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Biochar-Aided Tomato Cropping in Desert Sandy Soils. An Agronomic Value

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Abstract

Biochar amendment offers a promising strategy to enhance soil physicochemical performance and yield response in nutrient-poor sandy soils; however, its effectiveness depends strongly on feedstock type and application rate. This field study assessed the agronomic and sandy soil responses of tomatoes to biochars derived from date palm, maize, and potato residues, applied at 0, 2, 4, 8, and 16 t·ha^{-1} under desert conditions in southeastern Algeria. Biochars were characterized for physicochemical and structural properties, and their effects on soil carbon, nutrient availability, and tomato yield were evaluated. The results showed that biochar application significantly increased soil total organic carbon (TOC) and total yield, particularly at low application rates. Date palm biochar applied at 2 t·ha^{-1} produced the highest yield improvement, whereas excessive application tended to suppress yield. In contrast, soil N, P, and K did not show statistically significant differences among treatments, although slight numerical increases were observed compared to the control at medium application rates (4–8 t·ha^{-1}). These findings highlight the importance of optimizing biochar application rates according to feedstock type to maximize agronomic benefits. Overall, moderate biochar application represents a promising strategy for improving soil organic carbon status and crop productivity in desert sandy soils agroecosystems.

Keywords: biochar; desert sandy soil; tomato yield; nutrient dynamics; total organic carbon (TOC); sustainable soil management

1. Introduction

Sandy soils cover about 64.5% of the Earth's surface and are most extensive (51%) in Africa [1,2]. Despite their broad distribution, these soils are generally nutrient-poor, highly degradable, and characterized by low water and nutrient retention, limiting crop productivity particularly in arid and semi-arid regions, where food security concerns are most acute [3,4].

Algeria, the largest country in Africa is dominated by the Sahara, which covers more than 90% of its territory. In the northeast, the province El-Oued lies at the edge of the Grand Erg Oriental, where dune sands rich in α-quartz (≈80%) and alluvial sands with slightly lower silica (≈70%) but higher CaO content prevail. Minor fractions of calcite, gypsum, and trace oxides (Al_2O_3, Fe_2O_3, K_2O) are also present. This hyper-arid region is characterized by extreme temperatures exceeding 49 °C, annual rainfall below 130 mm, and the seasonal Sirocco winds sweeping northward from the desert [5].

Ensuring sustainable soil management in arid regions depends on restoring fertility, integrating innovative practices, and reinforcing resilience for future productivity [6,7]. Biochar has been widely investigated for its roles in enhancing soil fertility, managing waste, sequestering carbon, and generating renewable energy [8]. Its porous structure and high surface area support microbial habitats, enrich populations of bacteria, actinomycetes, and arbuscular mycorrhizal fungi, and thereby reduce nitrogen losses and improve nutrient cycling [9]. Biochar inputs also improve soil pH, electrical conductivity, organic carbon, cation exchange capacity (CEC), and water-holding capacity, while reducing leaching, immobilizing contaminants, and lowering greenhouse gas emissions [9–11]. These benefits are strongly linked to soil microbiome responses, which regulate nutrient dynamics; organic amendments such as biochar enhance microbial diversity and resilience, whereas excessive use of mineral fertilizers disrupts biological community stability [12].

Biochar further serves as a stable carbon source that enhances soil organic matter and provides niches for beneficial microbes, reinforcing nutrient cycling and decomposition [13]. Its influence depends on microbial groups, feedstock origin, and production methods, which shape nutrient cycling outcomes [14]. Feedstock type critically determines biochar properties such as porosity, density, pH, and CEC, thereby affecting soil health and crop response [14–18]. Converting crop and agroforestry residues into biochar thus provides a sustainable pathway to improve sandy soils quality and their resilience to climate change, and enhance food security [9].

In tomatoes (*Solanum lycopersicum* L.), one of the most consumed vegetables worldwide [19], biochar application improves soil fertility and plant performance. Studies have shown yield increases of 10–40%, depending on feedstock, rate, and soil condition [13,20] with positive effects on plant height, biomass, leaf number, and water status [21]. Optimal responses are typically observed at 10–30 $t \cdot ha^{-1}$, while excessive doses may cause nutrient imbalances or pH issues [20]. The response of sandy soil properties and tomato yield to increasing biochar application rates typically follows a positive, but sometimes non-linear, trend [13].

Evidence on biochar's effects in sandy soils remains limited and inconsistent, especially regarding amendment type, application rate, and tomato yield response. The absence of systematic dose–response studies further restrict the development of practical, evidence-based guidelines for sandy soil management.

This study addresses a knowledge gap by evaluating the effects of three locally available crop residues converted to biochar and their application rates on sandy soil properties and tomato yield without supplying any mineral fertilization. The findings offer insights for developing precise and sustainable soil management strategies.

2. Materials and Methods

2.1. Site Description

The experiment was conducted in open field conditions on a private farm in Guemar city (33°30′21.60″ N; 6°45′32.94″ E), located in the wilaya of El Oued, southeastern Algeria, to assess the effect of various biochar types on tomato yields and sandy soil properties. The soil type is classified as desert (Aridosols), where the mineral fraction constitutes almost all the sand, whereas the organic fraction is very low (less than 1%) [22]. This region is characterized by a very dry climate with extremely hot and dry summers and an average temperature of up to 45 °C and 1 °C in winter. Precipitations are characterized by high variability and scarcity, with an annual average of 80 mm. Winds are frequent, cyclical, and change their directions according to the season [23].

2.2. Palm, Potato, and Maize Biochar Preparation

Three diverse sources of dry plant waste common to the region were collected for biochar production: date palm (fruit holders, leaf bases), potato (all parts of the plant after potatoes harvest), and maize crop residues. Biochar was produced using a double-barrel pyrolysis unit. This method utilizes two barrels: a smaller 100 L inner barrel to hold the feedstock, and a larger 200 L outer barrel that serves as the combustion chamber. Heat is generated by controlled wood combustion in the outer chamber, which is regulated by a specific air intake hole and a chimney stack for gas exhaust (Figure

1a). The primary goal is to maintain the inner chamber's target temperature between 300 and 550 °C for at least three hours. After natural cooling, each type of pyrolyzed biochar was ground and screened with a 02 mm sieve (Figure 1b). The recovered powders were subjected to further physical and chemical analyses.

