Potential of Integrating Biochar and Deficit Irrigation Strategies for Sustaining Vegetable Production in Water-limited Regions: A Review

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Abstract. Water shortage is one of the major challenges faced by the current agricultural systems worldwide, especially in arid and semi-arid regions. Deficit irrigation (DI), a water-saving strategy of applying less water than crop evapotranspiration (ET_c) demands, has been extensively investigated in different crops, including water-intensive vegetables. The DI strategies such as regulated deficit irrigation (RDI) and partial root zone drying (PRD) generally increase water use efficiency (WUE) and have emerged as potential practices to save water for agricultural sustainability. However, in view of the sensitivity of shallow-rooted vegetable crops to water stress, DI is often associated with yield losses. A review of 134 DI reports of vegetable crops revealed significant reductions in yield under all DI levels in 52% of cases and yields statistically similar to those of full irrigation (100% ET_c in most cases) under small water deficits in 44% of cases, thereby raising concerns about the sustainability of vegetable production under DI. Biochar, a carbon-rich co-product of pyrolysis of organic matter, is increasingly undergoing study as a soil amendment to mitigate drought stress and is being explored as an additional practice with DI to minimize the yield losses due to water deficits. This work reviews the effects of biochar application on growth, yield, physiology, and WUE of different vegetable crops under DI regimes to determine the potential of biochar and DI used in combination to sustain vegetable productivity in water-limited areas. Overall, the addition of biochar under DI has helped to compensate for yield losses of vegetables and further enhanced WUE. However, field studies investigating long-term soil–biochar interactions that strongly conclude the impact of biochar under moisture stress conditions are lacking.

At present, global agriculture, especially vegetable production, is being challenged to meet the food and nutritional demands of the ever-increasing population. The growing food demand is placing pressure on natural resources such as land and water. Irrigated agriculture is undoubtedly the largest consumer of freshwater, accounting for approximately more than two-thirds of the total fresh water use (Chai et al., 2015). Agriculture is considered one of the most inefficient water users and causes exploitation of water resources in many areas worldwide (FAO, 1993). As a consequence, water scarcity has become a critical factor for crop production, especially in arid and semi-arid areas. For instance, the Ogallala aquifer, a major source of irrigation water in the Southern High Plains of the United States, experienced a

decrease of ≈ 4.8 m in the water level since the beginning of dominant extraction (1950s) and an overall decline of ≈ 0.2 m during 2013–15 (McGuire, 2017). Every year, approximately two-thirds of the world's population experience a severe water shortage for at least 1 month (Mekonnen and Hoekstra, 2016). Considering the conflict regarding water allocation for agriculture and other sectors, more restrictions on irrigation water with the current production systems are inevitable in the near future. Water shortages have frequently exposed crops to drought stress, which is often accompanied by heat and salinity stress. In contemporary agriculture, drought stress is, in fact, the key limiting factor responsible for growth and yield reductions of crop plants (Bodner et al., 2015). Recently, as a result, efficient use of irrigation water and increments in WUE of crop plants are major concerns of researchers and agronomists. Water conservation practices such as drip irrigation, protected cultivation, and mulching have significantly contributed to the improvement in WUE by reducing

evapotranspiration (ET) and runoff losses (Costa et al., 2007; Kirnak and Demirtas, 2006). However, there is still an opportunity to devise more cultural and irrigation strategies to make production systems more water-efficient and sustainable. The crop yields are generally highest with optimal water application, but crops can adapt and produce reasonably well under limited water supply conditions (FAO, 2002). Deficit irrigation (DI) is a strategy of applying less water than ET demands with the objective of improving WUE by eliminating the irrigation with a nonsignificant impact on yield (Kirda, 2002). The DI technique used for a number of crops, including vegetables in water-limited areas, exposes the plants to different levels of moisture stress. Many agronomic crops like cotton (*Gossypium hirsutum* L.), safflower (*Carthamus tinctorius* L.), and several fruit crops like grapevine (*Vitis vinifera* L.) and citrus, which are well-adapted to water stress, have been reported to produce yields statistically similar to those of full irrigation under DI regimes (Costa et al., 2007; Singh et al., 2016; Yang et al., 2015). For most vegetable crops, water deficit is often accompanied by yield losses and deterioration of quality due to high water sensitivity (Costa et al., 2007); however, fewer studies showing nonsignificant yield reductions in vegetable crops in response to DI have also been reported in literature (Ahmadi et al., 2014; Du et al., 2017; Nagaz et al., 2012). The water sensitivity of fast-growing vegetable crops is attributed to two main reasons. First, most vegetable crops have shallow root systems with effective root zone lying within the upper 60 cm of the soil (Lott and Hammond, 2013). Second, the sale of vegetable produce is based on appearance and fresh weight (Sorensen, 2005). The sensitivity of vegetable crops to water stress may lead to dramatic fluctuations in yield, especially in drought-prone arid and semi-arid regions. In this context, additional drought-adaptive strategies in combination with DI can be used to sustain vegetable productivity and quality and to save water for future use in water-limited arid and semi-arid regions of the planet.

