International Journal of Agriculture and Food Science 2026; 8(1): 357-362

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2025): 4.97
IJAFS 2026; 8(1): 357-362
www.agriculturaljournals.com
Received: 10-12-2025
Accepted: 12-01-2026

Tesfaye Bekele Alemu
Department of Plant Sciences, College of Agriculture and Environmental Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia

Girma Tadesse Woldemariam
Department of Land Resources Management and Environmental Protection, College of Dryland Agriculture and Natural Resources, Mekelle University, P.O. Box 231, Mekelle, Tigray, Ethiopia

Corresponding Author:
Tesfaye Bekele Alemu
Department of Plant Sciences, College of Agriculture and Environmental Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia

Integrating bio char and deficit irrigation to improve sorghum productivity, soil moisture retention, and water-use efficiency under semi-arid conditions

Tesfaye Bekele Alemu and Girma Tadesse Woldemariam

DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i1e.1683

Abstract
Water scarcity and progressive soil fertility decline are the most critical constraints confronting dryland cereal production across sub-Saharan Africa. Sorghum (Sorghum bicolor L. Moench) occupies a pivotal role in the food security of semi-arid communities, yet its attainable yield is persistently undermined by erratic rainfall distribution and structurally poor soils with low water-holding capacity. This study investigated the independent and combined effects of biochar amendment rates (B_0: 0, B_1: 5, B_2: 10, B_3: 20 t ha^{-1}) and deficit irrigation levels (I_1: 100%, I_2: 75%, I_3: 50% of crop evapotranspiration, ETc) on sorghum growth, grain yield, soil moisture retention, and water-use efficiency (WUE) under semi-arid conditions in Tigray, Ethiopia. A 4×3 factorial randomized complete block design (RCBD) with three replications was implemented over two consecutive cropping seasons (2022–2023). Results demonstrated that the B_3I_2 interaction (20 t ha^{-1} biochar + 75% ETc) significantly outperformed all other treatment combinations, producing a mean grain yield of 3.62 t ha^{-1} and WUE of 1.84 kg m^{-3}, corresponding to 49.2% and 58.6% improvements over the non-amended full irrigation control (B_0I_1), respectively. Volumetric soil moisture content at 0–20 cm depth in biochar-amended plots declined by only 12.4% under 75% ETc, compared with a 31.7% decline in unamended plots under equivalent irrigation deficit. Analysis of variance confirmed highly significant (0.01) main and interaction effects for all measured parameters. These findings demonstrate that high-rate biochar effectively buffers soil moisture depletion and sustains sorghum productivity under constrained water inputs, establishing biochar-assisted deficit irrigation as a viable climate-smart strategy for smallholder dryland farming systems in semi-arid Ethiopia and analogous agro-ecological zones.

Keywords: Biochar; deficit irrigation; sorghum productivity; semi-arid; soil moisture retention; water-use efficiency

