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RESEARCH ARTICLE

Comparative Yield Response and Sugar Contents of Four Sweet Corn Varieties Under Different Shallow Subsurface Drip Irrigation Treatments

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ABSTRACT

This study evaluated the impacts of three water application treatments—potential evapotranspiration (PET), crop-specific evapotranspiration (Crop-ET) and rainfed (no irrigation)—on the growth, yield and quality of sweet corn (*Zea mays*) via shallow subsurface drip irrigation. During the 2022 growing season, the study utilised a randomised split-plot design with four sweet corn hybrids (Ambrosia F1 SE, Temptress F1 SG, Honey and Cream F1 SU, and Peaches and Cream F1 HSE) and three irrigation replicates. PET-based irrigation calculated using the modified Penman–Monteith equation often results in overirrigation, especially during early growth stages. In contrast, Crop-ET, calculated with crop coefficients, more effectively matches crop water needs, improving irrigation efficiency and conserving resources. Compared with Crop-ET plots, rainfed plots were most vulnerable to dry spells and, on average, produced ~25–35% fewer ears ha^{-1} and ~30–45% lower total ear mass. Peaches and Cream F1 HSE demonstrated strong resilience and biomass production under all treatments, whereas Ambrosia F1 SE presented high sugar contents but greater sensitivity to water stress. Soil texture and moisture retention significantly influenced irrigation effectiveness and water availability. These findings emphasise the importance of tailored irrigation strategies based on crop-specific water requirements and soil properties, alongside drought-tolerant hybrid selection, to maximise yield and improve quality in water-limited regions. Future research should address multi-season variability and include deeper soil moisture dynamics.

RÉSUMÉ

Cette étude a évalué l'impact exercé par trois traitements d'application d'eau – évapotranspiration potentielle (PET), évapotranspiration spécifique à la culture (Crop-ET) et culture pluviale (sans irrigation) – sur la croissance, le rendement et la qualité du maïs (*Zea mays*) par l'irrigation goutte à goutte superficielle. Au cours de la saison de croissance 2022, l'étude a utilisé un plan en blocs aléatoire en parcelles divisées avec quatre hybrides de maïs (Ambrosia F1 SE, Temptress F1 SG, Honey and Cream F1 SU et Peaches and Cream F1 HSE) et trois répétitions d'irrigation. L'irrigation basée sur la PET, calculée à l'aide de l'équation modifiée de Penman-Monteith,

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entraîne souvent une irrigation excessive, en particulier pendant les premiers stades de croissance. En revanche, la Crop-ET, calculée à l'aide de coefficients de culture, correspond plus efficacement aux besoins en eau des cultures, améliorant ainsi l'efficacité de l'irrigation et permettant d'économiser les ressources. Par rapport aux parcelles Crop-ET, les parcelles pluviales étaient les plus vulnérables aux périodes de sécheresse et produisaient en moyenne environ 25 à 35% moins d'épis par hectare et environ 30 à 45% moins de masse totale d'épis. Les variétés Peaches and Cream F1 HSE ont démontré une forte résilience et une production de biomasse élevée sous tous les traitements, tandis que la variété Ambrosia F1 SE a présenté une teneur élevée en sucre, mais une plus grande sensibilité au stress hydrique. La texture du sol et la rétention d'humidité ont exercé un impact significatif sur l'efficacité de l'irrigation et la disponibilité en eau. Ces résultats soulignent l'importance de stratégies d'irrigation adaptées aux besoins en eau spécifiques de la culture et aux propriétés du sol, ainsi que la sélection d'hybrides tolérants à la sécheresse, afin de maximiser le rendement et d'améliorer la qualité dans les régions où l'eau est limitée. Les recherches futures devraient prendre en compte la variabilité multi-saisonnière et inclure une analyse plus approfondie de la dynamique de l'humidité du sol.

