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EDITED BY

Krishan K. Verma,
Guangxi Academy of Agricultural
Sciences, China

REVIEWED BY

Zina Flagella,
University of Foggia, Italy
Marcelo Pimentel,
Federal University of Western Pará, Brazil

*CORRESPONDENCE

Benpeng Yang
✉ yangbenpeng@itbb.org.cn

[†]These authors have contributed equally
to this work

RECEIVED 25 December 2025

REVISED 15 May 2026

ACCEPTED 05 June 2026

PUBLISHED 17 June 2026

CITATION

Wu Y, Mehdi F, Chen Y, Zhang S, Jiang S,
Cao Z, Gan Y, Zan L and Yang B (2026)
Carbon sequestration efficiency of
sugarcane across developmental stages.
Front. Sustain. Food Syst. 10:1775208.
doi: 10.3389/fsufs.2026.1775208

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Carbon sequestration efficiency of sugarcane across developmental stages

Yuanli Wu^{1,2†}, Faisal Mehdi^{1,2,3†}, Yimeng Chen^{1,2†},
Shuzhen Zhang^{1,2}, Shuting Jiang^{1,2}, Zhengying Cao^{1,2},
Yimei Gan^{1,2}, Limei Zan^{1,2} and Benpeng Yang^{1,2*}

¹Sanya Research Institute, Chinese Academy of Tropical Agricultural Sciences, Sanya, China, ²National Key Laboratory for Tropical Crop Breeding, Institute of Tropical Bioscience and Biotechnology, Chinese Academy of Tropical Agricultural Sciences, Haikou, China, ³The Key Laboratory of Plant Resources Conservation and Germplasm Innovation in Mountainous Region (Ministry of Education), Institute of Agro-Bioengineering/College of Life Sciences, Guizhou University, Guiyang, China

Global warming, driven by greenhouse gas emissions, requires innovative climate change mitigation strategies. Sugarcane (*Saccharum officinarum* L.), a highly efficient C4 plant with substantial biomass yield and carbon fixation abilities, offers a promising solution. This study investigates the distribution patterns and accumulation dynamics of biomass and carbon storage in sugarcane to inform breeding programs focused on developing high-biomass, carbon-sequestering varieties. Thirteen local sugarcane varieties were systematically analyzed for biomass and carbon storage across different plant tissues and growth stages, with the objective of contributing to net-zero carbon targets. The study revealed consistent trends in biomass (B) accumulation and carbon (C) storage across different sugarcane varieties. Notably, varieties such as ZT1 (B: 90.94; C: 45.32), ZT2 (B: 89.83; C: 43.74), ZT3 (B: 81.88; C: 40.65), GNY146210 (B: 89.83; C: 43.74), and YZ08-1609 (B: 90.94; C: 45.32) demonstrated superior performance in both parameters across all growth stages. In contrast, varieties such as GT44 (B: 75.16; C: 34.61) and ZT6 (B: 63.32; C: 32.20) exhibited comparatively lower levels of biomass and carbon storage. These findings highlight significant varietal differences in carbon sequestration potential, with certain genotypes offering promising advantages for ecological engineering and climate-smart agriculture. Further analysis elucidated distinct distribution patterns across sugarcane parts, with the stem predominating in biomass and carbon storage, thereby emphasizing its pivotal role in overall carbon sequestration among the varieties. Moreover, the study uncovered consistent accumulation patterns across growth stages, identifying the elongation stage as pivotal for maximal biomass and carbon sequestration. Particularly, high annual net carbon fixation capacity during leaf growth was observed across all varieties, with certain cultivars such as ZT1, ZT2, ZT3, ZT4 and GNY146210, and exhibiting notably superior performance. Annual assessments showed substantial variability in biomass, carbon storage, and photosynthetic net carbon fixation, with certain cultivars excelling. Strong positive correlations between biomass, carbon storage, and net carbon fixation were observed, emphasizing the intrinsic link between sugarcane biomass and its carbon fixation capacity ($R = 0.99$). These findings highlight the exceptional capacity of sugarcane, as a C4 plant, to excel in carbon absorption. In brief, these findings offer essential guidance for advancing breeding programs focused on developing high-performance sugarcane cultivars. Enhancing biomass production and carbon sequestration capabilities through these initiatives will markedly strengthen strategies for mitigating climate change.

KEYWORDS

biomass, breeding programs, carbon fixation, carbon sequestration, global warming, sugarcane

1 Introduction

Global warming, driven by excessive emissions of methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O), is a critical ecological challenge [United States Environmental Protection Agency (EPA), 2026]. Carbon dioxide (CO₂) is a major greenhouse gas that plays a significant role in global warming, making carbon capture and storage (CCS) crucial strategies to reduce its impact. Increasing greenhouse gas's emission (GHG) exacerbate the greenhouse effect, raising surface temperatures and causing adverse environmental impacts like rising sea levels, extreme weather, and biodiversity loss (Mey and Gore, 2021; Kumar et al., 2023). Urgent global action is essential to reduce emissions and combat global warming (Intergovernmental Panel on Climate Change (IPCC), 2024). In response to the threat of greenhouse gas emissions, global and regional efforts have intensified, adopting carbon reduction targets and promoting clean energy. Initiatives like the “Global Methane Commitment” and the Paris Agreement aim to significantly reduce emissions and limit global temperature rise (Zhou and Chen, 2022; Zhang et al., 2023). The European Union and the UK have set ambitious goals for emission cuts and carbon neutrality, high-lighting the need for coordinated actions towards a sustainable, low-carbon future. Advancing green and low-carbon agricultural practices is crucial for achieving dual carbon goals (Cao et al., 2023), as agricultural activities and forest (Qu et al., 2024), significantly contribute to greenhouse gas emissions. In China, each person emits around 10 metric tons of CO₂ per year on average. In contrast, the average CO₂ emission per person in the United States is about 14.4 metric tons annually, making the U.S. the top global CO₂ emitter (Statista, 2024). Agricultural emissions account for about 20% of global greenhouse gas emissions (Shao, 2024). Despite mitigation efforts, these emissions persist, necessitating innovative and sustainable reduction approaches. Achieving these goals also requires enhanced carbon sequestration, with biological sequestration through plant photosynthesis being a promising method (Nayak et al., 2022). Farmland ecosystems play a key role in carbon storage, contributing to over 10% of global terrestrial carbon storage (Weiskopf et al., 2024) and crops within these ecosystems are vital for carbon sequestration via photosynthesis (Golub et al., 2009).

The Kyoto Protocol's implementation in 1992 spurred global climate action, prompting nations like China to address greenhouse gas emissions and introduce “carbon sinks” through ecological methods like afforestation and vegetation restoration (Qu et al., 2024). Agricultural carbon sinks, reliant on photosynthesis, play a vital role in reducing CO₂ levels by storing it in plants, soil, and agricultural waste. Research on farmland ecosystems' carbon sinks, once focused nationally, now extends provincially, showing increasing trends in carbon sequestration across Chinese regions (Zhou et al., 2024). Ecosystems, vital for terrestrial carbon sequestration, offer flexible methods for enhancing carbon sinks through crop selection and improved farming practices (Cui et al., 2022). Recent studies underscore the importance of understanding carbon sink dynamics for ecosystem preservation and regional

planning (Yu et al., 2024). Additionally, the discourse on energy production highlights the potential for mitigating atmospheric greenhouse gas emissions through large-scale plantations of bio-energy crops like sugarcane (Popp et al., 2014; de Oliveira Bordonal et al., 2018).

Sugarcane (*Saccharum officinarum* L.), characterized by its high-yield C4 photosynthetic pathway, exhibits exceptional efficiency in photosynthesis and carbon fixation, rendering it essential for achieving carbon neutrality. An estimated 3934.5 kg ha⁻¹ of sequestered carbon, equivalent to 14,439.6 kg ha⁻¹ of atmospheric CO₂, was found in sugarcane farms (Azizi et al., 2019). Recent studies have reported that carbon sequestration in leaves and stalks is significantly higher, reaching 1239.65 kg ha⁻¹ (Kumar et al., 2024). The amount of sequestered carbon varies depending on factors such as soil type, climate, and management practices. After harvest, the sugarcane residue, including leaves and stalks, typically remains in the field, contributing to soil organic carbon and enhancing carbon sequestration. China ranks third globally in sugarcane cultivation, with approximately 12.05 million hectares under cultivation (Li et al., 2024). The extensive fields, prolonged growth cycle, and dense foliage of sugarcane contribute significantly to global warming mitigation by facilitating CO₂ uptake. Moreover, the biodiversity within sugarcane ecosystems enhances environment stability and augments carbon fixation processes, thereby emphasizing its pivotal role in sustainable agricultural systems and mitigating the impacts of climate change.

Top sugarcane-producing countries, including Brazil, China, India, and Australia, are actively implementing programs to monitor and reduce their carbon footprints through sustainable practices and technologies. India's “Sustainable Sugarcane Initiative” aims to cut emissions by enhancing management and technology (Bhatt et al., 2023), while Brazil has committed to reducing GHG emissions in agriculture as part of its Nationally Determined Contributions (Soterroni et al., 2023). Due to its high photosynthetic efficiency, is more effective at capturing and storing carbon compared to many C3 crops like rice (Sage et al., 2013). This efficiency makes sugarcane a valuable crop for achieving carbon reduction goals and demonstrates its significant role in managing CO₂ emissions. Sugarcane's efficiency stems from substantial aboveground biomass, effective photosynthesis, and agricultural practices like fertilization and straw return. In contrast, rice's contribution is lower, with higher carbon fixation costs (Gangopadhyay et al., 2022). Recent studies highlight sugarcane's lower GHG emissions compared to beet sugar (Shukla et al., 2022), underscoring potential to mitigate emissions in the future. Understanding sugarcane's carbon sequestration is pivotal for addressing climate change, promoting agricultural sustainability, and advancing the sugarcane industry.

The predominant focus of research on carbon storage in agricultural ecosystems has been on large-scale integrated agricultural systems, with limited exploration into individual crop ecosystems. While domestic studies on sugarcane biomass and carbon storage exist, they may lack relevance due to changes in cultivation practices. Foreign literature primarily emphasizes soil research (Naresh et al., 2021), byproducts of sugarcane (Aguilar-Rivera and

Olvera-Vargas, 2022) and energy consumption in the sugarcane industry, overlooking direct investigations into biomass and carbon storage (Powar et al., 2024).

Current research on biomass and carbon storage presents several challenges; however, a deeper understanding of these aspects is essential for accurately estimating crop carbon sequestration and addressing the impacts of climate change. In the context of China's growing emphasis on farmland ecological engineering, such research is particularly valuable for guiding sustainable agricultural practices through enhanced carbon fixation. While previous studies have explored crop biomass and carbon storage to some extent, the specific relationship between sugarcane biomass and carbon fixation across different plant organs and phenological stages remains largely unexamined.

This study aims to address this gap by evaluating various sugarcane varieties to assess their biomass production, carbon storage potential, and the distribution of carbon among different plant organs. Particular attention is given to their photosynthetic carbon fixation capacities throughout developmental stages. Given sugarcane's high biomass yield and efficient C4 photosynthetic pathway, it holds considerable promise for atmospheric carbon sequestration.

We hypothesize that different sugarcane varieties possess distinct capabilities for biomass accumulation and carbon storage, depending on organ type and growth stage. By analyzing these varietal differences, the study seeks to characterize cultivars with enhanced carbon fixation efficiency and targeted organ-specific carbon allocation. These findings will not only contribute to ecological engineering efforts but also support broader strategies aimed at mitigating greenhouse gas emissions and achieving long-term carbon neutrality in agriculture.

The research gap in current studies is that most focus on biomass and carbon storage at a broader level, with limited exploration into the genetic variability among different sugarcane cultivars for their sequestration potential. Despite the acknowledged importance of sugarcane's role in carbon fixation, little is known about how genetic differences influence traits like photosynthetic efficiency, biomass accumulation, and carbon partitioning across different plant organs and growth stages. Addressing this gap is essential for developing improved cultivars and management practices aimed at maximizing carbon sequestration.