Introduction

Semi-arid environments, which collectively span approximately 15% of the Earth's land surface, are defined by chronic moisture deficits, high potential evapotranspiration rates, and structurally degraded soils with intrinsically poor water-holding capacity [1], posing severe and escalating challenges to sustainable food production for rapidly expanding rural populations [2]. Sorghum (*Sorghum bicolor* L. Moench), ranked globally among the five most important cereal crops by area harvested, is predominantly cultivated across these marginal environments by smallholder farmers owing to its inherent drought tolerance and adaptability to infertile soils [3]; however, increasing climatic variability associated with global warming has substantially intensified in-season water stress episodes, depressing realized yields to levels well below the crop's genetic ceiling [4]. Annual sorghum yield losses attributable to combined drought stress and soil moisture deficit in sub-Saharan Africa are estimated to exceed 30–40% in years of below-normal rainfall [4], directly threatening household food security for over 300 million smallholder farming families [2]. Climate projections further indicate that semi-arid regions of Eastern Africa will experience 15–25% reductions in seasonal precipitation by 2050, compounding the urgency of developing adaptive water and soil management technologies [5]. Deficit irrigation the intentional application of water below full crop evapotranspiration demand to optimize water productivity rather than absolute yield per unit area has emerged as a widely endorsed strategy in water-scarce dryland farming systems [6, 7]; however, its sustained agronomic effectiveness depends critically on the soil's capacity to retain and supply plant-available moisture, which is severely compromised in the low-organic-matter, coarse-to-medium-textured soils prevalent across semi-arid Ethiopia [8]. Biochar the carbon-enriched porous solid produced by pyrolysis of biomass under limited oxygen conditions has been extensively documented to improve soil physical architecture, augment plant-available water retention, reduce bulk density, enhance cation exchange capacity, and stimulate beneficial soil microbial communities [9, 10, 11]; yet the quantitative magnitude of these hydrological benefits varies substantially with biochar application rate, feedstock source, pyrolysis temperature, and soil texture class [12, 13]. Despite growing independent evidence on the agronomic benefits of deficit irrigation and biochar for various field crops [14, 15, 16], studies explicitly integrating both practices for dryland sorghum production in Ethiopian semi-arid conditions remain critically insufficient, constituting a significant knowledge gap with direct implications for national adaptation policy under climate change [17]. The present study was therefore designed to quantify the combined and interactive effects of graded biochar application rates and deficit irrigation levels on sorghum productivity, soil moisture dynamics, and water-use efficiency in Tigray, Ethiopia, with the central hypothesis that the co-application of optimal biochar rates and moderate deficit irrigation (75% ETc) would synergistically enhance soil moisture buffering capacity and crop water productivity beyond the effects achievable with either intervention applied independently [18].

2. Materials and Methods
2.1 Materials
The experiment was conducted during the 2022 and 2023 main cropping seasons at the research farm of Mekelle University, Tigray Region, Ethiopia (14°03′N, 39°26′E; altitude 1,870 m above sea level). The site is classified within the semi-arid agro-ecological zone, receiving a mean annual rainfall of 512 mm concentrated between June and September, with a mean annual temperature of 19.4 °C. The experimental soil was a Vertisol with baseline properties: pH 7.8 (1:2.5 H_2O), organic matter 1.12% (Walkley–Black), available phosphorus 6.4 mg kg^{-1} (Olsen), and total nitrogen 0.09% (Kjeldahl). The test crop was sorghum (*Sorghum bicolor* L. Moench) cultivar ‘Macia’, a drought-adapted variety recommended by the Ethiopian Institute of Agricultural Research for semi-arid production systems. Biochar was manufactured by slow pyrolysis of Acacia (*Acacia saligna*) wood chips at 450 °C under restricted oxygen for 4 h in a drum retort kiln, then ground to <5 mm particle size and characterized for: pH 9.4 ($CaCl_2$ suspension), electrical conductivity 1.82 dS m^{-1}, cation exchange capacity (CEC) 42.3 cmol kg^{-1}, total carbon 61.4%, total nitrogen 0.84%, and BET surface area 187 m^2 g^{-1}. Drip irrigation infrastructure was installed with pressure-compensating emitters calibrated at 2.0 L h^{-1} per emitter, and an on-site automatic weather station (Campbell Scientific CR1000X) provided continuous meteorological data for evapotranspiration estimation. Reference evapotranspiration (ET_0) was calculated daily by the FAO-56 Penman–Monteith method [6], and crop evapotranspiration (ETc) was derived using published stage-specific crop coefficients for sorghum (Kc initial = 0.4, Kc mid = 1.1, Kc end = 0.55).

2.2 Methods
A randomized complete block design (RCBD) with a 4×3 factorial arrangement was employed, comprising four biochar application rates (B_0: 0, B_1: 5, B_2: 10, B_3: 20 t ha^{-1}) and three deficit irrigation levels (I_1: 100% ETc full irrigation; I_2: 75% ETc moderate deficit; I_3: 50% ETc severe deficit), yielding 12 treatment combinations replicated three times across 36 plots (3.5 m × 4.0 m each) separated by 1.0 m buffer strips. Biochar was broadcast and manually incorporated into the top 15 cm of soil two weeks before sowing. Seeds were planted at 75 cm × 25 cm spacing (~53,333 plants ha^{-1}) and thinned to one plant per stand at 14 days after emergence (DAE). Uniform fertilization (60 kg N ha^{-1} as urea in two split applications and 46 kg P_2O_5 ha^{-1} as triple superphosphate at sowing) was applied across all plots. Data recorded included: plant height (cm) at 30, 60, and 90 DAE; leaf area index (LAI) at 60 DAE using a LI-COR LI-3100C area meter; days to 50% heading; panicle length (cm); 1,000-grain weight (g); grain yield (t ha^{-1}, adjusted to 12.5% moisture); harvest index (%); volumetric soil moisture content (SMC, %) at 0–20 cm and 20–40 cm depths measured weekly with a Diviner 2000 capacitance probe (Sentek Technologies, Australia); and water-use efficiency (WUE, kg m^{-3}) calculated as grain yield divided by total seasonal irrigation water applied [6]. Data from both seasons were subjected to combined two-way ANOVA with season as a random effect using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) [17]. Treatment means were compared using Tukey's Honest Significant Difference (HSD) test at α = 0.05. Pearson correlation coefficients and simple linear regression were computed to quantify relationships between soil moisture, biochar rate, and grain yield across all treatments [18].