Figure 1. Palm, potato, and maize biochar preparation. (a) The double-barrel pyrolysis unit; (b) The biochar produced using a double-barrel pyrolysis unit.

2.3. Experimental Setup

The experiment took place from mid-August 2022 until mid-February 2023. A field plot measuring 50 m × 25 m, with no prior cultivation history was prepared by plowing to a depth of 30 cm, followed by leveling, installing windbreaks and a drip irrigation system (Figure 2a). Sandy soils are typically nutrient-poor and have low water-holding capacity, requiring substantial organic inputs to improve physical structure, increase nutrient retention, and enhance biological activity [24]. The application of organic amendments such as sheep manure has been widely reported to improve soil physicochemical properties, promote microbial activity, and supply nutrients in a slow-release form that supports crop establishment in degraded soils [25]. Due to the extremely sandy texture and very low fertility status of the experimental soil, sheep manure was applied at 40 $t{\cdot}ha^{-1}$ prior to planting, following the rate recommended by the Technical Institute for the Development of Saharan Agriculture [26], and commonly used by farmers in the region. In this study, sheep manure was used as the sole nutrient-based fertilizer source within a sustainable soil management approach, with no mineral fertilizers applied.


(a) (b)

Figure 2. Study area (a); Planting tomato seedlings (b).

Using a completely randomized design (RCBD), the area was divided into 39 subplots (each 2.20 m × 1.80 m) to accommodate 13 treatments with three replicates each. Treatments consisted of four biochar application rates (2, 4, 8, and 16 t·ha^{-1}) plus a control (no biochar) Table 1. Sheep manure first and biochars were incorporated into the soil to a depth of 20 cm.

Table 1. Treatments and rate of biochar.

Type	Treatments	Rate (t·ha^{-1})
Control	Control_0	0
Biochar date palm residues (DP)	DP_2	2
	DP_4	4
	DP_8	8
	DP_16	16
Biochar maize residues (MZ)	MZ_2	2
	MZ_4	4
	MZ_8	8
	MZ_16	16
Biochar potato residues (PT)	PT_2	2
	PT_4	4
	PT_8	8
	PT_16	16

Planting: On 1 September 2022, 25-day-old determinate tomato seedlings (Petra F1) were transplanted to the field at a density of six plants per subplot. The spacing was 0.80 m within rows and 1.20 m between rows, resulting in a planting density of 15252 plants/ha (Figure 2b).

Harvesting: During the period from 10 December 2022 to mid-February 2023 harvesting was performed in five phases. In each subplot, fruit number and weight were recorded, and fruit size was categorized by diameter as <50 mm, 5–7 mm, 7-10 mm and ≥10 mm.

End of experiment: After final harvest, 39 representative soil samples were collected at a depth of 0–20 cm from all the 39 plots using a hand auger. Following collection, the samples were air-dried and passed through a 2 mm sieve, before they were secured in polyethylene bags and transported for laboratory analysis.

2.4. Laboratory Procedures for Physicochemical Characterization of Biochar and Soil

The physicochemical properties of biochars date palm (DP), biochar maize (MZ), biochar potato (PT), and soils samples were determined at the Department of Agricultural Chemistry and Environmental Biogeochemistry at Poznan University of Life Sciences (Poland). The pH was measured by a pH meter (CPC 411, Elmetron, Zabrze, Poland) with a combination electrode (IJ44AT, Elmetron, Zabrze, Poland), respectively at 1 M KCl dm^{-3} (ratio soil /solution: 1:2.5) as well as aqueous solution at 1:2.5 ratio. The Total Specific Surface Area $SSA_{(EGME)}$ was determined using the Ethylene Glycol Monoethyl Ether (EGME) retention method, as described by [27] and further refined by [28]. The External Surface Area SSA (N_2) was quantified through the Brunauer-Emmett-Teller (BET) gas adsorption technique, utilizing nitrogen (N_2) as the adsorbated gas at cryogenic temperatures. By integrating both measurements, the Internal Surface Area (SSA_{int}) was subsequently calculated as the difference between SSA_{EGME} and SSA (N_2).

The amounts of both total carbon (C_{Total}) and sulphur (S_{Total}) were assayed by the loss-on-ignition (LOI) method at 900 °C with Eltra CS 580 (C and S Analyzer; Eltra GmbH), whereas total nitrogen (N_{Total}) was determined with the Kjeldahl steam distillation procedure [29].

Soil samples were analyzed also for mineral nitrogen (Nmin = N-NH4 and N-NO3). Briefly,10 g was weighed into 30 mL test tubes and deionized water was added to reach 25 mL. The whole slurry was mixed for 60 min. in a rotary shaker and then allowed to settle for next 60 min. before filtrating. Both forms of nitrogen were determined by Flow Injection Analyzer (FIAstar 5000 Analyzer).

The contents of alkaline elements (Ca, Mg, K, Na) have been evaluated with various testing procedures.

- water-soluble fractions of Ca, Mg, K, and Na were determined in aqueous extracts, after pH measurements.

- exchangeable pools of Ca, Mg, K, and Na have been extracted with 1 M CH3COONH4 dm^{-3} (pH 7.0; soil /solution ratio at 1:10). This procedure was used for assessing the cation exchange capacity (CEC) of the soils [30] Chemical elements such as phosphorus and micronutrients (Cu, Zn, Mn, Fe) critical for crop plants were extracted with the Mehlich-3 (M_3, pH 2.5) soil test [31] Ten grams soils were weighed into 100 mL (ratio 1:10) test tubes and M_3 was added at the volume of 100 mL. The whole solution was mixed for 30 min and then allowed to settle for 1 hour before filtrating. Phosphorus as orthophosphate ions was measured at wavelength 690 nm after first yellow molybdophosphate formation and its reduction with tin (II) chloride producing phosphomolybdate blue. Micronutrients have been determined by Atomic Absorption Spectrometer (AAS) Thermo iCE 3000 SERIES procedures.

