ± 0.2b	4.0 ± 0.2a	21.2 ± 0.6b	23.2 ± 0.5a	21.7 ± 0.7a	22.7 ± 0.5a
5	Lettuce	36.4 ± 1.3b	40.8 ± 0.9a	38.5 ± 1.2a	38.7 ± 1.2a	3.3 ± 0.2b	5.3 ± 0.2a	4.0 ± 0.2b	4.5 ± 0.3a	41.9 ± 1.1a	42.9 ± 1.0a	39.9 ± 1.1b	44.9 ± 0.8a
6	Amaranth	22.6 ± 0.8b	31.0 ± 1.4a	27.8 ± 1.2a	25.8 ± 1.5b	2.8 ± 0.1b	5.5 ± 0.1a	4.0 ± 0.3b	4.3 ± 0.3a	35.4 ± 1.0a	38.9 ± 1.1b	33.6 ± 0.9b	40.6 ± 0.9a
7	Jute mallow	29.6 ± 1.2b	53.6 ± 0.5a	41.7 ± 2.4a	41.9 ± 2.3a	3.5 ± 0.1a	3.6 ± 0.1a	3.5 ± 0.1b	3.6 ± 0.1a	21.5 ± 0.6a	23.5 ± 0.5b	20.6 ± 0.5b	24.4 ± 0.5a
8	Jute mallow	25.5 ± 1.0b	48.3 ± 1.2a	36.1 ± 2.4a	37.4 ± 2.3a	4.4 ± 0.2a	4.6 ± 0.2a	4.4 ± 0.2b	4.6 ± 0.1a	19.9 ± 0.6a	18.6 ± 0.7a	17.8 ± 0.7b	20.8 ± 0.5a
9	Amaranth	26.1 ± 1.0b	32.4 ± 1.5a	28.9 ± 1.3a	29.5 ± 1.5a	2.6 ± 0.2b	3.8 ± 0.1a	3.2 ± 0.2a	3.2 ± 0.2a	33.5 ± 1.4a	31.3 ± 1.2a	30.6 ± 1.5a	34.1 ± 1.0a
10	Jute mallow	21.9 ± 0.4b	32.8 ± 0.5a	27.2 ± 1.1a	27.5 ± 1.1a	4.6 ± 0.1a	4.5 ± 0.1a	4.4 ± 0.1a	4.6 ± 0.1a	23.7 ± 0.8b	26.1 ± 0.7a	26.5 ± 0.6a	23.4 ± 0.8b
11	Roselle	22.7 ± 0.6b	29.1 ± 0.9a	25.5 ± 0.8a	26.3 ± 1.1a	3.0 ± 0.1b	3.5 ± 0.1a	3.1 ± 0.1b	3.3 ± 0.1a	11.3 ± 0.3b	19.9 ± 0.4a	14.6 ± 0.8b	16.6 ± 0.9a
12	Lettuce	37.0 ± 1.4b	44.8 ± 1.1a	41.5 ± 1.4a	40.5 ± 1.4a	2.7 ± 0.1b	4.6 ± 0.1a	3.6 ± 0.2a	3.7 ± 0.2a	31.6 ± 0.7b	40.8 ± 0.6a	35.3 ± 1.0a	36.9 ± 1.1a
13	Carrot	20.2 ± 1.1b	25.4 ± 0.7a	22.8 ± 1.0a	22.8 ± 1.0a	2.9 ± 0.2b	3.2 ± 0.1a	3.1 ± 0.2a	3.0 ± 0.1a	11.9 ± 0.5b	14.7 ± 0.6a	12.2 ± 0.5b	14.4 ± 0.6a

Data show mean (n = 32) ± one standard error in a multi-factorial vegetable growing experiment in Tamale (northern Ghana) from May 2014 to April 2016

Means with different letters are significantly different according to Tukey's HSD at $p < 0.05$

nd not determined, *cw* clean water, *ww* wastewater and nutrient uptake varied among crops. It had a pronounced effect on nutrient concentrations during the two dry seasons when wastewater irrigation produced significant yield increases ($p < 0.0001$) on unfertilized plots compared with fertilized plots without wastewater. The seasonal difference is attributed to the higher quantities wastewater provided during the dry season, and thus the higher amount of added nutrients. This result is corroborated by the significant reduction in yields if wastewater irrigation was reduced (ww + r) but not in the case of reduction in clean water irrigation (cw + r). This implies that the nutrients contained in the wastewater were more important than the water in improving yields. Larger and well developed crops demand more water, therefore plant growth was only limited on well fertilized plots due to a reduction in irrigation water.

