Biochar Rate and Fertilizer Source Influence Tomato Growth, Mortality, Yield, and Profitability

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ABSTRACT. **Tomato (*Solanum lycopersicum*) production in southern Georgia contributes significantly to the agricultural economy but faces challenges from low-fertility soils and heavy reliance on chemical inputs. This study evaluated the effects of biochar application rates (0, 5, 10, 15, and 20 tons/acre) combined with conventional (granular and liquid) or poultry litter fertilizers on tomato growth, yield, fruit quality, and economic viability over two growing seasons (2023–24). Field trials were conducted on a Coastal Plain soil at the University of Georgia Tifton Campus, Hort Hill Farm, using a 5 × 2 factorial arrangement in a randomized complete block design (RCBD) with four replications. Results showed that poultry litter significantly improved plant height (+32%), stem diameter (+27%), and marketable yield (+39%) compared with conventional treatments. Biochar application had no significant effect on plant growth or yield but reduced fruit defects such as zippering by up to 47% at higher rates (15–20 tons/acre). Economic analysis revealed that combining poultry litter with biochar at 20 tons/acre achieved the highest profitability, with a cumulative benefit-cost ratio (BCR) of 2.08, while conventional treatments remained below the economic viability threshold (BCR <1). These findings suggest that integrating poultry litter with high biochar rates (15–20 tons/acre) can enhance soil health, improve crop resilience, and increase profitability in tomato production. This research provides actionable insights for growers in southern Georgia to optimize soil amendments, reduce reliance on synthetic fertilizers, and improve climate resilience in Coastal Plain soils.**

Southern Georgia is a vital hub for vegetable production in the United States, with tomatoes being one of the region's most important crops. According to the 2023 Georgia Farm Gate Value Report, tomatoes ranked fifth among the top vegetables in the state, contributing $90 million in production value, representing 6.8% of Georgia's total vegetable value (University of Georgia 2023). This significant economic contribution underscores the importance of sustaining and expanding tomato production in the region. However, tomato cultivation in southern Georgia faces many interconnected challenges that hinder productivity and sustainability. The region's soils, characterized by sandy loams to finer loams (Duffera et al. 2007; Swaby et al. 2016), exhibit low fertility due to their sandy texture, acidic pH, low cation exchange capacity, and limited organic carbon content (Novak et al. 2009). Consequently, farmers rely heavily on agricultural chemicals, increasing the risk of nutrient and pesticide runoff into adjacent water sources (Bosch et al. 2020). This reliance poses environmental risks and contributes to nutrient leaching, soil degradation, and increased greenhouse gas emissions (Chendev et al. 2000; Morse et al. 2012; Sigua et al. 2017).

American farmers face a harsh reality, as highlighted by Reiley and van Lohuizen (2023) in *The Washington Post*. Farmers are at a crossroads, grappling with the mounting impacts of climate change, shifting consumer preferences, and political pressures that threaten the sustainability of traditional "grow more, get bigger" farming models. Rising fertilizer, pesticide, and labor costs further strain profitability, while extreme weather events—such as droughts and floods—exacerbate the uncertainty. Although some farmers are turning to innovative approaches like indoor vertical farming and regenerative agriculture, these methods remain costly and risky, making them inaccessible to many.

Addressing these pressing issues requires innovative approaches, such as soil amendments that improve soil health and boost crop productivity. One promising solution is the integration of biochar into agricultural systems. Biochar, a carbon-rich material produced by the pyrolysis of organic waste (Lorenz and Lal 2018), has gained attention for its potential to improve soil properties by increasing nutrient and water retention, resulting in enhanced plant growth (Lustosa Filho et al. 2024). In addition, biochar is characterized by its high carbon content and stability, which makes it a promising material for long-term carbon sequestration (Wang et al. 2016). Research indicates that biochar can significantly enhance soil fertility in tomato production. Applying sewage sludge-made biochar improved soil organic carbon, nitrogen, and phosphorus content, enhancing tomato growth while minimizing heavy metal uptake in plants (Velli et al. 2021). However, Gelardi et al. (2024) found that while biochar improved several soil health indicators in processing tomato systems, it did not significantly increase crop yield within a 3-year field trial. Conversely, Lei et al. (2024) found that high biochar application rates can increase tomato yield by 29.55%, total soluble solids by 4.28%, and vitamin C content by 6.77%. Furthermore, Agbede and Oyewumi (2022) demonstrated that the benefits of biochar are amplified when combined with fertilizers, such as poultry litter.

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Georgia ranks as the top poultry-producing state in the nation, generating more than $4.3 billion in farm gate value and contributing more than $28 billion annually to the state's economy (Lawrence 2022). The poultry industry produces more than 2.0 million tons of poultry litter yearly (Cunningham et al. 2009). This organic material is rich in essential plant nutrients, including nitrogen, phosphorus, and potassium (Muduli et al. 2019), making it a valuable fertilizer. Its widespread availability in Georgia presents an opportunity to reduce reliance on conventional fertilizers while promoting sustainable and circular farming practices. However, to maximize its benefits while minimizing risks, farmers must adhere to established guidelines for manure use to prevent pathogen contamination and safeguard environmental and food safety (USDA 2024a). As the United States strives to fulfill its commitment to the Sustainable Development Goals (SDGs) (USAID 2024), this research is essential in supporting SDG 2 (Zero Hunger) by improving sustainable agricultural practices, SDG 12 (Responsible Consumption and Production) by promoting resource-efficient soil management, and SDG 13 (Climate Action) by using biochar's potential to sequester carbon and mitigate climate change.