2.5. Statistical Analysis of Experimental Data

The collected data for soil samples and yield were subjected to statistical analysis by conducting a one-way analysis of variance under RCBD. When the ANOVA indicated significant treatment effects, mean values comparisons were assessed using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$. All statistical analysis of the data was performed using R software v 4.5.0 [32].

3. Results

3.1. Biochar Characterization

The characterization of date palm (DP), maize (MZ), and potato (PT) biochars revealed distinct physicochemical and elemental properties that are critical for understanding their potential applications. The basic properties, as detailed in (Table 2), showed significant variations. Potato biochar exhibited the highest alkalinity (pH 10.2) and a remarkably high electrical conductivity (EC) of 30.2 mS·cm^{-1}, indicating a greater liming potential and higher soluble ion content compared to date palm (pH 9.34, EC 6.5 mS·cm^{-1}) and maize (pH 8.60, EC 10.3 mS·cm^{-1}) biochars. In terms of carbon content, date palm biochar possessed the highest total carbon (59.07%), closely followed by maize (54.90%), while potato biochar had a substantially lower carbon content (23.46%). Conversely, potato biochar contained the highest total nitrogen (2.13%) and consequently the narrowest C/N ratio (11), distinguishing it from date palm biochar which had a significantly wide C/N ratio (92.30), suggesting a higher potential for nitrogen immobilization.

Further characterization of the specific surface area (SSAEGME) presented in (Table 2) indicated that potato biochar consistently demonstrated the largest total SSA (1528.19 m^2·g^{-1}), external SSA (364.06 m^2·g^{-1}), and internal SSA (1164.13 m^2·g^{-1}). These values were significantly higher than those for date palm (Total SSA 878.50 m^2·g^{-1}) and maize (Total SSA 932.39 m^2·g^{-1}) biochars, implying a greater capacity for adsorption and water retention for potato-derived biochar.

Table 2. physicochemical properties of biochars investigated in the study.

Parameters	Biochar - Date palm	Biochar - Maize	Biochar - Potato
pH_{H2O}	9.34	8.6	10.21
EC (mS·cm^{-1})	6.5	10.3	30.2
Total C (%)	59.07	54.9	23.46
Total N (%)	0.64	1.63	2.13
C/N ratio	92.3	33.7	11.01
Total SSA (EGME) m^2·g^{-1}	878.5	932.4	1528.2
External SSA (N_2) m^2·g^{-1}	208.9	221.8	364.1
Internal $SSA_{(int)}$ m^2·g^{-1}	669.7	710.6	1164.1
Ca (%)	1.13	1.52	3.97
Mg (%)	1.31	0.46	2.31
K (%)	1.51	1.98	4.09
Na %	0.31	0.82	2.32
P (%)	0.17	0.35	0.49
S (%)	0.94	1.16	4.07
Cu (mg·kg^{-1})	7.94	9.56	10.41
Zn (mg·kg^{-1})	24.99	41.56	56.39
Mn (mg·kg^{-1})	11.63	28.75	38,0
Fe (mg·kg^{-1})	196.63	668.38	645.13

The elemental composition also varied notably among the biochar types. As shown in (Table 2), potato biochar generally contained the highest concentrations of macroelements, including calcium (3.97%), magnesium (2.31%), potassium (4.09%), sodium (2.32%), phosphorus (0.49%), and sulfur (4.07%). This suggests that potato biochar could serve as a more enriched source of essential plant nutrients compared to date palm and maize biochars. For instance, maize biochar showed noticeably lower magnesium content (0.46%) compared to the other two biochar types.

Regarding microelements, Table 2 revealed that potato and maize biochars generally had higher concentrations of zinc, manganese, and iron compared to date palm biochar. Specifically, maize biochar had the highest iron content (668.38 mg·kg^{-1}), while potato biochar led in zinc (56.39 mg·kg^{-1}) and manganese (38.00 mg·kg^{-1}) concentrations. All three biochars contained comparable levels of copper, with potato biochar having a slightly higher amount (10.41 mg·kg^{-1}).

3.2. Soil Physicochemical Characterization

Analysis of variance showed a significant impact of biochar treatments on soil total organic carbon (TOC) content ($p \leq 0.05$). The highest TOC value appeared under treatment PT_2, DP_2 and

PT_4 which was significantly higher than the control (Figure 3a). The lowest TOC content was recorded at MZ_16, showing a statistically significant difference compared with the other treatments (Figure 3a). These results show a general trend of increasing soil carbon with biochar types and application rate, particularly under low and medium (2 t·ha^{-1}, 4 t·ha^{-1}) application doses. However, other measured parameters, including pH, cation exchange capacity (CEC) did not exhibit statistically significant differences among treatment groups ($p > 0.05$), (Figure 3, b and c), indicating that biochar did not substantially alter these soil properties under the experimental conditions (Table 3).