Soil amendment using biochar has been suggested as a strategy to improve long-term productivity and increase nutrient and water use efficiency (Sarong and Orge, 2015; Sohi et al., 2010). Biochar is a high-carbon co-product of pyrolysis of organic matter that differs from charcoal by its intention of application as a soil amendment (Lehmann, 2007). The low density and large surface area of biochar provides the capacity for high adsorption, thus improving nutrient retention on the active surface and, consequently, reducing leaching and enhancing soil fertility (Nartey and Zhao, 2014). The porous structure of biochar can lower the bulk density of soil, thus increasing water retention. This ability to improve the water-holding capacity illustrates its application in regions where water deficit is a limiting factor for crop productivity (Briggs et al., 2005; Karhu et al., 2011). The potential soil factors altered

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by biochar addition, which may contribute to enhanced soil fertility and crop productivity, include soil physical properties (decreased bulk density, increased aeration, increased soil organic matter), chemical properties (increased nutrient availability, cation exchange capacity, decreased leaching), soil biological properties (provision of refuge and habitat, increased microbial activity due to high porosity and surface area), and plant properties, such as increased root growth and decreased disease incidence (Blanco-Canqui, 2017; Ding et al., 2016). Investing in such amendments can be especially beneficial for high-value vegetables because these crops generate much higher income per hectare for small farmers compared with staple crops (Abewoy, 2018). Several reports investigating the effects of biochar on growth, yield, physiology, and WUE of vegetable crops under deliberate water deficits are available in the literature. Ali et al. (2017) reviewed agricultural production (mainly agronomic crops) as affected by biochar amendments under drought and salt stress conditions. However, based on a survey of the literature, a comprehensive review abridging the role of biochar in vegetable production under deliberate water deficits is lacking. Therefore, we reviewed the potential of biochar as a soil amendment to alleviate yield losses and improve the growth and physiology of vegetable crops under DI, especially in water-limited regions of the world.

Impact of Deficit Irrigation Practices on Yield and Quality of Vegetable Crops

The DI strategy involves deliberate exposure of crops to certain levels of water deficit, which conserves a significant amount of irrigation water and often causes some yield reductions depending on the ability of the plants to endure moisture stress. The physiological responses to DI and its effect on yield are crop- and cultivar-specific (Costa et al., 2007). Comprehensive knowledge of crop responses to small water deficiencies is vital for the successful practice of DI strategies. The effects of DI strategies on crop growth, physiology, WUE, and yield have been extensively investigated in vegetable crops. We surveyed the available literature for the application of DI for vegetable crops to determine its effect on the performance of various vegetables and the overall impact on vegetable production. In addition to the classical DI strategy, RDI and PRD are two frequently used DI strategies (Capra et al., 2008). With RDI, various phases of the crop cycle are subjected to water deficit to determine the phase that is least sensitive and has a minimum reduction in yield. However, PRD exposes the plant roots to alternate wetting and drying cycles, during which half of the root zone is exposed to water stress at one time. The existing literature indicated that the effects of these DI strategies on vegetable crop growth and yield are variable, ranging from significant yield reductions with minimal water deficits to statistically

similar yields or even higher yields under DI in few cases (Table 1). Previously, a review of DI studies of horticultural crops by Costa et al. (2007) indicated that these strategies could be successfully practiced for several drought-tolerant fruit crops, but the outcomes are uncertain for stress-prone vegetable crops due to frequent losses in yield and quality. Capra et al. (2008) reviewed the feasibility of using DI strategies for different crops from the economic viewpoint of optimizing net returns. Recently, Sánchez-Blanco et al. (2019) performed a comprehensive review of the modifications in growth and adaption of ornamental plants in response to water deficits. The major responses of ornamental plants included decreased plant height, decreased leaf area, decreased shoot length, increased root length, increased root density, and increased root-to-shoot ratio. A comprehensive review of DI strategies used for vegetable crops is lacking because past reviews were based on a limited number of specific studies.