2 Materials and methods

2.1 Experimental site overview and climatic conditions

The year-long field experiment (February 2023–February 2024) was conducted at Lingao Experimental Base in Hainan Province, China, experiencing a tropical monsoon marine climate with no frost. Temperatures range from 16.9 °C (Jan) to 28.3 °C (July), with monthly averages typically between 17 and 18 °C, except for February and December. The daily average temperature exceeds 10 °C, accumulating to 8,562 °C annually. Wind speed is level 3, reaching 3–4 in winter and 2–3 in summer, with varying directions. Lingao County receives abundant rainfall, averaging 1,100–1800 mm annually.

2.2 Experimental site setting

Thirteen sugarcane varieties, including ZT1, ZT2, ZT3, ZT4, ZT5, ZT6, ZF1, GT44, GT49, GT55, GT58, YZ08-1609, and GNY146210, were selected for this study. The experimental site, located at the Hainan Sugarcane Experimental Base of the Institute of Tropical Biotechnology, Chinese Academy of Tropical Agricultural Sciences in Wenxian Village, Huangtong Town, Lingao County, Hainan Province, was chosen for the 2023–2024 sugar cane growing season. Before planting, the leaf tips were crushed and incorporated into the soil. The field was then plowed to a depth of 50 cm and leveled. A planter was used to place the bud segment stems into 40 cm deep planting trenches. The stems were covered with 5–8 cm of soil, drip irrigation tape was laid, and the area was covered with mulch. In January 2023, 39 plots with 5 rows per plot, each measuring 10 m × 10 m, were established at the research site to ensure uniform site conditions and density. Each variety was replicated three times, with plots spaced 1 m apart and row spacing of 1.4 m. Total area of 56 m². The planting density was maintained at 1881 double-bud seed stems per 667m². Each plot contained 316 planted buds. The experimental site consisted of clay-red soil with a pH of 4.6, containing an average organic matter content of 6.5 g kg⁻¹, available nitrogen of 101.3 mg kg⁻¹, available phosphorus of 18.5 mg kg⁻¹, and available potassium of 126.8 mg kg⁻¹. Fertilization was applied at the following rates: nitrogen fertilizer (urea) at 300 kg ha⁻¹, phosphorus fertilizer (P₂O₅) at 144 kg ha⁻¹, and potassium fertilizer (K₂O) at 216 kg ha⁻¹. Drip fertigation was carried out in five split applications throughout the crop growth period. Specifically, 10% of the total fertilizer amount was applied after completion of 80% seedling establishment, 15% during the tillering stage upon reaching 50% tiller development, and the remaining 75% was applied in three equal split doses during the elongation stage. Planting plots for each variety were assigned randomly, and the number of cane sprouts per plot was kept consistent. Field management practices were uniformly applied throughout the experiment.

2.3 Sample collection and determination

Sampling was collected across different growth stages: seedling (February–April), tillering (May–July), elongation (August–October), and maturity (November–January of the subsequent year). Fifteen representative samples of each sugarcane variety were obtained from each plot using the five-point sampling method. During collection, plants were extracted with intact root systems employing the full digging method. Sites with specific slope gradients were selected to facilitate proper sampling. Soil was excavated gradually from the base of the sugarcane stem outward and inward, minimizing root damage to preserve data accuracy. At the elongation stage, yellowing leaves and litter were gathered, with no organ distinction, and pooled for biomass and carbon analysis, ensuring a comprehensive assessment of growth dynamics and carbon sequestration potential.

2.4 Biomass estimation

After removing the soil from the roots, the samples were quickly brought to the lab and the roots were washed with tap water. Subsequently, the washed whole plant samples were segmented into leaves, sheaths, roots, and cane stems based on organ classification. These segments were then subjected to fixation at 105 °C for 30 min

and subsequently dried at 60 °C until reaching a constant weight (Jones and Case, 1990). The dry weight of each segment was measured, expressing biomass in terms of dry weight to facilitate the calculation of total sugarcane biomass. Total plant dry matter accumulation encompassed the cumulative dry weights of leaves, sheaths, roots, litter, and cane stems. The cane stem processing involved drying bagasse and cane juice obtained from cane stem squeezing at 60 °C until reaching a constant weight, with the dry weight of the cane stem being the summation of bagasse and cane juice dry weights.

The sum of the biomass of each organ is the total biomass. The annual total biomass of the experimental site can be calculated from the sample biomass. The total biomass of sugarcane samples is the sum of the biomass of each component of sugarcane. The calculation formula is as follows:

$$W_{\text{total}} = \sum_{i=1}^n W_i \quad (1)$$

In the formula, W_{total} represents the total biomass (g) of the sugarcane sample, while W_i represents the biomass of each sugarcane organ. Here, $n = 5$, corresponding to the five sugarcane components: roots, stalks, leaves, leaf sheaths, and litter. The value of i ranges from 1 to 5, representing these organs, respectively. The annual total biomass of sugarcane (t hm^{-2}) was subsequently calculated based on the planting density.

2.5 Carbon content estimation

The dried sample was ground into powder and passed through a 60-gauge sieve (0.25 mm). The carbon content of the sample was determined using the potassium dichromate-sulfuric acid oxidation colorimetric method. The principle is that under heating conditions, excess potassium dichromate-sulfuric acid solution oxidizes the organic carbon in the sample to carbon dioxide. Hexavalent chromium ions (Cr^{6+}) in potassium dichromate are reduced to trivalent chromium ions (Cr^{3+}), the content of which is directly proportional to the organic carbon content in the sample. The absorbance was measured at a wavelength of 585 nm, and the organic carbon content was calculated based on the content of trivalent chromium ions (Cr^{3+}).

The leaves, leaf sheaths, stalks, litter, and roots of sugarcane were cleaned and cut into small sections. The samples were dried in an oven at 60 °C until a constant weight was achieved. The dry matter weight of each component was recorded, with the stalk dry weight calculated as the sum of the dry weights of bagasse and juice. The dried samples were then ground into powder, and the carbon content was determined using the potassium dichromate-sulfuric acid oxidation colorimetric method. The carbon content of the stalk was calculated as the sum of the carbon contents of bagasse and juice. Subsequently, the total carbon storage of the sugarcane plant dry matter was calculated using the following formula:

$$W_{\text{total}} = \sum_i C_i = \sum_i G_i t_i \quad (2)$$

In the formula, C_{total} represents the total carbon storage of the sugarcane sample (g); i represents the i -th organ of sugarcane; C_i

represents the carbon sequestration of the i -th organ (g); G_i represents the dry weight of the i -th organ (g); and t_i represents the carbon content of the i -th organ (%).

2.6 Photosynthetic net carbon fixation estimation

Photosynthesis is crucial for plants to absorb CO_2 , storing part of it as carbon fixation while the rest returns to the atmosphere through leaf and root respiration. To prevent double counting of CO_2 released by root respiration, the net photosynthetic rate of sugarcane plants in each plot was monitored monthly for one year (February 2023–January 2024) using the LI-6800 portable photosynthesis measurement system (Beijing Ligaotai Technology Co., Ltd). The study conducted measurements of the net photosynthetic rate (P_n) of sugarcane leaves monthly during sunny and windless or lightly windy days. To minimize the impact of external environmental factors, a red and blue light leaf chamber sized 1 cm × 3 cm was utilized. CO_2 concentration in the environment at the time of measurement was maintained to replicate field conditions, with a gas flow rate set to 500 $\mu\text{mol} \cdot \text{s}^{-1}$. Measurements were taken daily from 8:00 to 18:00 using the LI-6800 portable photosynthesis measurement system. Fresh, healthy, and unobstructed leaves were selected for clamping in the leaf chamber, aiming to avoid veins to prevent data distortion. Data was recorded once the display value stabilized, with each measurement followed by replacing the leaf and repeating the process to ensure accuracy (Figures 1A,B).

2.7 Total leaf area estimation

To estimate the total leaf area of sugarcane, three representative leaves were selected from the upper portion of each plant. A 1 cm × 3 cm fresh leaf segment was collected from the middle section of each leaf and weighed. The total leaf area of the sugarcane plant was subsequently estimated based on the fresh leaf weight using the following formula:

$$LA = \frac{W_t}{W_0} \times \frac{3}{1000} \quad (3)$$

In the formula, LA represents the total leaf area of the entire sugarcane plant (m^2); W_0 represents the fresh weight of a leaf segment with an area of 1 cm × 3 cm (g); W_t represents the total fresh weight of the sugarcane sample leaves (g); 3 represents the area of the sampled leaf segment (3 cm^2); and 10,000 represents the conversion factor, where 1 m^2 equals 10,000 cm^2 . The calculation of photosynthetic carbon fixation in sugarcane was based on the results of diurnal variation measurements of the net photosynthetic rate. The daily net assimilation per unit leaf area of sugarcane was determined as the area enclosed between the portion of the diurnal photosynthetic rate curve above zero and the X-axis (Liu Jiajun et al., 2011; Wang et al., 2007; Zhang et al., 2013). The formula is as follows:

$$P = \sum_{i=1}^i \left(\frac{P_i + 1 + P_i}{2} (t_{i+1} - t_i) \times \frac{3600}{1000} \right) \quad (4)$$

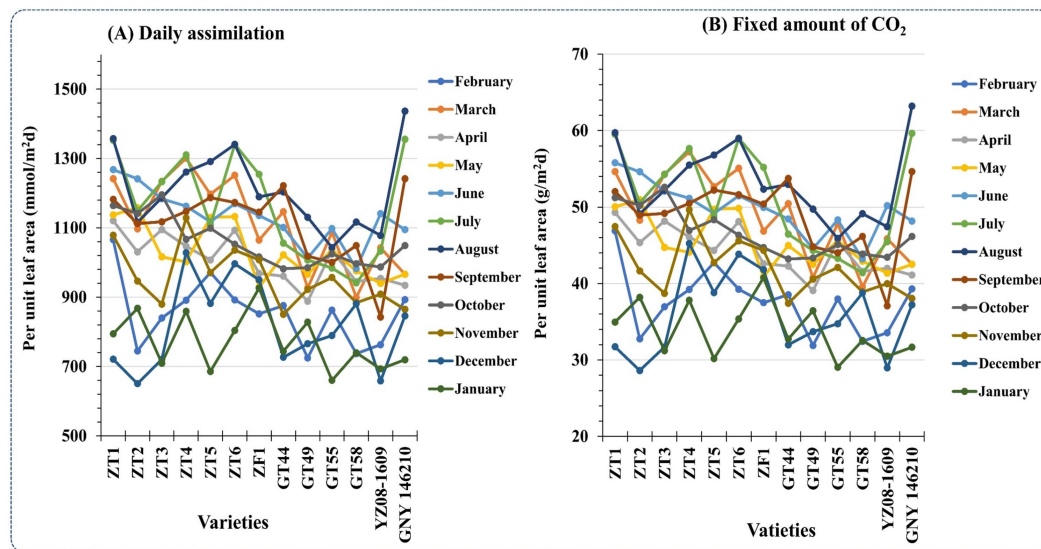


FIGURE 1

This graph illustrates (A) the daily assimilation rate per unit leaf area ($\text{mmol}/\text{m}^2/\text{day}$) and (B) the fixed amount of CO_2 per unit leaf area ($\text{g}/\text{m}^2/\text{day}$) across all growth stages of various sugarcane varieties. The growth stages are categorized as follows: seedling (February 2023–April 2023), tillering (May 2023–July 2023), elongation (August 2023–October 2023), and maturity (November 2023–January 2024).