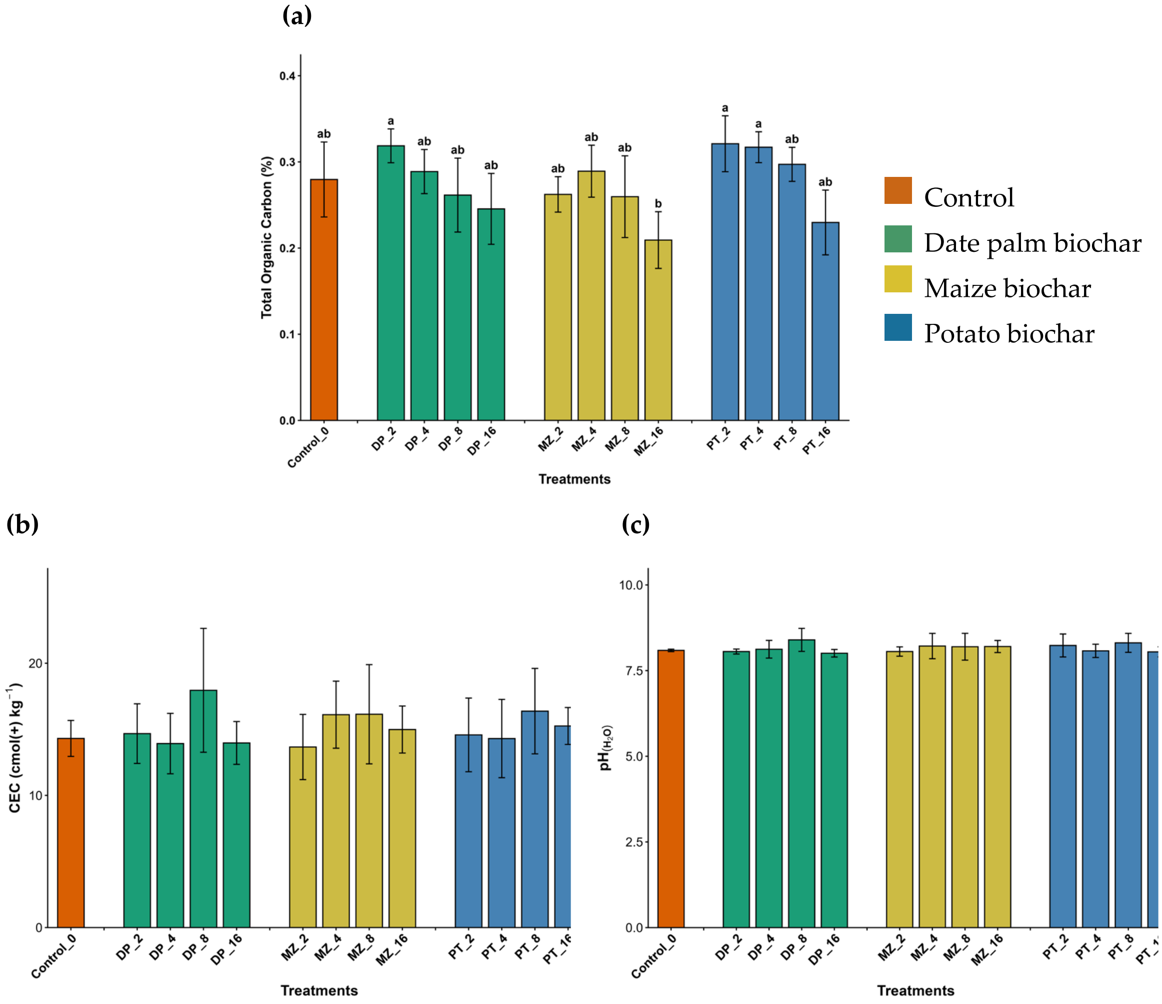

Figure 3. Effects of different treatments on (a) Soil Total Organic Carbon (TOC), (b) Cation Exchange Capacity (CEC) and (c) pH (H2O). Each bar represents the mean value (n=3), and error bars indicate the standard deviation (±SD). Different lowercase letters above the bars denote significant differences between treatments according to Tukey's HSD test ($p < 0.05$).

Table 3. Soil TOC, CEC and pH (Mean ± SE; n = 3) under biochar treatment.

Treatment	TOC (%)	CEC (cmol(+)· kg^{-1})	pH (H2O)
Control_0	0.28 ab ± 0.04	14.31 ± 1.36	8.09 ± 0.04
DP_2	0.32 a ± 0.02	14.67 ± 2.26	8.06 ± 0.07
DP_4	0.29 ab ± 0.03	13.92 ± 2.29	8.12 ± 0.26
DP_8	0.26 ab ± 0.04	17.95 ± 4.68	8.4 ± 0.34
DP_16	0.25 ab ± 0.04	13.97 ± 1.62	8.01 ± 0.11
MZ_2	0.26 ab ± 0.02	13.66 ± 2.47	8.06 ± 0.14

MZ_4	0.29 ab ± 0.03	16.11 ± 2.54	8.22 ± 0.37
MZ_8	0.26 ab ± 0.05	16.14 ± 3.75	8.2 ± 0.39
MZ_16	0.21 b ± 0.03	14.98 ± 1.78	8.2 ± 0.18
PT_2	0.32 a ± 0.03	14.58 ± 2.79	8.23 ± 0.34
PT_4	0.32 a ± 0.02	14.3 ± 2.96	8.08 ± 0.19
PT_8	0.3 ab ± 0.02	16.37 ± 3.23	8.31 ± 0.28
PT_16	0.23 ab ± 0.04	15.25 ± 1.4	8.05 ± 0.15

The linear correlation analysis revealed different relationships between total organic carbon (TOC) content and biochar application rates depending on biochar type (Figure 4). For DP biochar, a moderate negative correlation was observed ($r = -0.51$), which was marginally non-significant ($p = 0.054$). In contrast, MZ biochar showed a significant negative correlation between application rate and soil TOC content ($r = -0.61$, $p = 0.017$). Similarly, PT biochar exhibited a significant negative relationship ($r = -0.59$, $p = 0.020$). These results indicate that increasing biochar rates tended to be associated with a reduction in soil TOC levels, particularly under biochars MZ and PT.

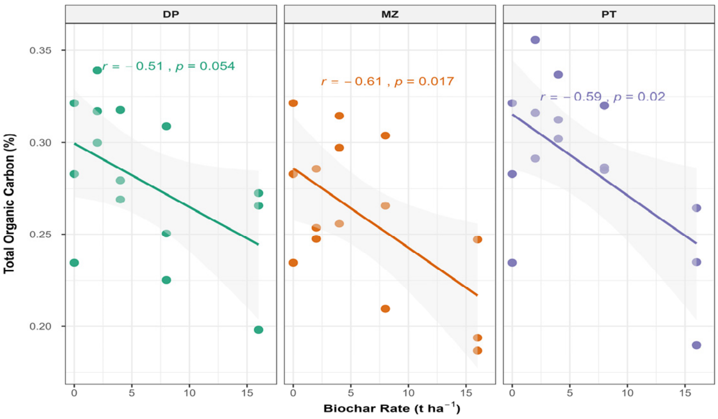

Figure 4. Correlation between biochar application rate and concentration of soil TOC with the control treatment (0 rate) included in the analysis.

