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RESEARCH PAPER

Biochar-Enriched Sheep Manure for Sustainable Maize Production: Increased Yield and Water Savings

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Abstract

H. Burezq, and F. Khalil. 2024. Biochar-Enriched Sheep Manure for Sustainable Maize Production: Increased Yield and Water Savings. Int. J. Agric. Nat. Resour. 85-98. This study aimed to boost maize crop production by utilizing animal manure enriched with biochar derived from date palm fronds. Two field experiments were conducted, featuring two treatments: Treatment 1 (T1) used standard manure from female Naeemi sheep fed only a basal diet, while Treatment 2 (T2) involved manure from Naeemi sheep fed a biochar-supplemented diet. Maize was grown using manure from both treatments, applied at rates of 5.0, 7.5, and 10 tons/hectare, with two irrigation levels: 60% and 100% of the crop's evapotranspiration (ETc). The results indicated that manure from T2 had significantly higher levels of phosphorus (15.6%), total organic carbon (16.4%), nitrogen (11.4%), and potassium (23.3%) compared to T1. Furthermore, applying 10 tons/hectare of T1 manure led to a 40% reduction in water usage and an 18.2% increase in fresh biomass compared to the control (60% ETc). In contrast, using 10 tons/hectare of T2 manure resulted in a 40% water saving and a significant 345.5% increase in fresh biomass compared to the control (60% ETc). In conclusion, applying T2 manure at rates of 5.0, 7.5, and 10 tons/hectare under deficit irrigation significantly ($P<0.0001$) enhanced fresh biomass production, with increases of 227.27%, 245.5%, and 345.5%, respectively, compared to T1 under similar irrigation conditions. The improved soil composition resulting from the incorporation of T2 manure could also support the growth of other crops, particularly in arid regions like Kuwait.

Keywords: biochar, carbon sequestration, deficit irrigation, fresh biomass, nutrient cycling, soil fertility, sustainable agriculture, water saving.

Highlights:

- Supplementing sheep feed with biochar significantly increases manure nutrient content.
- Applying biochar-enriched manure to maize under deficit irrigation boosts yield by 345.5% compared to controls.
- This approach offers a sustainable solution for improving soil health, crop productivity, and water conservation.

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Introduction

Biochar is produced through the pyrolysis of various biomass types in a low-to-no oxygen thermal process, typically carried out at temperatures ranging from 350 to 1,000 °C (Guyader et al., 2024; Hagemann et al., 2018; Dadhich, 2022). Biochar derived from pure stem wood is termed charcoal. In contrast, the term biochar includes a broad range of biogenic materials as potential feedstock. Biochar, activated carbon, and charcoal collectively fall under the category of pyrogenic carbon materials. The term 'biochar' specifically implies usage without rapid mineralization to CO_2, such as burning (Guyader et al., 2024; Mirheidari et al., 2020). In a broader context, biochar signifies its intended prolonged residence in the terrestrial environment, either as a soil amendment or for other material-use purposes (Schmidt et al., 2018). Due to the considerably slower decomposition rate of biochar carbon compared to the original biomass, its application is regarded as a terrestrial carbon sink, with effects extending over at least a century scale (Sandilya et al., 2024; Werner et al., 2018; Yıldızlı et al., 2021). The latter point makes biochar a promising negative emission technology, as acknowledged by the Intergovernmental Panel on Climate Change (IPCC, 2018).

As reported by Lehmann and Joseph (2015) and Sandilya et al. (2024), biochar was commonly evaluated as a soil amendment applied in its pure form to soils in extensive quantities (>10 tons hectare^{-1}). These applications revealed modest to substantial yield increases for a variety of crops in tropical regions but infrequently in temperate climates (Jeffery et al., 2017). Recently, it was reported that blending biochar with organic amendments, such as manure, cattle urine, or compost, may yield more significant increases and span a broader spectrum of climates and soils (McAvoy et al., 2020; Man et al., 2020; Lind et al., 2024; Schmidt et al., 2018).

Quality biochar is non-toxic, making it suitable for feeding and consumption (EBC, 2018; Yildizli et al., 2021; Besharati et al., 2020). The favourable combination of organic residues with biochar has encouraged researchers to conduct trials where biochar is not only mixed with manure but also integrated into animal farming systems. The gradual addition of biochar to silage, feed, bedding material, and liquid manure pits has demonstrated that biochar can be used in various ways.

When used in animal farming systems, biochar also reduces environmentally harmful ammonia loss through volatilization or nitrate loss via leaching (Emauel & Ernest, 2021; Borchard et al., 2019; Sha et al., 2019) and can reduce greenhouse gas emissions, such as nitrous oxide (N_2O) (Kammann et al., 2017; Hegarty et al., 2024; Borchard et al., 2019) or methane (CH_4) (Jeffery et al., 2016).

