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LIQUID FERTILIZATION AND BIOCHAR TO BOOST THE YIELD AND PROFITABILITY OF *Arachis hypogaea* L. IN DRYLAND AGROECOSYSTEMS

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ABSTRACT

Temporary water deficits during the rainy season adversely affect surface soil, limiting the solubilization of granular fertilizers applied in surface bands. The objective of this study was to evaluate the effectiveness of liquid and granular fertilization in combination with biochar on the yield and profitability of peanut (*Arachis hypogaea* L.) in rainfed agroecosystems. The study was carried out during the January-June period of both the 2023 and 2024 seasons. Four treatments were evaluated: liquid fertilization + biochar (LFB); conventional fertilization + biochar (CFB); conventional fertilization (CF); and a control treatment (no fertilization). The main variables recorded were seed yield, the partial factor productivity of NPK (PFP_{NPK}), and net economic benefit (NEB) of fertilization. The results showed that fertilization treatments significantly influenced ($p < 0.05$) seed yield and partial factor productivity of NPK (PFP_{NPK}). LFB produced the highest yield values with 2007 kg ha^{-1}, exceeding CFB, CF, and the control by 182, 396, and 637 kg, respectively. LFB also achieved the highest increases in PFP_{NPK} compared with CFB and CF, indicating greater nutrient use efficiency. The highest NEB of fertilization was obtained with LFB, with USD 518 ha^{-1}, compared with USD 377 and 186 ha^{-1} for CFB and CF, respectively. It is concluded that the combined application of liquid fertilizer and biochar is an economically viable and sustainable strategy for rainfed peanut production, particularly under surface soil water deficit.

Keywords: Peanuts, *Arachis hypogaea* L., rainfed agriculture, liquid fertilization, organic amendment, productivity

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INTRODUCTION

Peanut (*Arachis hypogaea* L.) is one of the most widely consumed oilseeds worldwide and is commercially valued for the production of bioactive compounds. It is an energy-dense food containing a high amount of fats, proteins, carbohydrates, as well as fat- and water-soluble vitamins and minerals that are important for human health (Ciftci and Suna, 2022; Bonku and Ju, 2023). In Ecuador, peanut cultivation occupies 15,000-20,000 hectares annually, mainly in the drylands of the provinces of Loja, Manabí, El Oro and Guayas (Guamán et al., 2014).

The implementation of more efficient and resilient agricultural practices can increase productivity per hectare, thereby reducing costs, minimizing impacts on natural resources, improving access to competitive markets, and promoting more sustainable production (Betiol et al., 2023; Taylor et al., 2024). Enhancing crop productivity under the current climate crisis is essential to improving farmers' profitability, ensuring food security, and strengthening local economies (Puppala et al., 2023; Gelaye and Luo, 2024).

Rainfed agriculture relies on annual rainfall cycles and is highly vulnerable to climate change. Extreme weather events, such as sudden and intense droughts during the rainy season, can lead to water deficits and have severe social and economic impacts on dryland production systems (Salmoral et al., 2018; Ahmed et al., 2022; Speer et al., 2024; Chen et al., 2025). In Ecuador, 76% of agriculture is rainfed; in the coastal area, 83% of annual rainfall is concentrated within a short period, typically between January and April, while short droughts during the rainy season have become increasingly frequent in recent years, adversely affecting the productivity of rainfed peanut crops. (Pérez et al., 2018; Matailo-Ramirez et al., 2023; INEC, 2023). Another factor affecting peanut production is the low water-holding capacity of the soils, which have lost approximately 50% of their organic carbon reserves due to the annual intensive burning of crop residue, a practice carried out on more than 87% of agricultural soils in Manabí, Ecuador, the province with the largest area under peanut cultivation (Mesías et al., 2018; INEC, 2023).

Temporary water deficits caused by sudden droughts during the rainy season reduce surface soil moisture, negatively affecting crop fertilization and nutrition by limiting the solubilization of granular fertilizers applied in surface bands, which in turn increases the loss of essential nutrients, such as nitrogen, through volatilization due to insufficient moisture and runoff when intense rains return (Siman et al., 2020; Lisboa et al., 2020; Yao et al., 2021; Furtak and Wolińska, 2023). When surface soil moisture is insufficient, fertilizers such as urea cannot dissolve and move effectively to deeper soil layers, leading to hydrolysis that produces ammonia (NH_3), which is easily lost as a gas, particularly under high temperatures that accelerate NH_3 volatilization (Motasim et al., 2024; dos Santos et al., 2025). After periods of sudden drought, intense rainfall often occurs in short periods, contributing to nitrogen loss through leaching. Excess water carries nitrates (NO_3^-) into deeper soil layers, beyond the reach of plant roots, because unlike ammonium ((NH_4^+), nitrate does not readily adhere to soil particles. This loss not only reduces the effectiveness of applied fertilizers but can also lead to groundwater contamination (Dong et al., 2022; Hina, 2024).

It has been well documented that nutrient availability and uptake by roots are closely linked to soil moisture and, consequently, plants can be simultaneously limited by both water and mineral nutrients during sudden drought events (Plett et al., 2020; Furtak and Wolińska, 2023). This is particularly serious in peanut cultivation, as a decrease in surface soil moisture increases resistance to penetration by gynophores, affecting their viability and the formation of pods and seeds (Haro et al., 2011). Furthermore, the mineral nutrition of peanuts can also be reduced when gynophores fail to penetrate the soil, since they are involved in the absorption of water and nutrients (Kumar et al., 2019).

Liquid fertilization applied near the roots using specialized equipment for injection and dosing emerges as an advantageous technology for dryland production systems, as nutrients are delivered in a diluted form that facilitates their movement toward the root zone, thereby improving nutrient uptake, particularly during periods of surface soil water deficit (Weeks and Hettiarachchi, 2019; Bogusz et al., 2021; Motasim et al., 2022). Moreover, biochar is widely recommended as a soil amendment to improve properties such as water and nutrient retention, particularly in drylands prone to sudden water deficits (Acharya et al., 2024). Previous studies have shown that biochar application significantly increases soil moisture as well as the availability of N, P, and K (Razzaghi et al., 2020; Bekchanova et al., 2024). Among the properties of biochar that contribute to improved soil moisture and nutrient retention is its highly porous structure, with micro- and mesopores that store water and nutrients. In addition, biochar has a high specific surface area, which facilitates greater interaction with soil water and nutrients (Qi et al., 2024;

Zhang et al., 2024). It also exhibits a high cation exchange capacity, as it develops negative charges that help retain cationic nutrients such as Ca^{2+}, Mg^{2+}, K^+ and NH_4^+, thereby reducing leaching. Biochar produced at low temperatures (<500 °C) is generally more hydrophilic, enhancing water retention in dry soils (Qi et al., 2024; Zhang et al., 2024).

The positive effects of combining liquid fertilization with biochar have not been evaluated in rainfed peanut systems in Ecuador, where temporary rainfall deficits can reduce surface soil moisture and negatively affect crop nutrition when granular fertilizers are applied. Applying liquid fertilization in combination with biochar to the root zone may enhance peanut yield. Therefore, the main objective of this study was to evaluate the effectiveness of liquid and granular fertilization combined with biochar on peanut yield and profitability in rainfed agroecosystems.