The application of mineral fertilizers led to higher yields in all crops and was generally accompanied by higher N and P contents in the crops. The P free urea applied on jute mallow (crops 7 and 8) likely led to the indifference in the plant tissue P. Complementary effects of inorganic fertilizer or biochar and wastewater on plant growth have been reported in other studies (Glaser et al. 2002; Gwenzi et al. 2015, 2016). On the other hand, significant interactions between biochar and fertilizer application occurred only once corroborating the findings of Biederman and Harpole (2013) and Carter et al. (2013).

A reduction in irrigation water led to a significant decline in crop yields, which was particularly pronounced on wastewater-irrigated plots. The potential of biochar to improve water holding capacity of soils has been shown in previous studies (Karhu et al. 2011; Novak et al. 2012; Ma et al. 2016; Xiaoa et al. 2016). With its porous structure, biochar is able to retain soil moisture (Herath et al. 2013; Githinji 2014). Karhu et al. (2011) observed a 11% increment in soil water holding capacity adding 9 t biochar ha^{-1} in Southern Finland, while Glaser et al. (2002) reported an 18% increment in water retention in biochar-rich Amazonian Anthrosols. On a sandy loam soil, Paneque et al. (2016) also recorded a relative increment of 7% water holding capacity with addition of biochar at a rate of 15 t ha^{-1} compared with an unamended plot. The ability of biochar to withhold moisture depends on the biochar applied, and on the soil characteristics, in particular its organic C content. Fertilized plots with biochar (FP_1 + BC) did not show significant difference in soil moisture compared with fertilized plots without biochar amendment (FP_1). On the other hand, a soil moisture increment of up to 9% in biochar amended plots (BC) compared with control (C) plots was observed. Specifically, for cabbage (crop 3) and amaranth (crop 6), BC plots had 4 and 7% higher soil moisture than biochar unamended (C) plots. A similar observation was reported from a pot experiment by Pfister and Saha (2016), who found significantly higher soil water holding capacity only in soil amended with a biochar rate of 50 t ha^{-1} but not of 25 t ha^{-1}.

This study in Tamale and that of Manka'abusi et al. (see this Special Issue) in Ouagadougou used the same methodology to compare the effects of biochar application, fertilization, and irrigation water quality and quantity on biomass production and plant nutrition. The main differences between the sites were organic fertilization in addition to mineral fertilization, the soil application of biochar made from corn cobs rather than rice huks a higher soil P content and lower soil acidity in Ouagadougou (Haering et al. 2017). The higher yields in Ouagadougou compared with Tamale are most likely a result of the combined use of organic and mineral fertilizer. The use of inorganic fertilizer alone led to severe soil acidification in Tamale (Haering et al. 2017). The addition of biochar increased yields across the entire study period in Ouagadougou, likely due to the high carbon and low Si concentration of the corn cob biochar. The positive effect of biochar on yields declined over time and not every crop showed pronounced yield increases. On average, both sites showed a 9% increment in yield at the end of the 2-year field study due to biochar additions. Biochar was effective on fertilized plots in Ouagadougou, indicating it being a valuable resource in improving fertilizer use efficiency under intensive UPA systems. A 33% reduction in farmers' irrigation quantities led to a decrease in yields in both cities. The use of wastewater for irrigation increased yields substantially, in Tamale, compared to Ouagadougou, this was attributed to the higher nutrient loads of wastewater used in Tamale.

Conclusions

The results of this study showed a short-term positive effect of rice husk biochar amendment on crop biomass and marketable yield mainly by improving plant available P and K and by stabilizing soil pH. Soil moisture retention was enhanced by 9% after biochar application. Fertigation with wastewater, however, had a pronounced effect throughout the 2-year experiment and contributed significantly to plant nutrition. During the second year, wastewater irrigation was more effective in improving crop yields than fertilizer application. Our wastewater was highly loaded with plant nutrients, and hence different results may be obtained at locations where diluted wastewater is used.

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