Integrating locally produced biochar with poultry litter offers a promising strategy for enhancing soil health and increasing tomato yields in the soils of southern Georgia. While existing research has individually highlighted the benefits of biochar and poultry litter, there is a limited investigation into their combined effects on tomato plasticulture using regionally sourced biochar. The properties of biochar can vary widely depending on the feedstock and production temperatures (Hassan et al. 2020), emphasizing the need for localized studies to optimize its application and effectiveness. Addressing this research gap is crucial for understanding how these amendments can improve soil fertility, boost plant nutrient uptake, and enhance crop resilience.

The objective of this study was to evaluate the effects of varying biochar application rates and different fertilizer sources on plant nutrient uptake, plant growth, disease suppression, tomato yield, fruit quality, and economic viability in the coastal plain soils of southern Georgia.

Materials and methods

Experimental site. Field trials were conducted during the Spring of 2023 and 2024 at the University of Georgia (UGA), Hort Hill Farm in Tifton, GA (lat. 31°28′14.96″N, long. 83°31′53.11″W). The soil at the study had an average composition of 82.12% sand, 5.88% silt, and 12.00% clay at a depth of 0 to 6 inches. To establish baseline conditions, composite pre-plant soil samples (0–6 inches) were collected in 2023 from across the experimental field by combining 50 individual cores. Samples were analyzed using the Mehlich 1 extraction method at Waters Agricultural Laboratory (Camilla, GA, USA). The initial nutrient profile included phosphorus (P) at 98 lb/acre, potassium (K) at 155.5 lb/acre, magnesium (Mg) at 72.7 lb/acre, and calcium (Ca) at 535.5 lb/acre. Soil pH was 5.8, organic matter content was 0.64%, and the cation exchange capacity (CEC) was 3.25 meq/100 g. Environmental conditions were relatively stable in terms of temperature (Fig. 1A), with average maximum temperatures during May and June ranging from 27.4 to 32.4 °C across both years. In contrast, rainfall (Fig. 1B) exhibited substantial year-to-year variability: early-season precipitation (March–May) was considerably higher in 2024 (164.6–194.6 mm/month) compared with 2023 (73.2–88.1 mm/month), whereaas June rainfall was lower in 2024 (45.2 mm) than in 2023 (183.6 mm).

Treatments. The experiment followed a 5 × 2 factorial arrangement in a randomized complete block design (RCBD), combining five biochar application rates (0, 5, 10, 15, and 20 tons/acre) with two fertilizer sources: conventional (granular and liquid) or poultry litter. Each treatment combination was replicated four times, resulting in a total of 40 experimental units. Each plot measured 180 ft^2 (6 ft wide × 30 ft long), and a 5-ft alley was maintained between replications to minimize soil movement and cross-contamination. Biochar was sourced from Wakefield Biochar (Valdosta, GA, USA), produced from pine wood chips through pyrolysis at 1112 °F. It was applied as a one-time surface amendment on 3 Mar 2023. No additional biochar applications were made in 2024. The same field parcels were used for both growing seasons to evaluate the residual and cumulative effects of biochar and fertilizer treatments under a plasticulture system. In both years, we targeted the nitrogen (N) fertilizer application rate recommended by the UGA Extension for tomato production, 225 lb N per acre (Kissel and Sonon 2008). The poultry litter fertilizer consisted of locally sourced, dry, uncomposted material from a broiler farm in Berrien County, GA, USA (lat. 31°18′45.51″N, long. 83°23′2.53″W). Poultry litter samples were analyzed for N content at Waters Agricultural Laboratory, Camilla, GA, USA. Nitrogen content was determined using a LECO-Combustion (LECO Corp., St. Joseph, MI, USA) analyzer. The N application rate was calculated based on the analysis of the estimated total available N content (lb/ton). This analysis 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–optical emission spectrometry (ICP-OES; iCAP series, Thermo Fisher Scientific, Madison, WI, USA) following open-vessel wet digestion using a DigiBlock 3000 system (LabTech, Wilmington, MA, USA). The physicochemical properties of biochar and poultry litter are shown in Table 1. During both years, poultry litter was applied pre-plant before the plastic mulch was laid. This practice followed the US Department of Agriculture's (USDA's) 90-d rule for manure application before harvest on aboveground vegetables to prevent pathogen contamination (USDA 2024a). The conventional fertilizer treatment involved a pre-plant application of 50 lb N per acre using a granular (10.0N–4.3P–8.3K; Rainbow Fertilizer LLC, Americus, GA, USA) fertilizer, also applied before laying plastic mulch on 3 Mar 2023 and 4 Mar 2024.

Raised beds were shaped following the application of pre-plant poultry litter and granular fertilizers. Irrigation drip tape (Typhoon™ Plus, Netafim, Fresno, CA, USA) and black, totally impermeable film plastic mulch (Guardian TIF 1116, DNM Ag Supply, Inc., Calabasas, CA, USA) were applied using a tractor-mounted single-row mulch layer (RMC-172, Reddick Equipment, Williamston, NC, USA).