A total of 90 published articles comprising 134 reports were investigated to document the effects of DI strategies on the growth and yield of vegetable crops. The yield effects of various DI strategies on different vegetable crops are summarized in Table 1. Based on the reviewed reports, the yield results were considered decreased or nonsignificant (statistically similar), with few studies reporting increased yields under DI regimes. In most of these reports, yield results were compared at a 5% level of significance. If any of the DI levels produced statistically similar or higher yields than control irrigation (full irrigation), then it was recorded as nonsignificant or increased, respectively. Of these compiled studies, ≈52% of the reports showed a significant decrease in yield with all DI levels. Approximately 44% of reports with statistically similar yields under mild water deficits (70% to 90% ET_c) were recorded, although higher levels of water deficits caused significant yield reductions. Among different vegetable crops, eggplant (*Solanum melongena* L.) and onion (*Allium cepa* L.) seem to perform well under water deficits, whereas leafy greens such as lettuce (*Lactuca sativa* L.) experienced consistent losses in yield

(Table 1). However, considering the differences among these studies with regard to the environment, cultivars, types of DI strategies, and DI levels, our ability to make strong conclusions using past literature is restricted. Because of these discrepancies, contrasting results have been reported, even within the same species. Lahoz et al. (2016) reported a 16.4% reduction in marketable tomato (*Solanum lycopersicum* L.) fruit yield with a mild water deficit (75% ET_c) compared with full irrigation (100% ET_c), whereas the total soluble solids (TSS) and lycopene content increased by 8.4% and 6.9%, respectively. Nangare et al. (2016) concluded that fruit yields statistically similar to those with 100% ET_c could be obtained either with DI at 80% ET_c throughout the growing season or with 60% ET_c during the vegetative growth phase and 100% ET_c during the remaining phases of the tomato crop. Recently, Hashem et al. (2018) observed 17.8% and 15.2% declines in tomato fruit yields using RDI and PRD with a 30% water deficit (70% ET_c), respectively. The yield losses were higher with RDI during the first year, whereas the lowest yield was obtained with PRD during the second year, which was in agreement with the transpiration rates. However, the ABA concentration in xylem was highest, and stomatal conductance (g_s) and photosynthesis were lowest with PRD during both years. The irrigation water use efficiency (IWUE) values were inconsistent because RDI treatment resulted in the lowest IWUE during the first year and the highest during the second year. Additionally, both water deficit treatments improved the TSS, titrable acidity, and vitamin C content of tomato fruits compared with full irrigation treatment. A potato (*Solanum tuberosum* L.) field study revealed that RDI and PRD treatments caused a substantial reduction in fresh as well as dry tuber yield compared with full irrigation treatment (Zin El-Abedin et al., 2017). The IWUE also declined under these DI treatments.

Ertek and Kara (2013) used four DI rates as a percentage of soil water deficit in sweet corn (*Zea mays* var. *saccharata*). It was suggested that 15% DI (85% of full irrigation) could serve as an alternative to full irrigation without any significant decrease in