Biochar was mixed with animal feed for the first time in Germany and Switzerland in 2012 (Graves et al., 2022). A substantial portion of industrially produced biochar in Europe since then has been dedicated to sales for applications in animal feed, bedding, manure treatment, and subsequent soil use (Kammann et al., 2017; Rathnayake et al., 2023). In 2016, acknowledging the surge in biochar use within animal-related sectors, the European Biochar Foundation introduced a distinct certification standard tailored for animal feed (EBC, 2018). This standard aims to facilitate quality control and compliance with European regulations for animal feed. When orally consumed, biochar has a proven ability to enhance nutrient absorption efficiency, adsorb toxins, and generally improve animal health (Schubert et al., 2021). Following numerous veterinary publications in the last century, an increasing number of scientific studies on biochar feeding have emerged since 2010. These studies explore biochar impacts on various animal species' health, feed efficiency, pathogen infestation, and greenhouse gas emissions. The present study assesses the current state of knowledge regarding the use of biochar as an additive in female Naeemi sheep feed. The main objective of the present study is to evaluate the female Naeemi sheep excreta from a chemical and nutritional point of view after mixing biochar with their feed. The collected manure was also used to grow maize crops to test these manures' effect on the chemical and physical composition of the soil and the fresh biomass produced. It is a well-established fact that excreta from grazing sheep has a significant number of nutritional elements. For example, over 95% of phosphorus (P) and calcium (Ca) are excreted in the manure, while most of the potassium (K) is excreted in urine (70-90%). Nitrogen (N) is evenly excreted through both manure (20-55%) and urine (45-80%) (Denninger et al., 2020; Burezq, 2019; Rajpoot et al., 2024; Abd'quadri-Abojukoro & Nsahlai, 2023).

A previous study investigated the use of biochar-enriched manure as an organic fertilizer and its effects on soil fertility and crop production. The findings revealed that biochar-enriched manure significantly improved root morphology and physiology by enhancing soil nutrients. Compared to the control treatment, this mixture has significantly improved morphological and physiological parameters. A significant increase in root physiology was observed with higher soil nutrient content, especially at the bud stage. The study concluded that biochar-enriched manure could positively influence cotton roots, recommending its use to enhance root health in continuous cropping systems (Zhang et al., 2020). Another study examined the use of biochar-enriched manure (from chickens and/or horses) as an organic tomato fertilizer. Results showed that the total fresh weight of tomato fruits was significantly ($P<0.05$) higher with the biochar-enriched manure compared to the control treatment, with a 63% crop yield increase compared to the control group and other treatments (Antonious, 2018; Man et al., 2020).

Therefore, to investigate the chemical and nutritional changes occurring in the manure of both female Naeemi sheep groups (i.e., those fed with the basal ration alone and those fed with the basal ration supplemented with biochar), manure was collected separately and analysed for different nutrients. Manure collected from both groups of Naeemi sheep was used to grow maize crops as well, and various growth parameters and crop yield were calculated.

Materials and Methods

Collection of sheep Manure

Female Naeemi sheep (12-16 months old) were assembled in a pen, allowing a 10-15 minutes waiting period for the collection of fresh samples. The samples were then gathered using a spoon and placed into sterile plastic bags. Finally, the samples were stored in a refrigerator until needed. Care was taken to avoid mixing the manure with animal bedding, ensuring no contamination that could affect nutrient level measurement. Around 5-6 kg of manure were collected from each group for nutrient analyses (NPK). The manure samples were analyzed in the labs for essential ingredients (organic matter, ash content, nitrogen, potassium, and phosphorus) using standard analytical procedures.

The manure storage structure used in the present study was covered with synthetic covers to increase the moisture content of the manure and reduce volatilization and evaporation losses. Collected manure samples were analyzed, revealing the following results: Water content (49.2%), total carbon (9.2%), total nitrogen (8.6 kg ton^{-1}), and total phosphorus (1.3 kg ton^{-1}).

Animal Feed

The basal ration used in the present study was formulated with 70% concentrate and 30% roughages (Muhammad et al., 2015). The concentrate consisted of a mixture of barley, corn, wheat bran, soybean meal, and vitamins/minerals, which were ground and mixed with (1%) biochar/animal/800g dry matter/day. The roughages included alfalfa hay and straws with 14% crude protein. Naeemi sheep were fed with 1% biochar per animal/day/800g dry matter and mixed with the basal ration for one month before collecting the manure.

Soil Chemical Analysis

Soil samples were analyzed for different parameters including EC, pH, Ca, total organic carbon, total nitrogen, P, and K. Soil reaction (pH), using standard procedures (Table 1).

Production of Biochar

Date palm fronds were collected from the Kuwait Institute for Scientific research (KISR) grounds and chopped to suitable sizes to feed into the pyrogenic carbon production machine. Pyrogenic date palm carbon is produced through the pyrolysis process at high temperatures (600 °C) and depleted oxygen environment. The prepared pyrogenic carbon was then ground to pass through a 2 mm sieve for unification (Aladin et al., 2017; Rombel et al., 2022) by slow pyrolysis of waste biomass (Sandilya et al., 2024).