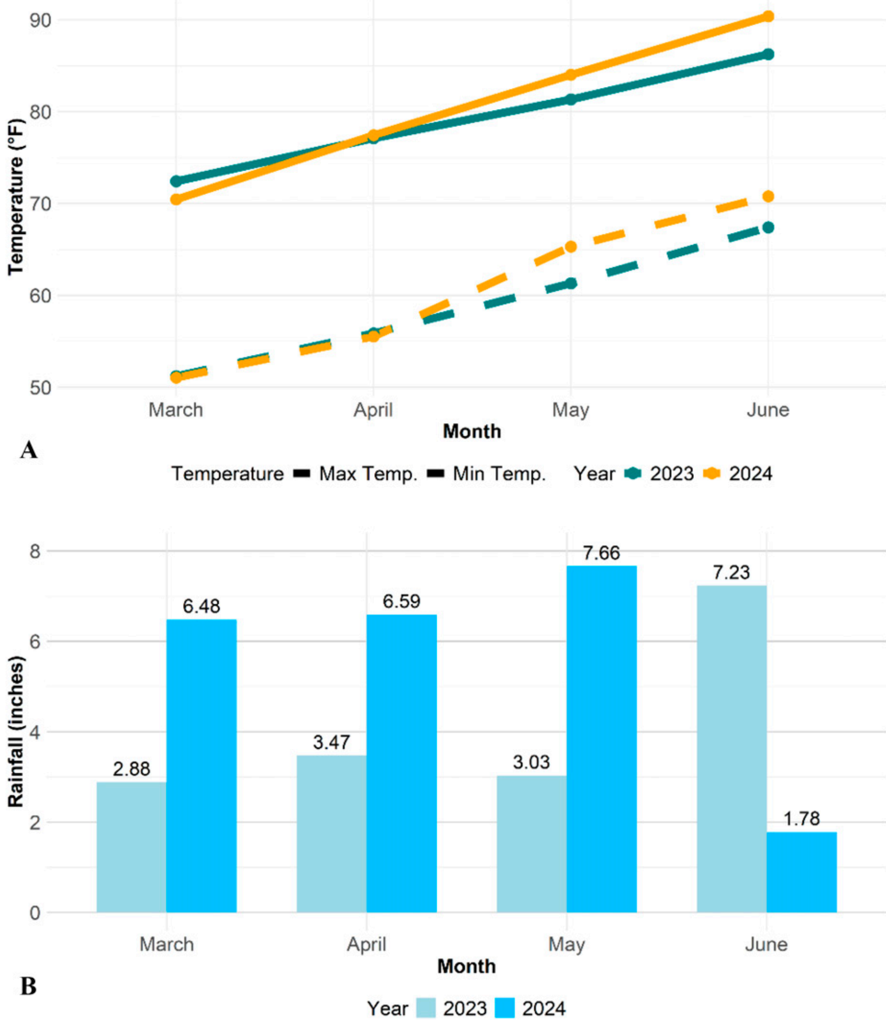

Fig. 1. Weather conditions during the tomato growing season (1 Mar to 30 Jun) in 2023 and 2024 at the Coastal Plain Experiment Station in Tifton, GA, showing (A) average daily air temperature (°F) and (B) cumulative rainfall (inch), based on data obtained from the University of Georgia Weather Network (https://weather.uga.edu).

Although soil fumigation is a common practice in plasticulture tomato systems, no fumigation was applied in this trial during either year. This process was repeated in 2024, with the mulch and irrigation systems removed on 28 Feb and re-installed on 6 Mar following the fertilizer applications. In the conventional fertilizer treatment, the remaining 175 lb N per acre were supplied weekly through fertigation starting a week after transplant using liquid fertilizer (7.0N–0P–5.8K, Nutrien Ag Solutions, Tifton, GA, USA), which was equally split into 10 applications over the growing season (17.5 lb N per acre per week). The 7N–0P–7K liquid fertilizer contained multiple N sources and amounts (3.17% nitrate-N, 1.25% ammonium-N, and 2.58% urea-N). Each plot on the field had an individual valve to ensure that organic treatments did not receive any conventional fertilizer.

Planting. Tomato 'Summer Heaven F1' (Seedway, Hall, NY, USA) was used. Tomato seedlings were sown and grown at Lewis Taylor Farms, a commercial transplant greenhouse nursery in Tifton, GA (lat. 31°26′49.32″N, long. 83°36′52.52″W); seeds were sown on 17 Feb 2023 and 26 Feb 2024. After 6 weeks of growth, the seedlings were picked up and transplanted to the trial field on 24 Mar 2023 and 2 Apr 2024. Seedlings were transplanted in single rows per bed, with beds spaced 6 ft apart and individual plants spaced 18 inches within the row (4840 plants per acre). Each plot contained 10 plants. Conventional fresh market stakes and production weave trellis were used. Herbicides, fungicides, and insecticides followed the standard UGA recommendations (Horton et al. 2014).

Data collection. Tomato harvesting began when the fruit reached the breaker stage—the first visible sign of ripening, characterized by a color change from green to pale pink or red (Reissig et al. 2021). For yield data collection, five plants were selected from the center of each plot, specifically the fourth through the eighth plants, while the first three and last two plants in each plot were excluded. Three rounds of harvesting were conducted during each growing season: in 2023, on 7 Jun, 16 Jun, and 30 Jun; and in 2024, on 7 Jun, 21 Jun, and 1 Jul. During each harvest, the fruit was separated into marketable and unmarketable categories. A mechanical grader (Market Maker, Tew Manufacturer Corp, Penfield, NY, USA) was used to separate marketable fruit by width and classified according to the Standards for Grades of Fresh Tomatoes (USDA 1991b), with size categories defined as small (2.13 to 2.28 inches), medium (2.25 to 2.53 inches), large (2.50 to 2.78 inches), and extralarge (XL) (2.75 inches or more). Counts and weights (lb) were recorded for each size category. Unmarketable or cull fruit was further separated by type of defect, such as misshapen appearance, blossom end rot, catfacing, zippering, and cracking, then counted. The number of boxes per acre was calculated for each treatment, using 25 lb of fruit per box (Kelley et al. 2010). For each cull category, the percentage was calculated by dividing the number of fruits with a specific defect by the sum of marketable and unmarketable fruit counts, then multiplying the result by 100.

