Effects of Biochar and Fertilizer Source on Sweet Corn Production: Nitrogen Uptake, Biomass, Yield, and Quality across Two Contrasting Years—Part I

Emilio Suarez[1], Juan C. Diaz-Perez[1], Kate Cassity-Duffey[2], Henry Y. Sintim[3], and Theodore McAvoy[1]

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ABSTRACT. Sweet corn (*Zea mays* convar. *Saccharata* var. *rugosa*) is a key crop in Georgia with high mineral nutrient demands that make soil fertility management essential for sustained productivity. This study evaluated the effects of locally sourced biochar at different application rates (0, 5, 10, 15, and 20 tons/acre) combined with inorganic (granular) or organic (poultry litter) fertilizer on nitrogen uptake, plant growth, yield, and ear quality of sweet corn. Field trials were conducted on sandy loam soil using a 5 × 2 factorial arrangement of treatments in a randomized complete block design with four replications. The results showed that higher biochar rates (15–20 tons/acre) increased nitrogen uptake by 9.5% to 13% when compared with the control, with the greatest uptake observed in 2023 under favorable rainfall conditions. Organic fertilizer improved the total soluble solids (TSS), a key indicator of ear quality, but neither biochar nor fertilizer type significantly affected plant growth, biomass, or yield. Environmental conditions, particularly early-season rainfall, strongly influenced outcomes, with heavy rainfall in 2024 reducing nitrogen uptake and ear quality compared with those in 2023. These findings suggest that biochar can enhance nitrogen retention in coastal plain soils, whereas organic fertilizers may improve ear quality. However, the limited duration of the study highlights the need for long-term research to fully assess the cumulative effects of biochar on soil health and yield stability. Moreover, the findings emphasize that rainfall plays a critical role in influencing the performance of soil amendments, thus underscoring the importance of considering environmental variability in nutrient management strategies. This study provides valuable insights into the use of soil amendments for optimizing sustainable sweet corn production in southern Georgia.

Sweet corn (*Zea mays* convar. *Saccharata* var. *rugosa*) is an important crop in Georgia that contributes significantly to the state's agricultural economy. According to the University of Georgia, Center for Agribusiness and Economic Development (2025), sweet corn ranked third among the top vegetables in the state and contributed $175 million in production value, representing 13.11% of Georgia's total vegetable value. Sweet corn thrives in well-drained soil with a pH of 6.0 to 6.5 and requires a warm growing season with a soil temperature above 60 to 90 °F for optimal germination and growth (Hussen 2021; Westerfield 2024). The crop has high nutrient demands, particularly nitrogen (N), which is critical for vegetative growth, ear development, and high yields (Gamit et al. 2023; Lei et al. 2020). Sweet corn requires consistent moisture throughout its growing season, particularly during tasseling, silking, and ear development, to maximize yield potential (Garcia et al. 2009; Stone et al. 2001). Although sweet corn is produced across Georgia, its cultivation faces challenges in regions with sandy loam soils, such as southern Georgia. Sandy loam soil typically has poor water retention, acidic soils, shifts in microbial communities, and nutrient leaching, thus limiting soil fertility and crop productivity (Huang and Hartemink 2020; Shaw et al. 2001; Siebielec et al. 2020).

The use of soil amendments in agriculture has become increasingly common because of their benefits, including improved soil structure, enhanced nutrient availability, and increased water retention (Larramendy and Soloneski 2016). However, the effectiveness of these amendments varies depending on factors such as the type of amendment, soil properties, and environmental conditions (Ma et al. 2024; Matisic et al. 2024). Biochar, produced through the thermochemical decomposition of biomass via processes such as pyrolysis (Cha et al. 2016), has gained significant attention because of its potential to sequester carbon, enhance microbial activity, and improve soil structure by increasing both water retention and nutrient availability (Ayaz et al. 2021; Hussain et al. 2017). Similarly, organic fertilizers, such as poultry litter—a byproduct of Georgia's robust poultry industry—are widely used in the state and play a crucial role in agricultural practices (Dunkley et al. 2014). Although poultry litter provides benefits similar to those of other organic amendments, its primary advantage is its capacity to supply essential nutrients such as N, phosphorus (P), and potassium (K) (Ashworth et al. 2020; Bolan et al. 2010). However, excessive or improper use of soil amendments can lead to negative effects, including nutrient imbalances, plant uptake of heavy metals, and environmental pollution (Moss et al. 2003).

Recent studies of sweet corn production have demonstrated the potential benefits of biochar for sweet corn cultivation. Singh et al. (2022) found that biochar application improves chlorophyll content, plant height, and vegetative dry biomass but offers limited benefits under water-limited conditions. Thapa et al. (2024) reported that biochar rates significantly influenced plant biomass and sugar content, whereas manure rates affected plant height, cob length, and cob diameter, with chicken manure accelerating tasseling and silking compared with dairy manure. Conversely, Cole et al. (2019) observed that biochar increased soil pH, base saturation, and phosphate availability but reduced sweet corn yield at application rates

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[1]Department of Horticulture, University of Georgia, Tifton, GA 31793, USA

[2]Department of Horticulture, University of Georgia, Athens, GA 30602, USA

[3]Department of Crop and Soil Sciences, University of Georgia, Tifton, GA 31793, USA

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T.M.A. is the corresponding author. E-mail: ted.mcavoy@uga.edu.