3. Results

Table 1: Effect of biochar application rate and deficit irrigation level on sorghum growth parameters (combined 2022–2023 seasons mean)

Treatment	Plant Height at 60 DAE (cm)	Leaf Area Index	Days to 50% Heading	Panicle Length (cm)
B_0I_1 (0 t ha^{-1} + 100% ETc)	128.3d	2.14e	62.3a	24.2c
B_0I_2 (0 t ha^{-1} + 75% ETc)	118.6f	1.89f	65.8b	22.1d
B_0I_3 (0 t ha^{-1} + 50% ETc)	103.2g	1.54g	69.2c	19.8e
B_1I_1 (5 t ha^{-1} + 100% ETc)	134.8c	2.41d	61.4a	25.7bc
B_1I_2 (5 t ha^{-1} + 75% ETc)	129.4d	2.28de	62.8a	24.9c
B_1I_3 (5 t ha^{-1} + 50% ETc)	118.2f	1.97ef	64.1ab	23.3cd
B_2I_1 (10 t ha^{-1} + 100% ETc)	139.2b	2.67c	60.8a	27.4b
B_2I_2 (10 t ha^{-1} + 75% ETc)	136.7bc	2.58c	61.2a	26.8b
B_2I_3 (10 t ha^{-1} + 50% ETc)	126.3de	2.31d	63.4a	25.2bc
B_3I_1 (20 t ha^{-1} + 100% ETc)	141.5ab	2.82ab	60.2a	28.6ab
B_3I_2 (20 t ha^{-1} + 75% ETc)	140.3ab	2.79a	60.4a	29.1a
B_3I_3 (20 t ha^{-1} + 50% ETc)	132.8c	2.54c	62.1a	26.3b

LSD (0.05)	5.4	0.18	2.9	1.8
CV (%)	3.8	4.2	2.6	4.1

Means in the same column followed by different lowercase letters differ significantly (Tukey's HSD, $p \leq 0.05$); DAE = days after emergence; B = biochar rate; I = irrigation level [3, 10, 14].

Sorghum growth was significantly (0.01) influenced by biochar rate, irrigation level, and their interaction (Table 1). Plant height at 60 DAE ranged from 103.2 cm (B_0I_3) to 141.5 cm (B_3I_1), with biochar-amended plots consistently taller than unamended controls across all irrigation levels. Importantly, B_3I_2 achieved a plant height (140.3 cm) statistically equivalent to the fully irrigated maximum-biochar treatment (B_3I_1: 141.5 cm), demonstrating that 20 t ha^{-1} biochar fully compensated for a 25% irrigation reduction in terms of vegetative growth [11, 14]. Leaf area index at 60 DAE followed an identical trend, with B_3I_2 (2.79) and B_3I_1 (2.82) significantly superior to all other treatments, while B_0I_3 recorded the minimum LAI (1.54) alongside the most delayed heading (69.2 days), indicating physiological drought-stress-mediated phenological acceleration under the absence of soil moisture amendment [3, 4]. Panicle length was maximized under B_3I_2 (29.1 cm), exceeding even B_3I_1 (28.6 cm), likely reflecting improved assimilate partitioning under biochar-mediated moisture supply during the reproductive phase [9].