Plant growth and development. Plant height was measured using a standard measuring tape from the base of the plant at the plastic mulch level to the growing point. The stem diameter was measured at the base of the plant using a caliper. These measurements were taken for all 10 plants in each plot immediately following the final harvest. During both years of research, Southern blight (*Agroathelia rolfsii)* affected the field (Fig. 2). Samples taken at different stages of growth were sent to the UGA Plant Disease Clinic, confirming the presence of *Agroathelia rolfsii*. Plant

Table 1. **Physicochemical properties of poultry litter and biochar applied before planting. Poultry litter values represent 2023–24 averages. Analyses were conducted by Waters Laboratories (Camilla, GA, USA). Biochar values represent 2023 and were analyzed by the International Biochar Initiative (IBI) Laboratory (Columbia, MO, USA).**

Parameter	Units	Poultry litter Spring 2023	Poultry litter Spring 2024	Biochar Spring 2023
pH		8.63	7.52	8.84
Total nitrogen	lb/ton	37.32	33.90	3.84
Total P_2O_5	lb/ton	38.60	55.80	2.38
Total K_2O	lb/ton	61.40	71.0	3.20
Total calcium	lb/ton	23.60	41.20	20.16
Total manganese	lb/ton	0.4	0.60	0.14
Total magnesium	lb/ton	9.0	13.40	2.24
CEC	meq/100 g	ND[i]	ND	18.40
Bulk density	lb/ft^3	ND	ND	10.6
Organic carbon	% of total dry mass	ND	ND	21.1
Total ash	% of total dry mass	ND	ND	57.0
Liming (neut. value as-$CaCO_3$)	% $CaCO_3$	ND	ND	5.50

[i] ND indicates no data available for the parameter.

mortality was assessed at the end of the season by counting wilting dead plants per plot. The percentage of plant mortality was calculated by dividing the number of plants with symptoms by the total number of plants per plot, then multiplying by 100.

Benefit/cost ratio. The economic analysis in this study evaluated the cumulative benefit-cost ratio (BCR) following the methodology of Shahzad et al. (2018), with modifications to account for varying biochar application rates in combination with conventional and organic fertilizers across the growing seasons of 2023 and 2024. Marketable yield (boxes per acre) was collected from plots treated with different biochar rates (applied once in 2023) and supplemented with conventional or organic fertilizers. Each year, the price per box of tomatoes was averaged based on June prices for each harvest using the USDA Agricultural Marketing Services platform (USDA 2024c). This approach estimated the additional income generated by each treatment, setting the price at $21.38 for 2023 and $20.17 for 2024 for a 25-lb carton of loose, mature greens tomatoes. The cost of poultry litter used as an organic fertilizer was $60 per ton, as suggested by the UGA Agricultural & Applied Economics Department (G. Hancock, personal communication, 18 Oct 2024). In 2023, 6.02 tons were applied per acre; in 2024, 6.63 tons were applied per acre, resulting in a total cost of $361.71 and $398.23 per acre, respectively. Conventional fertilizers, including granular and liquid applications, cost $680.88 per acre per year. Cost data for conventional fertilizers were sourced directly from the manufacturers. The cost of the biochar was calculated based on a price of $176 per ton (Supercritical 2024), which reflects the average spot price for biochar carbon removal credits and was included only for the 2023 growing season. The biochar application cost was $8 per ton (Sorensen and Lamb 2018). The additional income for each treatment was calculated by multiplying the yield difference between the treatment and the control (0 tons/acre biochar) by the average market price per box of tomatoes. For 2023, the total cost included both the cost of biochar and the type of fertilizer used, whereas for 2024, only the fertilizer costs were considered. The cumulative BCR was calculated by summing the additional income and total costs across both years for each treatment to assess the long-term economic viability. The cumulative BCR was then obtained by dividing the total additional income by the total cost. A cumulative BCR greater than 1 indicated sustained profitability over the two growing seasons, while a BCR below 1 represented a net loss over the same period.

Fig. 2. Damage caused by southern blight (*Agroathelia rolfsii*) in tomato plants. (A) Early growth stage tomato plant showing symptoms of southern blight. (B) Close-up of the stem exhibiting southern blight symptoms, including stem and the characteristic white mycelial mat. (C) Late-season southern blight symptoms on a mature tomato plant almost ready for harvest, characterized by plant wilting.

Data analysis. All statistical analyses were conducted in RStudio (Posit Team 2025). A linear mixed-effects ANOVA was performed using the "lme4" package (Bates et al. 2015), with Biochar (5 levels), Fertilizer (2 levels), and Year (2 levels) as fixed effects, and Replication and Plot nested within Replication as random effects. When significant effects were detected ($P < 0.05$), Tukey's honestly significant difference (HSD) was used for mean separation at a 95% confidence level. Assumptions of normality and homogeneity were tested using the Shapiro-Wilk and Levene's tests, respectively, and residual plots were visually inspected. Where needed, data were log-transformed to meet model assumptions, although untransformed values are reported for clarity. For significant interactions, estimated marginal means were computed using the "emmeans" package (Lenth 2016), and pairwise comparisons were adjusted using the Sidak method. Means sharing the same letter indicate no significant difference at $P < 0.05$).

Results

Plant growth, fruit weight, and plant mortality were significantly influenced by fertilizer type and year (Table 2). Biochar application rates had no significant effects on any measured variables, and no interactions among year, fertilizer, and biochar were observed. Plants treated with organic fertilizer were 32% taller and

Table 2. Effects of fertilizer and year on tomato plant growth, fruit weight, and mortality.