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higher than 2%, which are linked to lower stalk nitrate concentrations. These findings highlight the variability in biochar's effectiveness, which depends on factors such as feedstock type, pyrolysis temperature, and application rate (Huang et al. 2019; Olszyk et al. 2020).

A major challenge in modern agriculture is developing sustainable systems that produce high-quality food while preserving environmental resources (Calicioglu et al. 2019). This study addresses critical knowledge gaps by evaluating the effects of locally sourced biochar at different rates combined with inorganic or organic fertilizers on sweet corn production in southern Georgia. Specifically, this research examined biochar's influence on N uptake, plant growth, yield metrics, and ear quality across two distinct cropping years with varying rainfall conditions. By integrating biochar into sweet corn production systems, this research sought to advance sustainable agricultural practices, optimize productivity, and provide practical insights for farmers to enhance long-term productivity, improve soil health, and effectively implement soil amendments under changing environmental conditions.

Materials and methods

Experimental site

Field trials were conducted during the Spring of 2023 and 2024 at the University of Georgia, Hort Hill Farm in Tifton, GA, USA (lat. 31°28′14.96″N, long. 83°31′53.11″W). The soil at the site is classified as sandy loam, with an average composition of 86% sand, 12% silt, and 2% clay. A total of 50 composite preplant soil samples (0–6 inches) were collected from across the entire field and analyzed for nutrient content using the Mehlich 1 extract method at Waters Agricultural Laboratory (Camilla, GA, USA). The base soil nutrient analysis indicated P at 394.4 lb/acre, K at 99.8 lb/acre, magnesium (Mg) at 49.2 lb/acre, and calcium (Ca) at 714.2 lb/acre. Additionally, the analysis showed an organic matter content of 0.47%, soil pH of 6.3, and a cation exchange capacity of 3.55 meq/100 g. During the trial periods (March–June) in 2023 and 2024, the total rainfall measurements were 16.61 and 22.50 inches, respectively, with a 2-year average of 19.55 inches. Temperature ranges were recorded from 58.94 to 78.27 °F in 2023 and from 60.67 to 80.56 °F in 2024, resulting in an overall temperature range of 59.80 to 79.41 °F (Georgia Automated Environmental Monitoring Network 2024).

Treatments

The experiment included 10 treatments combining biochar at five different rates (0, 5, 10, 15, and 20 tons/acre) with two types of fertilizers [inorganic (granular and liquid) or organic (poultry litter)]. Treatments were applied to the same parcel of soil for 2 years. The trial used a 5 × 2 factorial arrangement of treatments in a randomized complete block design with four replications per treatment to account for spatial variability across the field. Each plot had an area of 180 ft^2 (6 ft wide × 30 ft long). A 5-ft alley was maintained between replicates to minimize soil movement and plot contamination. The biochar used in the study was sourced from Wakefield Biochar in Valdosta, GA, USA. Wakefield produces biochar from wood chips through pyrolysis at 1112 °F. According to the manufacturer's analysis results, which were certified by the International BioChar Initiative (IBI) Laboratory (Columbia, MO, USA), the biochar had the following properties: bulk density, 10.6 lb/cu ft; pH, 8.84 units; organic carbon content, 21.1% (total dry mass); hydrogen-to-carbon (H) molar ratio, 0.18 (less than the maximum of 0.7); total ash content, 57.0% (total dry mass); total N, 0.12% (total dry mass); electrical conductivity (EC), 0.152 dS/m; and liming value, 5.5% as $CaCO_3$. Biochar was spread as a one-time application on 20 Feb 2023. In both years, the targeted N application rate was 225 N pounds per acre, as recommended by the University of Georgia Extension for sweet corn production (Kissel and Sonon 2008). The organic fertilizer consisted of locally sourced uncomposted poultry litter from a broiler farm in Berrien County, GA, USA (lat. 31°18′45.51″N, long. 83°23′2.53″W). After obtaining the poultry litter, samples were sent to Waters Agricultural Laboratory in Camilla, GA, USA, for a manure test to determine the N content. The N content was analyzed using a LECO-Combustion analyzer (LECO Corp., St. Joseph, MI, USA), which measured the total N through high-temperature combustion followed by N gas detection. The analysis indicated availability of 37.32 lb N/ton in 2023 and 33.9 lb N/ton in 2024. Based on the analysis, this resulted in application rates of 6.02 tons per acre in 2023 and 6.63 tons per acre in 2024 to achieve the targeted N application rate previously mentioned. Other elements in the poultry litter sample were analyzed using inductively coupled plasma open-vessel wet digestion (Digi Block 3000; Labtech, Wilmington, MA, USA). During both years, the poultry litter was applied 32 d preplant and incorporated immediately. This practice followed the 90-d rule of the US Department of Agriculture for manure application before harvest on aboveground vegetables to prevent pathogen contamination (US Department of Agriculture 2024a). The inorganic fertilizer treatment involved a preplant application of 50 lb N per acre using a granular fertilizer (10.0N–4.3P–8.3K; Rainbow Fertilizer LLC, Americus, GA, USA), which was also applied on 27 Feb 2023. Raised beds were shaped after the application of preplant poultry litter and granular fertilizers. The remaining 175 lb N per acre were divided into two applications in inorganic fertilizer treatments: one at the V4 stage (four vegetative leaves) at an application of 100 lb N per acre using a granular fertilizer (10.0N–4.3P–8.3K; Rainbow Fertilizer LLC) on 25 Apr 2023 and 26 Apr 2024 and the other at an application of the remaining 75 lb N per acre at the VT stage (vegetative tasseling) using a granular fertilizer (46.0N–0P–0K; Rainbow Fertilizer LLC) on 10 May 2023 and 9 May 2024.