Statistical Analysis

Collected data were analyzed using the GraphPad Prism 9. Our commitment to maintaining our findings' precision and reliability was upheld through various Prism-driven processes, including calculating both mean and variance across distinct treatments, which let us accurately evaluate the statistical significance of disparities observed in our data. The *p*-values generated via the GraphPad Prism analysis (https://www.graphpad.com/) functioned as vital metrics, illuminating the significance of these observed distinctions.

Experimental Setup

Two field experiments were carried out to grow maize (2021/2022-2022/2023) at a private farm at Al-Abdali (N 29.987853, E 47.840433), and the harvest commenced at the end of each season (12-13 weeks). A randomized complete block design was used, with four replications for each treatment, and two irrigation rates for crop evapotranspiration at ETc 100% and ETc 60% were applied. The experimental setup was as follows; (1) standard manure collected from female Naeemi sheep fed with basal ration only, (2) manure collected from Naeemi sheep fed with (1%) biochar-supplemented ration. Different doses of the two different types of manure (5, 7.5, and 10 tons ha^{-1}) were used. Standard fertilizer (NPK) rates recommended for maize crops were dissolved in water and fertigated in the experimental area. Table 2 shows clearly the experimental design (Table 2).

Irrigation Requirement

Daily irrigation water requirements were determined using the equation previously described

Table 1. Parameters were analyzed with reference to procedures

Parameter	Units	Equipment	Method No
EC	mS/cm	Using EC meter	4F2b1
pH	-	Using pH meter	4C1a1a2
Ca	meq/l	Flame photometer/ Atomic absorption spectrophotometer)	4F2c1a1-4
Organic matter (loss on ignition at 400^{o}C)	%	Muffle furnace	5A
Total nitrogen	%	Kjeldahl apparatus (wet oxidation)	4H2a1-3
Available phosphorous	%	Spectrophotometer	4D5
Available potassium	%	Flame photometer	4B1a1b1-4

Soil Survey Staff (2014a) Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service (Soil Survey Staff. (2014a).

by Alhashimi et al. (2023) for either a full irrigation at ETc 100% (full irrigation), or at ETc 60% (deficit irrigation). A drip irrigation system was used throughout the field experiment. In the context of the irrigation period, ETc 100% denoted the essential irrigation volume required to meet the evapotranspiration demands of the crop (Alhashimi et al., 2023; FAO, 1998).

Water-Deficit Irrigation

Maize irrigation management involves the intentional implementation of controlled water scarcity. This strategy enhances efficient irrigation water resource use and encourages the growth of a more extensive root system, thus expanding the area of soil explored by the roots of the plant. During each irrigation cycle, the applied water volume deliberately falls short of the complete water requirements for maize, but this quantity is adjusted to prevent any substantial adverse impact on maize growth and productivity. This precise control of water quantity is achieved by adopting crop coefficient values set below the recommended standards (FAO, 1998). In this method of irrigation management, which involves the use of an irrigation water meter, the controlled water scarcity is established by regulating the water level in the evaporation reservoir. Specifically, the marker on the sliding rod is positioned at a lower point on the level ruler than the manufacturer-recommended position for each stage of crop development. Lowering the water level in the evaporation reservoir consequently reduces the evaporating surface area, leading to a decreased estimate of evapotranspiration for maize.

Table 2. Experimental Design

Sample ID	Soil	Control (60%)	Control (100%)	Standard Manure	Manure+ biochar	NPK
Control-1-R1	✓	✓	☒	☒	☒	✓
Control-1-R2	✓	✓	☒	☒	☒	✓
Control-1-R3	✓	✓	☒	☒	☒	✓
Control-1-R4	✓	✓	☒	☒	☒	✓
Control-2-R1	✓	☒	✓	☒	☒	✓
Control-2-R2	✓	☒	✓	☒	☒	✓
Control-2-R3	✓	☒	✓	☒	☒	✓
Control-2-R4	✓	☒	✓	☒	☒	✓
T1-R1	✓	☒	☒	5	☒	✓
T1-R2	✓	☒	☒	**5**	☒	✓
T1-R3	✓	☒	☒	**5**	☒	✓
T1-R4	✓	☒	☒	**5**	☒	✓
T11-R1	✓	☒	☒	**7.5**	☒	✓
T11-R2	✓	☒	☒	**7.5**	☒	✓
T11-R3	✓	☒	☒	**7.5**	☒	✓
T11-R4	✓	☒	☒	**7.5**	☒	✓
T111-R1	✓	☒	☒	**10**	☒	✓
T111-R2	✓	☒	☒	**10**	☒	✓
T111-R3	✓	☒	☒	**10**	☒	✓
T111-R4	✓	☒	☒	**10**	☒	✓
T2-R1	✓	☒	☒	☒	**5**	✓
T2-R2	✓	☒	☒	☒	**5**	✓
T2-R3	✓	☒	☒	☒	**5**	✓
T2-R4	✓	☒	☒	☒	**5**	✓
T22-R1	✓	☒	☒	☒	**7.5**	✓
T22-R2	✓	☒	☒	☒	**7.5**	✓
T22-R3	✓	☒	☒	☒	**7.5**	✓
T22-R4	✓	☒	☒	☒	**7.5**	✓
T222-R1	✓	☒	☒	☒	**10**	✓
T222-R2	✓	☒	☒	☒	**10**	✓
T222-R3	✓	☒	☒	☒	**10**	✓
T222-R4	✓	☒	☒	☒	**10**	✓