Effect	Height (inch)[i]	Stem (inch)[i]	Avg fruit weight (oz)	Mortality (%)
Fertilizer				
Conventional	27.16 b[ii]	0.59 b	1.43 a	29.25 a
Poultry litter	35.77 a	0.75 a	0.82 a	18.00 b
Year				
2023	34.40 a	0.75 a	7.12 a	13.50 b
2024	28.52 b	0.59 b	5.40 b	33.75 a
Significance[iii]				
Biochar	NS	NS	NS	NS
Fertilizer	0.0008***	0.0050**	NS	0.0214*
Year	0.0026**	0.0002***	<0.0001***	<0.0001***
Year × Biochar	NS	NS	NS	NS
Year × Fertilizer	NS	NS	NS	NS
Biochar × Fertilizer	NS	NS	NS	NS
Year × Biochar × Fertilizer	NS	NS	NS	NS

[i] Sample size n = 20 measurements were collected across 2 years (2023–24).
[ii] Means followed by different letters within a column are significantly different at $P \leq 0.05$, based on Tukey's honestly significant difference test.
[iii] For ANOVA significance, 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).

had stem diameters 27% larger than those treated with conventional fertilizer. Similarly, plants grown in 2023 were 21% taller and had stem diameters 27% larger compared with 2024. Average fruit weight decreased by 32% in 2024 compared with 2023, although fertilizer type had no significant impact on fruit weight. Mortality rates were 63% higher in plants treated with conventional fertilizer compared with organic treatments. In addition, plant mortality in 2024 was 150% higher than in 2023.

Table 3. Effects of fertilizer and year on fruit size distribution and total marketable yield of tomato.

	Fruit size distribution (boxes/acre)[i]				
Effect	Small	Medium[ii]	Large[ii]	Extralarge	Total marketable[iii]
Fertilizer					
Conventional	31 a[iv]	108 b	500 b	800 b	1468 b
Poultry litter	28 a	146 a	821 a	1049 a	2045 a
Year					
2023	13 b	52 b	437 b	1266 a	1797 a
2024	46 a	203 a	885 a	584 b	1717 a
Significance[v]					
Biochar	NS	NS	NS	NS	NS
Fertilizer	NS	0.0202*	0.0002***	0.0176*	0.0018***
Year	<0.0001***	<0.0001***	<0.0001***	<0.0001***	NS
Year × Biochar	NS	NS	NS	NS	NS
Year × Fertilizer	NS	0.0456*	0.0038**	NS	0.0146*
Biochar × Fertilizer	NS	NS	NS	NS	NS
Year × Biochar × Fertilizer	NS	NS	NS	NS	NS

[i] Fruit size distribution: boxes were calculated based on the count of fruits in each size category, determined by dividing the total fruit weight by 25 lb per box.
[ii] Data were log-transformed to meet normality assumptions; untransformed means are shown for clarity.
[iii] Total marketable yield: represents the sum of all size categories (small, medium, large, and extralarge) expressed in boxes per acre.
[iv] Means followed by different letters within a column are significantly different at $P \leq 0.05$, based on Tukey's honestly significant difference test.
[v] For ANOVA significance, P values was 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).

Boxes per acre. The yield, expressed as boxes per acre, was significantly influenced by fertilizer type and year, while biochar application rates had no notable effect on any yield category (Table 3). Plants treated with organic fertilizer consistently outperformed those treated with conventional fertilizer, producing higher yields across all marketable fruit size categories. Organic fertilizer increased medium fruit yields by 35%, large fruit yields by 64%, and extralarge fruit yields by 31%, resulting in a total marketable yield that was 39% higher compared with conventional treatments. The year of cultivation also significantly affected fruit size distribution. In 2024, small fruit yields increased by 254%, medium fruit yields by 290%, and large fruit yields by 103% compared with 2023. However, extralarge fruit yields decreased by 54% in 2024, reflecting a shift in size distribution. Despite these changes, total marketable yields were statistically similar between the two years, with 1797 boxes per acre in 2023 and 1717 boxes per acre in 2024.

No significant interactions were observed between biochar application rates and fertilizer type or between biochar and year for any yield category, emphasizing the dominant influence of fertilizer type and year on fruit size distribution and total yield.

Unmarketable yield and culls. The effects of biochar application rates, fertilizer type, and year on tomato quality were analyzed (Table 4). Year of cultivation significantly influenced most quality defects and total culls. In 2024, misshapen fruits were reduced by 59% compared with 2023, whereas blossom end rot decreased by 62%. Zippering also declined by 51%, dropping from 2.71% in 2023 to 1.34% in 2024. Cracking showed the most substantial improvement, with a 75% reduction in 2024 compared with 2023. Overall, total culls decreased by 59%, reflecting improved fruit quality in 2024. Fertilizer type also affected quality defects. Organic treatments reduced misshapen fruit by 34% compared with conventional treatments. However, organic fertilizer increased cracking by 148%, with organic treatments showing a higher incidence of cracking (9.60%) compared with conventional treatments (3.87%). While fertilizer type was significant in ANOVA (P = 0.0073), Tukey's HSD test did

Table 4. Effects of biochar, fertilizer, and year on fruit deformities and total culls in tomato.