Table 1. Review of deficit irrigation (DI) studies of vegetable crops

Crop	Number of reports	Growth and yield reports (%)		
		Decreased	No significant difference	Increased
Tomato	33	42	52	6
Pepper	16	69	25	6
Potato	19	63	37	0
Eggplant	5	20	80	0
Cucumber	8	75	25	0
Lettuce	12	66	33	0
Muskmelon	10	50	30	20
Watermelon	13	62	38	0
Squash	2	50	50	0
Onion	7	14	86	0
Sweet Corn	4	25	75	0
Green bean	5	40	60	0
Total	134	52	44	4

the sweet corn yield. The protein and sugar contents, two important quality parameters for sweet corn, decreased at the highest level of irrigation and were found to be highest at 70% DI. Using a greenhouse experiment, Rahil and Qanadillo (2015) found that the cucumber (*Cucumis sativus* L.) crop yields under 70% ET_c irrigation treatment were 4%, 6%, and 24% higher compared with 100% ET_c, farmer irrigation, and tensiometer-based irrigation treatments, respectively. The water applied using farmer irrigation corresponded to the traditional application based on growth stage and plant observation. The tensiometer-based irrigation treatment involved the application of water when the reading approached 50–60 kPa. The WUE was also found to be highest under 70% ET_c, thereby saving a large amount of water.

To enhance the water extraction abilities under water stress, plants undergo root adjustments that may vary with the soil type and cultural amendments. This ability of the plants to modify root distribution can be a key mechanism to counter drought stress. Sharma et al. (2018) found that the root length intensity of *reticulatus*-type muskmelon increased in the deeper layers of soil under DI (50% ET_c) compared with 100% ET_c. Similarly, the water shortage promoted root growth of sweet corn plants in deeper soil layers, displaying a significant increase in root dry matter with increasing water deficit for 2 consecutive years (Oktem, 2008). On the contrary, Wang et al. (2019) noted a decline in the total root volume, root surface area, and root weight density of a tomato crop with decreasing levels of irrigation. A greenhouse field study by Rahil and Qanadillo (2015) also revealed a decline in the underground biomass of cucumber plants when subjected to water deficit.

In most of the reviewed studies, small water deficits (70% to 90% ET_c) increased the WUE of the majority of vegetable crops (Alenazi et al., 2015; Çolak et al., 2017; Kuşçu et al., 2015; Rop et al., 2016; Sezen et al., 2019), but often there was a loss in yields (Abd El-Mageed et al., 2017; Ierna and Mauromicale, 2018; Sezen et al., 2014). Nevertheless, a considerable number of reports revealed that similar yields or marginal declines in yields could be achieved using mild DI levels, thus saving significant amounts of irrigation water. The use of DI strategies for vegetable crops have the potential to improve water productivity, but the ability of vegetable crops to sustain crop productivity is uncertain because of frequent losses in yields, as revealed by past literature. To minimize yield losses in vegetable crops when using DI, Costa et al. (2007) suggested the integration of DI with other strategies such as protected cultivation or mulching. During recent years, biochar amendment has gained popularity as a drought management tool that is increasingly being investigated to determine its combination with DI strategies to sustain the productivity of different crops, including vegetables.

How Might Biochar Improve Vegetable Productivity under Water Stress?

Understanding the underlying mechanisms by which biochar amendments can improve crop yields, particularly by alleviating drought stress, is of considerable interest. Evaluating the capacity of biochar to increase soil water content and plant available water (PAW) is a key factor for determining its potential as a soil amendment for sustaining crop growth in water-limited regions. The water-holding capacity and PAW are largely determined as functions of the physical properties of soil. In recent years, the effects of biochar on the physical, chemical, and biological properties of soil have been extensively investigated and reviewed (Atkinson and Aitkenhead, 2018; Blanco-Canqui, 2017; Ding et al., 2016). Based on the published reports and literature reviews, biochar application generally increases soil porosity and decreases particle density and bulk density, although the degree of responses may vary with respect to soil type, biochar feedstock, pyrolysis conditions, and study duration (Spokas et al., 2012). For instance, these effects are more pronounced in sandy soils with coarse textures compared with clay soils with fine textures (Blanco-Canqui, 2017). The alteration in soil physical properties due to biochar addition is mainly attributed to its low density compared with soil particles. Furthermore, being a product of pyrolysis of organic material, biochar can serve as a binder and stimulate aggregate formation because of the strong correlation between organic matter content and aggregate stability (Blanco-Canqui, 2017; Jien and Wang, 2013; Verheijen et al., 2010). The literature review showed that biochar application has a positive influence on soil aggregate formation by increasing the wet aggregate stability significantly and improving the stability of dry aggregates to some extent; in turn, this improves the soil porosity and water movement. As indicated by the published literature, the addition of biochar causes an alteration in water infiltration and hydraulic conductivity depending on soil texture (Blanco-Canqui, 2017). Generally, water infiltration and hydraulic conductivity decrease with biochar addition in soils with coarse textures, increase in soils with fine textures, and remain nearly the same in soils with medium textures (Busscher et al., 2011; Githinji, 2013; Novak et al., 2016). However, these results are based mostly on short-term laboratory studies; therefore, further long-term field investigations to gain a better understanding of soil texture–biochar interactions are necessary.