Planting

The sweet corn cultivar used in the experiment was Obsession (Seedway, Hall, NY, USA). Planting was conducted on 31 Mar 2023 and 2 Apr 2024 using a tractor mounted with a vacuum seed planter (Monosem 2-Row Planter; Edwardsville, KS, USA) to ensure precise seed placement and uniform spacing. Plots consisted of two rows that were spaced 3 ft apart and plants within rows were spaced 6 inches apart, achieving a target population density of approximately 30,000 plants per acre. Herbicides and insecticides used for the trial followed the standard University of Georgia recommendations (Horton et al. 2014).

Data collection

Throughout the trial in both years, the left row was selected and 10 plants in the middle were marked for data collection and harvest in each plot.

Plant growth and development

Plant height was measured using a standard measuring tape from the base of the plant at the soil line to the growing point, and the stem diameter was measured using a caliper at the base of the plant. After measurements, plants were carefully removed from the soil using a shovel. The aerial biomass was separated from the roots, which were thoroughly washed to remove soil residues. Shoot biomass and roots were placed in individually labeled paper bags. The shoot biomass was chopped into smaller pieces before being placed in paper bags. The samples were dried in a forced-air oven (13-261-28A; Grieve Corporation, Roud Lake, IL, USA) at 140 °F for 10 d to ensure consistent drying. Following drying, both shoot and root dry mass were measured using an electronic balance.

Nitrogen uptake

A composite sample of 30 leaves from each plot was collected on 26 May 2023 and 28 May 2024. These samples were sent to Waters Agricultural Laboratory in Camilla, GA, USA, to analyze the total N content. The total N content was measured using a LECO combustion analyzer (LECO Corp., St. Joseph, MI, USA), which provides precise measurements of the N concentration in plant tissue. The N concentration (%) was used in conjunction with the shoot dry weight to calculate N uptake. The N uptake (lb/acre) was calculated by multiplying the dry weight of the shoot biomass per acre by the N concentration in decimal form.

Yield

Sweet corn was harvested at the milking stage, which is the optimal market maturity for consumption, unlike other corn cultivars harvested at the dent stage when fully mature (Singh et al. 2014), on 13 Jun 2023, and on 14 Jun 2024. However, only the ears that met marketable quality standards were included in the analysis. The total number of marketable ears per plot was recorded, and the average number of marketable ears per plant was calculated by dividing the total number of marketable ears by the number of plants sampled per plot. To estimate the yield on an acre basis, the total number of marketable ears per acre was determined by multiplying the average number of marketable ears per plant by the plant population per acre, which was standardized to 30,000 plants per acre. Yield in bushels per acre was calculated by dividing the total number of marketable ears per acre by 48, which represented the number of ears in a standard bushel box (McAvoy and Coolong 2023).

Ear quality

Ear quality was assessed by classifying all harvested ears from the marked plants on each plot into marketable and unmarketable categories based on the Shipping Point and Market Inspection Instructions for Sweet Corn (US Department of Agriculture 1994b). A marketable ear that met the US Fancy grade standard was defined as an ear without a husk and a length of more than 6 inches (Fig. 1). Marketable ears must also be free from pollination issues, incomplete tip filling (more than 1/4 the length of the ear), and any damage caused by insects or birds. In contrast, an unmarketable ear is defined as one with a length less than 6 inches. Unmarketable ears (Fig. 2) are often affected by issues such as incomplete tip filling, poor pollination, or physical damage from insects or birds and may also exhibit fungal infections, such as Corn Smut (*Ustilago maydis*) (Fig. 3). The total number of harvested ears, marketable ears, and unmarketable ears were recorded for each plot. Subsequently, five marketable ears were randomly selected from each plot for further ear quality measurements. The selected ears had their husks removed, and their lengths and widths were measured using a measuring tape. Kernel rows were determined by cutting each selected ear in half and counting the number of rows of kernels. To assess the total soluble solids (TSS), a compound sample of kernels was prepared by pooling kernels from the five selected ears. This composite sample was homogenized, and the TSS content was measured using a digital handheld pocket refractometer (ATAGO Co. Ltd., Tokyo, Japan).

Fig. 1. Characteristics of a marketable Fancy grade sweet corn ear: length >6 inches, fully filled tip, and free from insect or bird damage.

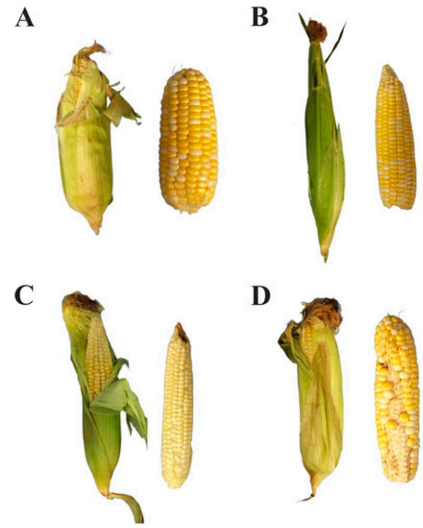

Fig. 2. Classification of unmarketable sweet corn. (A) Small ear (<6 inches). (B) Small ear (<6 inches) with incomplete tip filling. (C) Immature ear not ready for harvest. (D) Ear with pollination and size defects.