Effect	Tomato quality defects and total culls (%)					
	Misshapen[i]	Blossom end rot[i]	Catface	Zippering	Cracking	Total culls[i]
Biochar ton/acre						
0	1.06 a[ii]	3.46 a	0.66 a	2.85 a	3.96 a	11.28 a
5	1.35 a	4.05 a	0.70 a	1.82 ab	5.72 a	12.85 a
10	1.66 a	3.51 a	0.89 a	2.42 ab	4.72 a	11.86 a
15	1.23 a	2.73 a	0.80 a	1.54 ab	5.42 a	10.74 a
20	1.18 a	1.78 a	1.21 a	1.49 b	4.37 a	9.35 a
Fertilizer						
Conventional	1.56 a[ii]	3.05 a	0.93 a	1.95 a	3.87 b	9.79 b
Poultry litter	1.03 b	3.17 a	1.38 a	2.09 a	9.60 a	12.64 a
Year						
2023	1.84 a	4.49 a	0.88 a	2.71 a	7.73 a	15.89 a
2024	0.75 b	1.72 b	0.82 a	1.34 b	1.95 b	6.54 b
Significance[iii]						
Biochar	NS	NS	NS	0.0267*	NS	NS
Fertilizer	0.0372*	NS	NS	0.0073**	0.0004***	0.0161*
Year	<0.0001***	0.0002***	NS	<0.0001***	<0.0001***	<0.0001***
Year × Biochar	NS	NS	NS	0.0045**	NS	NS
Year × Fertilizer	NS	NS	NS	0.0050**	NS	0.0321*
Biochar × Fertilizer	NS	NS	NS	NS	NS	NS
Year × Biochar × Fertilizer	NS	NS	NS	NS	NS	NS

[i] Data were log-transformed to meet normality assumptions; untransformed means are shown for clarity.

[ii] Means followed by different letters within a column are significantly different at $P \leq 0.05$, based on Tukey's honestly significant difference test.

[iii] For ANOVA significance, P values was 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).

not detect significant differences between fertilizer treatments for zippering. Total culls were 29% higher under organic treatments than conventional treatments. Biochar application significantly influenced zippering. The highest biochar application rate (20 tons per acre) reduced zippering by 47% compared with the control, suggesting that higher biochar rates may help improve this specific quality defect. For other quality defects, biochar application rates showed limited effects, with year and fertilizer type being the dominant factors influencing tomato quality.

Interactions in tomato yield and quality. A significant year × fertilizer interaction (Table 5) was observed for medium fruit yield ($P = 0.0456$), large fruit yield ($P = 0.0038$), total marketable yield ($P = 0.0146$), zippering incidence ($P = 0.0050$), and total culls ($P = 0.0321$). In 2024, poultry litter significantly improved yield components compared with conventional fertilizer, with increases of 41.1% in medium fruit yield, 78.7% in large fruit yield, and 71.3% in total marketable yield. In 2023, poultry litter also outperformed conventional fertilizer, although to a lesser extent, with respective increases of 17.0%, 38.8%, and 15.1%. Zippering incidence, expressed as a percentage of total fruit, was highest in 2023 under poultry litter (3.23%) and significantly greater than both 2024 treatments. The lowest zippering rates were observed in 2024 under poultry litter (0.96%) and conventional fertilizer (1.72%), which were statistically similar. The 2023 conventional treatment (2.19%) showed an intermediate level of zippering and was not significantly different from other treatments. Total culls (% unmarketable fruit) followed a similar trend. The highest cull rate occurred in 2023 under poultry litter (18.57%), which was significantly greater than all other treatments. In contrast, the lowest cull rates were observed in 2024 under both fertilizer types (6.38% and 6.72%), with no significant difference between them.

Interaction of biochar and year on zippering incidence. A significant interaction between biochar rate and year ($P = 0.0045$) was observed for zippering incidence (Table 6). In 2023, the control treatment (0 tons/acre) had the highest zippering incidence at 4.64%, which was significantly greater than all other treatments that year. The 5 and 20 tons/acre treatments in 2023 had the lowest zippering values (2.05% and 1.39%, respectively), whereas the 10 and 15 tons/acre treatments were intermediate and not statistically different

Table 5. Interaction of year and fertilizer on tomato yield and quality parameters.

Year	Fertilizer	Medium (box/acre)	Large (box/acre)	Mkt. total (boxes/acre)	Zippering (%)	Total culls (%)
2023	Conventional	47 b[i]	366 c	1671 ab	2.19 ab	13.22 b
2023	Poultry litter	55 b	508 bc	1923 a	3.23 a	18.57 a
2024	Conventional	168 c	635 b	1266 b	1.72 b	6.38 c
2024	Poultry litter	237 a	1135 a	2168 a	0.96 b	6.72 c

[i] Pairwise comparisons were conducted and means followed by different letters within a column are significantly different at $P \leq 0.05$ using the Sidak method.

Table 6. Interaction of biochar and year on zippering incidence in tomato.

Biochar (ton/acre)	Year	Zippering (%)
0	2023	4.64 a[i]
5	2023	2.05 b
10	2023	3.10 ab
15	2023	2.36 ab
20	2023	1.39 b
0	2024	1.06 b
5	2024	1.60 b
10	2024	1.73 b
15	2024	0.72 b
20	2024	1.58 b

[i] Pairwise comparisons were conducted and means followed by different letters within a column are significantly different at $P \leq 0.05$ using the Sidak method.

from either extreme. In 2024, zippering incidence was uniformly low across all biochar rates, ranging from 0.72% to 1.73%, with no significant differences among treatments.

Benefit/cost ratio. The economic analysis evaluated the cumulative BCR across varying biochar application rates combined with conventional and organic fertilizers over the 2023 and 2024 growing seasons (Fig. 3). The cumulative BCR was used to assess the profitability of each treatment, with a value greater than 1 indicating economic viability.