In the formula, P represents the net assimilation per unit leaf area on the day of measurement ($\text{mmol}/\text{m}^2/\text{d}^{-1}$); P_i represents the instantaneous photosynthetic rate at the initial measurement point ($\mu\text{mol}/\text{m}^2/\text{s}^{-1}$); P_{i+1} represents the instantaneous photosynthetic rate at the subsequent measurement point ($\mu\text{mol}/\text{m}^2/\text{s}^{-1}$); t_i represents the initial measurement time (h); t_{i+1} represents the subsequent measurement time (h); and j represents the total number of measurements. The constant 3,600 represents the number of seconds in 1 h, while 1,000 represents the conversion factor from μmol to mmol .

The formula used to convert the total assimilation on the measurement day into the daily amount of fixed CO_2 was adopted from Wang et al. (2007):

$$\omega_{\text{CO}_2} = P \times \frac{44}{1000} \quad (5)$$

In the formula, ω_{CO_2} represents the mass of CO_2 fixed per unit leaf area ($\text{g}/\text{m}^2/\text{d}^{-1}$); 44 represents the molar mass of CO_2 (g/mol^{-1}); and 1,000 is the conversion factor from mmol to mol .

The daily net carbon sequestration of sugarcane was calculated using the following equation (Shi et al., 2011):

$$W_{\text{CO}_2} = \omega_{\text{CO}_2} \times LA \quad (6)$$

In the formula, W_{CO_2} represents the daily net carbon sequestration of sugarcane (g/d^{-1}), and LA represents the total leaf area of sugarcane (m^2). The annual photosynthetic carbon fixation (Q_{CO_2}) of sugarcane was estimated according to the growth characteristics of sugarcane. The daily carbon fixation values at each growth stage were multiplied by the corresponding duration of that stage to determine the photosynthetic carbon fixation during the seedling, tillering, elongation, and maturity stages. The cumulative sum of all growth stages was subsequently used to estimate the annual photosynthetic carbon fixation of sugarcane (Xiaohong et al., 2017).

2.8 Yield determination

As sugar cane varieties exhibit varying maturation periods, sequential harvesting is conducted according to their respective maturity stages. Within each plot, a 5 m^2 area is designated for harvesting to serve as a yield measurement plot. Following harvest, biomass quantification is carried out utilizing the biomass estimation method (see biomass estimation method). Subsequently, the harvested biomass undergoes oven drying at 105°C for a duration of 2 h, followed by further drying at 60°C until a constant weight is achieved. These procedures facilitate the determination of total plant biomass and carbon storage within each plot.

2.9 Soil organic carbon estimation

Soil organic carbon was determined using the potassium dichromate oxidation spectrophotometric method. Soil samples were collected at a depth of 40 cm during each growing period. The samples were placed in clean white porcelain trays and spread into a thin layer, approximately 2–3 cm thick. First, plants, insects, stones, and other debris were removed. The soil clods were then crushed with a wooden hammer and air-dried, with the soil being turned several times a day during the drying process. Once the soil was fully air-dried, it was mixed using the quarter method. Two portions were taken: one was retained, and the other was passed through a 2 mm soil screen for dry matter content determination. A 10–20 g sample was then extracted from the screened soil, finely ground, passed through a 60 mesh (0.25 mm) soil screen, and placed into a brown-stoppered glass bottle for measurement.

2.9.1 Draw the calibration curve

Measured 0.00, 0.50, 1.00, 2.00, 4.00, and 6.00 mL of glucose standard solution into 100 mL stopper digestion glass tubes. The

corresponding organic carbon masses were 0.00, 2.00, 4.00, 8.00, 16.00, and 24.00 mg, respectively. Added 0.1 g of mercury sulfate and 5.00 mL of potassium dichromate solution to each tube and shook them thoroughly. Subsequently, 7.5 mL of sulfuric acid was added slowly, and the tubes were shaken gently.

Turned on the thermostatic heater and set the temperature to 135 °C. When the temperature rose to close to 100 °C, you unplugged the glass tube with the stopper and placed it into the heating hole of the thermostatic heater. Started timing when the instrument temperature displayed 135 °C and heated it for 30 min. Then, turned off the thermostatic heater switch, took the stopper digestion glass tube to a water bath, and cooled it to room temperature. Slowly added about 50 mL of water to each stopper dissolving glass tube and continued to cool them to room temperature. Filled them with water to 100 mL for marking, added the plugs, and shook them well. At the wavelength of 585 nm, measured the absorbance separately with a 10 mm colorimetric dish and used water as the reference.

2.9.2 Statistical analysis

Data collection, calculation, and basic visualization tasks were conducted using Microsoft Excel 2019. Tukey's test for multiple comparisons to determine the significance of differences between treatments (at an alpha level of 0.05) and correlation coefficient regression analysis were performed using R software version 4.4.1. The bar graphs and heat map were generated using the online software BioRender.¹ The stack bar plot using the bioinformatic online tool.²

3 Results

3.1 Seedling stage

3.1.1 Leaf biomass and carbon storage of various sugarcane varieties

Significant variation in leaf biomass and carbon storage was observed among sugarcane varieties at the seedling stage. ZT1 showed the highest values (0.58 g biomass, 0.244 g carbon), while ZT6, ZF1, and GT44 had significantly lower levels. No notable differences were found among other varieties. Overall, higher leaf biomass consistently correlated with greater carbon storage across varieties (Figure 2A).

3.1.2 Sheath biomass and carbon storage of various sugarcane varieties

Significance analysis showed that varieties ZT1 (0.958 g biomass, 0.939 g carbon) and GNY146210 (0.93 g biomass, 0.42 g carbon) had significantly higher leaf sheath biomass and carbon storage. In contrast, ZT4, GT55, and another GT55 entry exhibited significantly

lower values. No significant differences were found among varieties like ZT2, ZT3, and GT59 for biomass, or ZT2, ZT5, ZT6, ZF1, GT44, and GT49 for carbon storage. Overall, higher leaf sheath biomass consistently correlated with increased carbon storage at the seedling stage (Figure 2A).

3.1.3 Root biomass and carbon storage of various sugarcane varieties

Maximum root biomass and carbon storage were recorded in ZT1 (0.930 g biomass, 0.411 g carbon) and GNY146210 (0.956 g biomass, 0.405 g carbon). Other varieties ranged from 0.548 to 0.849 g in biomass and 0.242 to 0.338 g in carbon storage. Overall, higher root biomass consistently correlated with increased carbon storage at the seedling stage across sugarcane varieties (Figure 2A).

3.1.4 Tillering stage

3.1.4.1 Leaf biomass and carbon storage of various sugarcane varieties

In leaf, the significance analysis indicated that ZT1, GYN146210, and ZT2 had significantly greater biomass and carbon storage compared to other varieties. Conversely, ZT6 exhibited significantly lower values. Notable differences were observed among the varieties (Figure 2B).

3.1.4.2 Sheath biomass and carbon storage of various sugarcane varieties

In the case of leaf sheath, the recorded biomass values were as follows: ZT1 (25.6 g), GNY 146210 (24.9 g), ZT3 (24.4 g), and ZT2 (23.4 g). For carbon storage, the values were: GNY 146210 (9.6 g), ZT1 (9.4 g), GT44 (9.0 g), and ZT4 (9.0 g). Conversely, both biomass and carbon storage for ZT6 were notably lower (Figure 2B).

3.1.4.3 Root biomass and carbon storage of various sugarcane varieties

The significance analysis showed that ZT1 and GYN146210 had significantly higher biomass and carbon storage than other varieties. In contrast, ZT6 had significantly lower biomass and carbon storage. Minimal root biomass and carbon storage were observed during the tillering period (Figure 2B).

3.1.5 Elongation stage

3.1.5.1 Leaf biomass and carbon storage of various sugarcane varieties

At the elongation stage, the data indicated that the variety ZT1 consistently exhibited the highest biomass value of 324.6 g and carbon storage of 152.7 g in the leaf. This trend was also observed in the leaf sheath and root carbon storage of the sugarcane. In contrast,

¹ <https://app.biorender.com/signin>

² <https://www.bioinformatics.com.cn/en?p=2>

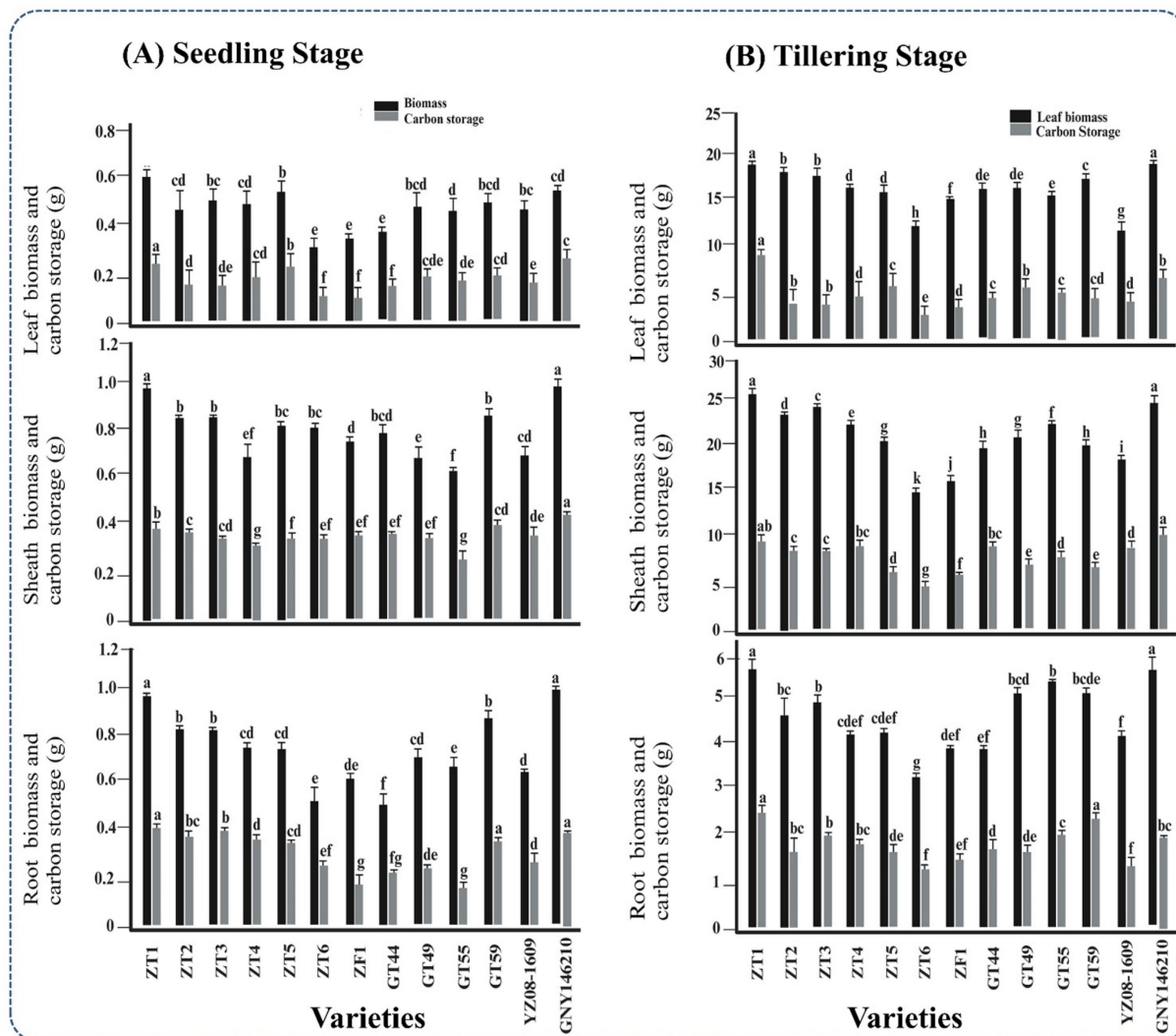


FIGURE 2

This graph represents the biomass and carbon storage of various tissues (root, sheath and leaf) at (A) seedling stage, (B) tillering stage. Different lowercase letters within the same series denote significant differences among sugarcane varieties ($p < 0.05$). Data are expressed as mean $\pm$ SE.