Data analysis

Statistical analyses were conducted using RStudio (R Core Team 2024). A linear mixed-effects model was used for the analysis of variance (ANOVA)

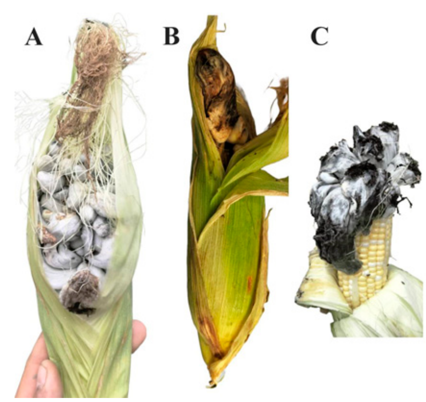

Fig. 3. Unmarketable sweet corn because of smut damage caused by *Ustilago maydis* ("Huitlacoche"). (A) Early-stage smut with firm kernels. (B) Mid-stage smut with kernel deterioration. (C) Late-stage smut with watery and mushy kernels.

using the "lme4" package (Bates et al. 2015). The model incorporated the biochar application rate (0, 5, 10, 15, and 20 tons/acre) and fertilizer type (organic and inorganic) as fixed effects as well as the year (2023 and 2024) to account for annual variability. Replications (four blocks) and plots were included as nested random effects to address block-level differences and variability within plots. Significant treatment effects ($P < 0.05$) were further examined using Fisher's least significant difference test at a 95% confidence level for mean comparisons. Residual diagnostics were conducted to validate the assumptions of the linear model. The Shapiro-Wilk test was used to assess residual normality, and Levene's test evaluated the homogeneity of variances. Residual plots were visually inspected to ensure the independence of errors. When the assumption of normality was violated, log transformation was applied to the data for analysis; however, untransformed means were reported in the results to aid interpretation. For significant interactions, estimated marginal means were calculated using the "emmeans" package (Lenth 2016). Pairwise comparisons were adjusted using the Sidak method to control family-wise error rates across multiple comparisons. Means sharing the same grouping letter, as presented in both tables and figures, were considered not significantly different at $P < 0.05$.

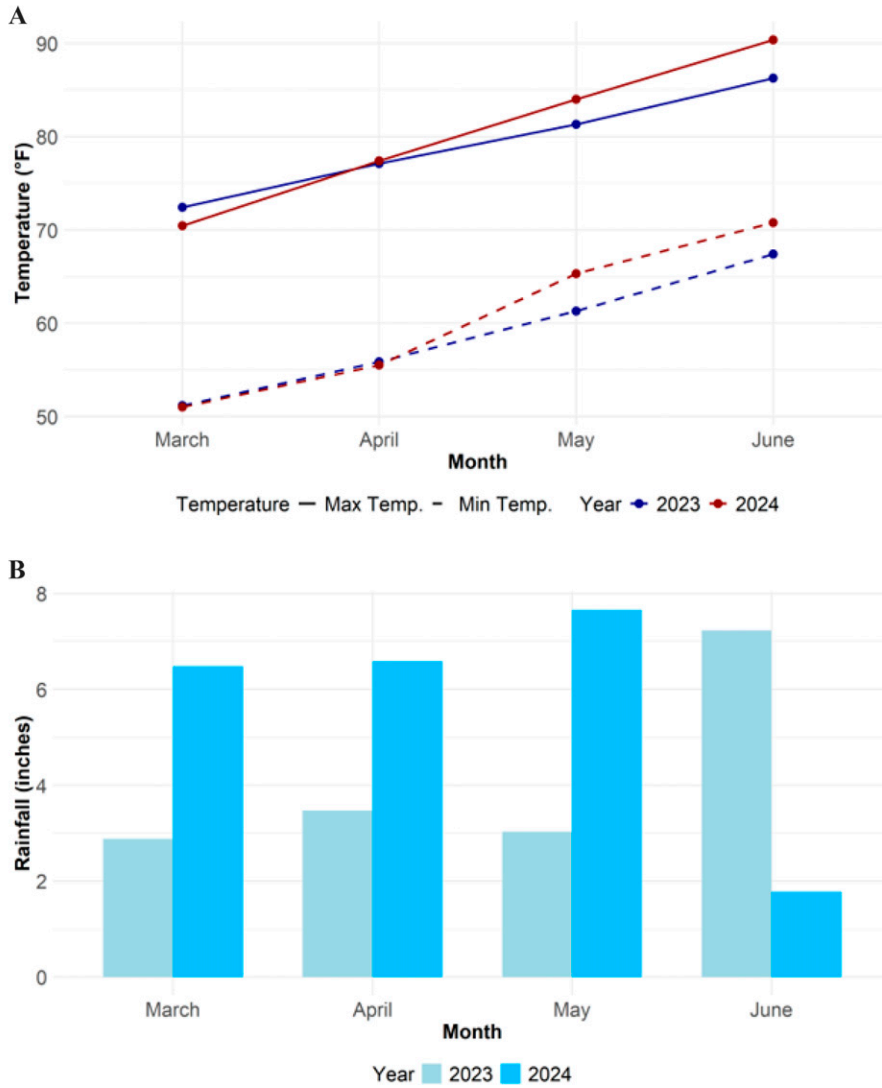

Fig. 4. Air temperatures and cumulative rainfall during the growing season (1 Mar–30 Jun) in 2023 to 2024 at the Tifton Coastal Plain Experiment Station based on data from the University of Georgia Weather Network (weather.uga.edu). (A) Maximum (solid line) and minimum (dashed line) temperatures, with blue representing 2023 and red representing 2024. (B) Cumulative rainfall (inches), with light blue indicating 2023 and deep sky blue indicating 2024.