For conventional fertilizer treatments, the highest cumulative BCR (0.75) was observed at the 20 tons/acre biochar application rate, generating a total additional income of $3775.44 against a total cost of $5041.76. The 15 tons/acre biochar treatment had a slightly lower BCR (0.69), reflecting an additional income of $2831.58 and a cost of $4121.76. The 10 tons/acre treatment produced a cumulative BCR of 0.59, indicating a moderate improvement over lower biochar rates, with an additional income of $1887.72 and a total cost of $3201.76. However, at 5 tons/acre, the BCR dropped to 0.41, suggesting lower profitability compared with higher biochar rates. Notably, all conventional fertilizer treatments resulted in BCR values below 1, indicating that the additional income did not fully offset the input costs.

For organic fertilizer treatments, the highest profitability was observed at the 20 tons/acre biochar application rate, achieving a cumulative BCR of 2.08, with a total additional income of $9232.69 against a total cost of $4439.96. The 15 tons/acre biochar treatment also demonstrated strong economic viability, with a BCR of 1.97, reflecting an additional income of $6924.52 and a cost of $3519.96. The 10 tons/acre treatment yielded a BCR of 1.78, whereas the 5 tons/acre treatment produced a BCR of 1.37, both surpassing the economic viability threshold. In contrast to the conventional treatments, all organic fertilizer treatments resulted in BCR values above 1, indicating that biochar application was profitable when combined with organic fertilizer.

Discussion

Impact of environmental conditions

The contrasting weather patterns between the spring seasons of 2023 and 2024 profoundly influenced tomato growth, yield, and fruit quality. In 2023, gradual temperature increases and consistent rainfall provided stable growing conditions, which supported strong plant vigor and higher fruit weights. Consistent soil moisture likely contributed to healthy root development and minimized stress during early growth stages (Li et al. 2023). On the other hand, 2024 presented a more challenging environment, with higher rainfall early in the season followed by a sharp decline in June. This fluctuation may have subjected plants to alternating periods of water excess and deficit, increasing physiological stress and reducing overall plant performance. These environmental differences also influenced the occurrence of fruit deformities. Misshapen fruits, often associated with stress during flower development, were more prevalent in 2023, possibly due to temperature and moisture variability during critical reproductive stages (Peet 2009a). In contrast, the reduced incidence of misshapen fruits in 2024 suggests more favorable conditions during flower formation despite the early-season rainfall. Blossom

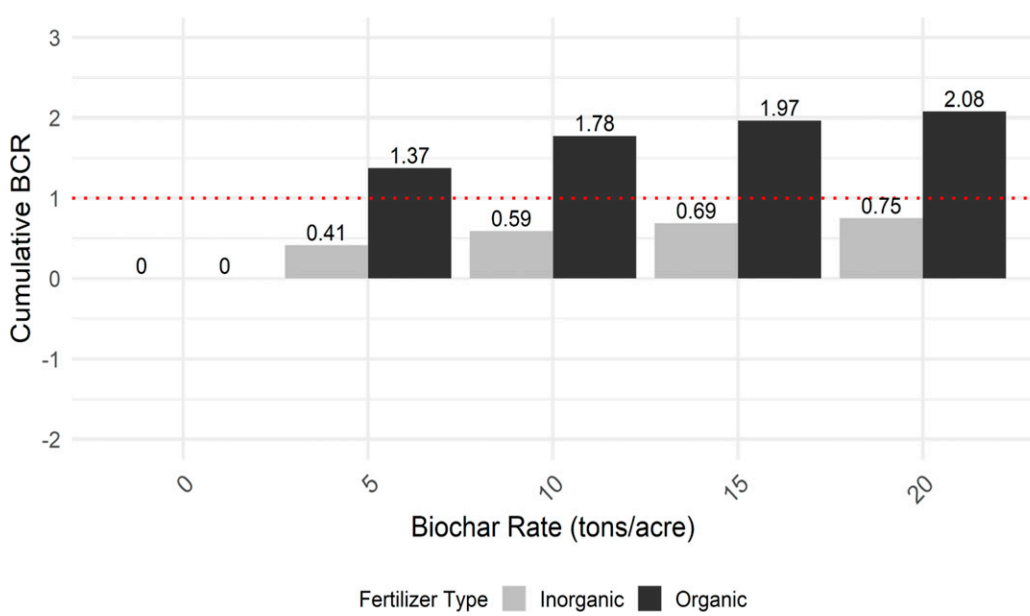

Fig. 3. Cumulative benefit/cost ratio (BCR) of tomato (*Solanum lycopersicum*) production under biochar and fertilizer treatments across two growing seasons (2023–24). The horizontal red dashed line at BCR = 1 represents the breakeven point, where additional income equals the total costs incurred.

end rot, a physiological disorder related to calcium imbalance and water stress, was significantly reduced in 2024, likely due to steadier moisture levels that supported better calcium distribution within the fruit (Mayorga-Gómez et al. 2020; Saure 2001). In addition, the lower rainfall in Jun 2024 may have helped minimize rapid fluctuations in water availability, reducing the occurrence of fruit cracking—a disorder triggered by irregular water uptake during fruit expansion (Niiuchi et al. 1960; Peet 1992b). Zippering, caused by anthers adhering to the ovary wall during early fruit development (Olson 2017), was also affected by seasonal conditions. The use of biochar appeared to reduce zippering incidence, particularly in 2023, suggesting that biochar's contribution to stabilizing soil moisture may have helped mitigate stress-related deformities.

Effect of fertilizer source

Conventional fertilizer. Inorganic fertilizers, which supply nutrients in readily available forms, can support early plant growth and development (Chen et al. 2018); however, they do not contribute to long-term improvements in soil structure or microbial activity (Zhang et al. 2021). In this study, tomato plants treated with conventional fertilizer had lower total marketable yields and smaller fruit sizes compared with those treated with poultry litter. In addition, higher plant mortality was observed under conventional fertilizer treatments, suggesting a reduced capacity to support sustained crop performance.