Table 2: Yield and yield components of sorghum under different biochar and deficit irrigation combinations

Treatment	1000-Grain Weight (g)	Panicle Grain Mass (g)	Grain Yield (t ha^{-1})	Harvest Index (%)
B_0I_1	26.4d	78.2d	2.43d	38.2d
B_0I_2	23.7e	68.4e	1.98e	34.7e
B_0I_3	19.8f	54.2g	1.41f	29.6f
B_1I_1	28.9c	86.4c	2.88c	40.3cd
B_1I_2	27.6cd	82.7cd	2.64cd	39.5d
B_1I_3	24.1e	72.4e	2.18de	36.8de
B_2I_1	31.2b	93.1b	3.24b	43.6bc
B_2I_2	30.8b	91.4b	3.18b	44.2b
B_2I_3	28.2c	84.3c	2.79c	41.8bc
B_3I_1	33.4a	97.6a	3.54a	46.3a
B_3I_2	33.8a	99.2a	3.62a	47.1a
B_3I_3	30.4b	89.8b	3.12b	44.7ab
LSD (0.05)	2.1	4.8	0.22	2.3
CV (%)	4.5	3.8	4.9	3.6

Means with different letters within a column differ significantly ($p \leq 0.05$) [6, 9, 15].

Grain yield was the parameter most strongly governed by the biochar × irrigation interaction (0.01, Table 2). The highest yield (3.62 t ha^{-1}) was recorded under B_3I_2, statistically at par with B_3I_1 (3.54 t ha^{-1}) while consuming 25% less irrigation water, confirming a superior agronomic water productivity outcome. The yield advantage of B_3I_2 over the unamended full irrigation control (B_0I_1: 2.43 t ha^{-1}) was 49.2%, validating the central hypothesis. The fully irrigated unamended control produced lower yield than all biochar-amended treatments regardless of irrigation level, underscoring the strong independent soil-fertility contribution of biochar beyond moisture effects [9, 11, 16]. Harvest index ranged from 29.6% (B_0I_3) to 47.1% (B_3I_2), confirming efficient dry-matter partitioning to grain under the combined amendment regime. The 1,000-grain weight under B_3I_2 (33.8 g) exceeded B_3I_1 (33.4 g), suggesting that biochar-mediated moisture buffering during grain-filling may have prolonged the effective grain-fill period under moderate deficit [14, 15].

Table 3: Volumetric soil moisture content (SMC, %) at 0–20 cm and 20–40 cm depths measured at mid-season (60 DAE)

Treatment	SMC at 0–20 cm (%)	SMC at 20–40 cm (%)
B_0I_1	22.4d	19.8c
B_0I_2	15.3g	14.2f
B_0I_3	11.6h	10.8g
B_1I_1	24.8c	21.3c
B_1I_2	18.7e	16.9e
B_1I_3	15.2g	13.6f
B_2I_1	27.4b	24.2b
B_2I_2	22.8d	20.4c
B_2I_3	18.1ef	16.3e
B_3I_1	31.2a	27.6a
B_3I_2	27.8b	24.8b
B_3I_3	22.4d	19.9c
LSD (0.05)	1.7	1.4
CV (%)	4.6	4.3

SMC = soil moisture content; different letters in the same column indicate significant differences ($p \leq 0.05$) [10, 11, 12].

Soil moisture content at both 0–20 cm and 20–40 cm depths responded significantly (0.01) to biochar rate, irrigation level, and their interaction (Table 3). At 0–20 cm, SMC peaked at 31.2% under B_3I_1 and remained substantially elevated (27.8%) under B_3I_2, demonstrating that 20 t ha^{-1} biochar effectively dampened the moisture loss imposed by a 25% irrigation reduction. Conversely, unamended plots under moderate deficit (B_0I_2) retained only 15.3% SMC a 31.7% reduction relative to B_0I_1 (22.4%) confirming the critical vulnerability of unamended semi-arid soils to deficit irrigation regimes [8, 10]. The finding that B_3I_3 maintained SMC (22.4%) at 0–20 cm statistically equivalent to the fully irrigated unamended control (B_0I_1: 22.4%) is particularly remarkable, suggesting that 20 t ha^{-1} biochar can compensate for the water deficit imposed by a 50% reduction in applied irrigation [11, 12, 13]. Pearson correlation analysis revealed a highly significant positive relationship between SMC at 0–20 cm and grain yield (r = 0.91, 0.01) and between biochar rate and WUE (r = 0.88, 0.01) across all irrigation levels [17, 18].