MATERIALS AND METHODS

Study site

The study was conducted during the 2023 and 2024 rainy seasons at the El Viento site, Tosagua, Manabí Province, Ecuador. The experimental site was located at 0°49′10.55″S and 80°18′01.2″W (Fig. 1), at an altitude of 61 meters above sea level.

Edaphoclimatic characteristics

The experimental site has an average annual temperature of 25.81 °C, annual precipitation of 500.80 mm, 1,038 hours of sunshine per year, and a relative humidity of 77%. Fig. 2 shows the ombrothermic diagram of the experimental site from January to June, which corresponds to the rainfed cropping season in Ecuador.

Initial soil analysis at the experimental site indicated a silty-loam texture (22% sand, 54% silt, and 24% clay), a pH of 7.1, and an organic matter content of 2.1%. Nutrient concentrations were as follows: N-NH_4 (19 mg kg^{-1}), P (21 mg kg^{-1}), K (0,38 $cmol_{(+)}$ kg^{-1}), Ca (9,1 $cmol_{(+)}$ kg^{-1}), Mg (2,2 $cmol_{(+)}$ kg^{-1}), S (26 mg kg^{-1}), Zn (3,2 mg kg^{-1}), Cu (6,6 mg kg^{-1}), Fe (26 mg kg^{-1}), Mn (9,4 mg kg^{-1}), and B (0,58 mg kg^{-1}).

N, P, K, Ca, Mg, Cu, Fe, Mn, and Zn were measured using the modified Olsen method, while B and S were extracted using monobasic calcium phosphate. Nutrient determination was performed using colorimetry for N, P, and B; atomic absorption spectrophotometry for K, Ca, Mg, Cu, Fe, Mn, and Zn; and turbidimetry for S. Soil pH was measured in a 1:2.5 soil:water suspension, and organic matter content was determined by the Welkley-Black method (Shamrikova et al., 2022).

Treatments, experimental design, and experimental units

The planting material used was the INIAP – 380, Valencia-type peanut variety, characterized by semi-erect growth, flower production on the main stem, and a productive cycle of 100-105 days. The treatments evaluated were as follows: Liquid Fertilization + Biochar (LFB); Conventional Fertilization + Biochar (CFB); Conventional Fertilization (CF); and a control treatment.

A randomized complete block design was used with four treatments and five replicates, totaling 20 experimental units. Each experimental unit consisted of 25 m^2 plots. Planting spacing was 0.50 m between rows and 0.20 m between plants, with two plants per hole, and a planting density of 200,000 plants ha^{-1}.

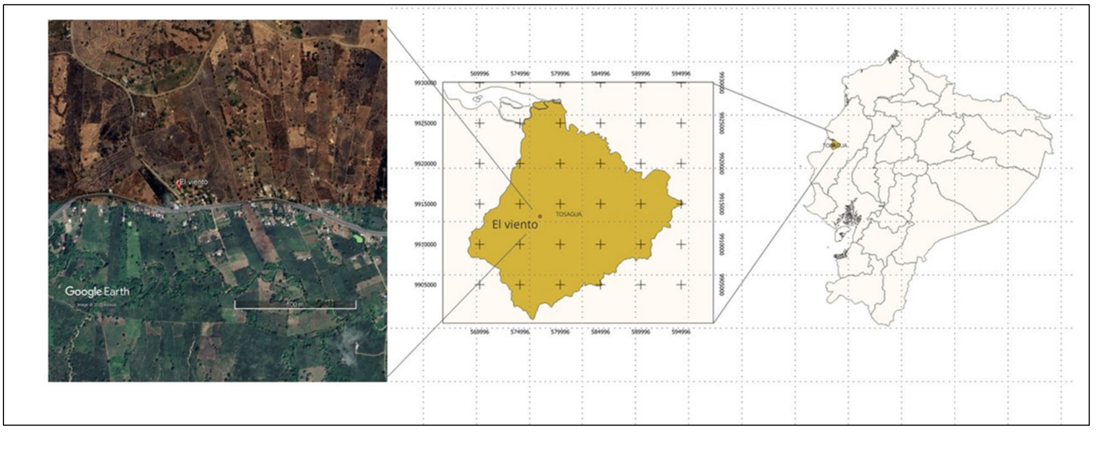

Fig. 1. Geographical location of the experimental site.

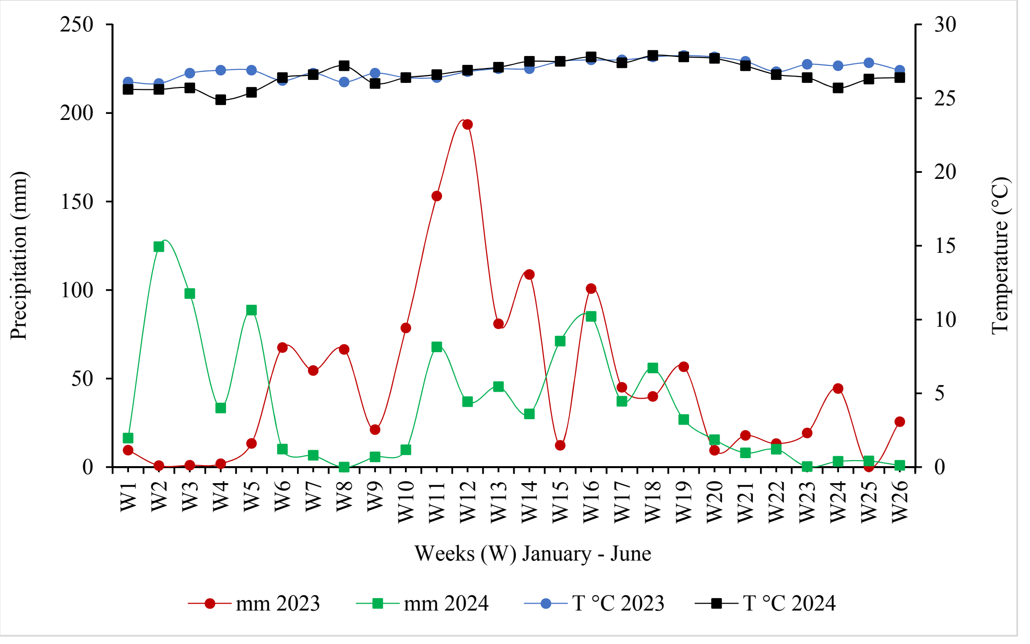

Fig. 2. Ombrothermic diagram for the January–June period of 2023 and 2024 in Tosagua, Ecuador.

Variables and data analysis

Yield components were recorded, including the number of pods and kernels per plant, as well as the weight of 100 pods and kernels. At harvest, ten plants were randomly sampled from the center of each experimental unit. From these samples, the number of pods and kernels per plant was counted, considering only fully formed pods of commercial quality. To determine 100-pod and 100-seed weights, random samples of 100 pods and 100 seeds were taken, and their weight (g) was measured using a Hanna precision analytical balance. Both pod and seed yields were determined 15 days after harvest, as the freshly pulled pods were still humid and had wet soil (mud) adhering to them. To facilitate drying, the plants were pulled and turned over to expose the pods to natural air-drying. After this period, the pods were threshed and then shelled.