Poultry litter. Using poultry litter significantly enhanced tomato plant growth, yield, and survival across both seasons. Its nutrient-rich composition, combined with its ability to improve soil cation exchange capacity (CEC) and water-holding capacity, likely contributed to improved soil conditions that support root development and microbial activity (Acosta-Martínez and Harmel 2006; Boitshwarelo et al. 2022; Bolan et al. 2010). Plots treated with poultry litter showed greater plant height, thicker stems, and consistently higher yields in all fruit size categories compared with conventional fertilizer. Total marketable yields surpassed the regional benchmark of 1500 boxes/acre (Kelley et al. 2010), indicating that poultry litter can enhance productivity beyond standard fertilization practices. In addition, lower plant mortality observed in poultry litter treatments may be partially attributed to enhanced soil biological activity. Poultry litter supports the development of beneficial microbial populations (Brooks et al. 2018). Furthermore, recent in vitro research has shown that poultry refuse extract can suppress Southern blight by inhibiting mycelial growth and sclerotia formation (Sultana et al. 2025).

Impact of biochar. Biochar application had limited effects on most measured parameters, including plant growth and yield, indicating it neither significantly enhanced nor hindered tomato production under the study conditions. One possible explanation is that the baseline soil fertility and properties were already sufficient for crop growth, minimizing the observable impact of biochar in the short term. However, biochar application rates significantly influenced zippering incidence; higher rates were associated with reduced occurrence of this fruit deformity. As previously discussed, zippering is linked to fluctuations in water availability during fruit development. The ability of biochar to enhance soil water retention and stabilize moisture likely helped mitigate these fluctuations, contributing to improved fruit quality in this aspect (Razzaghi et al. 2020). Although biochar did not significantly affect most growth or quality parameters during the 2-year trial, its long-term benefits may emerge over time. Biochar is known to gradually improve soil structure, microbial activity, and nutrient cycling (Hussain et al. 2017; Nepal et al. 2023). Therefore, the short-term findings of this study may underestimate its full potential, particularly in production systems with lower initial soil fertility or over longer-term applications.

Economic implications. The economic analysis indicated that higher biochar application rates (15–20 tons/acre) improved profitability, particularly when combined with organic fertilizers. The highest cumulative BCR was observed at 20 tons/acre for organic treatments (BCR = 2.08), while conventional treatments at the same rate remained below the economic viability threshold (BCR = 0.75). These results suggest that biochar can provide economic benefits under specific conditions by potentially enhancing soil properties and improving crop yields. Although the biochar $\times$ fertilizer interaction was not statistically significant for total marketable yield ($P = 0.8729$), the treatment means revealed a clear trend: organic fertilizer consistently outperformed conventional fertilizer across all biochar rates, with further increases at the higher biochar levels. For example, the 20 tons/acre treatment yielded 2335.0 boxes/acre under organic fertilizer compared with 1662.3 boxes/acre under conventional fertilizer. These numerical yield differences, while not statistically significant, translated into higher additional income, which explains the greater profitability reflected in the BCRs. This finding highlights the importance of integrating agronomic and economic evaluations—particularly when cumulative or indirect benefits (e.g., improved fruit quality, reduced defect rates) may not be captured through yield significance alone.

The lower BCRs at 5 and 10 tons/acre for conventional treatments underscore the need for careful cost-benefit consideration when integrating biochar into fertilizer programs. The inconsistency in profitability across treatments suggests that biochar's economic viability depends not only on application rate but also on fertilizer source and input costs. Although conventional treatments combined with biochar show a numerical trend toward improved profitability, further research is needed to evaluate whether even higher biochar rates—or alternative application methods—could enhance economic returns in conventional systems. Investigating biochar's effects on nutrient cycling and retention in these systems may help identify the profitability threshold. As biochar adoption expands in the United States, compliance with USDA Code 336 (USDA 2022d)—which outlines biochar management and application guidelines—will be essential for ensuring its sustainable and effective use. To maximize the economic feasibility of biochar, farmers should consider not only the cost of biochar and its application but also nutrient management strategies. Site-specific assessments of local environmental conditions and long-term production goals are critical to identifying the most profitable and sustainable biochar application strategies.

Conclusions

This 2-year study demonstrated that fertilizer source and seasonal weather conditions had the strongest influence on tomato growth, yield, and overall crop performance. Poultry litter consistently outperformed conventional fertilizer, resulting in taller plants, greater stem diameter, and a 39% increase in total marketable yield. The lower plant mortality and better fruit quality observed under organic treatments further highlight the agronomic advantages of poultry litter in plasticulture tomato systems. While biochar application did not significantly affect growth or yield, it reduced the incidence of zippering at higher rates. These outcomes suggest that biochar may play a role in fruit quality improvement even when direct yield effects are not observed. Economically, biochar combined with poultry litter at 15 to 20 tons/acre yielded the highest cumulative BCRs, exceeding 2.0 and demonstrating strong profitability. In contrast, biochar treatments under conventional fertilizer remained below the profitability threshold, although the highest rate (20 tons/acre) showed a positive trend. These results emphasize that economic viability depends on both the amendment rate and the fertilizer source. Overall, poultry litter proved to be a valuable fertilizer for tomato production, and biochar showed potential for enhancing quality and profitability when used in combination with alternative inputs. Future studies should focus on evaluating the long-term effects of biochar, determining profitability thresholds in conventional systems, and assessing performance across diverse soil types and environmental conditions.

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