The alterations in the water-holding capacity of soil have been widely studied (Paneque et al., 2016; Zhang et al., 2016). The application of biochar has shown a consistent increase in the water retention ability of soils, although the results are more noticeable in coarse-textured soils compared with fine-textured clay soils (Blanco-Canqui, 2017). By combining the available reports,

Blanco-Canqui (2017) found that the biochar addition increased the water-holding capacity of different soils in 90% of the studies. The increase in soil water content can improve PAW, which approximately occurs between field capacity and the permanent wilting point. However, an increase in water retention does not necessarily increase the PAW. Blanco-Canqui (2017) found that biochar had a positive effect on PAW in 72% of the reported cases.

Drought stress adversely affects the activity of soil microbes, which are known to have a crucial role in maintaining soil fertility, structure, soil respiration, and decomposition of soil organic matter (Tayyab, 2018). This is evident from the fact that ≈90% of the total soil organic matter is decomposed by soil microbes, which, in turn, determines the nutrient availability to the plants (Bastida et al., 2013). Among the soil microbial communities, the bacterial communities, which have a direct impact on soil structure and fertility, are highly affected by moisture stresses (York, 2012). Biochar benefits soil biota under drought stress by modifying the habitat, increasing available water, and stabilizing microbial activity during dry–wet cycles (Tayyab, 2018).

The improvements in water retention, PAW, and biological activity suggest that biochar incorporation may reduce the irrigation needs of vegetable crops and help save water in drought-prone regions without affecting crop productivity. Several studies combining the biochar amendment and reduced irrigation technique as an integrated approach with the aim of sustaining vegetable production in water-deficient areas were surveyed in literature, which will be further discussed in this review.

Impact of Biochar on Growth, Yield, and Quality of Vegetables under DI

Soil amendments using biochar have been reported to have positive effects on plant development, biomass production, and yield of many vegetable crops under moisture stress conditions. Mulcahy et al. (2013) observed an increase in the wilting resistance of tomato seedlings raised in pots with the application of 30% (v/v) biochar prepared from wood pellets. Another greenhouse pot experiment performed by Akhtar et al. (2014) found that 5% (w/w) application of rice (*Oryza sativa* L.) husk and cotton seed shell biochar increased the fruit yield of tomato plants subjected to 30% DI and partial root-zone drying irrigation by 6% and 13%, respectively. In this study, the full irrigation treatment involved daily irrigation of pots to water-holding capacity. Biochar application also improved the fruit quality by increasing the titratable acidity, but its effects on TSS and vitamin C were not significant. A fairly similar trend was observed by Agbna et al. (2017), who reported an increase in titratable acidity, vitamin C content, and sugar/acid content ratios of tomato fruits with biochar addition without significantly affecting the

TSS under all levels of irrigation. The plants exposed to water stress treatments had higher values for almost all of the quality parameters compared with the unstressed plants. During this greenhouse experiment, Agbna et al. (2017) found that the tomato plots that received 25 t·ha⁻¹ wheat straw biochar and water stress treatment had fruit yields that were statistically similar to those of the unstressed control plots. The increased yield was accompanied by increases in the plant height, number of leaves per plant, and fresh and dry plant weights. Li et al. (2018) drew similar conclusions from field experimentation; they reported that 30 t·ha⁻¹ biochar along with DI treatment can help save water without significantly affecting the total tomato productivity. In this experiment, increasing the application rates of maize straw biochar from 10 to 40 t·ha⁻¹ increased plant dry biomass and fruit yield, with higher application rates having nonsignificant effects or a negative impact on plant growth and yield. A cost–benefit analysis suggested that the net profit compared with that of nonbiochar treatment was positive with biochar applications of 10, 20, and 40 t·ha⁻¹ but negative with an application of 60 t·ha⁻¹. A quadratic function fitting net profit compared to the biochar application rate indicated that 27 t·ha⁻¹ was the optimal application rate. Recently, Langeroodi et al. (2019) observed maize straw biochar application of 10–15 t·ha⁻¹ was a critical application rate for improving the seed yield for a pumpkin (*Cucurbita pepo* L.) crop subjected to water deficit stress.