From each experimental unit, plants were collected from a 2 m^2 area in the center of the plot. Commercial pods were harvested, and their weight (g) was recorded and then converted to kg ha^{-1}. For seed yield, pods from the same 2 m^2 area were shelled, and seed weight (kg) and moisture content were recorded. Moisture content was standardized at 14% using Equation [1], and seed yield was expressed as kg ha^{-1}.

$$SW\ (14\ \%) = \frac{W\ (100-M)}{100-Md} \qquad [1]$$

Where:
SW = standardized weight, W = current weight (kg), M = current seed moisture (%), Md = desired seed moisture (14%).

The harvest index (HI%) was determined following the methodology proposed by Mukhtar et al. (2013). First, the total dry matter of the plants was estimated by collecting a sample of five plants per experimental unit, which were oven-dried at 70°C for 48 hours. The harvest index was then calculated using Equation [2]:

$$HI\ (\%) = \frac{seed\ yield\ per\ plant\ (g)}{Total\ dry\ matter\ per\ plant\ (g)}\ x\ 100 \qquad [2]$$

The partial factor productivity (PFP) of NPK was estimated using the methodology proposed by Jain et al. (2021a), using Equation [3].

$$PFP_{NPK}(kg\ kg^{-1}) = \frac{Seed\ yield\ (kg\ ha^{-1})}{Applied\ dose\ of\ NPK\ \ (kg\ ha^{-1})} \qquad [3]$$

Agronomic data were analyzed using one-way ANOVA, and means comparisons were performed using Tukey's test (α = 0.05). All statistical analyses were conducted using the InfoStat statistical package, version 2020.

The net economic benefit of the fertilization treatments was obtained using the methodology proposed by Duicela and Ponce (2015). First, the variable costs associated with each fertilization treatment (VCF) were estimated, including the cost of fertilizers, biochar, application labor, and harvesting labor. For the control treatment, variable costs related to fertilization and biochar were considered zero (VCF = 0). Total revenue (USD ha^{-1}) was calculated based on seed yields (kg ha^{-1}) and the unit sale price (USD kg^{-1}). The increase in revenue (USD kg^{-1}) was determined as the difference between the yields of the fertilization treatments and the control treatment. The increases in costs and revenue were then used to estimate the specific net benefits of the fertilization treatments.

Experimental management

Prior to sowing, the seeds were treated with Imidacloprid + Thiodicarb at a dose of 25 mL kg^{-1} of seed. During the fourth quadruple leaf stage and at full bloom, the crop was attacked by fall armyworm (*Stegasta bosqueella*), which was controlled with an application of Spinetoram at 0.1 L ha^{-1}, followed by a co-formulated insecticide based on Thiamethoxam + Lambda-cyhalothrin at 0.3 L ha^{-1}. Additionally, leafhopper (*Phyllophaga* sp,) damage occurred at crop emergence and was controlled with a drench application of Chlorpyrifos 1 L ha^{-1}.

Pre-emergence weed control was carried out with the herbicides Pendimethalin + Linuron at doses of 2.5 and 1.0 L ha^{-1} of each product, respectively. Post-emergence weed control was carried out with the selective herbicides Imazetapyr + Haloxyfop, at doses of 1 L ha^{-1} of each product.

Fertilization was carried out with 75, 23, and 50 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. In the conventional granular fertilization treatment, the following fertilizers were applied: urea (46 % N), di-ammonium phosphate (12% N and 46% P_2O_5), and potassium chloride (60% K_2O). Granular fertilization was applied in a surface band.

For the liquid fertilizer treatment, urea (46% N), soluble monopotassium phosphate (52% P_2O_5 and 34% K_2O), and soluble potassium chloride (60% K_2O) were used, with solubilities of 1,080, 225, and 200 g L^{-1} of water, respectively. In both treatments, fertilization was divided into two applications: the first at crop emergence and the second at the beginning of flowering, with 100% of the phosphorus applied in the first fraction.

For liquid fertilization, stock solutions were prepared in separate tanks, taking into account the solubility and compatibility of the fertilizers. For the first liquid fertilization, urea was dissolved in tank A and mono-potassium phosphate in tank B; the solutions were then mixed and brought to a final volume of 2,500 L of water (equivalent to 12.5 tanks of 200 L ha^{-1}). From this solution, 25 mL was applied per planting spot (two plants per hole) using a drench method with manual pressure-dosing pump (Guarany SP-0405.11). For the second liquid fertilization, a stock solution of urea + soluble potassium chloride was prepared in a single tank and brought to the same final volume of 2,500 L ha^{-1}, in order to apply the same solution volume per planting spot as in the first fertilization (25 mL).

Biochar was applied to the planting row at the time of planting at a dose of 50 g per linear meter, equivalent to 1 t ha^{-1}. The biochar used in this study was produced by pyrolysis of wood residues from the carob tree (*Prosopis pallida*). It was manufactured on a small scale using artisanal equipment based on the Anila stove design. Maximum temperatures during pyrolysis ranged from 350 to 550 °C, with process times at temperatures > 300 °C lasting up to 3 hours, due to the density of carob wood. Once produced, the biochar was ground in a stainless-steel mill (Sk100, Retsch, Germany) to a mesh size < 2 mm. Table 1 shows the physicochemical characteristics of the evaluated biochar.

RESULTS

Yield components were significantly affected ($p < 0.05$) by the fertilization treatments during the 2023 and 2024 seasons (Table 2). In 2023, pod production per plant was significantly higher under LFB, with increases of 11.76%, 17.24%, and 26.86% with respect to CFB, CF, and the control, respectively. A similar trend was observed in 2024, since LFB increased pod production by 11.83%, 19.50%, and 34.64% compared with CFB, CF, and the control, respectively (Table 2).

A similar effect was observed for seed production, where LFB achieved the highest mean values. In 2023, LFB increased seed production by 11.35%, 16.52%, and 26.65% compared with CFB, CF, and the control, respectively. This trend was also observed in 2024, with increases of 11.55%, 20.84%, and 33.06% with respect to the same treatments, respectively (Table 2).

For the 100-pod weight, the LFB treatment also produced the greatest gains, surpassing CFB, CF, and the control by 3.50, 6.43, and 13.40 g in 2023, and by 5.51, 10.09, and 19.77 g in 2024, respectively (Table 2). Similarly, 100-seed weight was highest under LFB, exceeding CFB, CF, and the control by 3.15, 4.61, and 12.77 g in 2023, and by 2.83, 5.21, and 10.80 g in 2024, respectively (Table 2).

Pod yield, seed yield, and harvest index were significantly influenced by the evaluated treatments ($p < 0.05$). All fertilization treatments

Table 1. Chemical characterization of the biochar used in the experiment.

Parameter	Unit	Carob wood
Dry Matter	%	92,9
Moisture	%	7,1
Bulk density	g L^{-1}	260
pH	-	7,5
EC	mS cm^{-1}	1,1
Organic matter	%	66,8
Carbon	%	38,8
Carbon-nitrogen ratio (C:N)	%	42/1
Total Nitrogen (N)	%	1,0
Phosphorus (P)	%	0,06
Potasium (K)	%	0,22
Calcium (Ca)	%	1,01
Magnesium (Mg)	%	0,08
Sodium (Na)	%	0,03
Iron (Fe)	mg kg^{-1}	194
Manganese (Mn)	mg kg^{-1}	12,6
Copper (Cu)	mg kg^{-1}	4,9
Zinc (Zn)	mg kg^{-1}	6,1
Boron (B)	mg kg^{-1}	33,4

Table 2. Effect of fertilization and biochar treatments on yield components in rainfed peanut production.