ZT6 demonstrated significantly lower biomass and carbon storage in both the leaf and roots (Figure 3A).

3.1.5.2 Sheath biomass and carbon storage of various sugarcane varieties

There was considerable variability in leaf sheath biomass and carbon storage. Further analysis indicated that ZT1 and GNY146210 had significantly higher levels of both biomass and carbon storage compared to the other varieties, whereas ZT6 had substantially lower values (Figure 3A).

3.1.5.3 Root biomass and carbon storage of various sugarcane varieties

There was significant variability in root biomass, as well as in carbon storage. The data revealed that ZT1 and GNY146210 had markedly

superior biomass and carbon storage compared to other varieties. Conversely, ZT6 and YZ08-1609 had lower levels of both metrics. Additionally, root biomass and carbon storage were notably lower than those in other plant parts, such as leaves and sheaths (Figure 3A).

3.1.6 Maturity stage

3.1.6.1 Leaf biomass and carbon storage of various sugarcane varieties

At maturity, the highest biomass was observed in ZT1 (426.3 g) and GNY146210 (424.3 g), with ZT1 also showing the greatest carbon storage (217.2 g), followed by ZT3 (206 g). In contrast, ZT6 recorded lower biomass (243.1 g), and varieties GT44 and GT49 exhibited reduced carbon storage. Overall, biomass and carbon storage increased progressively from seedling to maturity across all varieties, reflecting their individual storage capacities (Figure 3B).

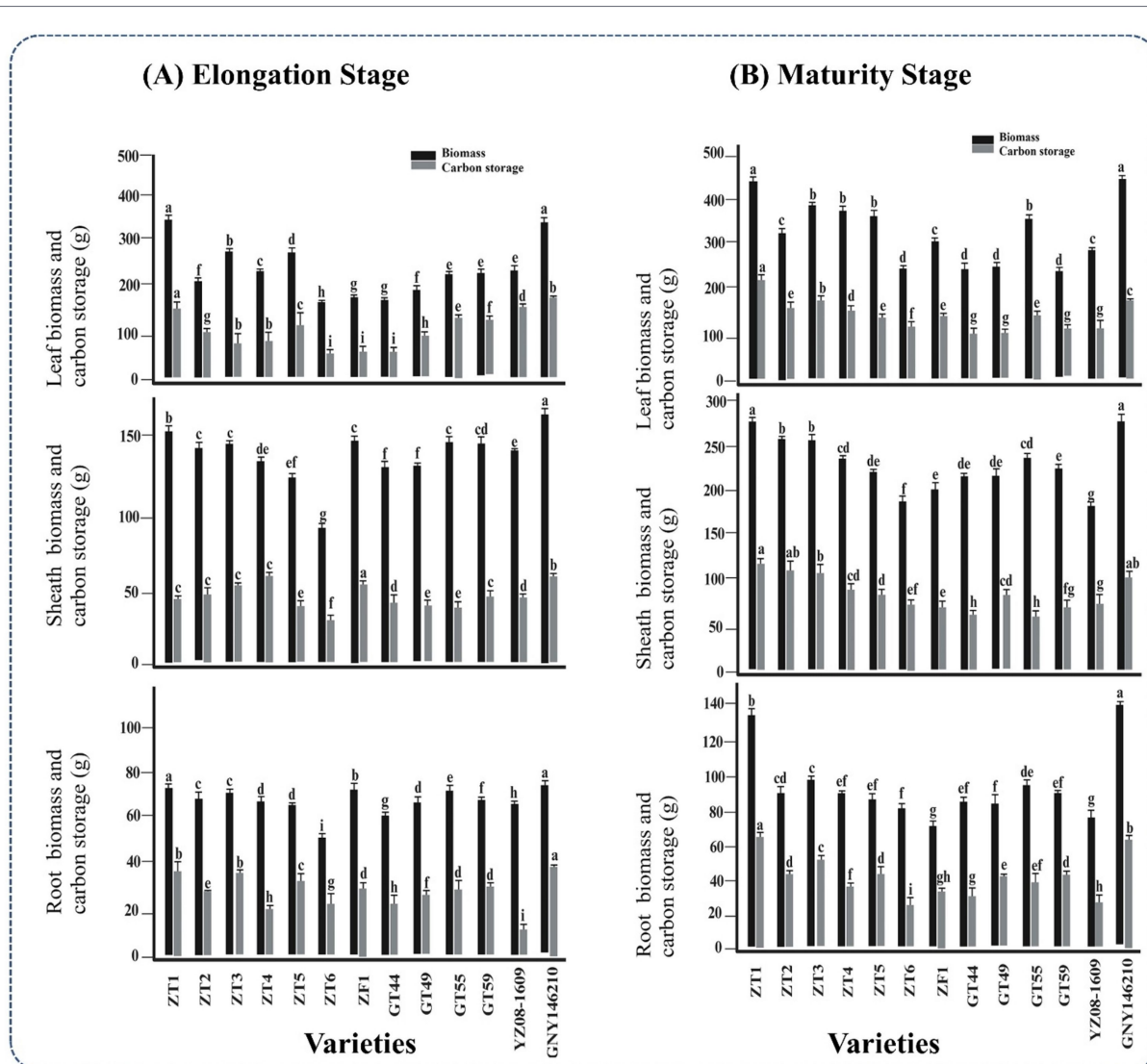


FIGURE 3

This graph represents the biomass and carbon storage of various tissues (root, sheath and leaf) at (A) Elongation stage, (B) Maturity Stage. Different lowercase letters within the same series denote significant differences among sugarcane varieties ($p < 0.05$). Data are expressed as mean $\pm$ SE.

3.1.6.2 Sheath biomass and carbon storage of various sugarcane varieties

Significant variability was observed in sheath biomass among the different sugarcane varieties, ranging from 168.533 g (YZ08-1609) to 279.500 g (ZT1). Similarly, notable differences were noted in carbon storage, spanning from 65.207 g (GT55) to 121.195 g (ZT1). Statistical analysis indicated that ZT1 and GNY146210 exhibited significantly higher sheath biomass and carbon storage compared to other varieties. In contrast, YZ08-1609 (168.5 g) and ZT6 (193.2 g) showed relatively lower biomass, while GT44 (67.4 g) and GT55 (65.2 g) displayed diminished carbon storage compared to the other varieties (Figure 3B).

3.1.6.3 Root biomass and carbon storage of various sugarcane varieties

Significant variations were observed in root biomass, ranging from 66.576 g (ZF1) to 141.9 g (GNY 146210), across the diverse

sugarcane varieties. Similarly, notable disparities were noted in carbon storage, spanning from 24.190 g (ZT6) to 68.720 g (ZT1). Further statistical analysis highlighted that ZT1, GNY 146210, ZT2, and ZT3 exhibited notably higher root biomass and carbon storage levels, significantly exceeding other varieties. In contrast, ZT6, YZ08-1609, and ZT44 displayed relatively lower biomass and carbon storage compared to their counterparts (Figure 3B).

3.1.6.4 Stem biomass and carbon storage of various sugarcane varieties

The biomass of sugarcane stems exhibited substantial variability, demonstrating a wide range of values. Similarly, carbon storage showed significant variation across different varieties. Detailed analysis revealed that ZT1, ZT3, and GNY146210 possessed marked advantages in both biomass and carbon storage, significantly surpassing other varieties. In contrast, ZT6 and YZ08-1609 showed comparatively lower levels of biomass and carbon storage. Although no significant differences were detected among the remaining varieties, a consistent trend was observed (Figure 4A).

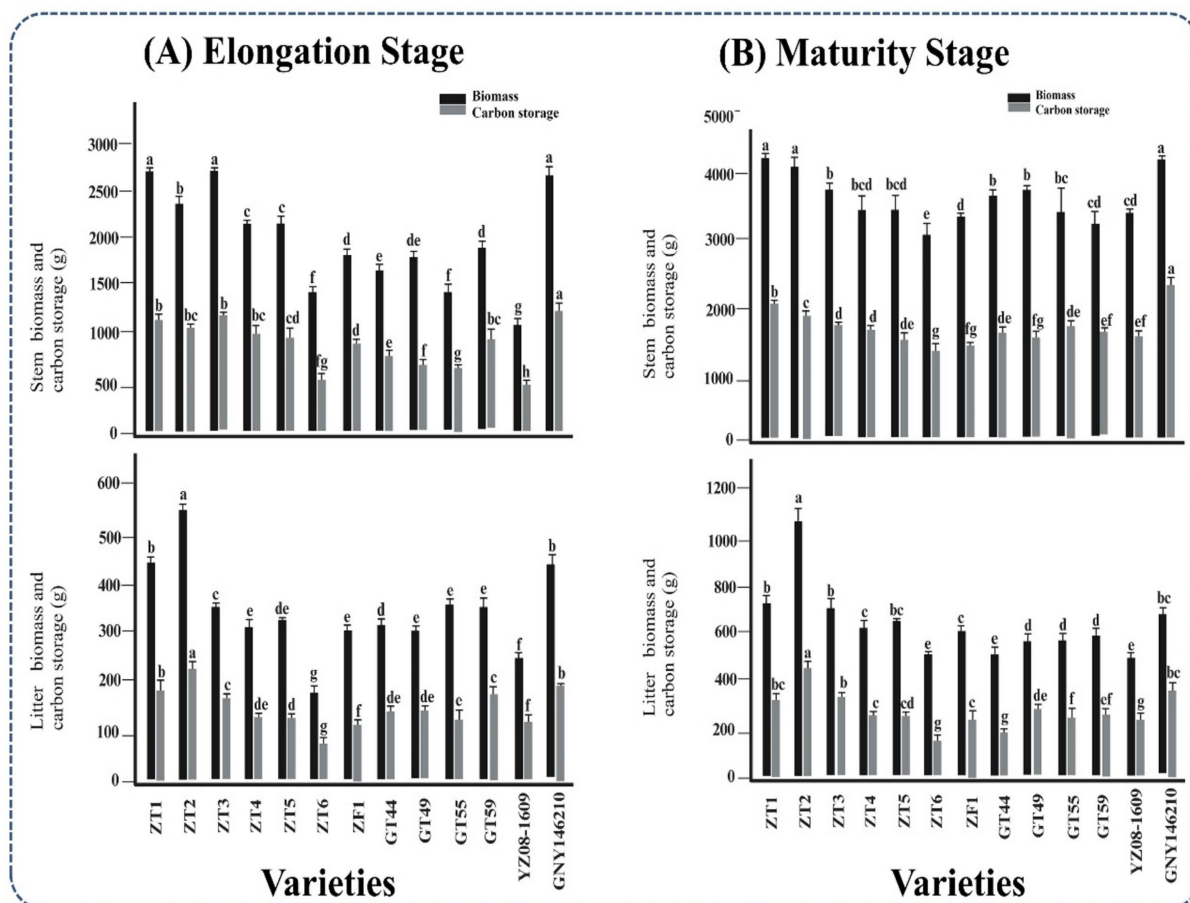


FIGURE 4

This graph represents the biomass and carbon storage of litter and stem at (A) Elongation stage, (B) Maturity stage. Different lowercase letters within the same series denote significant differences among sugarcane varieties ($p < 0.05$). Data are expressed as mean $\pm$ SE.

3.1.6.5 Litter biomass and carbon storage of various sugarcane varieties

The variety ZT2 displayed superior litter biomass and carbon storage, significantly exceeding other varieties. This advantage was attributed to ZT2's efficient defoliation capability. In contrast, ZT6 and YZ08-1609 exhibited comparatively lower litter biomass and carbon storage levels compared to their counterparts (Figure 4A).