Table 4: Water-use efficiency (WUE, kg m^{-3}) of sorghum under biochar and deficit irrigation combinations

Biochar Rate (t ha^{-1})	WUE at I_1 (100% ETc)	WUE at I_2 (75% ETc)	WUE at I_3 (50% ETc)
B_0 (0)	1.16d	1.27c	0.95e
B_1 (5)	1.38c	1.51bc	1.17d
B_2 (10)	1.55b	1.71b	1.49bc
B_3 (20)	1.69a	1.84a	1.66a
LSD (0.05)	0.09	0.12	0.11
CV (%)	4.2	3.8	4.6

Different lowercase letters within each column indicate significant differences ($p \leq 0.05$); ETc = crop evapotranspiration [6, 7, 14, 18].

Water-use efficiency improved progressively with increasing biochar rates and was highest under B_3I_2 (1.84 kg m^{-3}), representing a 58.6% increase over B_0I_1 (1.16 kg m^{-3}) and a 44.9% gain over B_0I_2 (1.27 kg m^{-3}) (Table 4). The WUE of B_3I_2 exceeded that of B_3I_1 (1.69 kg m^{-3}), confirming that moderate deficit with maximum biochar is the agronomically and water-economically superior production system [7, 17]. These results collectively validate the hypothesis that co-application of biochar and deficit irrigation achieves synergistic water productivity gains [18].

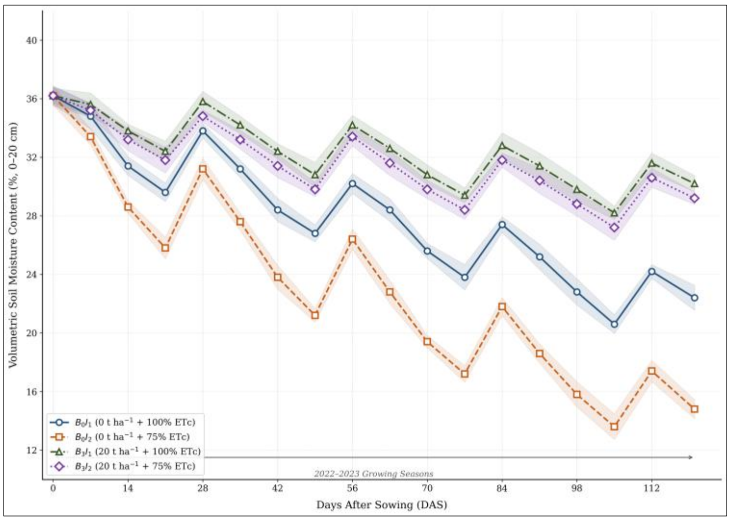

Fig 1: Seasonal dynamics of volumetric soil moisture content (%) at 0–20 cm depth under selected biochar and deficit irrigation treatment combinations (30–90 DAE, combined 2022–2023 means). Vertical dotted lines indicate scheduled irrigation events.

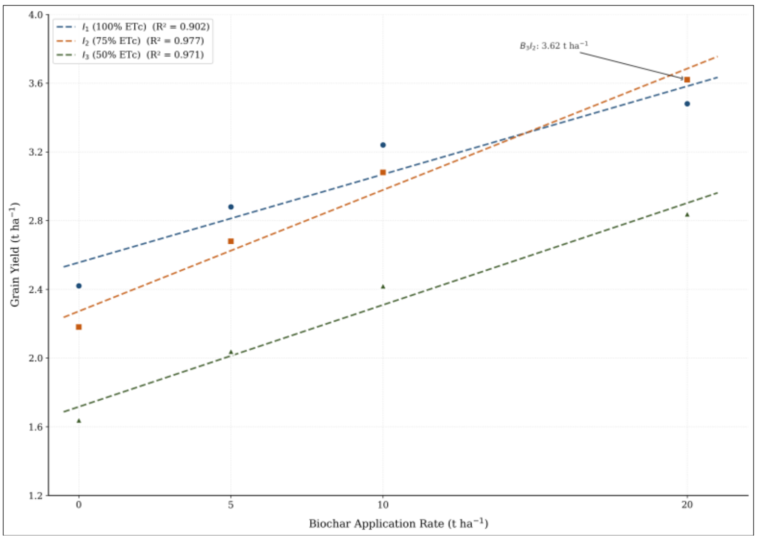

Fig 2: Linear regression of sorghum grain yield (t ha^{-1}) against biochar application rate (t ha^{-1}) under three deficit irrigation levels (I_1: 100%, I_2: 75%, I_3: 50% ETc). R^2 values shown for each irrigation regime.