Treatments	Pods per plant	Seeds per plant	Weight of 100 pods (g)	Weight of 100 seeds (g)
Year 2023				
LFB	24.65 a[1/]	85.75 a	143.00 a	68.12 a
CFB	21.75 b	76.02 b	139.50 ab	64.97 a
CF	20.40 b	71.58 b	136.57 b	63.51 a
CT	18.03 c	62.90 c	129.60 c	55.35 b
p-value ANOVA	0.0001	0.0001	0.0001	0.0007
C.V. %	5.72	5.07	1.79	5.62
Year 2024				
LFB	25.03 a	84.44 a	142.16 a	67.79 a
CFB	22.07 ab	74.69 b	136.65 b	64.96 ab
CF	20.15 b	66.84 b	131.26 c	62.58 b
CT	16.36 c	56.52 c	122.39 d	56.99 c
p-value ANOVA	0.0001	0.0001	0.0001	0.0001
C.V. %	8.06	7.08	1.78	3.12

[1/] Different letters within the same column indicate significant differences according to Tukey's test (α = 0.05). LFB: Liquid fertilization + biochar; CFB: Conventional fertilization + biochar; CF: Conventional fertilization; CT: Control treatment.

(LFB, CFB, and CF) resulted in higher mean values compared to the non-fertilized control. Moreover, fertilization combined with biochar (LFB and CFB) further enhanced yields and harvest index, with the liquid fertilization producing the highest significant values. LFB recorded the highest pod yield, with a significant additional increase of 214.75, 380.00, and 686.67 kg ha^{-1} in the 2023 season, and 195.55, 602.22 and 917.77 kg ha^{-1} in the 2024 season, with respect to CFB, CF, and the control, respectively (Table 3). A similar trend was observed for seed yield, as

Table 3. Effect of fertilization and biochar treatments on pod yield, seed yield, and harvest index in rainfed peanut production.

Treatments	Pod yield (kg ha^{-1})	Seed yield (kg ha^{-1})	Harvest index (%)
Year 2023			
LFB	2748.89 a[1/]	1983.71 a	23.30 a
CFB	2534.14 ab	1794.81 b	20.65 b
CF	2368.89 bc	1610.38 b	19.58 b
CT	2062.22 c	1395.45 c	16.71 c
p-value ANOVA	0.0004	0.0001	0.0001
C.V., %	7.30	4.49	6.04
Year 2024			
LFB	2884.44 a	2031.05 a	23.62 a
CFB	2688.89 ab	1854.98 a	21.88 ab
CF	2282.22 b	1613.55 b	20.31 b
CT	1966.67 c	1345.91 c	17.90 c
p-value ANOVA	0.0002	0.0001	0.0001
C.V., %	9.64	6.89	5.68

[1/] Different letters within the same column indicate significant differences according to Tukey's test ($\alpha = 0.05$). LFB: Liquid fertilization + biochar; CFB: Conventional fertilization + biochar; CF: Conventional fertilization; CT: Control treatment.

LFB recorded the highest values, with significant increases of 188.90, 373.33, and 588.26 kg ha^{-1} in the 2023 season, and 176.07, 417.70, and 685 kg ha^{-1} in the 2024 season, compared with the same treatments (Table 3). Regarding the harvest index, the same trends were observed as for pod and seed yield, with LFB achieving increases of 11.37, 15.97, and 28.28% in the 2023 season and 7.37, 14.01, and 24.22% in the 2024 season with respect to CFB, CF, and the control, respectively (Table 3).

Partial factor productivity (PFP_{NPK}) is an important indicator of fertilization efficiency. The results showed that it was significantly influenced ($p < 0.05$) by the fertilization treatments evaluated, where the greatest responses observed under the LFB treatment (Table 4). In the 2023 season, LFB produced an additional FPP_N of 2.52 and 4.18 kg of seed per kg of applied N, compared with CFB and CF, respectively. Additionally, LFB achieved significant increases of 8.21 and 13.63 kg of seed per kg of applied P_2O_5 for FPP_P; and 3.77 and 6.26 kg of seed per kg of applied K_2O for FPP_K, compared with CFB and CF treatments, respectively (Table 4). In the 2024 season, LFB achieved the highest average values of FPP_N, FPP_P and FPP_K, although there were statistically similar to those of CFB. For FPP_N, LFB recorded increases of 1.01 and 5.57 kg of seed per kg of N applied, compared with CFB and CF, respectively. For FPP_P, LFB recorded increases of3.31 and 18.16 kg of seed per kg of P_2O_5 applied relative to the same treatments, respectively. The FPP_K was also statistically higher in LFB, with increases of 1.52 and 8.35 kg of seed per kg of K_2O applied, compared with CFB and CF treatments, respectively.

Table 5 presents the total economic benefits of the crop and the net benefits of the fertilization treatments. In the 2023 season, LFB achieved a net economic benefit of USD 441 ha^{-1}, which resulted in a net increase of USD 152 and 297 ha^{-1} over CFB and CF, respectively. For the 2024 season, LFB reached a net economic benefit of USD 596 ha^{-1}, corresponding to net gains of USD 131 and 368 ha^{-1} with respect to CFB and CF, respectively (Table 5). The greater economic benefits observed in the fertilization treatments that included biochar (LFB and CFB) compared with conventional fertilization (CF) are due to greater increases in yield and revenues, indicating that the use of biochar is an economically viable technology for enhancing fertilization effects. Likewise, the higher economic benefit of liquid fertilization (LFB) compared with conventional fertilization (CFB and CF) indicates that, in rainfed peanut production where surface soil moisture may be reduced by temporary rainfall deficits, the use of liquid formulations can be a more economically effective alternative than the application of granular fertilizers (Table 5).

DISCUSSION

The results for the yield components are consistent with those reported by Jain and Meena (2015) and Jain et al. (2021a), who reported

Table 4. Effect of fertilization and biochar treatments on the partial factor productivity (PFP) of N, P, and K in rainfed peanut production.

	PFP (kg of seeds kg^{-1} NPK)		
Treatments	N	P_2O_5	K_2O
Year 2023			
LFB	26.45 a[1/]	86.25 a	39.67 a
CFB	23.93 b	78.04 b	35.90 b
CF	22.27 c	72.62 c	33.41 c
p-value ANOVA	0.0003	0.0024	0.0001
C.V. %	3.71	3.96	4.07
Year 2024			
LFB	27.08 a	88.31 a	40.62 a
CFB	26.07 a	85.00 a	39.10 a
CF	21.51 b	70.15 b	32.27 b
p-value ANOVA	0.0005	0.0002	0.0014
C.V. %	5.72	5.44	5.68

[1/] Different letters within the same column indicate significant differences according to Tukey's test (α = 0.05). LFB: Liquid fertilization + biochar; CFB: Conventional fertilization + biochar; CF: Conventional fertilization

Table 5. Net economic benefit of the fertilization treatments on rainfed peanut production.