3.1.6.6 Stem biomass and carbon storage of various sugarcane varieties

Considerable variability was observed in stem biomass among different sugarcane varieties, ranging from 2969.233 g to 4215.867 g. Similarly, significant differences were noted in carbon storage, spanning from 1594.190 g to 2355.131 g. Specifically, ZT1 (4,172 g) and GNY146210 (4,216 g) exhibited high stem biomass, with corresponding carbon storage values of 1,006 g and 1,013 g, respectively. In contrast, varieties GT49 (447 g) and ZT6 (2,969 g) showed lower biomass and carbon storage levels. ZT6 and YZ08-1609 also displayed relatively diminished biomass and carbon storage compared to other varieties. While no significant differences were detected in biomass and carbon storage among the

remaining varieties, a consistent trend emerged: higher stem biomass in sugarcane corresponded to increased carbon storage in the stems at maturity across various growth stages (Figure 4B).

3.1.6.7 Litter biomass and carbon storage of various sugarcane varieties

In litter biomass, which ranged from 502.233 to 1076.767 g, and carbon storage, spanning from 206.421 to 469.041 g, were observed across all varieties at the maturity stage. The maximum values for litter biomass and carbon storage were noted. Further significance analysis highlighted that ZT2 exhibited relatively high litter biomass (1,010 g) and carbon storage (440 g) compared to other varieties. Conversely, YZ08-1609 displayed relatively lower litter biomass (502 g) and carbon storage (206 g) compared to the remaining varieties. Although no significant discrepancies were discerned in biomass and carbon storage among the remaining varieties, a consistent pattern emerged (Figure 4B).

3.1.6.8 Stem and litter biomass and carbon storage of various sugarcane varieties

Significant variation was observed in stem and litter biomass and carbon storage across sugarcane varieties. At the elongation stage, ZT1, ZT3, and GNY146210 exhibited the highest stem biomass and

carbon storage, while ZT6 and YZ08-1609 showed the lowest (Figure 4A). ZT2 demonstrated superior litter biomass and carbon storage due to efficient defoliation, whereas ZT6 and YZ08-1609 had the lowest values. At maturity, stem biomass ranged from 2969.2 g to 4215.9 g and carbon storage from 1594.2 g to 2355.1 g. ZT1 (4,172 g, 1,006 g) and GNY146210 (4,216 g, 1,013 g) had the highest values, while GT49 and ZT6 had the lowest. Litter biomass ranged from 502.2 g to 1076.8 g, and carbon storage from 206.4 g to 469.0 g, with ZT2 again showing the highest values and YZ08-1609 the lowest (Figure 4B).

3.1.6.9 Biomass and carbon storage in bagasse and juice

At the maturity stage, the highest bagasse biomass was recorded in ZT2 (3,063 g), while maximum carbon storage in bagasse was observed in GNY146210 (1,342 g) (Figure 5A). GNY146210 also showed the highest juice biomass (1,175 g) and carbon storage (398 g) at the same stage. At the elongation stage, GNY146210 again exhibited the highest juice biomass (2089 g) and carbon storage (950 g) (Figure 5C). In juice, varieties ZT1, ZT3, GT44, and GT49 recorded maximum biomass and carbon storage during both elongation (Figure 5B) and maturity stages (Figure 5D). Overall, both biomass and carbon storage increased progressively toward maturity in all varieties.

3.1.6.10 Proportion of biomass ratio (%)

The data indicated that cultivar GNY146210 exhibited the highest leaf blade biomass at the seedling stage (BM-S) (33.7%), which increased to 46.3% at the tillering stage (BM-T), then declined sharply during the elongation (BM-E) and maturity stages (BM-M). In contrast, cultivars GT44 (47.2%) and ZT6 (46.2%) showed the highest leaf sheath biomass at the seedling stage (BM-S), with a general decline observed by the maturity stage (BM-M). For root biomass, ZT4 recorded the highest value (42.1%), followed by GT49 and GT58 (40.7% each). Litter biomass peaked in ZT2 during the elongation (BM-E) and maturity (BM-M) stages (17.8 and 18.1%, respectively). The highest stem biomass during the elongation stage (BM-E) was observed in ZT3 (75%), followed by ZT4 and ZT5 (74 and 74.4%, respectively). At the maturity stage (BM-M), GT44 (76.6%), YZ08-1609 (77.1%), and GT49 (76.1%) had the highest stem biomass, while GNY146210 recorded the lowest (32.6%) during elongation (BM-E). Biomass values in the remaining varieties did not differ significantly during the elongation (BM-E) and maturity (BM-M) stages (Figure 6).

3.1.6.11 Proportion of carbon storage ratio (%)

The present data illustrate carbon storage distribution in sugarcane plant organs across different growth stages. At the seedling

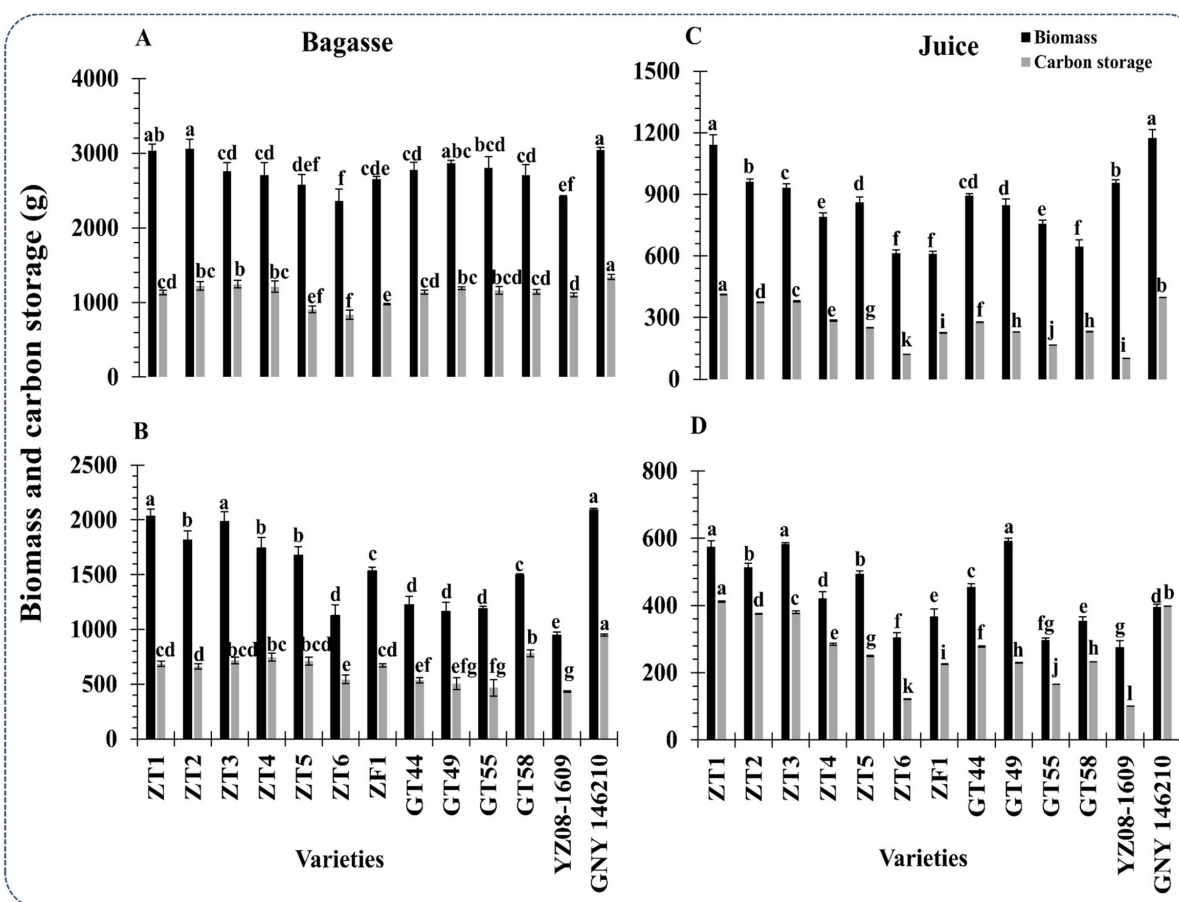


FIGURE 5

This graph represents of biomass and carbon storage in bagasse (A,C) maturity stage and (B,D) elongation stage of sugarcane.

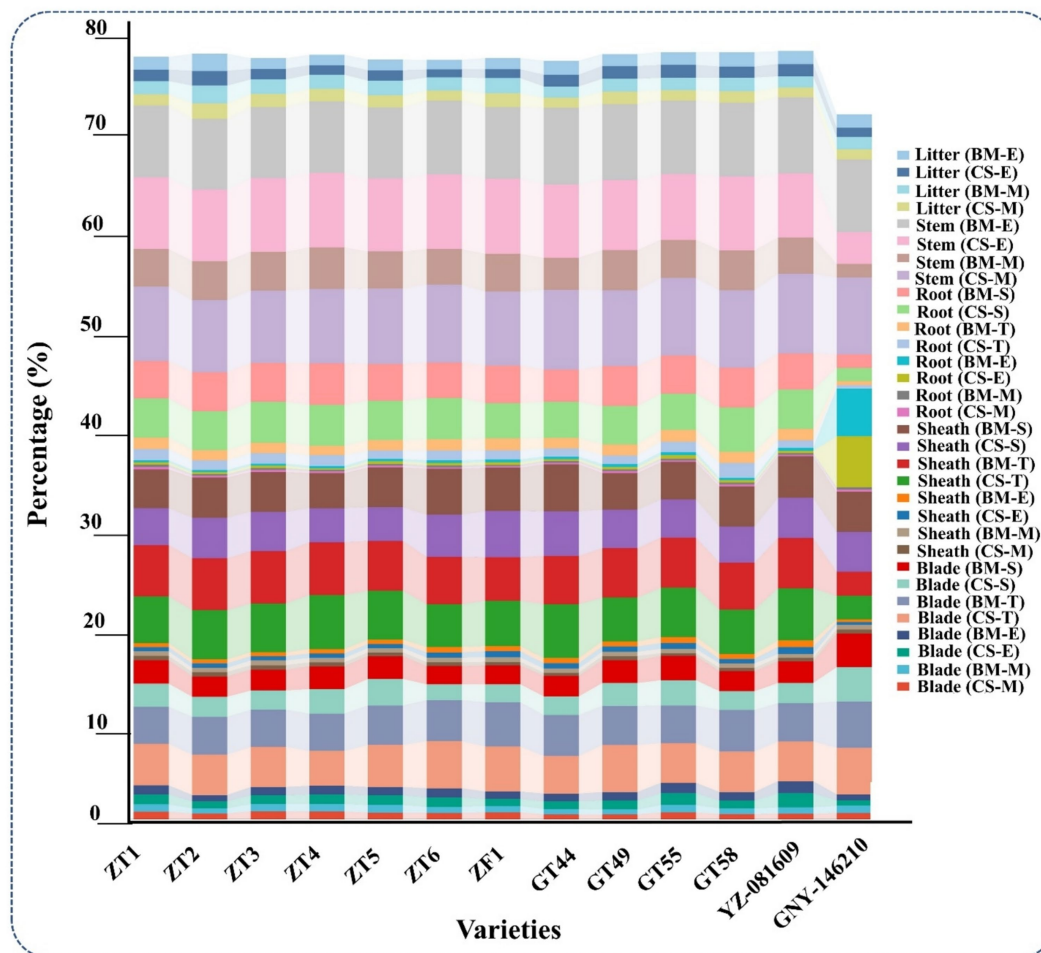


FIGURE 6

This stack bar plot represents the proportion of carbon storage (CS) and biomass (BM) ratios (%) of each organ of sugarcane at different growth stages. CS-S, Carbon storage ratio at seedling stage; BM-S, Biomass ratio at seedling stage; CS-T, Carbon storage ratio at tillering stage; BM-T, Biomass ratio at tillering stage; CS-E, Carbon storage ratio at elongation stage; BM-E, Biomass ratio at elongation stage; CS-M, Carbon storage ratio at maturity stage; BM-M, Biomass ratio at maturity stage.

stage, GNY146210 exhibited the highest blade carbon storage (34.6%), while GT49 and ZT6 showed equal blade biomass (47%) at the tillering stage. Blade biomass increased from the seedling to tillering stage but declined thereafter. In GNY146210, leaf sheath biomass was 39.9% at the seedling stage and declined to 23.6% at tillering, showing a downward trend across all varieties toward maturity. The highest root biomass was recorded in GT58 (44.6%) at the seedling stage, decreasing sharply in subsequent stages. ZT2 exhibited the highest litter biomass at elongation (14.8%) and maturity (15.9%). For stem biomass, ZF1 peaked at elongation (75.5%), while YZ08-1609 and GT44 recorded the highest values at maturity (80.1%), followed by ZT4, ZT6 (74.9%), GT44 (73.5%), and GT58 (74.4%) (Figure 6).