3.3. Soil N, P and K Contents

Analysis of variance showed no significant treatment effects on soil Nmin (soil mineral nitrogen), phosphorus (P) or potassium (K) ($p > 0.05$) (Figure 5), indicating that nutrient responses may reflect cumulative or longer-term processes rather than short-term changes. Nevertheless, a numerical increase in N, P, and K levels was observed under biochar treatments compared with the control, particularly for MZ and PT biochars across application rates, as well as DP_4 and DP_8 (Table 4).

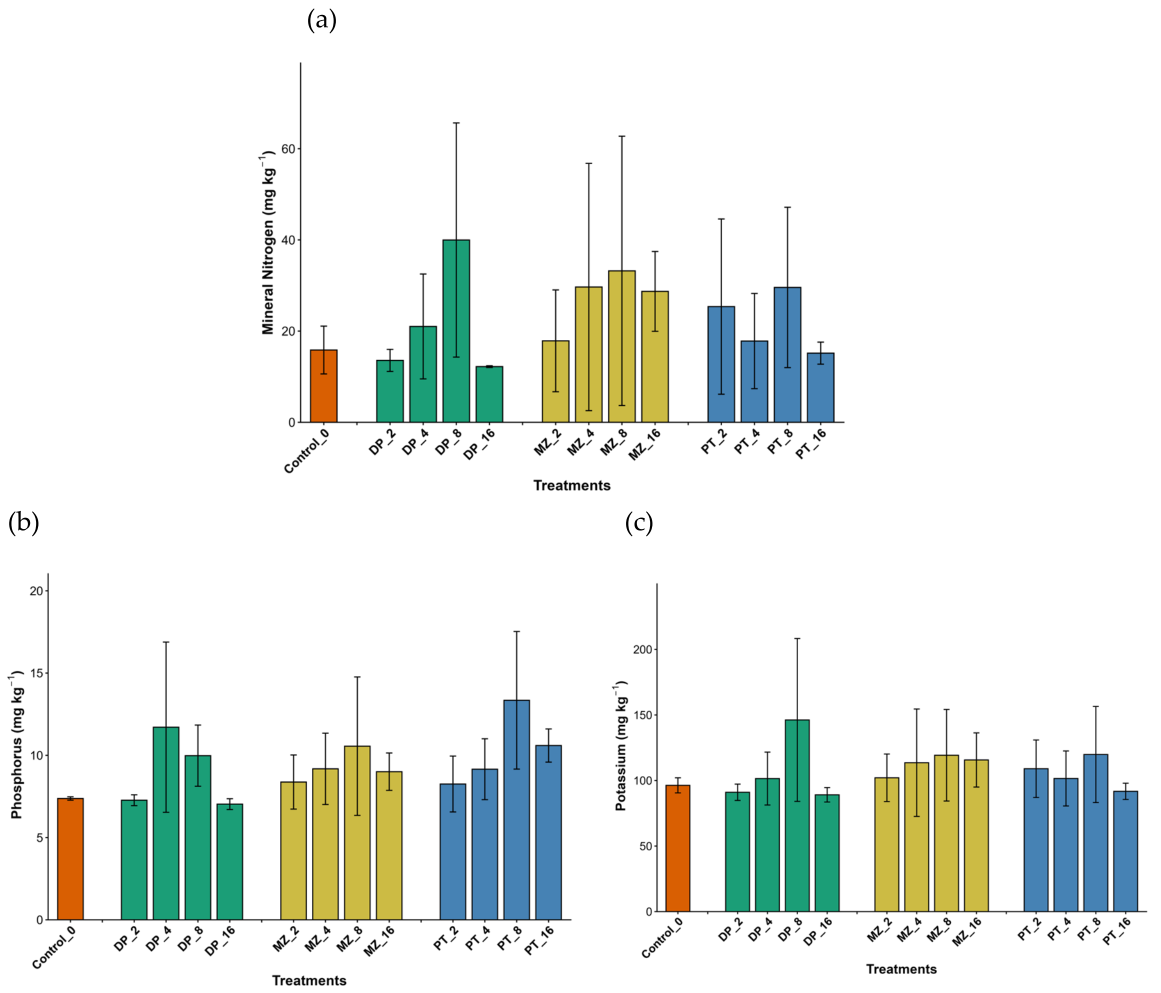

Figure 5. Mean values of soil macronutrients (a) Mineral Nitrogen; (b) Phosphorus; (c) Potassium across treatments.

Table 4. Soil Nmin, P and K (Mean ± SE; n = 3) under biochar treatment.

Treatment	Nmin (mg·kg^{-1})	P (mg·kg^{-1})	K (mg·kg^{-1})
Control_0	15.85 ± 5.25	7.38 ± 0.1	96.31 ± 5.75
DP_2	13.57 ± 2.42	7.27 ± 0.33	91.03 ± 6.23
DP_4	21.02 ± 11.5	11.71 ± 5.17	101.5 ± 20.18
DP_8	39.98 ± 25.68	9.98 ± 1.86	146.2 ± 62.13
DP_16	12.21 ± 0.2	7.03 ± 0.33	89.1 ± 5.51
MZ_2	17.86 ± 11.16	8.38 ± 1.64	102.07 ± 18.14
MZ_4	29.68 ± 27.12	9.18 ± 2.17	113.58 ± 40.98
MZ_8	33.21 ± 29.53	10.56 ± 4.21	119.27 ± 34.93
MZ_16	28.71 ± 8.76	9 ± 1.14	115.68 ± 20.66
PT_2	25.38 ± 19.22	8.25 ± 1.7	108.98 ± 21.93
PT_4	17.82 ± 10.44	9.16 ± 1.85	101.55 ± 20.97
PT_8	29.58 ± 17.58	13.34 ± 4.18	119.86 ± 36.65

PT_16	15.17 ± 2.42	10.59 ± 1.01	91.75 ± 6.2

3.4. Tomato Yield Response

Biochar effects on crop productivity were evaluated through both total yield (Figure 6b) and fruit size class distributions (Figure 6a). Statistically significant differences were revealed in total yield between treatments (p = 0.031). The DP_2 treatment produced the highest total tomato yield (56.90 t·ha^{-1}) followed by MZ_8 (54.35 t·ha^{-1}) and PT_2 (52.39 t·ha^{-1}). While these values were not all statistically higher than the control (48.50 t·ha^{-1}), they illustrate a positive trend at low to moderate doses. In contrast, DP_16 resulted in the lowest yield (30.95 t·ha^{-1}), indicating that excessive application rates may inhibit productivity, potentially due to nutrient imbalances, soil toxicity, or physical constraints in the root zone.