Treatments	TC	NVCF	VCF	IVCF	YLD	IYLD	USP	RIF	TR	TEB	NEB
Year 2023											
LFB	1,800	1,000	800	500	1,984	588	1.6	941	3,174	1,374	441
CFB	1,650	1,000	650	350	1,795	399	1.6	638	2,872	1,222	289
CF	1,500	1,000	500	200	1,610	215	1.6	344	2,576	1,077	144
CT	1,300	1,000	300	---	1,395	---	1.6	---	2,233	933	---
Year 2024											
LFB	1,800	1,000	800	500	2,031	685	1.6	1,096	3,250	1,450	596
CFB	1,650	1,000	650	350	1,855	509	1.6	814	2,968	1,318	465
CF	1,500	1,000	500	200	1,614	268	1.6	429	2,582	1,082	228
CT	1,300	1,000	300	---	1,346	---	1.6	---	2,153	853	---

TC: Total costs (USD ha^{-1}), NVCF: Costs that do not vary with fertilization – USD ha^{-1} (seed, land preparation, sowing, phytosanitary control), VCF: Costs that vary with fertilization – USD ha^{-1} (fertilizers, biochar, applications, and harvest costs), IVCF: Increase in costs that vary with fertilization – USD ha^{-1} (IVCF = VCF treatments – VCF control), YLD: Yield (kg ha^{-1}), IYLD: Increase in yield of fertilization treatments in relation to the control (IYLD = YLD treatments – YLD control), USP: Unit sale price (USD ha^{-1}), RIF: Revenue increase from fertilization in relation to the control – USD ha^{-1} (RIF = IYLD * USP), TR: Total revenue USD ha^{-1} (TR = YLD * USP), TEB: Total economic benefit – USD ha^{-1} (TEB = TR – TC), NEB: Net economic benefit of fertilization – USD ha^{-1} (NEB = RIF – IVCF).

higher pod and seed production per plant, as well as higher seed and pod weights, when liquid fertilization was applied via drip irrigation compared with surface application of granular fertilizers, which resulted in significantly lower values.

Regarding the effect of biochar application, the results of the present study agree with those of Zheng et al. (2021), who reported higher pod and seed production and increased seed weight per plant in biochar + fertilization treatments compared with the control without biochar. Biochar improved yield components even under varying levels of water stress. Similarly, Shikha et al. (2023) observed higher 100-pod and 100-seed weights when biochar was combined with biofertilizers, compared with treatments without biochar. Furthermore, the productivity levels observed in this study are similar to those described by Jain and Meena (2015), who reported yields of pod and seed yields of 2.67 and 1.82 t ha^{-1}, respectively, when fertilization was applied through fertigation, compared with significantly lower yields under conventional fertilization. AJain et al. (2021a) reported pod and seeds yields of 3,791 and 2,657 kg ha^{-1} with fertigation, compared with 3,161 and 2,100 kg ha^{-1} under conventional fertilization, which shows the greater effectiveness of liquid fertilization. Similarly, the yields achieved with the combination of fertilizer and biochar (LFB and CFB) are consistent with those reported by Agegnehu et al. (2015), who observed yield increases of 18–24% with combined fertilizer and biochar applications in peanuts, compared with the 12–20% increases obtained in the present study. Additionally, Gao et al. (2017) reported yield increases of up to 16.8% in peanut production when biochar-based fertilizers were applied, compared with treatments without biochar. Comparable results were also reported by Shikha et al. (2023), who reported an average yield of 2.30 t ha^{-1} with biochar and fertilization, in contrast to 1.74 t ha^{-1} obtained with fertilization alone.

Regarding the harvest index, our results align with those described by Jain and Meena (2015) and Samanhudi et al. (2023), who observed a higher harvest index in peanuts when liquid fertilization was combined with biochar.

Regarding fertilizer use efficiency, the results of the present study highlight the superior performance of the combined use of liquid fertilization and biochar in rainfed peanut production. These findings are consistent with those reported by Jain et al. (2021a), who observed increases in FPP_{NPK} ranging from 3.6 to 24.4 kg of seeds per kg of fertilizer applied under fertigation, compared with conventional fertilization. Similarly, the results align with Jain et al. (2021b), who reported increases in N, P, and K uptake in peanut biomass production of up to 17.5, 4.4, and 10.6 kg ha^{-1}, respectively, under fertigation relative to conventional granular fertilizer.

In the present study, the results indicate that liquid fertilization can be an agronomically and economically efficient technology to improve the nutrition and productivity of rainfed peanut crops. When rainfall is lacking for several days and the soil surface retains only limited moisture, as occurred during weeks 1-5 of 2023 and weeks 6-10 of 2024 (Fig. 2), liquid fertilization applied near the roots enhances nutrient mobility to deeper soil layers, where residual moisture remains, facilitating easier nutrient uptake by the roots. In this context, a study conducted by Aakash et al. (2022) on rainfed corn revealed that when surface soil moisture evaporates, nitrogen fertilizer cannot penetrate and is easily lost by volatilization, while at depths below 35 - 40 mm, the soil retains sufficient moisture for nutrients remain available to the roots. The authors concluded that fertilization should be scheduled when 14 - 15 mm of rainfall is expected, ensuring that the surface soil is adequately moistened and that nutrients can be effectively transported to the moisture-retaining soil layers.

Given that water is essential for mobilizing, dissolving, and releasing nutrients provided from fertilizers, several authors have described that liquid formulations enhance nutrient availability, particularly during drought periods, and thus their use is economically justified. Reduced soil moisture limits mass flow and diffusion, reducing the amount of nutrients reaching the root surfaces (Bogusz et al., 2021; Alaoui et al., 2022; Barłóg et al., 2022). Furthermore, liquid fertilization has been documented to increase nitrogen uptake by plants and decrease losses due to volatilization and leaching (Motasim et al., 2021 a and b). Moreover, as it facilitates nutrient uptake and allows for uniform application, recent research has focused on developing field equipment capable of accurately dosing and injecting fertilizers into the soil (da Silva and Magalhães, 2017, 2019; Stamate et al., 2024).

Regarding the use of biochar, the results of the present study show a significant improvement in productivity, profitability, and fertilization efficiency, indicating that biochar enhances nutrition of peanut cultivated in dryland conditions. This improvement is likely attributable to the ability of biochar to retain soil moisture during periods of water scarcity and to conserve nutrients applied through fertilizers, particularly when intense rainfall follows a dry period, increasing the risk of nutrient loss due to runoff and leaching. In this context, previous studies have shown that different types of biochar mitigate the effects of soil drying through physical and biological mechanisms associated with greater sorption capacity due to their porosity and surface charge, which also helps reduce nutrient losses through leaching (Hossain et al., 2020; Thao et al., 2024). This is consistent with Razzaghi et al. (2020), who reported that biochar application increased available soil moisture by 14%, 21%, and 45% in fine-, medium-, and coarse-textured soils, respectively.

A meta-analysis by Hosseini et al. (2022) indicated that biochar application can increase crop yield by up to 25.3%, with an additional 10% increase in yield when combined with fertilizers. Furthermore, Bekchanova et al. (2024) reported that the biochar application increased the availability of N, P, and K by 36%. When incorporated into the soil, biochar helps improve soil physical structure, increasing porosity and moisture retention, thereby facilitating aeration and promoting root growth. Its high cation exchange further enhances the availability of essential nutrients, while its activity on soil microbiota fosters beneficial microbial communities that enhance the rhizosphere. Together, these factors create a more favorable environment for root development and pod formation, leading to higher pod and seed yields (Rassem and Elzobair, 2023; Yang et al., 2023; Luo et al., 2024). By improving the soil environment for root development and microbial activity, biochar can enhance plant metabolism through greater water and nutrient availability, thereby supporting enzymatic activities, metabolite biosynthesis, photosynthetic activity, nitrogen fixation, and stress tolerance, which all promote plant development and productivity (Zhang et al., 2023; Wang et al., 2024; Barbosa et al., 2024; Zaheer et al., 2024).