3.2 Total annual photosynthetic net carbon fixation of sugarcane plants

All sugarcane varieties demonstrated annual photosynthetic carbon fixation above 40 kg. ZT1 (86.80 kg) and GNY146210 (82.51 kg) exhibited the highest fixation, followed by ZT3 (63.07 kg) and ZT4 (62.50 kg). Medium fixation levels were observed in ZT5, ZF1, GT55, GT58, GT49, and ZT2 (47.71–55.61 kg). In contrast,

GT44, YZ08-1609 (42.18 kg), and ZT6 (45.83 kg) showed comparatively lower fixation capacities (Supplementary Figure S1).

3.3 Relationship between sugarcane biomass and its carbon sequestration capacity

Figure 7 illustrates the correlation regression analysis between biomass and carbon storage in different sugarcane organs, including leaf blade, leaf sheath, root, litter, bagasse, juice, and total plant biomass, across 13 sugarcane varieties at four growth stages. A strong and highly significant positive relationship was observed between biomass and carbon storage at all developmental stages. At the seedling stage (Figure 7A), biomass showed a very strong positive correlation with carbon storage, with a coefficient of determination of $R^2 = 0.98$ and a highly significant probability level ($p < 0.001$; $n = 52$). Similarly, during the tillering stage (Figure 7B), the relationship remained extremely strong, showing the highest correlation among all stages with $R^2 = 0.99$ ($p < 0.001$; $n = 52$). During the elongation stage (Figure 7C), biomass and carbon storage also exhibited a strong positive association, with $R^2 = 0.98$ ($p < 0.001$; $n = 91$). At the maturity

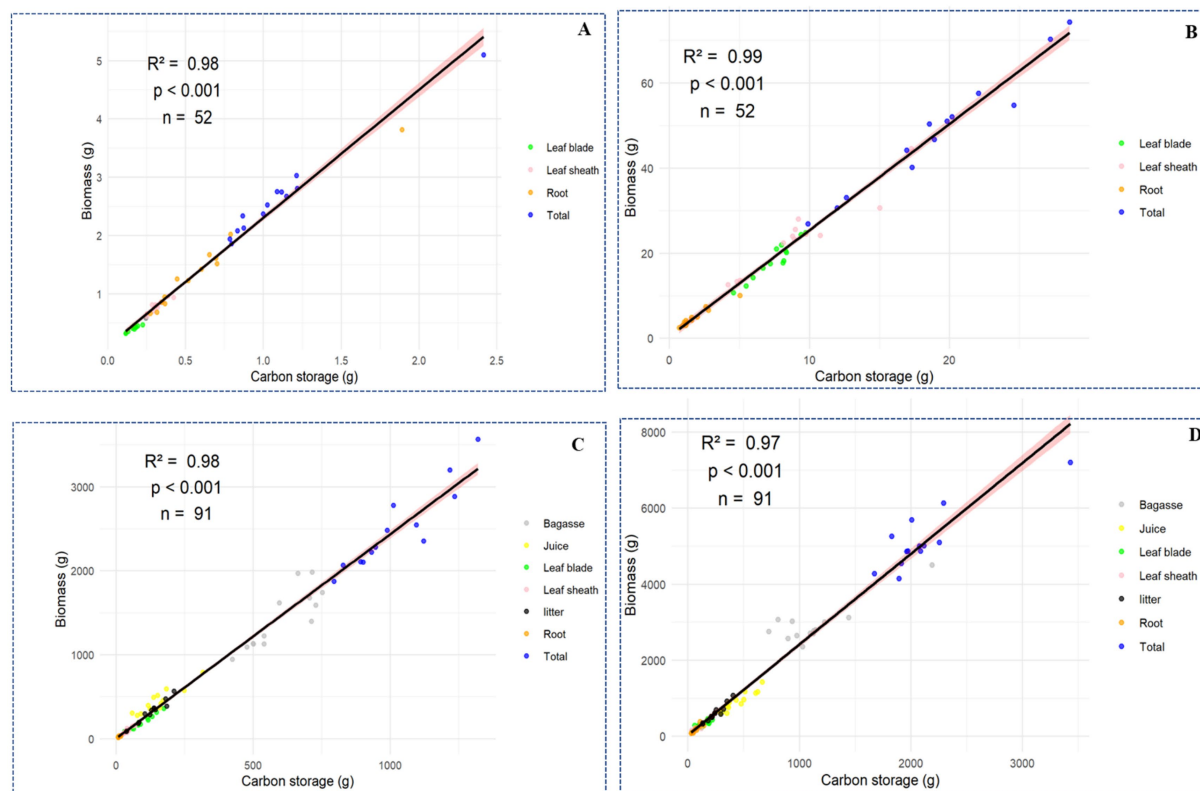


FIGURE 7

This graph presents the correlation regression analysis between biomass and carbon storage in various sugarcane organs, including litter, bagasse, juice, and the total biomass and carbon storage per plant, across all 13 varieties at different growth stages. The stages are categorized as follows: (A) seedling stage, (B) tillering stage, (C) elongation stage, and (D) maturity stage.

stage (Figure 7D), the correlation remained highly significant, although slightly lower compared to earlier stages, with $R^2 = 0.97$ ($p < 0.001$; $n = 91$). Collectively, the results demonstrate that carbon storage increased proportionally with biomass accumulation throughout sugarcane development. The consistently high R^2 values across all growth stages indicate that biomass is a strong predictor of carbon storage in sugarcane plants under the studied conditions.

3.4 Sugarcane biomass and carbon storage accumulation patterns

As shown in Figure 7B and Table 1, biomass and carbon storage patterns varied significantly across sugarcane growth stages. Average biomass increased 47.5 times from the seedling (0.418 g) to tillering stage and 3.44 times from tillering to elongation, peaking during elongation before declining sharply (80.58 times) at maturity. ZT1 had the highest seedling biomass (0.58 g), GT55 at tillering (23.76 g), and ZF1 at elongation (77.55 g). Similarly, carbon storage increased 110.4 times from seedling to tillering and 4.25 times to elongation, then dropped by 80.10 times at maturity. Peak carbon storage was recorded in ZT2 (0.24 g) at seedling, GT44 (22.78 g) at tillering, and GNY146210 (94.44 g) at elongation. Overall, elongation was the peak stage for both biomass and carbon storage.

3.5 Photosynthetic carbon fixation capacity and leaf area of sugarcane at different growth stages

Daily carbon fixation per unit leaf area varied significantly among sugarcane varieties across growth stages. ZT1 showed the highest fixation at the seedling ($150.80 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) and tillering ($165.58 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) stages. At elongation, GNY146210 recorded the maximum ($164.01 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), while ZT4 followed closely. The lowest fixation was observed in GT49 (seedling: 111.79), GT58 (tillering: 127.93), and GT55 (elongation: 134.55). At maturity, ZT3 showed the lowest value (101.83). Overall, significant differences in carbon fixation per unit leaf area were found across varieties, with consistent trends across growth stages, except at maturity, where fixation declined (Table 2). Variety ZT1 exhibited the highest leaf area, measuring 0.00072 m^2 at seedling, 0.2258 m^2 at tillering, 3.3159 m^2 at elongation, and 2.7706 m^2 at maturity stages. No significant differences were noted among other varieties. Conversely, ZT6 had the lowest leaf area, with values of 0.0026, 0.1322, 1.8344, and 1.5152 m^2 across the same stages. Generally, leaf area increased from seedling to elongation but slightly declined at maturity (Supplementary Table S1).

TABLE 1 Sugarcane biomass (BM) and carbon storage (CS) pattern at different growth stages.

Variety	Biomass (BM) and carbon storage (CS) growth pattern at different stages				
	Parameters	Seedling	Tillering	Elongation	Maturity
ZT1	BM	0.58 ± 0.03 ^a	19.14 ± 0.74 ^{ef}	71.95 ± 3.28 ^{bc}	0.59 ± 0.08 ^{ef}
	CS	0.24 ± 0.01 ^a	18.32 ± 1.2 ^{de}	74.77 ± 2.73 ^d	0.88 ± 0.68 ^{def}
ZT2	BM	0.43 ± 0.02 ^{bcd}	20.53 ± 0.52 ^{cd}	71.62 ± 1.10 ^{bc}	0.72 ± 0.06 ^{de}
	CS	0.17 ± 0.01 ^{cde}	19.07 ± 0.86 ^{cd}	81.86 ± 0.57 ^c	0.92 ± 0.87 ^{cde}
ZT3	BM	0.45 ± 0.01 ^{bcd}	20.74 ± 0.50 ^{cd}	72.64 ± 1.96 ^b	0.52 ± 0.05 ^f
	CS	0.16 ± 0.01 ^{de}	19.80 ± 0.83 ^c	81.55 ± 1.33 ^c	0.74 ± 0.06 ^{fg}
ZT4	BM	0.42 ± 0.03 ^{cd}	21.94 ± 0.48 ^b	67.78 ± 3.07 ^{cd}	0.67 ± 0.02 ^{de}
	CS	0.18 ± 0.01 ^{cd}	21.41 ± 0.22 ^b	82.30 ± 1.90 ^c	0.80 ± 0.48 ^{ef}
ZT5	BM	0.47 ± 0.01 ^b	18.54 ± 0.59 ^{fg}	72.30 ± 2.61 ^b	0.66 ± 0.12 ^{de}
	CS	0.22 ± 0.01 ^b	16.93 ± 0.85 ^{ef}	85.96 ± 5.22 ^{bc}	0.85 ± 0.11 ^{def}
ZT6	BM	0.32 ± 0.01 ^e	15.25 ± 0.28 ^j	67.73 ± 4.30 ^{cd}	1.04 ± 0.06 ^e
	CS	0.11 ± 0.01 ^g	13.66 ± 0.59 ^g	83.15 ± 4.84 ^c	1.30 ± 0.07 ^b
ZF1	BM	0.33 ± 0.02 ^c	18.07 ± 0.46 ^{gh}	77.54 ± 1.50 ^a	0.74 ± 0.04 ^d
	CS	0.11 ± 0.01 ^{fg}	18.12 ± 0.65 ^{def}	94.24 ± 3.04 ^a	0.86 ± 0.23 ^{def}
GT44	BM	0.35 ± 0.03 ^c	21.15 ± 0.65 ^{bc}	62.35 ± 2.94 ^e	1.00 ± 0.12 ^c
	CS	0.13 ± 0.01 ^f	22.78 ± 0.71 ^a	65.49 ± 2.32 ^{ef}	0.98 ± 0.05 ^{cd}
GT49	BM	0.43 ± 0.01 ^{bcd}	19.96 ± 0.26 ^{de}	60.77 ± 2.28 ^e	0.99 ± 0.07 ^c
	CS	0.17 ± 0.01 ^{cde}	18.32 ± 1.00 ^{de}	67.00 ± 7.91 ^{de}	1.07 ± 0.16 ^c
GT55	BM	0.39 ± 0.02 ^d	23.76 ± 0.41 ^a	53.55 ± 0.46 ^f	1.20 ± 0.09 ^b
	CS	0.17 ± 0.01 ^{de}	22.54 ± 0.30 ^{ab}	60.01 ± 5.95 ^{fg}	1.43 ± 0.20 ^b
GT58	BM	0.43 ± 0.03 ^{cd}	17.52 ± 0.43 ^{hi}	66.55 ± 1.24 ^d	0.70 ± 0.08 ^{de}
	CS	0.17 ± 0.01 ^{cd}	14.63 ± 0.55 ^g	91.50 ± 4.65 ^{ab}	0.62 ± 0.08 ^g
YZ08-1609	BM	0.40 ± 0.01 ^d	16.80 ± 0.42 ⁱ	56.28 ± 0.95 ^f	1.34 ± 0.02 ^a
	CS	0.16 ± 0.01 ^c	16.79 ± 0.52 ^f	58.27 ± 2.53 ^g	1.59 ± 0.08 ^a
GNY146210	BM	0.45 ± 0.03 ^{bc}	19.92 ± 0.45 ^{de}	70.47 ± 0.64 ^{bcd}	0.65 ± 0.02 ^{de}
	CS	0.19 ± 0.01 ^c	17.37 ± 0.91 ^{ef}	94.44 ± 1.87 ^a	0.71 ± 0.01 ^{fg}

Significance among sugarcane varieties is denoted by different lowercase letters in the same column ($p < 0.05$). Data are expressed as mean ± standard error (SE). Biomass (BM), Carbon storage (CS).