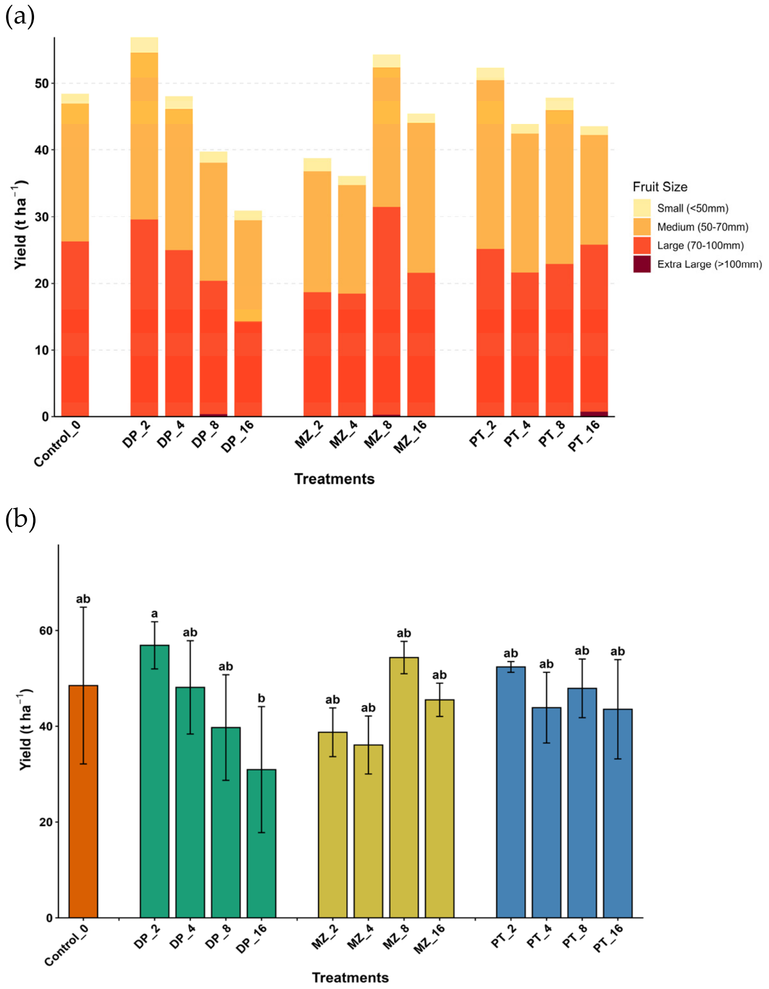

Figure 6. Mean fruit weight as affected by biochar treatments: (a) across different fruit size classes; (b) total yield.

Interestingly, while biochar application significantly boosted total yield, they had no statistically discernible impact on the distribution of fruit size categories (Small, Medium, Large, and Extra-Large) as seen in (Figure 6a). This stability in size grading suggests that the biochar treatments primarily enhanced overall biomass or fruit count, rather than altering the inherent physiological or genetic patterns that govern fruit sizing in this specific cultivar.

Pearson correlation analysis revealed varying relationships between different biochar application rates and yield (Figure 7). Specifically, biochar DP demonstrated a significant, moderately negative correlation with yield (r = -0.62, p = 0.015), indicating that higher application rates within the tested range were associated with a decline in overall production. Conversely, no statistically significant correlations were observed for the remaining treatments. Biochar MZ exhibited a weak positive relationship with yield (*r* = 0.17, *p* = 0.55), whereas biochar PT showed a weak negative correlation (*r* = -0.24, *p* = 0.40). These findings indicate that while biochar DP significantly impacts yield, biochar MZ and PT do not exert a consistent linear effect.

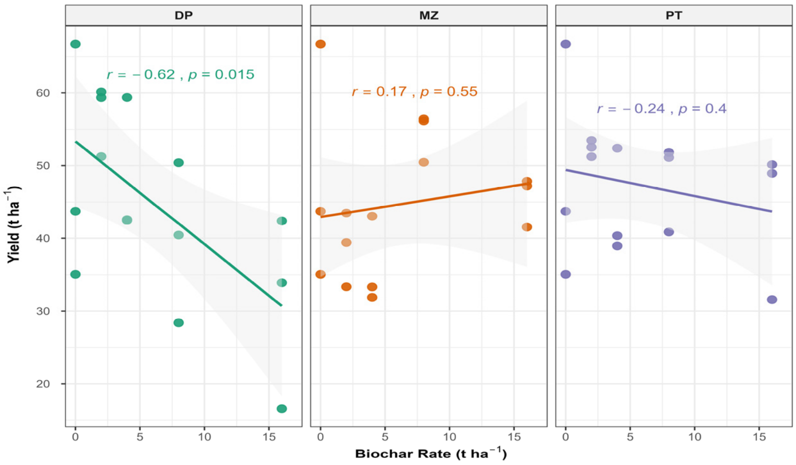

Figure 7. Relationship between biochar rate and tomato yield for three biochar types (DP, PT, and MZ).

The statistical results of this analysis are mapped out in the correlation matrix (Figure 8). The Pearson correlation matrix revealed that total organic carbon was positively associated with yield (*r* = 0.52, *p* < 0.05), while soil pH correlated with N, P, K, and CEC, and significant interrelationships were also observed among CEC, N, and K, indicating coordinated nutrient dynamics across treatments (*p* < 0.05).