Overall, the results of the present study, in line with those of previous research, demonstrate that the combined use of liquid fertilization and biochar can be an effective, sustainable, and economically viable technology for fertilizing peanut crops under the short-term drought conditions of dryland agricultural systems. However, during normal rainy seasons where soil moisture is not limited, conventional granular fertilization remains an effective practice that can continue to be adopted by rainfed farmers. Furthermore, given the positive effects observed in the present research and those documented in the literature, biochar should be incorporated into integrated crop management, regardless of whether fertilization is applied in liquid or granular form. The findings of this study contribute to the expanding knowledge of peanut production under rainfed conditions, where increasingly frequent climatic events such as sudden droughts directly threaten the livelihoods of small farmers who depend on this production system.

CONCLUSIONS

Locally applied liquid fertilization was more effective than granular fertilization in increasing yield and profitability of peanuts under rainfed conditions, especially during periods of several consecutive days without rainfall.

The use of biochar enhances the effectiveness of fertilization, irrespective of whether liquid or granular fertilizers are applied. However, during periods of water deficit in the rainy season, the combination of liquid fertilization and biochar more effectively increases yield and productivity components of peanuts, while also achieving greater economic benefits. Conversely, under consistently wet conditions that maintain sufficient surface soil moisture, granular fertilization in a surface band may be more appropriate due to its lower cost.

Future long-term studies are recommended to evaluate the persistence of biochar effects or to optimize biochar dosages and types for different soils and other rainfed crops.

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Author contributions

Adrián Alexander Moreira Cevallos: conducted field experiments and recorded data; Galo Alexander Cedeño García: designed the experimental design, managed financial resources, and revised the manuscript; Saskia Valeria Guillen Mendoza: performed data analysis and prepared tables and figures; Edison Fabian Medranda Vera: assisted with data recording and contributed to manuscript writing; Benny Alexander Avellán Cedeño: managed experimental logistics and contributed to manuscript writing; Leonardo Xavier León Castro: conducted economic analysis and contributed to manuscript writing. All authors approved the final version of the manuscript.

LITERATURE CITED

Agegnehu, G., A. Bass, P. Nelson, B. Muirhead, G. Wright, and M. Bird. 2015. Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. Agriculture, Ecosystems and Environment 213: 72-85. https://doi.org/10.1016/j.agee.2015.07.027

Ahmed, M., R. Hayat, M. Ahmad, M. ul-Hassan, A. Kheir, F. ul-Hassan, M. ur-Rehman, F. Shaheen, M. Raza, and S. Ahmad. 2022. Impact of climate change on dryland agricultural systems: A review of current status, potentials, and further work need. International Journal of Plant Production 16: 341-363. https://doi.org/10.1007/s42106-022-00197-1

Acharya, B., S. Dodla, J. Wang, K. Pavuluri, M. Darapuneni, S. Dattamudi, B. Maharjan, and G. Kharel. 2024. Biochar impacts on soil water dynamics: knowns, unknowns, and research directions. Biochar 6: 34. https://doi.org/10.1007/s42773-024-00323-4

Aakash., N. Thakur, M. Singh, L. Bhayal, K. Meena, S. Choudhary, N. Kumawat, R. Singh, U. Singh, S. Singh, P. Sanodiya, A. Kumar, and A. Singh. 2022. Sustainability in rainfed maize (*Zea mays* L.) production using choice of corn variety and nitrogen scheduling. Sustainability 14: 3116. https://doi.org/10.3390/su14053116

Alaoui, I., O. El-ghadraoui, S. Serbouti, H. Ahmed, I. Mansouri, F. El-Kamari, A. Taroq, D. Ousaaid, W. Squalli, and A. Farah. 2022. The mechanisms of absorption and nutrients transport in plants: A Review. Trop. J. Nat. Prod. Res. 6:8–14. https://doi.org/10.26538/tjnpr/v6i1

Barbosa, F., J. Santos, J. Mota, M. Costa, A. Araujo, K. Garcia, M. Almeida, I. Nascimento, E. Medeiros, O. Ferreira, A. Souza Filho, L. Fregolente, H. Sousa, W. Borges, and A. de Araujo. 2024. Potential of biochar to restoration of microbial biomass and enzymatic activity in a highly degraded semiarid soil. Sci. Rep. 14: 26065. https://doi.org/10.1038/s41598-024-77368-9

Bekchanova, M., L. Campion, S. Bruns, T. Kuppens, J. Lehmann, M. Jozefczak, A. Cuypers, and R. Malina. 2024. Biochar improves the nutrient cycle in sandy-textured soils and increases crop yield: a systematic review. Environ. Evid. 13: 3. https://doi.org/10.1186/s13750-024-00326-5

Betiol, O., D. Bolonhezi, ERP. Leal, CE. Gruener, MD. Michelotto, CE. Furlani, and FF. Ruiz. 2023. Conservation agriculture practices in a peanut cropping system: Effects on pod yield and soil penetration resistance. Rev. Bras. Cienc. Solo. 47: e0230004 https://doi.org/10.36783/18069657rbcs20230004

Barłóg, P., W. Grzebisz, and R. Łukowiak. 2022. Fertilizers and fertilization strategies mitigating soil factors constraining efficiency of nitrogen in plant production. Plants 11(14): 1855. https://doi.org/10.3390/plants11141855

Bonku, R. and J. Yu. 2023. Health aspects of peanuts as an outcome of its chemical composition, Food Science and Human Wellness 9(1): 21-30. https://doi.org/10.1016/j.fshw.2019.12.005

Bogusz, P., P. Rusek, and M. Brodowska. 2021. Suspension fertilizers: how to reconcile sustainable fertilization and environmental protection. Agriculture 11(10):1008. https://doi.org/10.3390/agriculture11101008

Chen, Y., Y. Wang, C. Wu, A. da Rosa Ferraz, M. Fang, L. Yao, G. Liu, Q. Xu, L. Chen, and X. Tang. 2025. Drought-induced stress on rainfed and irrigated agriculture: Insights from multi-source satellite-derived ecological indicators. Agricultural Water Management 307: 109249. https://doi.org/10.1016/j.agwat.2024.109249

Çiftçi, S. and G. Suna. 2022. Functional components of peanuts (*Arachis hypogaea* L.) and health benefits: A review. Future Foods 5: 100140. https://doi.org/10.1016/j.fufo.2022.100140

Da Silva, M. and P. Magalhães. 2017. A liquid injection dosing system for site-specific fertiliser management. Biosystems Engineering 163:150-158. https://doi.org/10.1016/j.biosystemseng.2017.09.005

