Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 120 No. 1 (2019) 55-62

https://doi.org/10.17170/kobra-20190613557 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Combining biochar with low rate of chemical fertiliser boosts maize biomass yield, regardless of tillage system, under humid conditions

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Abstract

Biochar application to soils increases biomass and crop yields, especially with rates higher than 100 t ha^{-1}. Yet, there is limited knowledge on the combined effect of biochar and chemical fertiliser under different tillage systems. The objective of this study is to investigate the effect of maize-cob biochar (BC) (rates of 5 and 10 t ha^{-1}) combined with chemical fertiliser micro-dosing (MD) at a rate of 25 % of the recommended quantity on total shoot dry matter (DM) and plant height of maize cultivated under flat (F) and tied-ridge (R) practices during a humid season in Tanzania. The results indicate that combining 5 t ha^{-1} BC with 25 % MD increases DM at harvest by 83 % (4.16 t ha^{-1}) compared to the control (2.27 t ha^{-1}) and was in the same range as the DM obtained from the treatment with the recommended fertiliser rate (100 % FD). The treatments with single applications of 25 % MD, 5 t ha^{-1} BC, and 10 t ha^{-1} BC only tended to exceed the control of DM yield. Therefore, we recommend that small-scale farmers aiming at DM for livestock or grain yield with limited access to chemical fertilisers to combine biochar with 25 % MD, rather than applying biochar or low chemical fertiliser rates alone.

Keywords: biochar, chemical fertiliser, tied-ridge, maize, biomass

1 Introduction

Meta-analyses of field experiments, in most cases, show a positive effect of biochar on crop yields (Jeffery *et al.*, 2011). Improved soil fertility and water-holding capacity (Gurwick *et al.*, 2013), soil microbial activity (Thies & Rillig, 2009), electric conductivity (Asai *et al.*, 2009,) and soil pH-value (Chan *et al.*, 2009) are known benefits of biochar application to low quality soils. Moreover, adding biochar to cultivated soils contributes to mitigating climate change through carbon sequestration (Lehmann, 2007, Downie, 2011). However, the effect of biochar on plant development differs based on plant species, soil type, and the feedstock used for pyrolysis (Nooker, 2014).

There is a need to quantify the influence of biochar feedstock and its related effects on soil properties and crop yields (Zhao *et al.*, 2013). Studies suggest deriving the biochar from wooden material (Kloss *et al.*, 2012). Alternatively, biochar is also a by-product of the pyrolysis process using shelled maize cobs (cobs of Zea mays L.), which typically are left on the field to rot or are burnt, especially in developing countries (Silayo *et al.*, 2016). Through pyrolysis, these materials are transformed at temperatures between 300 and 1000°C, becoming valuable soil amendments (Verheijen *et al.*, 2010). This pyrolysis process can be done while simultaneously cooking and heating if a Top-Lit Updraft (TLUD) burner is used, which can be built using locally available materials in rural areas of developing countries (Silayo *et al.*, 2016; Romuli *et al.*, 2015).

In low income countries, there is increasing scepticism toward using chemical fertilisers. They are expensive, have limited availability, and the long-term effects on agroecosystems are uncertain (Oladele & Braimoh, 2014). Therefore, to improve soil fertility and crop yields, it has been recommended to combine chemical fertilisers with biochar (Atkinson

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Published online: 4 November 2019 – Received: 10 November 2018 – Accepted: 28 May 2019

et al., 2010). Schulz & Glaser (2012) find in pot experiments with sandy soils that overall plant growth and soil fertility increase when biochar is combined with organic compost versus chemical fertiliser application.

Application rates of 25 % of the recommended rate of chemical fertiliser may increase maize grain yields by 50 to 100 % compared to soil without inputs (Germer *et al.*, 2016; Sime & Aune, 2014). However, yield benefits can be limited due to soil erosion accompanying the loss of fertiliser on sloping terrain, especially following heavy rainfall.