3.6 Daily net carbon fixation by photosynthesis of sugarcane plants at different growth stages

Daily net photosynthetic carbon fixation in sugarcane varieties across growth stages, revealing significant temporal changes. Carbon fixation is low during the seedling stage, with ZT1 showing significantly higher rates than others. At tillering, fixation increases notably, with ZT1 having the highest growth rate and ZT6 the lowest. The elongation stage marks the peak carbon fixation for all varieties. During maturity, fixation declines in most varieties except GT55, GT58, and ZT5, which maintain stable rates. Overall, carbon fixation follows the pattern: elongation > maturity > tillering > seedling, reflecting dynamic changes during growth (Supplementary Table S2).

3.7 Annual total biomass, carbon storage, and photosynthetic net carbon fixation of sugarcane

The annual total biomass, carbon storage, and photosynthetic carbon fixation of sugarcane across varieties. Biomass ranged from

63.32 to 91.30 t·hm⁻², carbon storage from 32.20 to 48.09 t·hm⁻², and photosynthetic carbon fixation from 666.42 to 1371.46 t·hm⁻². Varieties GNY146210, ZT1, and ZT3 exhibited the highest values, while ZT4, ZT5, GT49, GT55, and GT58 showed moderate levels. GT44, YZ08-1609, and ZT6 had relatively lower biomass, carbon storage, and carbon fixation (Table 2).

3.8 Relationship between sugarcane biomass and its carbon storage

Sugarcane absorbs CO₂ via photosynthesis, distributing it throughout the plant. Assessing net photosynthetic carbon fixation requires whole-plant analysis, combining total biomass with fixation rates. Results show a significant positive correlation between total biomass and net photosynthetic carbon fixation in sugarcane varieties, with correlation coefficients ranging from 0.680 to 0.848.

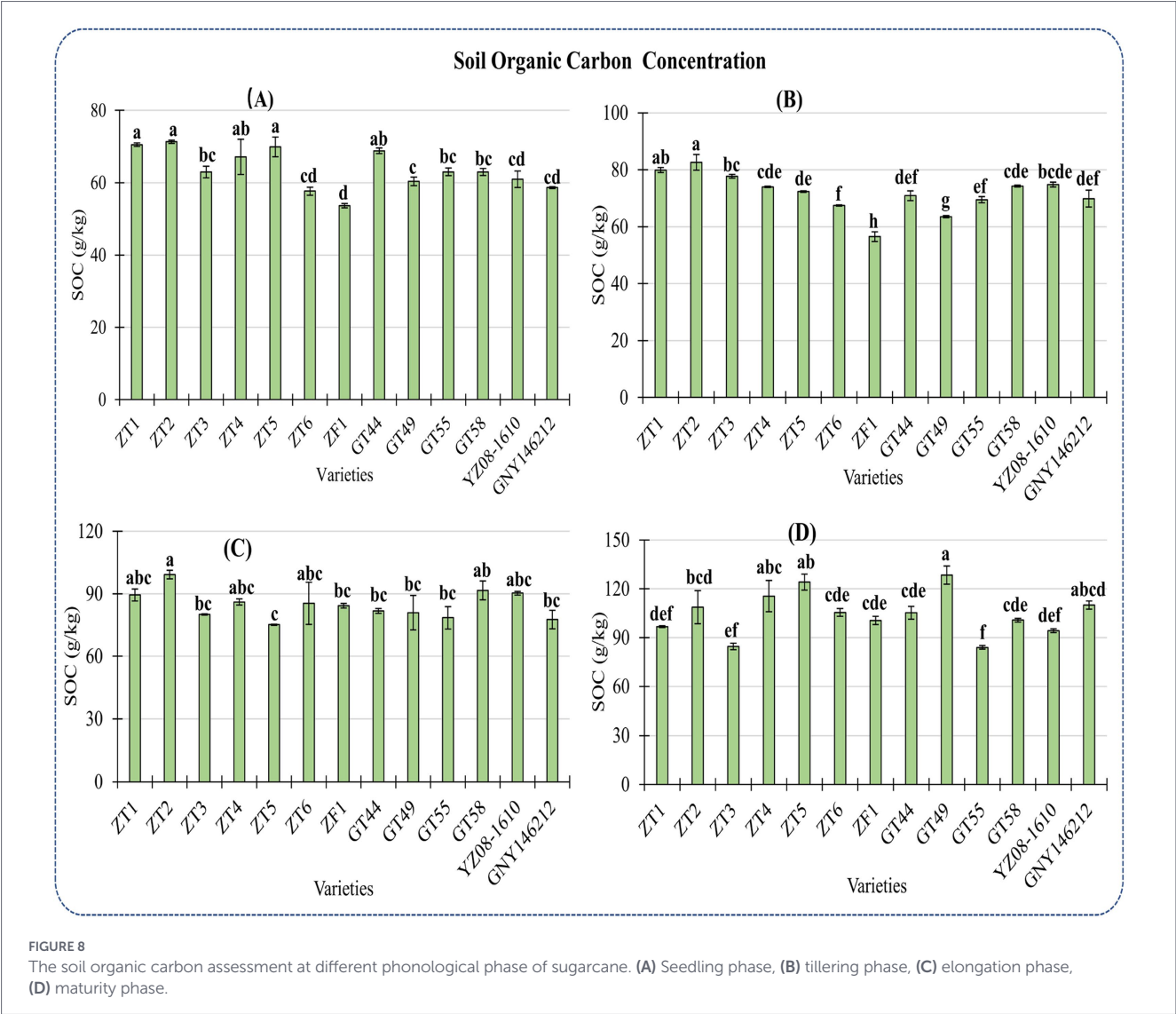
3.9 Soil organic carbon estimation

Regarding soil organic carbon concentrations across different growth stages of sugarcane, distinct variations were observed among

TABLE 2 The correlation analysis between whole plant biomass and net photosynthetic carbon fixation, along with annual totals of biomass, carbon storage, and net carbon fixation in sugarcane.

Variety	Total carbon storage, biomass, and photosynthetic carbon fixation (t hm−2)			Correlation coefficient
	Total biomass	Total carbon storage	Total photosynthetic carbon fixation	
ZT1	90.94 ± 3.16 ^a	45.32 ± 0.93 ^b	1303.59 ± 52.99 ^b	0.775**
ZT2	89.83 ± 3.15 ^a	43.74 ± 1.58 ^b	801.41 ± 7.76 ^{fg}	0.764**
ZT3	81.88 ± 1.87 ^b	40.65 ± 0.81 ^c	996.49 ± 37.95 ^c	0.818**
ZT4	77.02 ± 3.43 ^c	39.13 ± 1.55 ^{de}	987.45 ± 9.19 ^c	0.848**
ZT5	76.21 ± 3.38 ^c	38.09 ± 0.95 ^{ef}	878.69 ± 11.55 ^d	0.761**
ZT6	63.32 ± 3.53 ^f	32.20 ± 1.43 ⁱ	724.11 ± 18.05 ^h	0.729**
ZF1	71.58 ± 0.26 ^{de}	35.00 ± 0.14 ^{gh}	860.65 ± 12.19 ^{de}	0.776**
GT44	75.16 ± 1.99 ^{cd}	34.61 ± 0.22 ^h	753.84 ± 25.31 ^{gh}	0.680*
GT49	77.10 ± 0.69 ^c	34.01 ± 0.34 ^h	858.92 ± 8.39 ^{de}	0.711**
GT55	76.36 ± 2.52 ^c	36.58 ± 0.88 ^g	815.61 ± 51.96 ^{ef}	0.791**
GT58	71.66 ± 3.12 ^{de}	34.90 ± 0.79 ^{gh}	772.33 ± 31.18 ^{gh}	0.785**
YZ08-1609	90.94 ± 3.16 ^a	45.32 ± 0.93 ^b	1303.59 ± 52.99 ^b	0.733**
GNV 146210	89.83 ± 3.15 ^a	43.74 ± 1.58 ^b	801.41 ± 7.76 ^{fg}	0.690*

*Indicates a significant correlation at the $p = 0.05$ level. **Indicates a strongly significant correlation at the $p = 0.01$ level.



both growth phases and genotypes. At the seedling phase, varieties ZT2, ZT1, and ZT5 recorded organic soil carbon concentrations of 70.51, 71.33, and 69.91 g/kg, respectively (Figure 8A). During the tillering phase, ZT1 (79.88 g/kg), ZT2 (82.63 g/kg), and ZT3 (77.71 g/kg) exhibited relatively higher accumulation (Figure 8B). At the elongation phase, GT58 (91.60 g/kg) and YZ08-1610 (90.30 g/kg) showed the greatest concentrations (Figure 8C). At phase, GT49 (128.48 g/kg) and ZT5 (124.17 g/kg) maintained the highest organic carbon levels (Figure 8D). These findings indicate that soil organic carbon concentration generally increased with plant developmental stage, peaking at maturity, and varied significantly among varieties depending on their physiological traits and root exudate profiles. The accumulation of soil organic carbon differed significantly across growth stages and among genotypes, with GT49, ZT5, and GT58 identified as the top three varieties contributing to higher organic carbon concentrations in the soil.

3.10 Correlation analysis

Correlation analysis revealed a strong positive relationship between plant carbon, biomass, and soil carbon across all sugarcane varieties and phenological stages ($R^2 = 0.99$, $p < 0.001$; Supplementary Figure S2). This highlights the integral role of sugarcane growth in enhancing soil carbon sequestration, supporting its potential for climate mitigation.