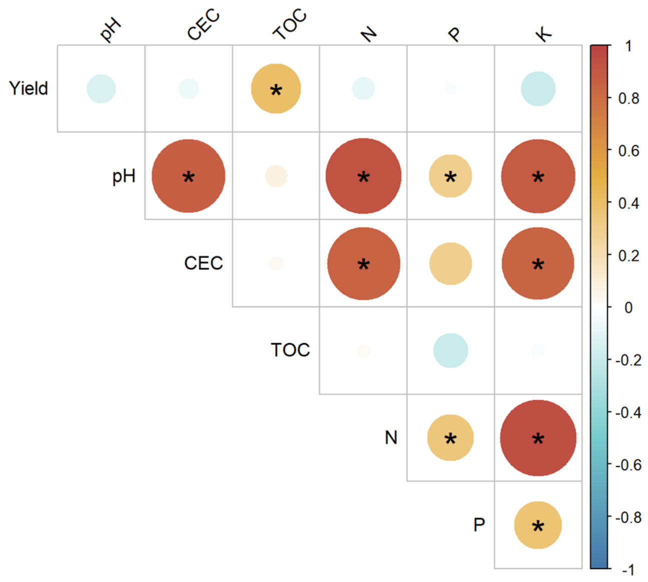

Figure 8. Pearson correlation matrix showing the interrelationships between soil chemical properties and crop yield. Asterisks (*) indicate significant correlations at $p \leq 0.05$.

4. Discussion

This study compared biochars from potato, maize, and date palm residues and assessed their effects on desert sandy soil fertility and tomato yielding. The results revealed strong feedstock- and dose-dependent differences, with low to moderate applications improving soil carbon and crop performance, while higher rates were less effective or even detrimental.

4.1. Physicochemical and Structural Properties of Biochars

The three biochars derived from potato, maize, and date palm residues exhibited marked contrasts in their chemical and structural characteristics, (Table 2) confirming that feedstock composition largely dictates biochar functionality [33,34]. Potato biochar displayed the highest alkalinity (pH 10.21) and electrical conductivity (30.2 mS/cm), reflecting an abundance of soluble salts and ash-related alkaline oxides. Similar findings have been reported by [35–37]. who linked the high salinity of potato-based biochars to their elevated K and Na contents. By contrast, maize biochar showed moderate alkalinity (pH 8.60) and EC (10.3 mS/cm), while date palm biochar, though also alkaline (pH 9.34), had a relatively low EC (6.5 mS/cm), consistent with observations on woody feedstocks producing less soluble salts [38,39].

Carbon and nitrogen dynamics further differentiated the biochars. Date palm biochar contained the highest total C (59.1%) but very low N (0.64%), yielding an extremely wide C/N ratio (92.3) and suggesting strong stability but poor short-term nutrient release. Potato biochar had the lowest C (23.5%) but the highest N (2.13%), producing a narrow C/N ratio (11) favorable for nutrient mineralization. Maize biochar combined relatively high C (54.9%) with moderate N (1.63%), resulting in a balanced C/N ratio (34). These results align with previous studies showing that lignocellulosic materials generate C-dense, stable biochars, while protein- or starch-rich residues yield N-rich, more labile biochars [40–42].

Surface area (SSAEGME) also varied considerably, with potato biochar exhibiting a value of 1528 $m^2 \cdot g^{-1}$ - almost double that of maize (932 $m^2 \cdot g^{-1}$) and date palm (879 $m^2 \cdot g^{-1}$). This highlights potato biochar's strong potential for water and nutrient adsorption, consistent with the general trend that herbaceous feedstocks yield more porous structures than woody residues [43]. Elemental analysis revealed potato biochar as the most nutrient-enriched, particularly in K (4.09%), Ca (3.97%), Mg (2.31%), and S (4.07%). Maize biochar, meanwhile, was notable for its high Fe content (668 $mg \cdot kg^{-1}$), which may be advantageous in Fe-deficient sandy soils [42].

4.2. Effects of Biochar on Sandy Soil Properties

Biochar addition led to significant increases in soil total organic carbon, particularly at low to moderate application rates [44], confirming its role as an organic carbon input and long-term stabilizer in desert sandy soils. The largest improvement was observed with DP_2 (0.32%) and PT_2 (0.32%) followed by PT_4, which MZ_4 exceeded control levels. These outcomes highlight that the alkaline nature of date palm and potato biochars emerged as a key driver for carbon stabilization. This alkalinity likely facilitated the formation of cationic bridges (such as Ca^{2+} and Mg^{2+}) between the biochar's functional groups and the soil matrix , providing physical protection to organic carbon against microbial oxidation. However, this protective mechanism is superseded at higher concentrations, where the microbial 'priming effect' becomes the dominant factor governing carbon mineralization. Similar carbon enrichment effects of biochar on sandy soils have been documented by [45] and [46] who emphasized the role of biochar in building soil organic matter under arid conditions.

The observed negative correlation between biochar application rates and total organic carbon (TOC), (Figure 4) strongly suggests a pronounced 'priming effect' [47]. In this study, the incorporation of sheep manure likely acted as a metabolic catalyst, stimulating intense microbial activity [48,49], that accelerated the mineralization of soil organic carbon (SOC). Notably, this microbially-driven decomposition targeted not only the labile organic fractions, but also the ostensibly stable carbon pool originating from the biochar. While biochar is typically recognized for its chemical recalcitrance and long-term sequestration potential [50], the influx of labile carbon from the sheep manure triggered a co-metabolic process, providing the microbial community with the energy required to degrade the complex aromatic structures of the biochar [51].

This synergistic degradation was significantly exacerbated by the inherent pedological properties of the experimental site. The sandy soil texture—characterized by high macroporosity and optimal aeration—coupled with elevated ambient temperatures and constant humidification from irrigation, transformed the soil matrix into a functional 'bioreactor.' These conditions collectively maximized microbial metabolic rates and enzymatic efficiency, leading to the rapid turnover of sequestered carbon [52].

The lack of significant response in soil pH and cation exchange capacity (CEC) following biochar application (Figure 3) can be attributed to several site-specific factors. In sandy soils, the inherently low buffering capacity and high macroporosity often lead to the rapid leaching of carbonates and soluble cations provided by biochar [53]. Although biochar is typically expected to increase CEC, this effect is often time-dependent. Fresh biochar, such as that used in this study, may possess limited surface functional groups. As noted by [54], the development of negative charge on biochar surfaces (oxidation) is a slow process that requires "aging" in the soil environment, which might not have fully occurred within the timeframe of this experiment. Nevertheless, the numerical increases observed in some treatments (DP_8, MZ_8, PT_8 and MZ_4) could be interpreted as an early indicator of a soil transition toward enhanced chemical stability, which would potentially reach statistical significance with extended biochar 'aging' periods [53].