Da Silva, M. and P. Magalhães. 2019. Modeling and design of an injection dosing system for site-specific management using liquid fertilizer. Precision Agriculture 20:649–662. https://doi.org/10.1007/s11119-018-9602-5

dos Santos, MH., FC. Ferreira, and AdS. Ferreira. 2025. Temporal change of urea biochemical transformations and temperature sensitivity of ammonia volatilization in soil textural classes in the brazilian Cerrado. Front. Environ. Sci. 13: 1498282. https://doi.org/10.3389/fenvs.2025.1498282

Dong, Y., J. Yang, X. Zhao, S. Yang, J. Mulder, P. Dörsch, and G. Zhang. 2022. Nitrate leaching and N accumulation in a typical subtropical red soil with N fertilization. Geoderma 407: 115559. https://doi.org/10.1016/j.geoderma.2021.115559

Duicela, L., y L. Ponce. 2015. Uso de fungicidas sistémicos en el control de la roya del cafeto (*Hemileia vastatrix* Berk. & Br.) en la provincia de Manabí. Revista La Técnica 15: 15-17. https://dialnet.unirioja.es/servlet/articulo?codigo=6087680

Furtak, K. and A. Wolińska. 2023. The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture – A review. Catena 231: 107378. https://doi.org/10.1016/j.catena.2023.107378

Gelaye, Y. and Luo, H. 2024. Optimizing Peanut (*Arachis hypogaea* L.) Production: Genetic insights, climate adaptation, and efficient management practices: Systematic Review. Plants 13(21): 2988. https://doi.org/10.3390/plants13212988

Guamán, R., J. Ullauri, H. Mendoza, y F. Tapia. 2014. INIAP 383 – PINTADO: Nueva variedad de maní para zonas semisecas del Ecuador. INIAP, Estación Experimental Litoral Sur. Guayaquil, Ecuador. Boletín divulgativo N° 437. 10 p. https://repositorio.iniap.gob.ec/handle/41000/2010

Haro, R., A. Mantese, M. and Otegui. 2011. Peg viability and pod set in peanut: Response to impaired pegging and water deficit, Flora - Morphology, Distribution, Functional Ecology of Plants 206(10): 865-871. https://doi.org/10.1016/j.flora.2011.05.003

Hina, N. 2024. Global meta-analysis of nitrate leaching vulnerability in synthetic and organic fertilizers over the past four decades. Water 16(3): 457. https://doi.org/10.3390/w16030457

Hosseini, S., N. Omidvar, M. Gallart, W. Kämper, I. Tahmasbian, M. Farrar, K. Singh, G. Zhou, B. Muqadass, C. Xu, R. Koech, Y. Li, T. Nguyen, and L. van Zwieten. 2022. Combined effects of biochar and fertilizer applications on yield: A review and meta-analysis. Science of The Total Environment 808: 152073. https://doi.org/10.1016/j.scitotenv.2021.152073

Hossain, M., M. Bahar, B. Sarkar, S. Donne, Y. Sik-Ok, K. Palansooriya, M. Kirkham, S. Chowdhury, and N. Bolan. 2020. Biochar and its importance on nutrient dynamics in soil and plant. Biochar 2: 379–420. https://doi.org/10.1007/s42773-020-00065-z

INEC (2023). Módulo de información ambiental y tecnificación agropecuaria. Instituto Nacional de Estadísticas y Censos. Boletín técnico 2023. https://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Modulo_Ambiental_ESPAC/2023/DOC_TEC_MOD_AMB_ESPAC_2023_04.pdf

Jain, N., and H. Meena. 2015. Improving productivity of groundnut (*Arachis hypogaea*) by using water soluble fertilizer through drip irrigation. Indian Journal of Agronomy 60 (1): 109-115. https://doi.org/10.59797/ija.v60i1.4423

Jain, N., R. Yadav, and R. Jat. 2021a. Productivity, profitability, enzyme activities and nutrient balance in summer peanut (*Arachis hypogaea* L.) as influenced by NPK drip fertigation. Communications in Soil Science and Plant Analysis, 52(5): 443-455. https://doi.org/10.1080/00103624.2020.1854287

Jain, N., R. Yadav, and R. Jat. 2021b. Drip fertigation influences yield, nutrient uptake and soil properties of peanut (*Arachis hypogaea*). Indian Journal of Agricultural Sciences 91 (2): 258–62. https://doi.org/10.56093/ijas.v91i2.111652

Kumar, R., M. Pandey, S. Roychoudhry, H. Nayyar, S. Kepinski, and R. Varshney. 2019. Peg Biology: Deciphering the molecular regulations involved during peanut peg development. Front. Plant Sci. 10:1289. https://doi.org/10.3389/fpls.2019.01289

Lisboa, M., R. Schneider, P. Sullivan, and T. Walter. 2020. Drought and post-drought rain effect on stream phosphorus and other nutrient losses in the Northeastern USA. Journal of Hydrology: Regional Studies 28: 100672. https://doi.org/10.1016/j.ejrh.2020.100672

Luo, X., D. Wang, Y. Liu, Y. Qiu, J. Zheng, G. Xia, A. Elbeltagi, and D. Chi. 2024. Partial substitution of phosphorus fertilizer with iron-modified biochar improves root morphology and yield of peanut under film mulching. Frontiers in Plant Science 15: 1459751. https://doi.org/10.3389/fpls.2024.1459751

Matailo-Ramirez, L., A. Luna, J. Chabla, y P. Gálvez. 2023. Modelización del rendimiento con Aquacrop-FAO en el cultivo de maní (*Arachis hypogaea* L.), Ecuador. Manglar 20(1): 51-58. http://doi.org/10.57188/manglar.2023.006

Mesías, F., A. Hernández, L. Vera, A. Guzmán, A. Cedeño, K. Ormaza, y G. López. 2018. Reservas de carbono orgánico en suelos de la llanura fluvial Calceta-Tosagua, Manabí, Ecuador. Cultivos Tropicales 39(4): 27-33. http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S0258-59362018000400004

Motasim, A., A. Samsuri, A. Sukor, and A. Adibah. 2021a. Nitrogen dynamics in tropical soils treated with liquid and granular urea fertilizers. Agriculture 11: 546. https://doi.org/10.3390/agriculture11060546

Motasim, A., A. Samsuri, A. Sukor, and A. Adibah. 2021b. Gaseous nitrogen losses from tropical soils with liquid or granular urea fertilizer application. Sustainability 13: 3128. https://doi.org/10.3390/su13063128

Motasim, A., A. Samsuri, A. Sukor, and A. Amin. 2022. Split application of liquid urea as a tool to nitrogen loss minimization and NUE improvement of corn – A review. Chilean Journal of Agricultural Research 82(4): 645-657. https://doi.org/10.4067/S0718-58392022000400645

Motasim, A., A. Samsuri, A. Nabayi, A. Akter, M. Haque, A. Abdul, and A. Adibah. 2024. Urea application in soil: processes, losses, and alternatives—a review. Discov Agric. 2: 42. https://doi.org/10.1007/s44279-024-00060-z

Mukhtar, A., B. Babaji, S. Ibrahim, H. Mani, A. Mohammad, and A. Ibrahim. 2013. Dry matter production and harvest index of groundnut (*Arachis hypogaea* L.) Varieties under irrigation. Journal of Agricultural Science 5(8): 153-162. http://dx.doi.org/10.5539/jas.v5n8p153