To avoid soil and fertiliser losses due to erosion, tied-ridge tillage can be applied. For example, Grum *et al.* (2016) observe that the use of tied-ridges can reduce the loss of nitrogen (N) and phosphorus (P) by 59 % and 52 %, respectively, compared to flat cultivation practices. Wiyo *et al.* (2000) find that tied-ridges benefit maize crops under low rainfall conditions of 500 mm to 900 mm. Graef *et al.* (2018) find a higher effect of small doses of fertilizer and biochar with tied ridges on maize grain under low irrigation conditions compared to humid conditions. However, under tied ridges, the question still remains with respect to other parameters, such as maize biomass, plant height, and soil moisture benefit in wet seasons (Araya, 2010).

Hence, the objectives of this study, carried out under humid conditions, are to add to the findings of Graef *et al.* (2018) by (i) determining the effects of maize cob biochar and chemical fertiliser rates on maize growth; (ii) comparing the performance of maize biomass treated with biochar and chemical fertiliser under flat and tied-ridge tillage methods; and (iii) giving greater emphasis to the biochar production processes and its economics.

2 Materials and methods

2.1 Study location and climate

The experiment was conducted between April and September, 2016, at the Sokoine University of Agriculture (SUA) experimental field located in Morogoro, Tanzania, East Africa (S6°50'18.5", E37°38'27.2"), which is 508 m above sea level. The prevailing soils are Neogene colluvium soils derived from plagioclase and quartz-rich metasedimentary rocks (Msanya *et al.*, 2003). The experimental field consisted of well-drained sandy clay soil with an effective soil depth of more than 1 m and a hyper-thermic temperature regime (Kaaya *et al.*, 1994). This soil is characterised by a moderate to low natural fertility and has a slope of 5.3 %. The soil before amendment was acidic (pH = 5.2) with undetectable plant-available P, as well as medium potassium (K) and magnesium (Mg) content, as shown in Graef *et al.* (2018). The experimental field, previously used for maize production for several seasons, lay fallow for one year before the trial started.

The climate of the study area is sub-humid (Kaaya *et al.*, 1994) with an average rainfall of 327 and 445 mm during the dry and wet seasons, respectively (Mahoo *et al.*, 1999). The average relative humidity is 63–88 % from March through May (wet season) and 46–82 % from July to September (dry season) (Mkomba & Mjemah, 2011). Throughout the study period (from April to September 2016; hence, mainly during the dry season) rainfall data was collected from the weather monitoring centre located at the Sokoine University of Agriculture (SUA). Total rainfall was 93.1 mm, while the average temperature was 22.6 °C and humidity 52.5 %. Plants were regularly irrigated about every three days, if there was a dry spell. Accordingly, the plants did not experience any drought-stress, thus simulating a wet season situation. The water quantity received by each treatment, therefore, was not considered as a treatment. Hence, the experiment intended to determine the effect of biochar, fertiliser, and tied-ridge tillage system in a wet season situation with well distributed rainfall events, which, in the Morogoro area, ranges around 500 to 800 mm annually (Mkonda, 2014).

2.2 Biochar production (pyrolysis)

The feedstock for biochar production was derived from fresh shelled maize cobs. About 1.1 tons of maize cobs were collected from farming households in the Morogoro municipality. The maize cobs were transformed to biochar using a manually built drum, simulating a pyrolysis plant (Romuli *et al.*, 2015). Yet, several modifications were done as follows (Fig.1): (i) eight holes were added at the bottom (Ø 3 cm); (2) the drum height was reduced 50 % to increase the ignition rate and portability; and (3) in order to reduce human health risks, a chimney was added to redirect the smoke during pyrolysis, as described in Yustas *et al* (2018). Processing of up to 12 kg of fresh cobs required an average temperature of 350 °C to produce about 5 kg of biochar over a period of 60 to 70 minutes. Thereafter, the hot biochar was sprinkled with water to extinguish the fire, partially burnt cobs were subsequently removed, and only the completely transformed biochar chips were packed in polyethylene bags. The biochar cobs were manually crushed within the bags using a beating stick and sieved through a 3 mm sieve to obtain the final powder for field application (Agegnehu *et al.*, 2016). Samples of each bag of crushed biochar were taken at this stage to determine moisture content. The biochar was alkaline (pH = 9.41), containing 529.8 mg P kg^{-1}, 12,125.0 mg K kg^{-1} and 315.8 mg Mg kg^{-1} (Graef *et al.*, 2018).