Results

Characteristics of Soil Used in the Present Field Experiment

Native sandy soil was used in the field experiment. The soil was characterized for important physical and chemical characteristics. The soil taxa was Typic Gypsiargid, fine-loamy, mixed, hyperthermic, based on Kuwait Soil Taxonomy (Soil Survey for the State of Kuwait, 1999). Soil reaction (pH) and electrical conductivity (EC) were measured by using two methods: soil:water, and saturated soil paste (Tables 1 and 3). The pH of the native sandy soil is moderately alkaline (7.8), and it is very slightly saline (Soil Survey for the State of Kuwait, 1999).

Assessment of N, P, K, TOC, and Ash in Collected Samples

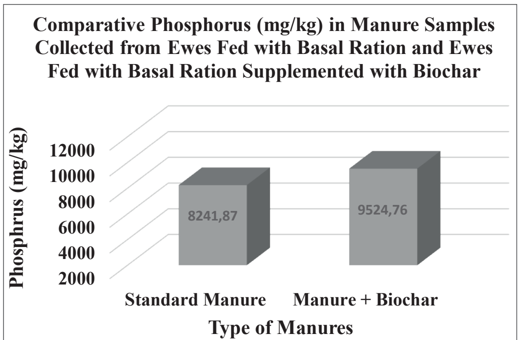
Figure 1 shows a significant (*P*<0.0001) 15.6% increase in phosphorus concentration in the manure of female Naeemi sheep fed with a biochar-supplemented ration. Figure 2 shows a significant (P<0.0001) 16.4% rise in total organic carbon (TOC) content. The higher TOC in the manure of female Naeemi sheep fed with the biochar-supplemented ration, in comparison to the control treatment (standard manure), indicates a greater potential for carbon capture (carbon sequestration), preventing its release into the atmosphere and contributing to greenhouse gas (GHG) emissions reduction. Figure 3 also shows a significant (*P*<0.0001) 11.4% increase in nitrogen (%) content in the manure of female Naeemi sheep fed with a biochar-supplemented ration. Figure 4 exhibits a substantial (*P*<0.0001) 48.2% increase in potassium concentration in the manure of female Naeemi sheep fed with a biochar-supplemented ration. Lastly, figure 5 displays a significant (*P*<0.0001) 54.7% decrease in ash (%) content in the manure of female Naeemi sheep fed with a biochar-supplemented ration.

Measurements of pH, EC, Organic Carbon, $CaCO_3$, and Physical properties for Native Sandy Soil

The pH values of the native sandy soil are slightly alkaline (7.93), and slightly saline (2.837). The content of organic matter is very low (0.1%) (Table 3).

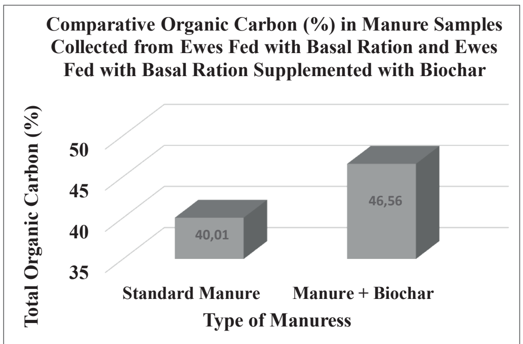
Hydraulic Properties of Native Sandy Soil

The following hydraulic properties are presented (Table 4) for the sandy soil used in the experiment: permanent wilting point, field capacity, available



P value	<0.0001
P value summary	****
Significantly different (P<0.05)?	Yes
One- or two-tailed P value?	Two-tailed
t, df	t=110007, df=8
Test?	t-test

Figure 1. Comparison of Phosphorus (mg kg^{-1}) in Manures Collected From both Animal Groups



P value	<0.0001
P value summary	****
Significantly different (P<0.05)?	Yes
One- or two-tailed P value?	Two-tailed
t, df	t=1122, df=8
Test?	t-test

Figure 2. Comparison of Total Organic Carbon (%) in Manures Collected from both Animal Groups

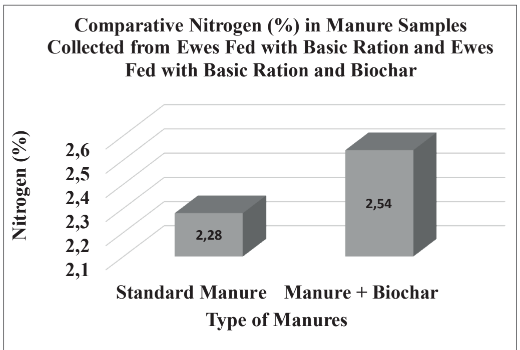
water, bulk density, and hydraulic conductivity (mm/hour).