Pérez, R., E. Cabrera, y M. Hinostroza. 2018. Régimen de riego de cultivos en Manabí-Ecuador: estudio climatológico. Revista Ciencias Técnicas Agropecuarias 27(1): 5 – 12. http://scielo.sld.cu/pdf/rcta/v27n1/rcta01118.pdf

Plett, D., K. Ranathunge, V. Melino, N. Kuya, Y. Uga, and H. Kronzucker. 2020. The intersection of nitrogen nutrition and water use in plants: new paths toward improved crop productivity. Journal of Experimental Botany 71(15): 4452–4468. https://doi.org/10.1093/jxb/eraa049

Puppala, N., SN. Nayak, A. Sanz-Saez, C. Chen, MJ. Devi, N. Nivedita, Y. Bao, G. He, SN. Traore, DA. Wright, MK. Pandey, and V. Sharma. 2023. Sustaining yield and nutritional quality of peanuts in harsh environments: Physiological and molecular basis of drought and heat stress tolerance. Frontiers in Genetics 14: 1121462. https://doi.org/10.3389/fgene.2023.1121462

Qi, S., A. Degen, W. Wang, M. Huang, D. Li, B. Luo, J. Xu, Z. Dang, R. Guo, and Z. Shang. 2024. Systemic review for the use of biochar to mitigate soil degradation. GCB Bioenergy: Bioproducts for a Sustainable Bioeconomy 16(6): e13147. https://doi.org/10.1111/gcbb.13147

Razzaghi, F., P. Bilson Obour, and F. Arthur. 2020. Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma 361: 114055. https://doi.org/10.1016/j.geoderma.2019.114055

Rassem, A., and K. Elzobair. 2023. The combined effect of biochar and organic fertilizer (goat manure) on the growth and yield of peanut crop (*Arachis hypogaea* L.). Journal of Pure & Applied Sciences 22(3): 172–176. https://doi.org/10.51984/jopas.v22i3.2766

Shamrikova, E., B. Kondratenok, E. Tumanova, E. Vanchikova, E. Lapteva, T. Zonova, E. Lu-Lyan-Min, A. Davydova, Z. Libohova, and N. Suvannang. 2022. Transferability between soil organic matter measurement methods for database harmonization. Geoderma, 412: 115547. https://doi.org/10.1016/j.geoderma.2021.115547

Samanhudi., M. Rahayu, A. Sakya, G. Handoyo, and B. Priambodo. 2023. Growth and yields of some peanut varieties with application of palm fiber biochar. E3S Web of Conferences 467: 01018. https://doi.org/10.1051/e3sconf/202346701018

Salmoral, S., K. Khatun, F. Llive, and C. Madrid. 2018. Agricultural development in Ecuador: A compromise between water and food security?. Journal of Cleaner Production 202: 779-791. https://doi.org/10.1016/j.jclepro.2018.07.308

Siman, F., F. Andrade, and R. Passos. 2020. Nitrogen fertilizers and NH_3 volatilization: effect of temperature and soil moisture. Communications in Soil Science and Plant Analysis 51(10): 1283-1292. https://doi.org/10.1080/00103624.2020.1763384

Stamate, N., U. Ranta, A. Gheţe, O. Marian, C. Bogdan, and A. Irimie. 2023. Equipment and systems for the application of liquid fertilizers in field crops - news and perspectives. Agriculture 3-4: 127-128. https://doi.org/10.15835/agr.v128i3-4.14757

Speer, M., J. Hartigan, and L. Leslie. 2024. Machine learning identification of attributes and predictors for a flash drought in eastern Australia. Climate 12(4): 49. https://doi.org/10.3390/cli12040049

Shikha, F., M. Rahman, N. Sultana, M. Mottalib and M. Yasmin. 2023. Effects of biochar and biofertilizer on groundnut production: a perspective for environmental sustainability in Bangladesh. Carbon Research 2: 10. https://doi.org/10.1007/s44246-023-00043-7

Taylor, W., A. Borron, J. Holt, and S. Monfort. 2024. Assessing farmers' perceptions of best management practices: An exploration of the viewpoints of cotton and peanut farmers in Georgia using Q methodology. Journal of Applied Communications 108: 2. https://doi.org/10.4148/1051-0834.2523

Thao, T., M. González, R. Ryals, R. Dahlquist-Willard, G. Diaz, and T. Ghezzehei. 2024. Biochar impacts on soil moisture retention and respiration in a coarse-textured soil under dry conditions. Soil Science Society of America Journal 88(6): 1919-1931. https://doi.org/10.1002/saj2.20746

Wang X, M. Wu, C. Sun, M. Liu, L. Yang, H. Liang, Q. Wu, and P. Shen. 2024. Biochar distribution mode in soil affects the vegetative peanut growth, nitrogen uptake and nitrogen-fixing bacteria activity. Plant Soil Environ. 70(12): 783-798. https://doi.org/10.17221/228/2024-PSE.

Weeks, J. and G. Hettiarachchi. 2019. A review of the latest in phosphorus fertilizer technology: Possibilities and Pragmatism. Journal of Environmental Quality 48: 1300–1313. https://doi.org/10.2134/jeq2019.02.0067

Yang, L., H. Liang, Q. Wu, and P. Shen. 2023. Biochar alleviated the toxic effects of microplastics-contaminated geocarposphere soil on peanut (*Arachis-hypogaea* L.) pod development: roles of pod nutrient metabolism and geocarposphere microbial modulation. Journal of the Science of Food and Agriculture 104(5): 2990–3001. https://doi.org/10.1002/jsfa.13191

Yao, Y., Q. Dai, R. Gao, Y. Gan, and X. Yi. 2021. Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China. PLoS ONE 16(3): e0246505. https://doi.org/10.1371/journal.pone.0246505

Zaheer, M., M. Rizwan, N. Aijaz, A. Hameed, I. Ikram, H. Haider Ali, Y. Niaz, H. Usman Aslam, S. Manoharadas, M. Waheed Riaz, N. Ahmed, R. Bibi, M. Aamir Manzoor, and. S. Rehman. 2024. Investigating the synergistic effects of biochar, trans-zeatin riboside, and *Azospirillum brasilense* on soil improvement and enzymatic activity in water-stressed wheat. BMC Plant Biol 24: 314. https://doi.org/10.1186/s12870-024-05038-z

Zhang, J., X. Liu, Q. Wu, Y. Qiu, D. Chi, G. Xia, and E. Arthur. 2023. Mulched drip irrigation and maize straw biochar increase peanut yield by regulating soil nitrogen, photosynthesis and root in arid regions. Agricultural Water Management 289: 108565. https://doi.org/10.1016/j.agwat.2023.108565

Zhang, H., Y. Cheng, Y. Zhong, Y. Zhong, J. Ni, R. Wei, and W. Chen. 2024. Roles of biochars' properties in their water-holding capacity and bound water evaporation: quantitative importance and controlling mechanism. Biochar 6: 30. https://doi.org/10.1007/s42773-024-00317-2

Zheng, J., S. Wang, R. Wang, Y. Chen, K. Siddique, G. Xia, and D. Chi. 2021. Ameliorative roles of biochar-based fertilizer on morpho-physiological traits, nutrient uptake and yield in peanut (Arachis hypogaea L.) under water stress. Agricultural Water Management 257: 107129. https://doi.org/10.1016/j.agwat.2021.107129