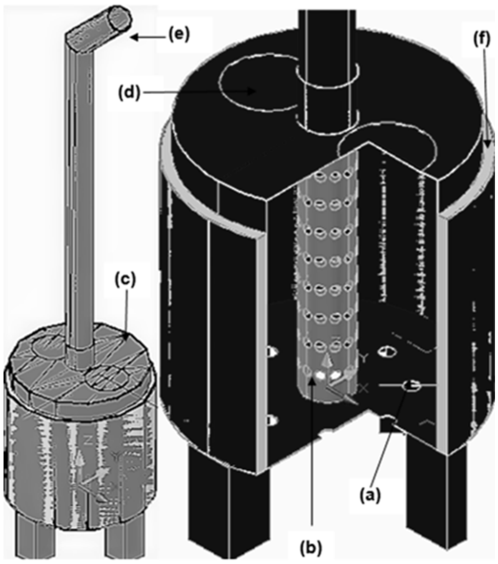

Fig. 1: *Top-Lit Updraft (TLUD) burner (Pyrolyser) for cooking and heating of raw maize cobs to produce biochar. It is made using locally available iron. The left scheme presents the general assembly of the Top-Lit Updraft (TLUD) burner. The right scheme presents the cross-section of Top-Lit Updraft (TLUD) burner. a = aerating holes, b = perforated pipe, c = top lid, d = cooking plate, e = chimney, f = insulation material, (after Yustas et al., 2018)*

2.3 Layout of field trial and application of biochar and chemical fertilisers

An experimental field of 23 × 60 m, with a slope of 5.3 % transverse to the direction of the tied-ridges, was ploughed to a depth of 0.3 m using a tractor followed by harrowing. The tied-ridges (R) and the flat (F) blocks were randomly assigned within the six blocks as the first factor of the split-plot design. The second factor consisted of the fertiliser treatments (rates and type, chemical and/or biochar). The 3 × 5 m plots containing the fertiliser treatments were distributed within the main blocks. Each treatment was conducted at three repetitions. Using a spring balance and polyethylene bags of about 13.5 kg and 27 kg of wet biochar (moisture content 44.5 %) representing 5 and 10 t biochar ha^{-1} application rates, respectively, were weighed. The biochar was spread evenly on the soil and incorporated with the top soil (0-10 cm), as recommended by Asai *et al*., (2009) and Major (2010). The R were spaced 0.75 m apart with a width of 0.375 m and were prepared using hand hoes as described by Hulugalle (1989; see Fig. 2b. The depth of the furrow between the ridges was 0.3 m (Tesfahunegn *et al*., 2008). Sowing was conducted on April 27, 2016, for all treatments. Two maize seeds (Shoka variety) were planted per hole at a spacing of 30 x 75 cm, on the flat and at the top centre on ridges, which was equivalent to 44,000 plants ha^{-1}. The rate of chemical fertiliser applied was 1.25 g (25 %) and 5

Fig. 2: *Planting maize, application of biochar (5 or 10 t ha^{-1}), and establishment of the cultivation methods. Fig. 2a shows the maize plants under different treatments and Fig.2b shows the preparation of tied-ridges (R), where biochar is distributed on a plot of 15 m^2 and then incorporated into the top soil (0-10 cm) to make the R.*

g (100 %) per pocket as Diammonium phosphate, based on recommended rate of 200 kg ha^{-1} (Mowo *et al*., 1993). The rates were placed at a distance of 5 cm from each planting hole. Nitrogen was fertilised as top dressing via urea and NPK at 28 (7th leaf stage) and 92 (during tasselling) days after planting, respectively, as recommended by Kisetu *et al*. (2014) and Mowo *et al*. (1993). The amount of urea and NPK was applied according to the treatments for chemical fertiliser, i.e. 25 % and 100 % of the recommended rate (Marandu *et al*., 2014), which were equivalent to 1.25 g and 5 g per pocket, respectively. All plots were managed equally in terms of agronomic practices including weeding and thinning. Overhead irrigation with hoses was done twice a week, unless rainfall justified a reduction in frequency. The total amount of water (irrigation + rainfall) used was 598 mm; this amount was within the annual range of rainfall (500 – 800 mm) in the Morogoro area of Tanzania (Mkonda, 2014).