Table 3. Characteristics of native soil used in the present study (Soil Survey for the State of Kuwait, 1999)

Soil parameter	Value (unit)	Class
$pH_{1:1}$	7.93	Moderately alkaline
pHs	7.55	Slightly alkaline
$EC_{1:1}$	0.787 mS/cm	Very slightly saline
$ECe/EC_{1:1}$	2.837	Very slightly saline
Organic carbon	0.1%	Very low
$CaCO_3$ equivalent	7.4%	Slightly calcareous
Munsell soil color	10 YR 6/4	Light yellowish brown
Sand	%	98.36
Silt + clay	%	1.64
Texture class	USDA-NRCS	Sand

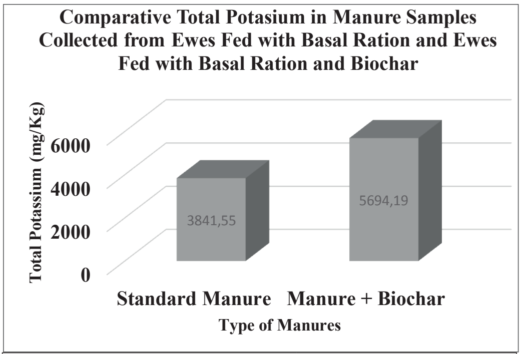
Table 4. Soil Hydraulic Properties

Hydraulic Properties	Values (Unit)
Sand	98.36%
Silt + Clay	1.64%
Wilting point	0.029 cm^3 water cm^{-3} soil
Field capacity	0.087 cm^3 water cm^{-3} soil
Available water	0.054 cm^3 water cm^{-3} soil
Saturation	0.26 cm^3 water cm^{-3} soil
Bulk density	1.60 g cm^{-3}
Porosity	30.94%
Draining rate	217 mm/hour



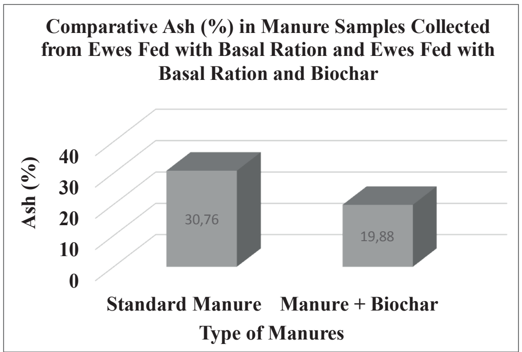
P value	<0.0001
P value summary	****
Significantly different (P < 0.05)?	Yes
One- or two-tailed P value?	Two-tailed
t, df	t=24.00, df=8
Test?	t-test

Figure 3. Comparison of Nitrogen (%) in Manures Collected from both Animal Groups



P value	<0.0001
P value summary	****
Significantly different (P < 0.05)?	Yes
One- or two-tailed P value?	Two-tailed
t, df	t=57340, df=8
Test?	t-test

Figure 4. Comparison of Potassium Concentration (mg kg^{-1}) in Manures Collected from both Animal Groups



P value	<0.0001
P value summary	****
Significantly different (P<0.05)?	Yes
One- or two-tailed P value?	Two-tailed
t, df	t=1319, df=8
Test?	t-test

Figure 5. Comparison of Ash (%) in Manures Collected from both Animal Groups

Fresh Biomass Production

Data were obtained from four replicates, and the average was computed for each treatment. It bears mentioning that no statistically significant differences were observed between the data collected from the two field experiments at two different farms. When comparing the results, it was found that control-1 with ETc 60% (deficit irrigation) achieved a fresh biomass yield of 1.1 tons/hectare, while control-2 with full irrigation rate (ETc 100%) yielded 1.2 tons/hectare. This indicates a 9% increase in fresh biomass for control 2 compared to control 1. However, it is essential to note that control 1 offers the advantage of conserving 40% of irrigation water.