Regarding the macronutrients, the statistical analysis revealed no significant differences in soil concentrations of nitrogen (N), phosphorus (P), and potassium (K) among treatments. Nevertheless, several biochar treatments showed numerically higher nutrient levels compared with the control (Figure 5). The absence of statistical significance, despite the additional inputs from sheep manure and biochar, may be attributed to the high mobility of these elements in sandy soil matrices. As reported by [55–57], the coarse texture and high infiltration capacity of sandy soils often promote rapid downward leaching of soluble nutrients, particularly nitrate (NO_3^-) and exchangeable potassium (K^+), potentially masking the enrichment effect of soil amendments.

Furthermore, the stabilization of these nutrients is closely linked to soil organic carbon dynamics. The observed priming effect and the associated decline in total organic carbon (TOC) in high-dosage treatments may have reduced the soil's capacity to adsorb and retain nutrients. The nutrient-holding capacity of biochar is largely governed by its surface functional groups, charge characteristics, and porous structure [58–60]. However, following incorporation into soil, biochar surfaces may become coated with organic matter and microbial biofilms, which can modify or partially block sorption sites and thus influence nutrient retention processes.

For phosphorus, the lack of a significant response may also be related to rapid fixation or precipitation processes occurring in the rhizosphere. In calcareous and sandy soils, phosphorus bioavailability is frequently controlled by complex interactions with calcium minerals and soil surfaces rather than by the total amount of P applied. In addition, interactions between biochar surfaces and soil minerals may regulate P adsorption–desorption dynamics, thereby influencing its plant availability [57,61,62]. Consequently, the numerical increases observed in some treatments likely represent a transient nutrient pool that did not translate into statistically stable enrichment within the timeframe of the experiment.

4.3. Tomato Yield Response

Tomato yield responses mirrored the soil fertility outcomes, showing significant improvement under low to moderate biochar rates (Figure 6b), but suppression at the highest levels. The best-performing treatments were DP_2 (56.90 $t \cdot ha^{-1}$), MZ_8 (54.35 $t \cdot ha^{-1}$), and PT_2 (52.39 $t \cdot ha^{-1}$), all of which produced yields above the control (48.5 $t \cdot ha^{-1}$). These gains are consistent with previous reports that biochar enhances productivity in sandy soils primarily through improved nutrient supply and water-use efficiency [8,37,63].

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The positive effect of DP_2 highlights that even small additions of stable, carbon-rich biochar can improve soil conditions enough to stimulate yield. However, increasing the rate to DP_16 sharply reduced yield (30.95 t·ha^{-1}), suggesting that excessive stabilization with limited nutrient release and possible changes in soil porosity may have restricted root performance. Such non-linear dose responses are common in biochar studies, with high application rates sometimes leading to physical or chemical imbalances [64]. Maize biochar at 8 t·ha^{-1} (MZ_8) proved particularly effective, producing a 12% yield increase compared with the control. This reflects its intermediate profile, combining carbon enrichment with sufficient nutrient release to sustain plant growth. Previous studies similarly identified maize biochar as a balanced amendment capable of delivering both short- and long-term agronomic benefits [42]. Potato biochar produced mixed results: at 2 t·ha^{-1}, it enhanced yield (52.39 t·ha^{-1}), but at higher doses its high EC appeared to limit growth despite the abundant nutrient content. This finding underlines that nutrient-rich biochars must be applied cautiously, as their salinity risks may outweigh fertility benefits under desert sandy soil conditions.

Fruit size distribution (Figure 6a) did not differ significantly among treatments, though the slight increase in larger fruit classes under DP_2 and MZ_8 suggests potential indirect effects of improved nutrient balance on fruit development. These subtle differences may become more pronounced under longer-term application or in seasons with higher water stress.

Taken together, the yield results emphasize that optimal biochar application is not simply a matter of “more is better.” Instead, the type of feedstock and dose must be carefully matched to soil constraints and crop requirements. In desert sandy soils, where nutrient retention is poor and salinity risks are high, small to moderate rates (2–8 t·ha^{-1}) appear most beneficial.

The Pearson correlation matrix (Figure 8) highlighted strong interactions among soil chemical properties and crop productivity. Soil pH showed significant positive correlations with N, P, K, and CEC, confirming its key role in regulating nutrient availability in sandy soils [65]. Cation exchange capacity (CEC) was also positively associated with N and K, indicating improved nutrient retention across treatments, consistent with the capacity of biochar to enhance soil cation exchange processes [66]. A significant positive correlation between TOC and yield suggests that organic carbon enrichment was a major driver of productivity, which has also been reported in sandy soils amended with biochar [67].

5. Conclusions

In summary, this study demonstrates that biochar feedstock and application rate can influence soil fertility and crop productivity in desert sandy soils. Low application rates, particularly date palm biochar at 2 t·ha^{-1}, significantly enhanced soil total organic carbon (TOC) and total yield, while excessive application tended to suppress yield. Soil N, P, and K showed only numerical increases, suggesting that their availability may require longer-term monitoring to detect cumulative effects. These findings indicate that moderate biochar applications, tailored to feedstock type and integrated with organic or balanced fertilizers, offer a practical strategy for improving soil quality and sustainable crop production in nutrient-poor sandy soils. Future research should focus on long-term trials integrating soil chemistry, microbial activity, and plant physiological responses to better understand the sustainability of these benefits. From a practical perspective, the results indicate that farmers working in desert sandy soils may achieve yield improvements by applying biochar at moderate rates (2–8 t·ha^{-1}), depending on the biochar feedstock. Integrating biochar with compost or balanced fertilizer management may further optimize soil fertility and reduce the risks associated with excessive biochar application.

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Abbreviations

The following abbreviations are used in this manuscript:

TOC	Total organic carbon
Nmin	Mineral nitrogen
DP	Date palm
MZ	Maize
PT	Potato
SSA	Specific surface area

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