Results

Environmental conditions

During the study, temperatures remained relatively consistent between 2023 and 2024, with only minor variations (Fig. 4). For instance, maximum temperatures in May and June averaged 81.33 and 86.26 °F in 2023, and they increased slightly to 84.00 and 90.38 °F in 2024. Similarly, minimum temperatures increased modestly from 61.31 and 67.40 °F in 2023 to 65.31 and 70.79 °F in 2024. In contrast, rainfall patterns exhibited significant differences. Early-season precipitation (March–May) was substantially higher in 2024, with totals of 6.48, 6.59, and 7.66 inches for March, April, and May, respectively, compared with 2.88, 3.47, and 3.03 inches during 2023. However, rainfall (1.78 inches) measurements in Jun 2024 were markedly lower than those in Jun 2023 (7.23 inches). These pronounced shifts in rainfall, particularly the increased precipitation during the critical early growth phase in 2024, likely substantially impacted crop performance, N uptake, and treatment responses.

Nitrogen uptake

Effect of biochar. The N uptake varied significantly across the different biochar application rates (Fig. 5). Higher biochar rates (15 and 20 tons/acre) led to the most significant N uptake, with 15 tons/acre increasing uptake by approximately 13% and 20 tons/acre increasing uptake by 9.5% compared with the control treatment (0 tons/acre). In contrast, the lowest rate (5 tons/acre) resulted in a notable decrease in N uptake, which was approximately 23% lower than the highest uptake observed at 15 tons/acre. Moderate rates (10 tons/acre) showed intermediate uptake levels approximately 6% lower than the control, suggesting that biochar application rates less than 15 tons/acre may not consistently enhance N uptake.

Effect of year. The N uptake differed significantly between the two years of the study, with 2023 showing substantially higher uptake than that of 2024 (Fig. 6). The N uptake in 2023 was approximately 67% greater than in 2024, highlighting the influence of annual environmental conditions on nutrient dynamics. The higher uptake in 2023 aligned with more favorable and

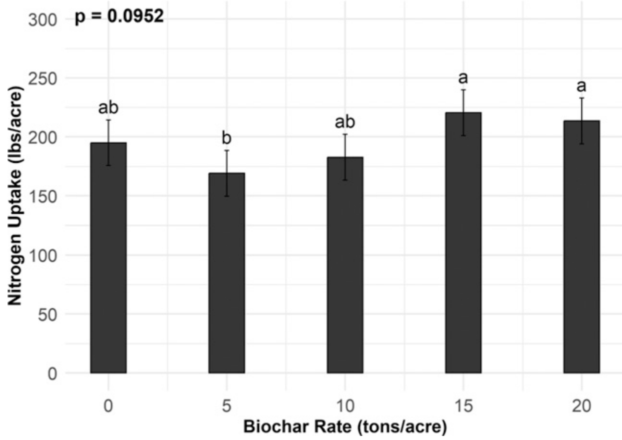

Fig. 5. Effect of biochar application rates on nitrogen uptake (2023 to 2024 combined). The x-axis represents biochar application rates (tons/acre), and the y-axis represents nitrogen uptake (lb/acre). $P = 0.0952$ according to the analysis of variance (marginally significant, $0.05 < P \leq 0.10$). Letters above bars indicate significant differences between treatments based on the least significant difference test at $P < 0.05$. Treatments that share the same letter are not significantly different.

consistent rainfall patterns during fertilization. In contrast, the heavy rainfall observed in 2024 during the same period likely increased N leaching, thus reducing its availability for plant uptake.

INTERACTION OF BIOCHAR × YEAR. The biochar application rate × year interaction significantly influenced N uptake (Table 1). However, the effects of biochar varied between the two years of the study. In 2023, there were no significant differences in N uptake across the various biochar application rates. The 20 tons/acre treatment recorded the highest uptake (272.02 lb/acre), but this increase was not statistically different compared with that of the control treatment (217.66 lb/acre). In 2024, N uptake also showed no significant differences between biochar rates. However, uptake values were numerically lower across all treatments compared with those of the previous year. Significant differences in N uptake were observed between years for several biochar rates. Specifically, uptake with 5, 15, and 20 tons/acre was significantly higher in 2023 than in 2024. In contrast, the 10 tons/acre and control (0 tons/acre) treatments showed no significant differences between years.

INTERACTION FERTILIZER × YEAR. The fertilizer type × year interaction (Table 2) significantly influenced N uptake. In 2023, no significant difference in uptake between inorganic and organic fertilizers was observed. Similarly, in 2024, N uptake did not differ between fertilizer types. However, within each fertilizer type, N uptake was significantly higher in 2023 than in 2024. Inorganic fertilizer showed greater uptake in 2023 compared with that in 2024, and the same pattern was observed for organic fertilizer.