2.4 Plant and soil measurements

Total shoot dry matter (DM), plant height, and soil moisture content were determined throughout the growing period of maize (April 27-September 2, 2016). To measure DM, eight randomly selected plants on each plot were harvested, with the first measurement on June 20 and the final on September 2. Plant samples were dried in the oven at 70 ° for 72 hours and weighed to estimate the total shoot dry matter. Starting from June 10th, four weekly measurements of plant height were taken for two plants per plot, while the fifth, and final, measurement was taken on August 2, after a one month break. The soil moisture content was measured shortly before irrigation as well as directly after irrigation. For the R treatment, the tops of the ridges were chosen. We used a Delta T-device (Cambridge, England, Model: HH2; range: zero to saturation, 0 to 1500 mV; accuracy: 0.13 % of mV reading + 1.0 mV); size: 150 x 80 x 40 mm, 450 g) equipped with an ML2x Theta-Probe.

2.5 Evapotranspiration

To estimate the sum of soil water evaporation (E) and plant transpiration (T) for each treatment, the evapotranspiration was estimated based on the difference between the amount of water in the soil before irrigation and the amount of water in the soil after irrigation.

2.6 Statistical analysis of data

Analysis of variance (ANOVA) was carried out to determine the differences of dependent variables using SPSS version 16.0. Means were separated using Tukey's honestly significant difference (HSD) test at a significance level of 0.05.

3 Results

3.1 The effect of biochar application and chemical fertiliser rates on shoot dry matter of maize

The results for maize DM at two different growth stages (Table 1) indicate that during the harvest stage, 5 t ha^{-1} BC +25 % MD increased DM by 83 % compared to the control and it was at the same level as DM from 100 % FD. No significant differences were detected among amended treatments during all the observed growth stages.

At the six leaves stage, maize DM tended to be higher for single or combined treatments than for the control. However, due to the high standard deviation of some treatments, there were few significant differences among means. Significantly higher yields at this stadium were only found when comparing the control with the 100 % FD treatment.

Table 1: *Total shoot dry matter of maize as affected by biochar and chemical fertiliser application rates over time (ANOVA, Post-hoc Tukey's 95 % confidence interval.)* [2]

Treatment	*Six leaves stage*	*At harvest*
	Mean [t DM ha^{-1}]	Mean [t DM ha^{-1}]
Control [0 %]	1.20 [a]	2.27 [a]
5 t BC ha^{-1}	1.56 [ab]	2.92 [ab]
10 t BC ha^{-1}	1.89 [ab]	3.24 [ab]
25 % MD	2.41 [ab]	3.16 [ab]
5 t BC ha^{-1} +25 % MD	3.33 [ab]	4.16 [b]
10 t BCha^{-1} + 25 % MD	3.11 [ab]	3.40 [ab]
100 % FD	4.13 [b]	4.24 [b]
ANOVA (p-value)	0.02	0.03

DM = Total shoot dry matter, BC = biochar in t ha^{-1}, 25 % MD = 25 % fertiliser application of the recommended rate, 100 % FD = recommended rate of fertiliser application. Different letters indicate significantly different means according to Tukey's HSD (95 % confidence interval).

3.2 Effects of tillage system and soil amendment combinations on dry matter of maize

The tillage system had no effect on the DM of maize at the two growth stages measured (Table 2). Plant heights in the treatment with 100 % FD, 25 % MD, and 5 or 10 t ha^{-1} of biochar application rate were higher than in other treatments over time (Fig. 3). This result is consistent with the DM response. Yet, plant height is consistently higher on measurement days (June 10, 17, 24, and July 1) in treatments with soil amendments than for the control ($p = 0.001$).