After a 6-week greenhouse pot experiment, Batool et al. (2015) reported increases in leaf area, plant height, and dry weight of water-stressed okra (*Abelmoschus esculentus* L. Moench) plants with the addition of 1% (w/w) biochar prepared from stems of *Lantana camara*. Remarkably, the dry weight of stressed plants raised in biochar-amended pots was significantly higher compared with nonstressed untreated pots. Yakubu (2016) found that biochar improved the okra fruit yield under DI but had no significant effect under ET_c-based full irrigation, indicating that biochar effects are more prevalent in water-limited environments. A lysimeter experiment revealed that biochar application to sandy soil could enhance the growth, dry matter accumulation, and pod yield of green pea (*Pisum sativum* L.) plants under low water availability (Youssef et al., 2018). Pine wood biochar application (2% w/w), alone or its combination with compost and/or plant growth promoting rhizobacteria (PGPR), has been reported to be a promising strategy to enhance cucumber plant growth under drought stress (Nadeem et al., 2017). The addition of biochar to pots subjected to water deficit increased the root and shoot fresh weights and length of cucumber plants. However, the highest fresh weights and lengths were obtained when biochar, compost, and PGPR were applied in combination. Recently, Ali et al. (2018) observed that the application of biochar to cucumber field plots

increased fresh and dry aboveground and underground biomass and the total yield of cucumber plants undergoing stress due to water deficit. In agreement with prior reports, biochar addition compensated for the loss in yields due to water deficit. On the contrary, Liu et al. (2017) reported a decrease in total plant biomass in biochar-treated potato pots under a reduced irrigation regime. This decline in biomass was correlated with reduced nitrogen (N) and phosphorus (P) uptake by plants, with the former having a greater impact. Additionally, biochar application also suppressed the activity of Arbuscular mycorrhizal fungi.

In general, the literature affirmed that biochar application could improve growth and minimize yield losses due to water deficits in vegetable crops, although the degree of response varied with crop species, soil type, and biochar material (Table 2). The addition of biochar also had beneficial effects on some quality parameters, but a limited number of reports are available. As expected, effective rates of biochar varied substantially among different soil types, and some of these inconsistencies in critical biochar rates may also be due to different crop species. One of the limitations of these biochar–DI studies was that most of these studies were conducted as greenhouse pot experiments. In potted soils, the natural structure of the soil is altered, thus disturbing soil biota and the balance between air and water, thereby modifying important soil physical properties such as bulk density, porosity, and water-holding capacity. Therefore, the pot experiments may not provide a true reflection of crop performance under natural field conditions.

Impact of Biochar on Vegetable Physiology under DI

Several physiological and morphological modifications occur in crop plants in response to drought stress. Loss of turgor due to moisture stress restricts cell elongation and division, leading to reduced plant growth (Lawlor and Cornic, 2002), which reduces the light interception. Water stress reduces the chlorophyll content and g_s , subsequently moderating the photosynthetic activity. There is considerable evidence in the literature showing improvements in the physiology of water-stressed crop plants, including vegetables, with biochar application. The studies that explored the effects of biochar–DI interactions on the physiology of vegetable crops are summarized in Table 2. Akhtar et al. (2014) reported that biochar addition significantly increased the photosynthetic rate (P_n) and relative water content (RWC) of tomato plants exposed to water deficiency, but that the chlorophyll content was higher in untreated plants. The reduction in the chlorophyll content of biochar-treated plants may be attributed to the adsorption of NH₄⁺ ions on the biochar surface, resulting in reduced N uptake, which was evident from the lower leaf N content observed in biochar-treated plants compared with nonbiochar plants.