According to Hart et al. (2010), sweet corn's optimal N uptake range is 150 to 200 lb/acre. In 2023, plants exhibited vigorous growth and maintained a healthy green coloration with no visible symptoms of N deficiency. The N uptake for inorganic fertilizer was 265.36 lb/acre and that for organic fertilizer was 224.97 lb/acre; both were above the optimal range. In contrast, plants in 2024 exhibited common symptoms of N deficiency, such as yellowing (chlorosis) of older leaves and stunted growth. The N uptake for inorganic fertilizer was 146.22 lb/acre, and that for organic fertilizer was 148.22 lb/acre; both were below the optimal threshold.

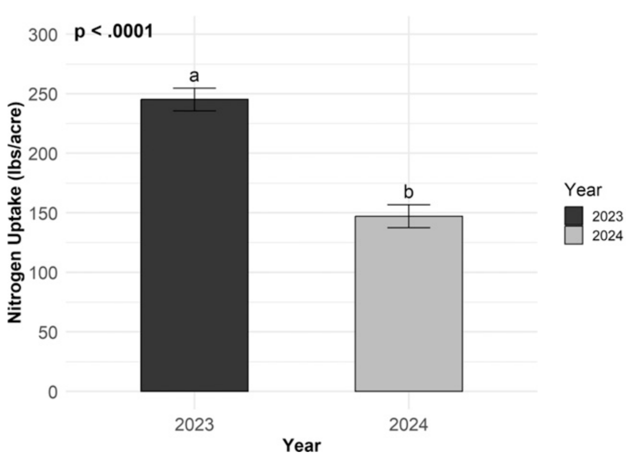

Fig. 6. Effect of year on nitrogen uptake. The x-axis represents the year (2023 and 2024) and the y-axis represents nitrogen uptake (lb/acre). $P = 0.001$ according to the analysis of variance (highly significant, $P \leq 0.001$). Letters above bars indicate significant differences between treatments based on the least significant difference test at $P < 0.05$. Treatments that share the same letter are not significantly different.

Plant growth and development

No significant effects were observed for biochar, fertilizer, or their interactions with plant growth variables. However, the year significantly affected all measured plant growth and biomass parameters, including height, stem diameter, shoot dry biomass, root dry biomass, and total dry biomass (Table 3). In 2023, sweet corn plants exhibited greater growth and biomass accumulation compared with those in 2024. Plant height was 11% taller in 2023, while stem diameter was 23% thicker. Similarly, shoot dry biomass, root dry biomass, and total dry biomass were 18%, 96%, and 47% greater, respectively, in 2023 compared with those in 2024.

Ear quality and yield

Year significantly influenced ear length, width, and kernel rows, with longer and wider ears with more kernel rows produced in 2023 than in 2024 (Table 4). Ear length in 2023 was approximately 8% greater than that in 2024, while ear width and kernel rows decreased by 8% and 10%, respectively. Fertilizer type significantly affected TSS, with organic fertilizer resulting in higher TSS levels than inorganic fertilizer. No significant differences were observed between years

Table 1. Interaction effect of biochar × year on nitrogen uptake (lb/acre) on sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*).

Interaction	Nitrogen uptake (lb/acre)		
Biochar × year	2023	2024	*P* value
0	217.66 Aa[i]	172.26 Aa	0.0559
5	215.98 Aa	122.16 Ab	<0.0001
10	214.79 Aa	150.55 Aa	0.0536
15	205.39 Aa	135.57 Ab	<0.0001
20	272.02 Aa	155.03 Ab	<0.0001
P value	0.0337	0.0596	

[i] Means followed by different letters indicate significant differences at $P \leq 0.05$ based on pairwise comparisons with the Sidak adjustment for multiple comparisons. Capital letters indicate comparisons within columns, and lowercase letters indicate comparisons within rows.

or fertilizer types for marketable ears, unmarketable ears, or total ears. Yield revealed no significant effects of biochar application rate, fertilizer type, or year on yield. Additionally, none of the interactions between these factors were statistically significant.

Interaction of year × fertilizer on ear quality. The interaction between the year × fertilizer type significantly influenced ear quality parameters, including ear length, width, and kernel rows (Table 5). In both 2023 and 2024, no significant differences were observed between inorganic and organic fertilizers for these parameters, indicating that fertilizer type did not affect ear quality within each year. However, a significant change occurred when comparing each fertilizer type between years. For ears grown with inorganic fertilizer, ear length decreased by approximately 9.6%, ear width decreased by 11.4%, and kernel rows decreased by 13.9% in 2024 compared with those in 2023. Similarly, for organic fertilizer, ear length declined by 5.4%, ear width declined by 6.0%, and kernel rows declined by 6.9% between years. These results demonstrate that ear quality was considerably higher in 2023 than in 2024, suggesting that year-to-year environmental variability had a stronger influence on ear quality than fertilizer type.

Discussion

Influence of rainfall and yearly variability. The distinct differences in rainfall patterns between 2023 and 2024 emerged as a key factor in this study. Adequate rainfall is crucial for sweet corn cultivation because it supports plant growth, biomass accumulation, and stable yields (Garcia et al. 2009; Ren et al. 2008; Stone et al. 2001). Additionally, rainfall maintains favorable soil conditions by preventing excessive drying and enhancing nutrient availability and uptake (Cherr et al. 2007; Schreiber 1999). However, in 2024, heavy rainfall likely caused N leaching and denitrification, which reduced N uptake and hindered plant growth. Paranhos et al. (2023) and Sexstone et al. (1985) noted that water-saturated conditions from heavy rainfall can lead to waterlogging, creating anaerobic environments that restrict root growth and accelerate nutrient loss and availability. Similarly, Simelane et al. (2024) and Abramova and Buchkina (2022) highlighted the increased risk of leaching in N under such conditions, further impacting plant development.