Table 2: *Influence of tillage system on total shoot dry matter of maize at different stages of growth (n=21).*

	Six leaves stage	*At harvest*
Tillage system	Mean [t DM ha^{-1}]	Mean [t DM ha^{-1}]
Flat	2.80	3.50
Tied-ridge	2.23	3.19
ANOVA (p-value)	0.27	0.39

3.3 The effect of soil amendments and tillage system on soil moisture content and evapotranspiration

Interestingly, the F tillage system resulted in significantly higher soil moisture content (18.8 %) than R (14.1 %), as indicated in Fig. 4 ($p < 0.001$), irrespective of biochar and/or chemical fertiliser treatment, indicating that under humid conditions, such as in this study, F can be more favourable in terms of soil water availability.

The estimated evapotranspiration between two irrigation events was significantly higher ($p < 0.001$) in treatments under F (19.3 %) than under R (14.2 %), regardless of the treatments with biochar and chemical fertiliser rates (Fig. 5). Evapotranspiration was not significantly affected by the soil amendments (biochar or chemical fertiliser) applied.

4 Discussion

The synergistic effects of 25 % MD combined with 5 t biochar ha^{-1} resulted in higher DM at harvest compared to the control. This is in accordance with the grain yield increases after combining 25 % MD with 5 or 10 BC compared to the control reported by Graef *et al.* (2018). Related plant performance is also observed in the existing literature after combinations of biochar with fertiliser (Doan *et al.*, 2015; Agegnehu *et al.*, 2016). This DM increase can be attributed to nutrient adsorption to the biochar surface and a slow nutrient release, allowing a more consistent nitrogen supply and reduced nutrient losses due to leaching (Downie,