Similarly, Agbna et al. (2017) observed a significant improvement in P_n and leaf transpiration rates in stressed as well as nonstressed tomato plants treated with biochar. Biochar application ameliorated the declines in g_s and transpiration rates, and it significantly improved the P_n of okra plants exposed to drought stress over a period of 6 weeks (Batool et al., 2015). Water stress can induce physical and chemical modifications in biological membranes, subsequently affecting the membrane stability with respect to the leakage of ions such as sodium and potassium. Electrolyte leakage, measured as electrical conductivity due to effused ions from the leaves, is regarded as an indicator of membrane stability to moisture stress. Biochar application reduced electrolyte leakage from water-stressed as well as nonstressed cucumber plants (Nadeem et al., 2017). The chlorophyll content and RWC significantly decreased with increasing water deficits; however, biochar application displayed a compensatory effect by improving both these parameters (Nadeem et al., 2017). In a lysimeter experiment, Youssef et al. (2018) also reported an increase in chlorophyll content and RWC with biochar application for pea plants exposed to drought stress. Langeroodi et al. (2019) also reported a similar trend in a pumpkin field trial wherein P_n , g_s , chlorophyll content, transpiration rate, and RWC increased with increasing biochar rates from 0 to 20 t·ha⁻¹, although the increase was more evident in irrigation regimes with 75% and 90% of maximum allowable depletion of available soil water than irrigation treatments with 45% and 60% maximum allowable depletion, respectively.

Impact of Biochar on WUE of Vegetable Crops under DI

In water-limited arid and semi-arid regions, WUE serves as a good indicator of crop productivity as it relates to water use. Improvement in WUE implies decreased susceptibility of plants to water stress in drought-prone areas. The WUE could be increased by applying reduced irrigation and exposing the plants to small water deficits. However, drought-sensitive crops, especially vegetables, may show stress signs and losses in yield and quality. Biochar has been known to further increase the WUE of vegetables and alleviate drought stress symptoms. A summary of some reports used in this review is presented in Table 2. Akhtar et al. (2014) and Agbna et al. (2017) reported that biochar amendment improved the WUE of tomato plants exposed to water stress as well as nonstress treatments. A 2-year tomato field experiment revealed that water productivity (calculated as yield/actual ET) increased with biochar additions of 10, 20, 30, and up to 40 t·ha⁻¹ and decreased with higher application rates of 60 t·ha⁻¹ (Li et al., 2018). Similarly, biochar application increased the WUE of okra plants subjected to water deficit; the highest WUE was observed in biochar-treated pots maintained at 60% field capacity.

Table 2. Effect of biochar on growth, yield, physiology and water use efficiency (WUE) of vegetable crops under deficit irrigation (DI) regimes.

Crop	Soil type	Feedstock	Growth and yield	Physiology	WUE	Reference
Tomato	Sand/loam; pots	Wood pellets	30% (v/v) treatment increased wilting resistance of seedlings	—	—	Mulcahy et al. (2013)
Tomato	Sandy loam; greenhouse pots	Rice husk and cotton seed shells	5% (w/w) treatment increased fruit yield by 13% under PRD irrigation	5% (w/w) application increased P_n and RWC under PRD irrigation	Increased WUE of stressed and nonstressed plants	Akhtar et al. (2014)
Okra	Sandy loam; pots	Stems of <i>Lantana camara</i>	1% (w/w) treatment produced higher dry matter in stressed plants than untreated nonstressed plants	1% (w/w) biochar + 60% FC treatment gave highest P_n	1% (w/w) biochar + 60% FC treatment gave highest WUE	Batool et al. (2015)
Cucumber	Clay loam; greenhouse pots	Pine wood	2% (w/w) treatment increased root and shoot fresh weight	Increased chlorophyll content and RWC and decreased electrolyte leakage	—	Nadeem et al. (2017)
Tomato	Loam-clay loam; greenhouse plots	Wheat straw	25 t ha ⁻¹ biochar + water stress treatment resulted in yield similar to those of untreated nonstressed plants	Increased P_n and leaf transpiration of stressed and nonstressed plants	Increased WUE of stressed and nonstressed plants	Agbna et al. (2017)
Potato	Sandy loam; greenhouse pots	Birch wood	0.74% (w/w) application reduced plant biomass	—	Decreased	Liu et al. (2017)
Cucumber	Clay loam; field plots	—	20 t ha ⁻¹ treatment under 60% DI resulted in growth and yield similar or higher than those of untreated 100% irrigation plots	—	Increased WUE under all irrigation treatments	Ali et al. (2018)
Tomato	Sandy loam; field plots	Maize straw	Increased yield up to 40 t ha ⁻¹ treatment.	—	Water productivity increased up to 40 t ha ⁻¹ treatment	Li et al. (2018)
Green pea	Sand; lysimeter	Orange wood	1% (w/w) treatment increased pod yield of stressed and nonstressed plants	Increased chlorophyll content and RWC, especially in stressed plants	—	Youssef et al. (2018)
Pumpkin	Silty loam; field plots	Maize straw	Increased yield; critical biochar application rate: 10–15 t ha ⁻¹	Increased chlorophyll content and RWC, P_n nonsignificant	Increased WUE under all irrigation treatments	Langeroodi et al. (2019)