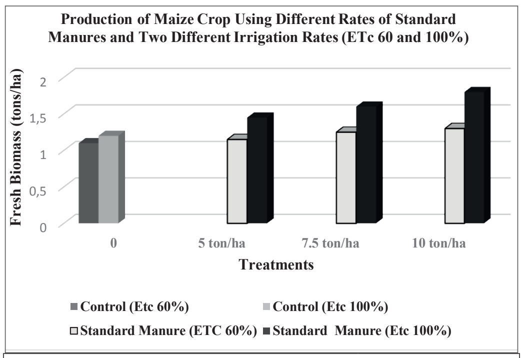
Applying varying rates of standard female Naeemi sheep manure at the rates of 5.0, 7.5, and 10 tons hectare^{-1} in conjunction with deficit irrigation led to a significant (*P*<0.0001) increase in fresh biomass. This increase ranged from 4.5-18.2 % compared to the control group (Control-1), as illustrated in Figure 6. Using standard Naeemi sheep manure at the same rates (5.0, 7.5, and 100 tons hectare^{-1}) also resulted in a significant (*P*<0.0001) increase in fresh biomass ranging from 31.8-63.6% when employing a complete irrigation rate of ETc 100% (Figure 6), as compared to control-1.

Figure 7 illustrates that the application of various rates of female Naeemi sheep manure mixed with biochar (5.0, 7.5 and 10 tons hectare^{-1}) in conjunction with deficit irrigation rates (ETc 60%) resulted in a significant (*P*<0.0001) increase of fresh biomass, with yields reaching 3.6, 3.8, and 4.9 tons hectare^{-1}, while achieving a 40% reduction in water usage. Using manure mixed with biochar at the same rates (5.0, 7.5, and 10 tons hectare^{-1}) under full irrigation conditions (ETc 100%) resulted in a significant (*P*<0.05) boost in fresh biomass production as well, with yields of 4.0, 5.3 and 6.4 tons hectare^{-1}, respectively, and no water savings.

Comparing the results achieved through the application of various application rates (5.0, 7.5, 10 tons hectare^{-1}) of standard manure and manure with biochar under deficit irrigation, the findings revealed a significant (*P*<0.0001) increase in fresh biomass. Specifically, when compared to the use of standard manure at the same rates, the application of manure mixed with biochar led to a significant (*P*<0.0001) enhancement in fresh biomass, with improvements ranging up to 227.27%, 245.5%, and 345.5%, respectively.

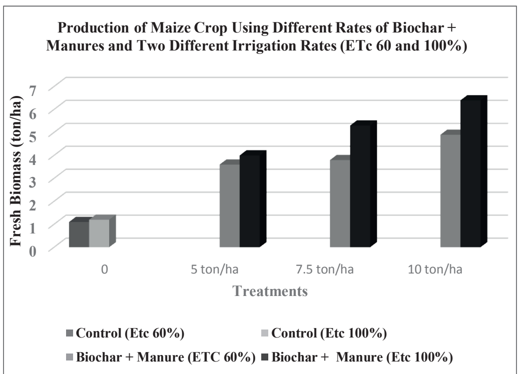
Soil Analyses after Harvesting Maize Crop

Soil samples were collected from the upper 15 cm of soil, and analyzed for EC, pH, and organic carbon. Results are shown in Table 5.



Brown-Forsythe test	
F (DFn, DFd)	6.676e+029 (7, 24)
P value	<0.0001
P value summary	****
Are SDs significantly different (P < 0.05)?	Yes
Test?	On-Way-Anova

Figure 6. Production of maize using different rates of standard manure and different irrigation rates



Brown-Forsythe test	
F (DFn, DFd)	4.015e+028 (7, 24)
P value	<0.0001
P value summary	****
Are SDs significantly different (P<0.05)?	Yes
Test?	One-Way-Anova

Figure 7. Production of maize using different rates of manures mixed with biochar and different irrigation rates

Table 5. Post Harvesting Soil Analyses for Soil EC and Soil Reaction (pH)

Treatments	EC	pH	Organic C (%)
60% ETc control	0.553	8.43	0.113
100 % ETc control	0.386	8.51	0.084
Standard manure (60% ETc)			
5.0 tons ha^{-1}	0.734	8.31	0.203
7.5 tons ha^{-1}	0.665	8.26	0.255
10 tons ha^{-1}	0.862	8.05	0.314
Standard manure (100% ETc)			
5.0 tons ha^{-1}	0.637	8.21	0.254
7.5 tons ha^{-1}	0.558	8.33	0.284
10 tons ha^{-1}	0.553	8.27	0.302
Manure + Biochar (60% ETc)			
5.0 tons ha^{-1}	0.600	8.32	0.162
7.5 tons ha^{-1}	0.652	8.26	0.230
10 tons ha^{-1}	0.771	8.21	0.283
Manure + Biochar (100% ETc)			
5.0 tons ha^{-1}	0.600	8.30	0.231
7.5 tons ha^{-1}	0.521	8.37	0.276
10 tons ha^{-1}	0.546	8.30	0.278

Soil EC: Using manure in large quantities can create soil EC problems. Soil EC assessment was carried out for all collected soil samples from both treatments. In all treatments where sheep standard manure and sheep manure + biochar were used, the soil EC slightly increased compared to the control treatment with no sheep manure, regardless of the irrigation rates (Table 5).