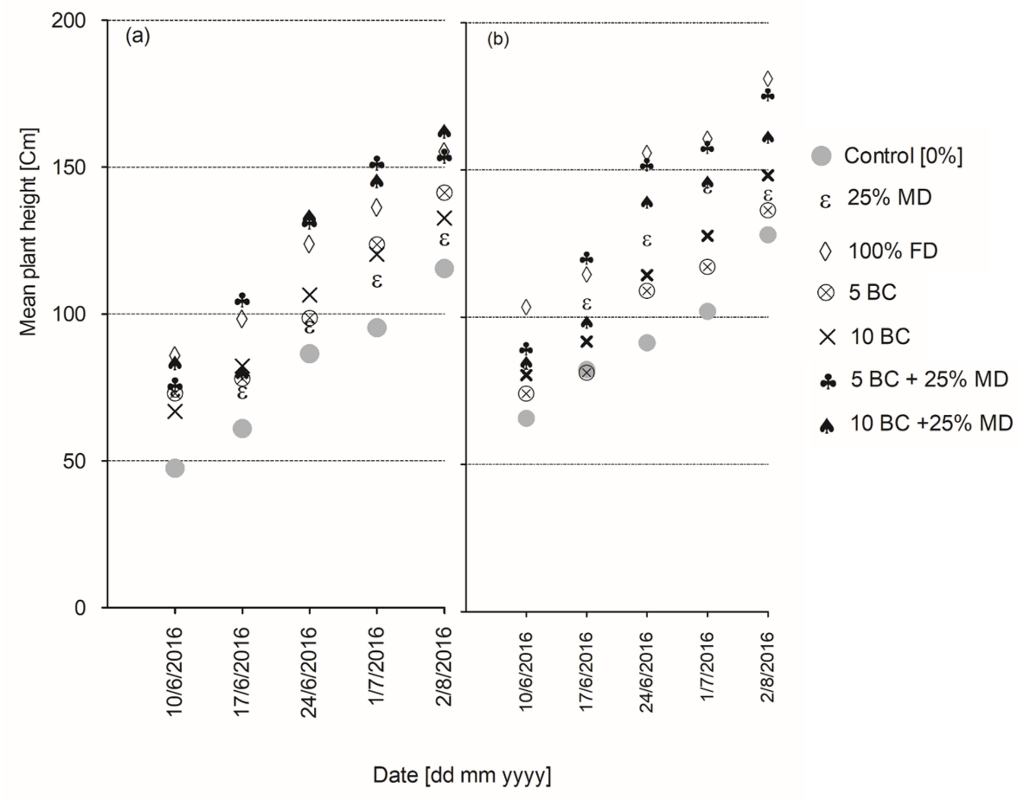

Fig. 3: *The effect of biochar and chemical fertiliser rates, within tillage methods, on height of maize over time (dates). Fig 3a and Fig. 3b show the flat and tied ridge tillage systems, respectively. 25 % MD: rate of chemical fertiliser 25 % of the recommended; 100 % FD: full rate of chemical fertiliser, BC: biochar in t ha-1 (n=3)*

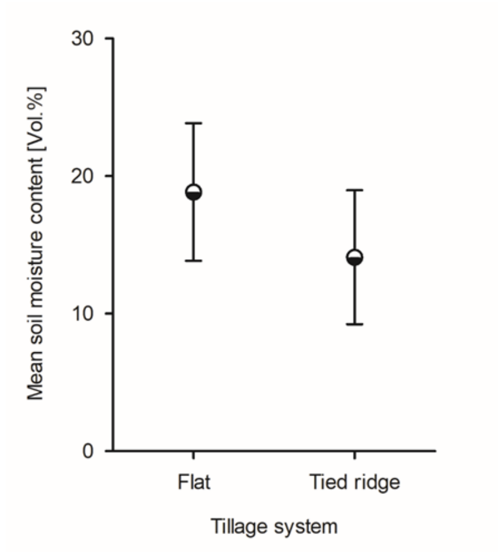

Fig. 4: *Effect of flat and tied ridge tillage system on average and standard deviation of soil moisture content (%) measured before irrigation under similar high irrigation (n = 210). Error bars indicate standard deviation.*

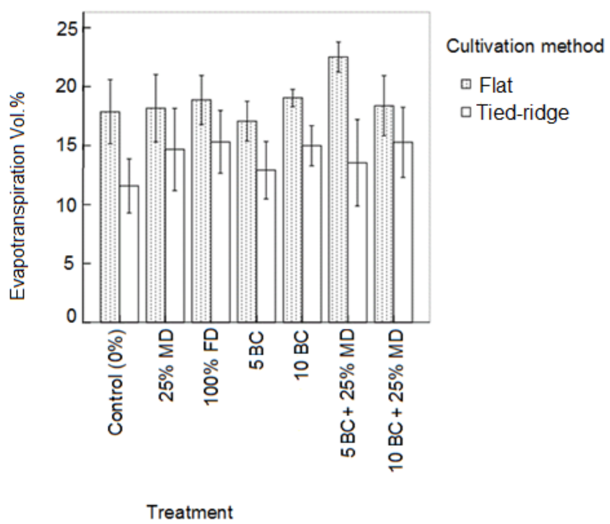

Fig. 5: *Averaged evapotranspiration of maize between two irrigation events for treatments with biochar (BC, in t ha^{-1}) and chemical fertiliser rates under flat and tied-ridge tillage. 25 % MD: rate of chemical fertiliser 25 % of the recommended; 100 % FD: full rate of chemical fertiliser.*

2011, Zheng *et al.*,2013). Single biochar or 25 % MD treatments did not increase biomass yield compared to the control. Thus, less fertiliser (25 % MD) is needed to increase biomass yield if combined with 5 BC.