Furthermore, the observed yield stability despite lower N uptake in the wetter year underscores the complex interplay between crop physiology and environmental stresses (Campos et al. 2004), suggesting that sweet corn, similar to other maize genotypes, may exhibit certain resilience strategies such as adjusting root architecture or internal nutrient use efficiency (Fageria and Baligar 2005). Nevertheless, the results highlight the need for adaptive management practices that account for potential extreme weather events—an issue expected to become more critical as climate change intensifies precipitation variability (Shortridge 2019).

Role of biochar in nitrogen uptake. High biochar application rates (15–20 tons/acre) in this study improved N uptake by 9.5% to 13% relative to zero-biochar treatments. These findings align with those of studies that demonstrated that biochar application significantly enhanced plant N uptake. This effect is attributed to improved soil N availability and the stimulation of microbially mediated N cycling processes, such as mineralization, nitrification, and N fixation (Liu et al. 2018; Zhang et al. 2021). The observation that biochar alone does not consistently lead to higher yields reflects the complex and variable outcomes highlighted by the meta-analysis by Jeffery et al. (2017), whose work underscored that the effectiveness of biochar is highly context-dependent and influenced by factors such as soil properties and climatic conditions.

Organic fertilizer effect. Differences in yield between organic and inorganic fertilizer treatments were minor and not statistically significant across both years. However, organic fertilizer showed a slight improvement in ear quality, as reflected by the higher TSS, which is a measure linked to sweetness and flavor perception in sweet corn (Wiley et al. 2021). This slight yet positive quality difference aligns with consumer preference trends for sweeter corn (Yu et al. 2023). The marked differences in rainfall between 2023 and 2024 highlight how climatic factors, particularly intense rainfall, can diminish the effectiveness of fertilizer applications. Heavy rainfall alters soil moisture levels, affecting microbial activity, N cycling, and nutrient availability in sandy loam soils (Gu and Riley 2010). Under these conditions, both inorganic and organic fertilizers may become less effective. Inorganic fertilizers are prone to N leaching during heavy rainfall (Kaur et al. 2020), while organic fertilizers may contribute to greater N and P runoff, limiting their nutrient availability to crops (Liu et al. 2012).

Table 2. Interaction effect of fertilizer × year on nitrogen uptake (lb/acre) on sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*).

Interaction	Nitrogen uptake (lb/acre)		
Fertilizer × year	2023	2024	*P* value
Inorganic	265.36 Aa[i]	146.22 Ab	<0.0001
Organic	224.97 Aa	148.22 Ab	<0.0001
P value	0.0889	0.8811	

[i] Means followed by different letters indicate significant differences at $P \leq 0.05$ based on pairwise comparisons with the Sidak adjustment for multiple comparisons. Capital letters indicate comparisons within columns, and lowercase letters indicate comparisons within rows.

Table 3. Effect of year on plant growth and development of sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) for combined years (2023 and 2024).

Effect	Height (inches)[iii]	Stem (inches)[iii]	Dry shoot biomass (lb)[iii]	Dry roots biomass (lb)[iii]	Total dry biomass (lb)[iv]
Year					
2023	56.10 a[i]	0.92 a	1.71 a	1.78 a	3.49 a
2024	50.61 b	0.75 b	1.45 b	0.91 b	2.37 b
Significance[ii]					
Biochar	NS	NS	NS	NS	NS
Fertilizer	NS	NS	NS	NS	NS
Year	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
Year × biochar	NS	NS	NS	NS	NS
Year × fertilizer	NS	NS	NS	NS	NS
Biochar × fertilizer	NS	NS	NS	NS	NS
Year × biochar × fertilizer	NS	NS	NS	NS	NS

[i] Means followed by different letters within a column are significantly different at $P \leq 0.05$ based on the least significant difference test.
[ii] According to the analysis of variance, significant P values were interpreted as follows: $P \leq 0.001$, highly significant (***); $0.001 < P \leq 0.01$, very significant (**); $0.01 < P \leq 0.05$, significant (*); $0.05 < P \leq 0.10$, marginally significant; and $P > 0.10$, not significant (NS).
[iii] Sample size ($n = 20$) measurements were collected across two years (2023 and 2024).
[iv] The sum of the dry shoot biomass and the dry root biomass.

Additionally, extreme rainfall events can inhibit soil respiration, disrupt microbial activity, and slow the decomposition of organic materials, further impacting nutrient cycling (Chen et al. 2017; Zhang et al. 2019).

Implications for sustainable sweet corn production. Managing rainfall variability is critical for sustainable sweet corn production because of its significant influence on nutrient dynamics, crop quality, and overall yield. Mitigation strategies include adjusting fertilizer application timing to align with crop demand and anticipated rainfall patterns. Split applications, for instance, are recommended to achieve yields comparable to higher fertilizer rates while minimizing N loss (Lei et al. 2020). However, farmers often respond to heavy rainfall by increasing fertilizer application rates as a risk-reducing strategy to counteract nutrient leaching and prevent yield losses (Tremblay et al. 2012). Although this approach may address immediate concerns, it can lead to inefficiency and environmental tradeoffs.