PRD = partial root zone drying; RWC = relative water content; P_n = photosynthesis; FC = field capacity; WUE = water use efficiency.

Conclusion

Water scarcity is emerging as a major challenge for the agriculture sector, not only in water-limited arid and semi-arid areas but also in those regions that were originally water-sufficient. Agricultural sustainability demands serious adoption of water conservation strategies, especially in water-intensive vegetable production systems. The previous literature revealed that DI strategies improve the WUE of vegetable crops and could be used to save significant amounts of irrigation water. This has even greater relevance in water-scarce areas where water productivity is given more emphasis than production per unit area, with expected water use restrictions and higher water prices in the near future. However, an extensive review of DI for vegetable crops suggested that these practices are usually associated with yield losses, thereby causing uncertainty concerning the sustainability of vegetable productivity. Soil amendment using biochar is emerging as an effective water stress management practice. Improvement in the water retention capacity and PAW and the promotion of biological activity are the major mechanisms by which biochar benefits crop plant under moisture stress. Published reports have shown that biochar application under DI can compensate for the yield losses, improve crop physiology, and further increase the WUE of vegetable crops. In a broad sense, this review concluded that the combination of DI strategies and biochar amendments has the potential to serve as an effective approach to save water and sustain vegetable productivity. Nevertheless, there is ample opportunity and need to explore multiple soil/DI/biochar/plant interactions and close the research gaps by focusing on the following areas:

- Integration of DI and biochar has been studied in few vegetable species, and only a few reports exist. These interactions need to be investigated in more species. Simultaneous experimentation in different species will provide a perspective to compare the responses to these practices.

In a cucumber field experiment, WUE decreased significantly with decreasing irrigation levels; however, biochar application improved WUE under all levels of irrigation treatments (Ali et al., 2018). Recently, Langeroodi et al. (2019) observed a similar trend with biochar addition to pumpkin plots under different water stress levels. In contrast to these reports, Liu et al. (2017) witnessed a significant decrease in WUE with a corresponding decrease in plant biomass for biochar-treated potato pots compared with untreated pots under water stress. This decrease in WUE with biochar application was associated with decreased yield, which was attributed to reduced N and P uptake by the plants. Nevertheless, published reports indicated an overall increase in WUE with biochar addition, especially under moisture stress conditions.

- Most of these investigations have been performed in greenhouse or laboratory settings. With large variability in soil and climatic conditions, biochar effects under open field conditions may differ from controlled laboratory and greenhouse pot experiments. To extend practical recommendations, more open-field studies need to be conducted before large-scale deployment in the fields.
- Published results are largely based on short-term studies (≤ 2 years). Biochar reactions and interactions with soil particles may vary over time, which would modify the physical and chemical properties of the soil. Long-term field studies could only verify the viability of these applications in the long-term. Collaboration with local farmers and starting with small acreage are some of the possibilities when initiating such long-term field experiments.
- The economic feasibility of DI and biochar amendments needs to be investigated and reviewed. In light of expected increments in water prices and restrictions in the near future, water productivity should also be taken into account. Biochar costs can be curtailed by testing and promoting the use of locally available organic material (e.g., crop residue) as feedstock.
- The crop simulation modeling approach could be followed to optimize DI levels and biochar rates for different vegetable crops under diverse soil and climate conditions.

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