Soil pH: The soil pH in both control treatments was higher than in all other treatments, where either standard sheep manure or biochar + manure was applied, under both irrigation levels, and three application rates. The most significant decrease in soil pH was seen at 10 tons/hectare using a 60% ETc irrigation level, and sheep standard manure. However, achieving the optimal pH range may take time, especially with consistent manure usage by farmers (Table 5) (i.e. When soil pH is above the neutral range, it is challenging to bring it back to the neutral range (6.7-7.3). This difficulty is often due to the soil being rich in calcium carbonates, as seen in Kuwait. Calcium carbonates increase soil buffering capacity, meaning that it resists pH changes even when acidic products are added. The calcium carbonates neutralize the acid, preventing the addition of hydrogen ions needed to lower the pH. At high pH levels, nutrients like phosphorus, iron, copper, manganese, and zinc become insoluble as they form complexes with calcium carbonates. Adding biochar raises soil pH because biochar itself has a high pH. Decomposing manure releases organic acids that can lower the pH if the soil does not have a high buffering capacity; however, the buffering capacity is very high in Kuwait.

Soil Carbon: An upward trend of organic soil carbon is observed as the application rate of sheep manure increases, regardless of the irrigation levels used. The increase in soil organic carbon is more obvious in all treatments when 100% ETc level is used compared to 60% ETc, mainly due to the higher plant growth resulting from greater water application (Table 5).

Residual Soil Nitrogen After Harvesting: Table 6 shows an increase of soil nitrogen in all soil samples where both types of sheep manures were used compared to the control treatment without any manure application. This increase was in the range of 18-76% when biochar manure was added, compared to 56-66% when standard manure was added with deficit irrigation.

Discussion

The objective of this study was to develop a novel sheep ration aimed at enhancing the quality of excreted manure for agricultural use. Manure from two distinct groups of Naeemi sheep, as outlined in the materials and methods section, were collected. The first group received a biochar-supplemented ration, while the second group was fed a basal ration alone. Results indicated a significant nutrient content increase in the collected manure+biochar samples, including phosphorus, potassium, nitrogen, and total organic carbon, suggesting improved nutritional value with potential benefits for soil fertility and plant growth. The presence of biochar also suggested a potential for carbon capture, helping cut GHG emissions (Jankó et al., 2017; Manuel & Ernest, 2021; Hegarty et al., 2024; Rajpoot et al., 2024).

Soil analysis demonstrated that all soil samples treated with sheep manure, regardless of the type, exhibited increased soil nitrogen compared to the control without the addition of sheep manure. The increase was less pronounced under full irrigation (100% ETc), suggesting that higher irrigation rates released more nitrogen from the sheep manure, enhancing plant growth and resulting in higher fresh biomass. Soil EC was influenced by irrigation levels, with lower EC observed in the control and samples treated with 100% ETc, indicating the leaching effects of higher irrigation rates. Overall, soil EC results did not show significant increases in the root zones across different treatments.

The control treatments consistently had higher soil pH values than those with sheep manure application, indicating the acidic effects of decomposed manures. The application of biochar or standard sheep manure led to a pH drop, with the most significant shift observed at 10 tons hectare^{-1} using 60% ETc, suggesting a positive trend toward the neutral range. When soil pH is above the neutral range, it is challenging to lower it to the neutral range (6.7-7.3). This difficulty is often due to the soil being rich in calcium carbonates, as seen in Kuwait. Calcium carbonates increase the buffering capacity of the soil and neutralize the acid, making the soil resist changes in pH even when acidic products are added and preventing the addition of hydrogen ions needed to lower the pH. At high pH levels, nutrients like phosphorus, iron, copper, manganese, and zinc become insoluble as they form complexes with calcium carbonates. Adding biochar raises the pH of the soil because biochar itself has a high pH. On the other hand,

Table 6. Quantitative Assessment of Residual Nitrogen in Post-Harvest Soil Samples

Treatments	N (mg kg^{-1})	% increase over 60 % ETc control
Control 60%ETc	500	0.0
Control 100%ETc	540	8.0
Biochar+manure 60% ETc		
5.0 tons ha^{-1}	590	18.0
7.5 tons ha^{-1}	880	76.0
10 tons ha^{-1}	880	76.0
Biochar+manure 100% ETc		
5.0 tons ha^{-1}	710	42.0
7.5 tons ha^{-1}	820	64.0
10 tons ha^{-1}	790	58.0
Standard manure 60% ETc		
5.0 tons ha^{-1}	780	56.0
7.5 tons ha^{-1}	700	40.0
10 tons ha^{-1}	830	66.0
Standard manure 100% ETc		
5.0 tons ha^{-1}	700	40.0
7.5 tons ha^{-1}	700	40.0
10 tons ha^{-1}	640	28.0

decomposing manure releases organic acids that can lower the pH if the soil does not have a high buffering capacity; however, the buffering capacity is very high in Kuwait.