Higher biochar application rates offer potential benefits, such as enhanced N retention and long-term soil health improvements. However, these advantages must be carefully weighed against the associated cost and logistical challenges (Lehmann and Joseph 2015). Similarly, organic fertilizers can support product differentiation in markets such as organic farming, where enhanced flavor, nutritional value, and sustainability credentials are highly valued (Massey et al. 2018). Organic fertilizers also contribute to stable yields and improved soil health over the long term, making them a viable alternative to inorganic options (Hou et al. 2020).

Overall, a holistic approach to sweet corn production—including a combination of precise nutrient management, soil amendments such as biochar, and resilience-focused agronomic practices—can enhance economic viability and environmental sustainability. Such strategies are particularly important in the context of intensifying climate variability, where adaptive and sustainable practices are essential for maintaining productivity and meeting market demands.

Conclusion

This study revealed key trends in how biochar application rates and

Table 4. Effect of year and fertilizer on ear quality parameters in sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) for combined years (2023 and 2024).

Effect	Ear length (inches)	Ear width (inches)	Kernel rows (units)	Total soluble solids	Bushel box per acre
Year					
2023	7.41 a[i]	1.83 a	17.14 a	15.20 a	547 a
2024	6.86 b	1.68 b	15.35 b	14.82 a	528 a
Fertilizer					
Inorganic	7.13 a	1.74 a	16.08 a	14.74 b	537 a
Organic	7.15 a	1.76 a	16.41 a	15.27 a	538 a
Significance[ii]					
Biochar	NS	NS	NS	NS	NS
Fertilizer	NS	NS	NS	0.0275	NS
Year	<0.0001***	<0.0001***	<0.0001***	NS	NS
Year × biochar	NS	NS	NS	NS	NS
Year × fertilizer	0.0608·	0.0571·	0.0781·	NS	NS
Biochar × fertilizer	NS	NS	NS	NS	NS
Year × biochar × fertilizer	NS	NS	NS	NS	NS

[i] Means followed by different letters within a column are significantly different at $P \leq 0.05$ according to the least significant difference test.
[ii] According to the analysis of variance, significant P values were interpreted as follows: $P \leq 0.001$, highly significant (***); $0.001 < P \leq 0.01$, very significant (**); $0.01 < P \leq 0.05$, significant (*); $0.05 < P \leq 0.10$, marginally significant; and $P > 0.10$, not significant (NS).

Table 5. Interaction effects of year and fertilizer on ear quality parameter in sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*).

	Interaction effect fertilizer × year on ear quality			
Variable	Fertilizer × year	2023	2024	*P* value
Ear length (inches)	Inorganic	7.49 Aa[i]	6.77 Ab	<0.0001
	Organic	7.35 Aa	6.95 Ab	<0.0001
	P value	0.2146	0.1407	
Ear width (inches)	Inorganic	1.85 Aa	1.64 Ab	<0.0001
	Organic	1.82 Aa	1.71 Ab	<0.0001
	P value	0.1556	0.1026	
Kernel rows (units)	Inorganic	17.29 Aa	14.88 Ab	<0.0001
	Organic	17.00 Aa	15.82 Ab	<0.0001
	P value	0.4447	0.1391	

[i] Means followed by different letters indicate significant differences at $P \leq 0.05$ based on pairwise comparisons with the Sidak adjustment for multiple comparisons. Capital letters indicate comparisons within columns and lowercase letters indicate comparisons within rows.

fertilizer sources affect N uptake and ear quality of sweet corn, with outcomes strongly influenced by year-to-year rainfall variability. Although treatment effects were not consistently significant, higher biochar rates (15–20 tons/acre) showed a trend toward improved N uptake, indicating potential benefits for nutrient retention in sandy soils. Organic fertilizer applications enhanced TSS, suggesting a quality advantage for fresh market corn. Despite minimal effects on plant growth, biomass accumulation, and overall yield, these findings provide valuable insights for tailoring nutrient strategies under variable environmental conditions. The study's 2-year timeframe may not have been sufficient to capture the longer-term benefits of biochar or organic amendments on soil health and productivity. Importantly, this research contributes to the limited literature regarding the use of biochar for sweet corn (*Zea mays* convar. *Saccharata* var. *rugosa*) production systems. Most existing studies focused on field corn (*Zea mays*), making this work a valuable reference for future researchers interested in the effects of biochar on fresh-market corn crops.

The observed variability in weather between years also reinforces the understanding that the effectiveness of soil amendments like biochar and organic fertilizers is highly dependent on environmental conditions. This insight emphasizes that outcomes from soil management strategies are not uniform and must be interpreted within the context of climatic variability, particularly rainfall distribution during critical crop development stages. Future research should explore the cumulative effects of biochar over multiple seasons, especially its capacity to reduce N losses during high rainfall periods. Incorporating tools such as lysimeters or ceramic suction cups would enable direct measurement of leaching losses and provide stronger evidence for biochar's role in nutrient retention. Expanding trials across different soil types and regions will also enhance the relevance of recommendations for diverse growing conditions. Importantly, integrating economic assessments will help determine the practicality of biochar use at scale. Ultimately, refining biochar application rates in combination with fertilizer strategies offers a promising path to improving nutrient efficiency and promoting sustainable sweet corn production.

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