4 Discussion

The carbon storage of each organ exhibited consistent trends of variation among the different varieties. Overall, the biomass and carbon storage of each organ in ZT1, ZT2, ZT3, GNY146210, GT49, ZT5, and GT58 remained at high levels throughout the growth period. In contrast, the biomass and carbon storage of GT44, ZT6, and YZ08-1609 were comparatively low. This consistency may be attributed to the fact that sugarcane varieties with high biomass typically possess stronger growth potential and higher photosynthetic efficiency, enabling them to accumulate organic matter carbon more effectively. Consequently, these varieties exhibit advantages in both biomass and carbon storage. The biomass and carbon storage of various sugarcane organs are influenced by factors such as varietal characteristics, growth environment, growth period, organ function, and management practices (Mao et al., 2023). The proportional distribution of biomass and carbon storage (Figure 6) among the different organs of the 13 varieties exhibited a consistent order: stem > litter > leaf > leaf sheath > root. The stem's proportion of the total biomass and carbon storage is significantly higher than that of other organs, indicating that the stem is the primary repository of biomass and carbon in sugarcane. As the plant grows, the biomass and carbon storage in the stem accumulate the fastest. The patterns of biomass accumulation and carbon sequestration show consistent trends across different growth stages, with exponential increases compared to earlier stages. Biomass and carbon storage start quickly, peak in the middle, and then slow down as the maturity period. The annual total carbon storage of the examined sugarcane varieties ranges from 32.20 to 48.09 t-hm⁻², similar result was reported by Zhang et al. (2015). However, some varieties show slightly

lower values, possibly due to differences in sampling techniques, processing methods, and climate conditions. Carbon storage is a crucial part of sugarcane biomass, distributed across the plant's stems, leaves, roots, leaf sheaths, and litter. This study found strong correlation coefficients for carbon storage with biomass: 0.987 to 1.000 for leaves, 0.971 to 1.000 for leaf sheaths, 0.978 to 1.000 for roots, 0.991 to 0.999 for stems, and 0.994 to 1.000 for litter. The increase in carbon storage alongside biomass growth highlights the plant's continuous accumulation of carbon. Further, the data revealed that energy crops such as sugarcane enhance soil organic carbon (SOC), consistent with previous research in cropland soil (Kieffer et al., 2023; Xu et al., 2025; Forfora et al., 2024). The varieties ZT1, ZT2, ZT3, and GNY146210 exhibited greater biomass and carbon storage values, suggesting these varieties may be more suitable for cultivation due to their superior biomass production and carbon sequestration potential under field conditions. This superiority is attributed to the greater root biomass of ZT1, ZT2, ZT3, and GNY146210 compared to other varieties, which can stimulate greater soil aggregation, thereby enhancing the protection of root-derived carbon and its chemical recalcitrance (Blanco-Canqui and Lal, 2004; Rasse et al., 2005). In the case of soil organic carbon, maximum carbon was observed deposited by the varieties ZT1, ZT2, GT49, and ZT5 (Figures 8A,D). This observation was validated by the strong positive correlation between biomass and carbon sequestration in sugarcane (above ground) and SOC (below ground) (Supplementary Figure S2). These results are further supported by Martani et al. (2023), who reported that switching from perennial energy crops to annual arable crops increases soil organic carbon (SOC) sequestration. This indicates that perennial energy crops like sugarcane can boost bioenergy production and aid in climate change mitigation by storing carbon in the soil. Furthermore, the varieties ZT1, ZT2, ZT3, and GNY146210 also demonstrated greater aboveground biomass and carbon accumulation than other varieties such as GT44, ZT6, and YZ08-1609, highlighting their potential for bioenergy production (Fu et al., 2022). Thus, the ZT1, ZT2, ZT3, and GNY146210 sugarcane varieties have significant potential to maximize crop yield, bioenergy production, and carbon neutrality for large-scale agricultural cultivation.

High correlation coefficients indicate a highly significant positive correlation between the biomass of various sugarcane organs and their respective carbon storage across all varieties (Figure 7). This strong correlation underscores the critical role of organ-specific biomass in determining sugarcane's carbon storage capacity. Additionally, strong positive associations were observed between plant and soil biomass and carbon storage. This finding indicates that sugarcane, as a C4 species efficient in photosynthesis, absorbs substantial amounts of CO₂ from the atmosphere and stores it in both its biomass and the soil (Muhie, 2022). The capability of sugarcane for carbon sequestration is further enhanced by its high biomass and perennial nature. Sugarcane has potential as a carbon sink due to its excellent growth traits and productive capability. It accumulates substantial amounts of carbon relatively quickly, storing it in roots, stems, and contributing to soil organic carbon (Kumar et al., 2024). Carbon sequestration represents an effective strategy for mitigating the climate impact of modern agriculture. All parts of the sugarcane plant, including the root, stem, leaf, and litter, contribute to carbon sequestration. This finding aligns with

the observations of [Nazir et al. \(2022\)](#), who noted that natural ecosystems stabilize soil carbon levels. Augmenting carbon input through processes such as leaf litter incorporation and root exudation significantly enhances carbon sequestration. Furthermore, soil organic carbon sequestration is enhanced by crop residues and farmyard manure in Chinese cropland ([Zuo et al., 2023](#)).

Sugarcane is widely recognized as a C4 plant with exceptionally high photosynthetic efficiency, which plays a central role in its carbon accumulation potential. Its daily net carbon fixation per unit leaf area is higher than that of many other crops ([Lyu et al., 2021](#)). Therefore, identifying high-light-use-efficiency cultivars and understanding their photosynthetic carbon fixation potential is of great importance ([Wei et al., 2024](#)). However, studies focusing on photosynthetic carbon fixation in sugarcane remain relatively limited. Previous approaches have estimated plant-level carbon fixation by combining daily net photosynthetic rates with whole-plant leaf area. In this context, photosynthetic rate is a key indicator reflecting both growth potential and carbon assimilation capacity. Importantly, the present study demonstrates that high photosynthetic efficiency at the leaf level does not necessarily translate into high whole-plant carbon fixation. Some cultivars exhibited high daily net carbon fixation per unit leaf area, but their overall plant-level carbon fixation remained limited due to relatively small total leaf area. This pattern, also reported by [Li et al. \(2012\)](#), highlights that leaf-level efficiency alone is insufficient for evaluating cultivar performance. For instance, GT44 and GT58 showed high leaf-level carbon fixation but comparatively lower whole-plant carbon fixation due to limited canopy development. Therefore, a holistic plant-level assessment integrating both photosynthetic efficiency and canopy structure is essential for accurately evaluating sugarcane carbon assimilation potential. At a broader scale, sugarcane has strong carbon sequestration capacity due to its high biomass production, C4 photosynthetic pathway, low CO₂ compensation point, and ability to store carbon in phytoliths, contributing to reduced greenhouse gas emissions and enhanced soil carbon storage ([Bhatt et al., 2023](#)). However, it is critical to emphasize that cultivar performance in terms of biomass accumulation and carbon sequestration is strongly influenced by specific pedoclimatic and agronomic conditions. Variations in soil type, temperature, water availability, and nutrient management can significantly alter plant growth and carbon dynamics, indicating that the results of this study are specific to the experimental conditions and should not be generalized across all environments without caution. At the cropping system level, sugarcane contributes significantly to carbon sequestration through high above- and below-ground biomass production and residue retention, which improve soil organic carbon and overall soil health while reducing greenhouse gas emissions ([Pradhan et al., 2023](#)). However, sugarcane-based systems show strong environmental variability in their carbon outcomes. Studies across contrasting agroecological zones indicate that irrigated tropical systems generally achieve higher soil carbon accumulation due to sustained biomass input, whereas semi-arid environments often show reduced carbon stabilization because of faster organic matter decomposition. These findings confirm that environmental conditions are a major determinant of carbon sequestration efficiency in sugarcane systems. Management practices further influence these outcomes. Residue retention has been widely reported to

enhance soil carbon fractions, improve nutrient cycling, and increase long-term carbon storage; however, these effects are highly site-specific and depend on soil texture and climatic conditions ([Thorburn et al., 2012](#)). In systems where residue burning is replaced with green cane harvesting, improvements in soil organic carbon are commonly observed, although the magnitude of change varies across cultivars and management strategies. This again reinforces that carbon dynamics in sugarcane systems are not uniform but are shaped by local agronomic practices and environmental conditions. Cultivar selection is another critical factor determining carbon storage potential. High biomass-producing sugarcane varieties generally contribute greater carbon inputs to soil and exhibit higher carbon accumulation potential across diverse environments, making them important candidates for bioenergy-oriented production systems ([Tirado-Corbalá et al., 2015](#)). However, genotype × environment interactions significantly affect biomass partitioning and carbon allocation, indicating that cultivar performance is highly location-dependent rather than universally stable. In addition, as a C4 crop, sugarcane demonstrates inherently high photosynthetic efficiency, which can be further enhanced through optimized nutrient management, leading to improved carbon assimilation and soil organic carbon storage under field conditions ([Kumar et al., 2024](#)). Combined with appropriate residue management strategies, these practices not only increase soil carbon stocks but also reduce greenhouse gas emissions compared to residue burning, reinforcing the environmental benefits of sustainable sugarcane cultivation ([Thorburn et al., 2012](#)). Despite its strong carbon sequestration potential, accurate field-based estimation of sugarcane carbon stocks remains challenging due to labor-intensive measurements and spatial limitations. Recent advances have shown that integrating UAV-based remote sensing with machine learning techniques enables precise and scalable estimation of sugarcane carbon dynamics, offering a powerful approach for monitoring carbon stocks under variable field conditions and supporting sustainable agricultural management strategies ([Sawatwongchai et al., 2026](#)). Finally, previous studies have established a strong relationship between crop growth, yield, and photosynthesis ([Wang et al., 2021](#)). In the present study, total biomass across all sugarcane cultivars showed a significant positive correlation with whole-plant net photosynthetic carbon fixation, with correlation coefficients ranging from 0.680 to 0.848 ([Table 2](#)). This relationship reflects the direct influence of photosynthetic carbon fixation on growth rate and biomass accumulation. Enhanced carbon fixation improves CO₂ assimilation efficiency, leading to increased biomass and carbon storage. A strong positive relationship was also observed between organ-specific biomass and corresponding carbon storage, as well as between overall biomass and photosynthetic carbon fixation across cultivars. These results demonstrate that sugarcane biomass is closely linked to its carbon fixation capacity, confirming its biological characteristic as a high-biomass and high-carbon-sequestration crop. However, this study also highlights that both biomass production and carbon fixation are strongly influenced by cultivar type and environmental conditions. Overall, this work provides a comprehensive understanding of sugarcane carbon dynamics across physiological, plant, and system levels, offering valuable insights for cultivar selection, agronomic optimization, and future assessment of carbon footprints in sugarcane-based ecosystems.

5 Conclusion

This study demonstrates significant variation among sugarcane cultivars in biomass production and carbon storage, with ZT1, ZT2, ZT3, GNY146210, GT49, ZT5, and GT58 showing superior performance, while GT44, ZT6, and YZ08-1609 exhibited lower values. Across all cultivars, stems were identified as the primary site of carbon accumulation, and a strong positive correlation was observed between biomass and carbon storage in all plant organs. Carbon accumulation followed a consistent growth-stage pattern, increasing rapidly during early and mid-growth stages and slowing at maturity. The findings also confirm that high-biomass cultivars contribute more effectively to soil organic carbon and overall carbon sequestration, although their performance is strongly influenced by specific pedoclimatic and agronomic conditions. Importantly, these results provide valuable guidance for varietal selection and cultivation strategies aimed at improving sugarcane productivity and reducing its carbon footprint. The identification of high-performing cultivars such as ZT1, ZT2, ZT3, and GNY146210 can support future breeding programs and management practices focused on enhancing both biomass yield and carbon sequestration potential under field conditions. However, to ensure the reliability and broader applicability of these findings, further experiments across different years, locations, and environmental conditions are essential to validate the observed differences among cultivars and to better understand their stability and performance variability. From a future perspective, integrating multi-environment trials with physiological, molecular, and remote sensing approaches will further strengthen the understanding of carbon dynamics in sugarcane. Additionally, combining superior cultivars with optimized agronomic practices will enhance carbon sequestration efficiency and bioenergy productivity, contributing to climate-smart and sustainable sugarcane production systems.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

YW: Methodology, Writing – review & editing. FM: Conceptualization, Writing – original draft, Writing – review & editing. YC: Software, Writing – review & editing. SZ: Investigation, Supervision, Writing – review & editing. SJ: Visualization, Writing – review & editing. ZC: Data curation, Formal analysis, Writing – review & editing. YG: Investigation, Software, Writing – review & editing. LZ: Validation, Visualization, Writing – review & editing. BY: Funding acquisition, Resources, Supervision, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was funded by the Project of Sanya Yazhou Bay Science and Technology City, Grant No; SKJC-JYRC-2024-84.

Acknowledgments

The authors express their gratitude to the Institute of Tropical Bioscience and Biotechnology, Chinese Academy of Tropical Agricultural Sciences, Haikou, 571101, Hainan, P. R. China, for supporting this project.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1775208/full#supplementary-material>

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