Higher rates of sheep manure application showed an increasing trend in organic soil carbon, with a more noticeable rise under 100% ETc. The study suggests that manure+biochar application positively contributes to mitigating greenhouse gas emissions by enhancing soil carbon sequestration and supporting photosynthesis, leading to increased fresh biomass. Notably, applying 10 tons/hectare of standard sheep manure resulted in a 40% water savings and an 18.2% increase in fresh biomass. In contrast, applying the same rate of biochar-manure under deficit irrigation (60% ETc) resulted in a 40% water savings and a remarkable 345.5% increase in fresh biomass.

The study provides evidence that essential nutrients, such as phosphorus, calcium, and potassium, are excreted in sheep manure, emphasizing the importance of nutrient management in grazing systems. Biochar with higher ash content was highlighted as a valuable source of essential minerals for Naeemi sheep feed. Feeding sheep with biochar-supplemented rations showed dual benefits, increasing fresh biomass and residual soil nitrogen, and potentially reducing the need for nitrogen application in subsequent crops.

The application of biochar-enriched sheep manure to agricultural land was found to enhance soil fertility, nutrient availability, water-holding capacity, and soil structure. The study emphasized the positive role of biochar in nutrient retention within the digestive system of Naeemi sheep and its gradual release in agricultural lands, promoting sustainable nutrient cycling. Biochar also helped improve soil structure, water infiltration, and drainage, reducing the risk of erosion and waterlogging. Biochar also acts as a stable form of carbon, contributing to long-term carbon sequestration in the soil and mitigating GHG emissions. In summary, the study underscores the potential of a biochar-supplemented sheep ration in improving the quality of excreted manure for agricultural use, with positive implications for soil fertility, plant growth, and environmental sustainability.

Conclusions

Supplementing sheep feed with biochar significantly boosts the nutrient content of manure. Applying this nutrient-rich fertilizer at rates of 5.0, 7.5, and 10 tons per hectare, in combination with deficit irrigation, led to substantial increases in crop production—227.27%, 245.5%, and 345.5%, respectively—while reducing irrigation water usage by 40%. These results highlight the potential of biochar-enriched rations to enhance soil fertility and crop yield, suggesting a promising strategy for sustainable agriculture in arid regions.

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Resumen

H. Burezq, y F. Khalil. 2024. Estiércol de oveja enriquecido con biocarbón para la producción sostenible de maíz: Aumento del rendimiento y ahorro de agua. Int. J. Agric. Nat. Resour. 85-98. El objetivo de este estudio era aumentar la producción de maíz utilizando estiércol animal enriquecido con biocarbón derivado de hojas de palmera datilera. Se realizaron dos experimentos de campo, con dos tratamientos: En el Tratamiento 1 (T1) se utilizó estiércol estándar de ovejas Naeemi hembras alimentadas únicamente con una dieta basal, mientras que en el Tratamiento 2 (T2) se utilizó estiércol de ovejas Naeemi alimentadas con una dieta suplementada con biocarbón. El maíz se cultivó con estiércol de ambos tratamientos, aplicado en dosis de 5,0, 7,5 y 10 toneladas/hectárea, con dos niveles de riego: 60% y 100% de la evapotranspiración (ETc) del cultivo. Los resultados indicaron que el estiércol de T2 tenía niveles significativamente más altos de fósforo (15,6%), carbono orgánico total (16,4%), nitrógeno (11,4%) y potasio (23,3%) en comparación con T1. Además, la aplicación de 10 toneladas/hectárea de estiércol T1 produjo una reducción del 40% en el uso de agua y un aumento del 18,2% en biomasa fresca en comparación con el control (60% ETc). Por el contrario, la aplicación de 10 toneladas/hectárea de estiércol T2 supuso un ahorro de agua del 40% y un aumento significativo del 345,5% de la biomasa fresca en comparación con el control (60% ETc). En conclusión, la aplicación de estiércol T2 a dosis de 5,0, 7,5 y 10 toneladas/hectárea bajo riego deficitario mejoró significativamente (P<0,0001) la producción de biomasa fresca, con incrementos del 227,27%, 245,5% y 345,5%, respectivamente, en comparación con T1 bajo condiciones de riego similares. La mejora de la composición del suelo resultante de la incorporación de estiércol T2 también podría favorecer el crecimiento de otros cultivos, especialmente en regiones áridas como Kuwait.

Palabras clave: Agricultura sostenible, ahorro de agua, biocarbón, biomasa fresca, ciclo de nutrientes, fertilidad del suelo, secuestro de carbono, riego deficitario.

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