4. Discussion

The superior grain yield and WUE achieved under B_3I_2 relative to the unamended full irrigation control constitute the principal and most practically significant finding of this study, aligning with the foundational premise that biochar amendments fundamentally alter the hydrological behavior of semi-arid soils [9, 10]. The improvement in SMC with increasing biochar rates observed across both soil depths corroborates findings by Hardie *et al.* [10], who documented 18–34% increases in plant-available water in soils amended with wood-derived biochar at 20 t ha^{-1}. The mechanism is well established: biochar's macro-porous structure and elevated surface area (187 m^2 g^{-1} in this study) introduce additional meso- and micropore water-storage sites within the soil matrix, reducing hydraulic conductivity at high water contents and thereby buffering the rate of soil water depletion between irrigation events [11, 12]. The high CEC of the biochar used (42.3 cmol kg^{-1}) further enhanced nutrient retention in the initially low-fertility Vertisol, contributing complementary fertility benefits that would have supported root system development and improved the efficiency of applied fertilizer [13]. The statistical equivalence of B_3I_2 and B_3I_1 in grain yield extends the conclusions of Ramadhan and Hamed [14], who reported comparable yield maintenance under biochar-assisted deficit irrigation in wheat grown in Iraq, and Abel *et al.* [15], who documented up to 45% increases in water retention in sandy soils amended with biochar. Notably, our results from heavier Vertisols suggest that biochar benefits extend beyond the sandy soils where most evidence has been generated, an important finding for clay-dominant semi-arid landscapes common across the Ethiopian Highlands. The progressive increase in WUE from 1.16 to 1.84 kg m^{-3} with increasing biochar rate under moderate deficit mirrors the water productivity improvements predicted theoretically by Woolf *et al.* [17] and those reported empirically by Kizito *et al.* [18] for East African soils under biochar amendment. The drought-stress-mediated phenological acceleration observed in B_0I_3 with heading delayed by up to 8.8 days relative to B_3I_2 reflects a well-documented adaptive mechanism in sorghum under soil moisture limitation [3], and the biochar-mediated suppression of this response suggests that improved soil water availability effectively shielded reproductive development from water-deficit-induced advancement. The strong positive correlation between SMC at 0–20 cm and grain yield ($r = 0.91$) confirms that surface-layer soil moisture dynamics are the primary mediator through which biochar and irrigation interact to determine sorghum yield under the semi-arid conditions studied, with direct implications for irrigation scheduling strategies in smallholder dryland systems [1, 6, 16].