Therefore, without taking labour into consideration, our results show that it is economically viable to combine low rates of biochar and chemical fertiliser to boost maize yields. It may also help to reduce much of the effort needed to produce biochar. For example, based on the local equipment used in this study, the production time itself is 60-70 minutes per 5 kg biochar, meaning that about 1000 hours are needed to produce 5 tons of biochar. The use of full-dose of chemical fertiliser resulted in the highest DM yield, confirming the results of Graef *et al.* (2018). In the short run, this may be more profitable compared to the combined use of biochar and 25 % MD. Nevertheless, over the long term, the biochar amendment, which is applied once, is more likely to have a continual boosting effect on crop production than the one time application of chemical fertiliser. Biochar material is characterised by high specific surface area that is chemically stable and can provide habitat for microorganisms in the soil, helping to improve and develop soil organic matter.

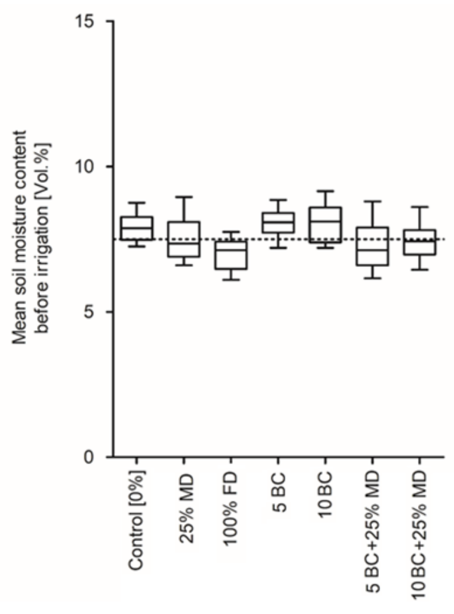

Fig. 6: *Averaged soil moisture content in treatments with maize-cob biochar (BC, in t ha^{-1}) and chemical fertiliser rates between two irrigation events in a sandy clay soil of Tanzania. 25 % MD: rate of chemical fertiliser 25 % of the recommended; 100 % FD: full rate of chemical fertiliser. (n=6)*

Maize control plants and in treatments with biochar application alone (5 or 10 t biochar ha-1) use less water between consecutive irrigations than plants in treatments with chemical fertiliser application. These differences in water consumption and soil moisture content are likely related to higher biomass production and less favourable water retention characteristics. Increased biomass development due to application of chemical fertiliser can lead to an increasing need for water (Dalla *et al.*, 1997). Unexpectedly, biochar application did not lead to a higher soil water content over the control (Fig. 6). This can be attributed to (i) the excessive water availability due to humid conditions, and (ii) to the soil type, as the biochar effect is expected to be more pronounced on sandy soils than on the sandy clay soils in this study (Abel *et al.*, 2013).

Finally, R did not increase soil water availability, biomass, and plant height when compared to F, very likely due to the humid conditions, as Araya & Stroosnijder (2010) suggest. Excessive water supply may even lead to waterlogging in fine-textured soils (Wiyo *et al.*, 2000), hence suppressing crop development if the ties within the ridges remain closed. Hence, under humid conditions, F can be more favourable in terms of soil water availability; however, this effect must be balanced against the positive R effect of reduced soil erosion (Grum *et al.*, 2016). Hence, further investigation on the usefulness of R in biochar application strategies, rainfall conditions, and different soil types is needed to derive conclusive results.

5 Conclusions

This study was carried out under tropical humid conditions and aimed to determine the performance of maize under a combination of biochar and chemical fertiliser application rates, using two tillage systems. The combination of biochar amendment and chemical fertiliser rates lower than recommended increased maize DM yield over the control. Small-scale farmers in poor regions could apply this combination of soil amendment and chemical fertiliser to improve crop production under marginal conditions. Tied ridges compared to flat cultivation under these humid rainfall and soil conditions did not positively affect maize biomass yields, while also resulting in less favourable soil water conditions.

Competing interests

The authors declare no competing interest.

Acknowledgements

This research was supported under grant No. 031A249A of the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Cooperation and Development (BMZ).

We thank Dr. Hamisi Tindwa for proofreading this manuscript before submission. We also thank Mr. Werenfrid

Michael for his help in drawing the reactor (Pyrolyser). We thank Mr Chacha Mwita and Mr. Yusto Yustas for contributing the idea of modifying the reactor (Pyrolyser).

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