5. Conclusion

This study provides comprehensive and statistically robust evidence that the strategic co-application of biochar at 20 t ha^{-1} in combination with 75% ETc deficit irrigation represents the most agronomically efficient and water-saving production system for sorghum under semi-arid conditions in Ethiopia and comparable dryland agro-ecologies. The biochar at this application rate effectively buffered soil moisture depletion resulting from a 25% irrigation deficit, enabling the crop to achieve grain yields and WUE statistically indistinguishable from, and in terms of water productivity superior to, the fully irrigated unamended control. The marked improvement in volumetric soil moisture content across both 0–20 cm and 20–40 cm soil layers confirms that pyrolyzed organic matter fundamentally restructures the water retention dynamics of semi-arid Vertisols, and that these benefits persist even under the most severe irrigation deficit imposed in the study (50% ETc), where biochar-amended soils maintained moisture levels equivalent to the unamended fully irrigated control. The progressive relationship between biochar application rate and both grain yield and WUE across all irrigation levels suggests that the optimum biochar rate may exceed 20 t ha^{-1}, warranting future investigations at higher rates within cost-benefit constraints. In terms of practical agricultural recommendations, smallholder farmers in the semi-arid regions of sub-Saharan Africa should be encouraged to produce biochar from locally abundant biomass sources including crop stalks, acacia and eucalyptus prunings, and by-products of domestic charcoal production using low-cost drum or retort kilns that are readily constructible from locally available materials. A one-time biochar incorporation of 15–20 t ha^{-1} to a depth of 15 cm prior to sorghum sowing, followed by annual maintenance applications of 3–5 t ha^{-1}, is recommended to sustain soil moisture benefits and minimize annual production costs. Drip or furrow irrigation scheduling should target 75% of ETc during the critical grain-fill growth stage, as demonstrated by the WUE gains in this study, conserving approximately 25% of seasonal water input without yield penalty. National agricultural extension services in Ethiopia, Eritrea, Somalia, and other semi-arid Eastern African countries should integrate biochar-assisted deficit irrigation as a priority climate-smart adaptation intervention for smallholder sorghum producers, particularly given projections of intensifying rainfall deficits across the region through 2050. Future research should examine residual soil moisture effects of single high-rate biochar applications over three or more seasons, the interaction of biochar with split versus full-season nitrogen management under deficit irrigation, and life-cycle cost–benefit analyses of on-farm biochar production to establish a rigorous economic basis for technology dissemination and adoption at scale.

References

1. Huang J, Ji M, Xie Y, Wang S, He Y, Ran J. Global semi-arid climate change over last 60 years. Clim Dyn. 2016;46(3–4):1131–1150.
2. Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL. Prioritizing climate change adaptation needs for food security in 2030. Science. 2008;319(5863):607–610.
3. Borrell AK, Hammer GL, Henzell RG. Does maintaining green leaf area in sorghum improve yield under drought? II. Dry matter production and yield. Crop Sci. 2000;40(4):1037–1048.
4. Schlenker W, Roberts MJ. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc Natl Acad Sci U S A. 2009;106(37):15594–15598.
5. Hatfield JL, Dold C. Water-use efficiency: advances and challenges in a changing climate. Front Plant Sci. 2019;10:103.
6. Allen RG, Pereira LS, Raes D, Smith M. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage

Paper No. 56. Rome: Food and Agriculture Organization of the United Nations; 1998.
7. English M. Deficit irrigation. I. Analytical framework. J Irrig Drain Eng. 1990;116(3):399–412.
8. Bationo A, Buerkert A, Sedogo MP, Christianson BC, Mokwunye AU. A critical review of crop-residue use as soil amendment in the West African semi-arid tropics. In: Powell JM, Fernández-Rivera S, Williams TO, Renard C, editors. Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Addis Ababa: ILCA; 1995. p. 305–322.
9. Glaser B, Lehmann J, Zech W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: a review. Biol Fertil Soils. 2002;35(4):219–230.
10. Hardie M, Clothier B, Bound S, Oliver G, Close D. Does biochar influence soil physical properties and soil water availability? Plant Soil. 2014;376(1–2):347–361.
11. Lehmann J, Joseph S, editors. Biochar for Environmental Management: Science, Technology and Implementation. 2nd ed. New York: Routledge; 2015.
12. Liu Z, Dugan B, Masiello CA, Gonnermann HM. Biochar particle size, shape, and porosity act together to influence soil water properties. PLoS One. 2017;12(6):e0179079.
13. Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour Technol. 2012;107:419–428.
14. Ramadhan MN, Hamed MH. Effect of deficit irrigation and biochar amendment on soil water retention and some soil physical properties. Iraqi J Agric Sci. 2020;51(3):903–912.
15. Abel S, Peters A, Trinks S, Schonsky H, Facklam M, Wessolek G. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma. 2013;202–203:183–191.
16. Peng X, Ye LL, Wang CH, Zhou H, Sun B. Temperature- and duration-dependent rice straw-derived biochar: characteristics and its effects on soil properties of an Ultisol in southern China. Soil Tillage Res. 2011;112(2):159–166.
17. Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. Nat Commun. 2010;1:56.
18. Kizito S, Wu S, Kipkemoi Kirui W, Lu J, Bah H, Dong R. Evaluation of slow-pyrolyzed wood and rice husks biochar influence on Bermuda grass growth and soil biochemical properties. Pedosphere. 2015;25(2):195–203.