1 | Introduction

Sweet corn, a high sugar content maize, has been part of agriculture and cuisine in North America for centuries (Erdal et al. 2011). The corn variety is characterised by its halted stage of development, which prevents standard corn starch formation, resulting in tender, sweet kernels (Erwin 1951). Currently, sweet corn is one of the most valuable and culinarily versatile vegetable crops. Among processed vegetables, it holds the second highest farm value after tomatoes, and among fresh vegetables, it ranks sixth in the United States (Tracy 1993). Sweet corn is primarily grown in the Midwest and Northeast Regions, with more than 500,000 farms producing nearly 60 million hundredweights (cwt) annually, valued at approximately $775 million (NASS 2022). In 2019, the United States generated more than 380 million cwt of sweet corn with a market value exceeding $2 billion.

Water resources are under increasing strain, yet agriculture remains one of the largest water consumers. Irrigation alone represents 42% of total freshwater withdrawals in the United States (Dieter et al. 2018). Although irrigated lands constitute less than 20% of the nation's harvested cropland, they contribute more than half of total crops sold, underscoring irrigation's critical role in agricultural productivity (Dieter et al. 2018). Sweet corn production is highly water dependent. Therefore, effective irrigation management is essential for maintaining high yields and crop quality.

Subsurface drip irrigation (SDI) is one of the most water-efficient methods. SDI delivers water directly to the root zone, reducing evaporation and runoff losses. Research shows that SDI matches or outperforms other irrigation methods in improving crop yield across multiple crops (Camp 1998). Studies have demonstrated that SDI can reduce net irrigation needs by up to 25% while maintaining high yields (Lamm et al. 1998). For example, Lamm (2005) reported a 25% increase in water-use efficiency in corn production when using SDI compared to sprinkler irrigation. Specifically, for sweet corn, SDI offers precise water delivery that supports optimal growth and productivity. According to Soussa and Soussa (2010), SDI improved vegetable productivity by 18% compared with that of conventional drip irrigation systems, underscoring its potential in improving both crop yield and water use efficiency.

Sweet corn was chosen for this study because of its high water needs and economic importance. There are also knowledge gaps, especially regarding quality traits such as sugar content under subsurface drip irrigation (SDI). While SDI studies on sweet corn exist, much of the research has focused on yield and water efficiency. Few studies have examined how different irrigation levels affect crop quality and varietal performance, especially regarding quality traits such as sugar content under SDI. This study addresses existing knowledge gaps by examining the responses of four sweet corn varieties—Ambrosia F1 SE (Ambrosia), Temptress F1 SG (Temptress), Honey and Cream F1 SU (H & C), and Peaches and Cream F1 HSE (P & C)—to three different irrigation strategies in terms of yield, aboveground biomass and sugar content. The irrigation treatments included (1) potential evapotranspiration (PET), which focused solely on atmospheric water demand; (2) crop-specific evapotranspiration (Crop-ET), which integrates crop-specific coefficients (Kc) along with PET; and (3) rainfed treatment. A shallow SDI system was utilised across all the treatments in this study. We hypothesise that compared with PET, Crop-ET will improve irrigation efficiency and yield, whereas rainfed conditions will result in reduced yields, and irrigation will not affect sugar content.

2 | Study Area and Research Design

The study was conducted at the University of Missouri's South Farm Research Center (Figure 1). The irrigation system, implemented through a flat drip tape, was employed for the PET and Crop-ET treatments. The rainfed treatment relied solely on natural rainfall, except during the first 10 days after planting when irrigation was applied to support seed germination and plant establishment. The drip tape was buried in the soil at a depth of 7.6 cm. The irrigation system featured emitters spaced at 15.2 cm intervals and was connected to main lines with 1.9 cm diameter polyethylene pipes. The water source was the public water supply, and timers regulated the irrigation schedules for the different treatments. The study plot consisted of 36 raised beds, each planted with a sweet corn variety, with two additional rows planted between each pair of beds to minimise border effects. Each added row contained the same sweet corn variety as the adjacent bed. There were irrigation lateral lines only on the plant rows located on the beds (only those that were considered for the studies). The study plot was 150 m long and 46 m wide, and sweet corn rows were spaced 76.2 cm apart. The plot was fertilised on July 7 (during the initial phase) with Urea 46% Nitrogen (Super U) at an application rate of 5021 kg ha^{-1}.

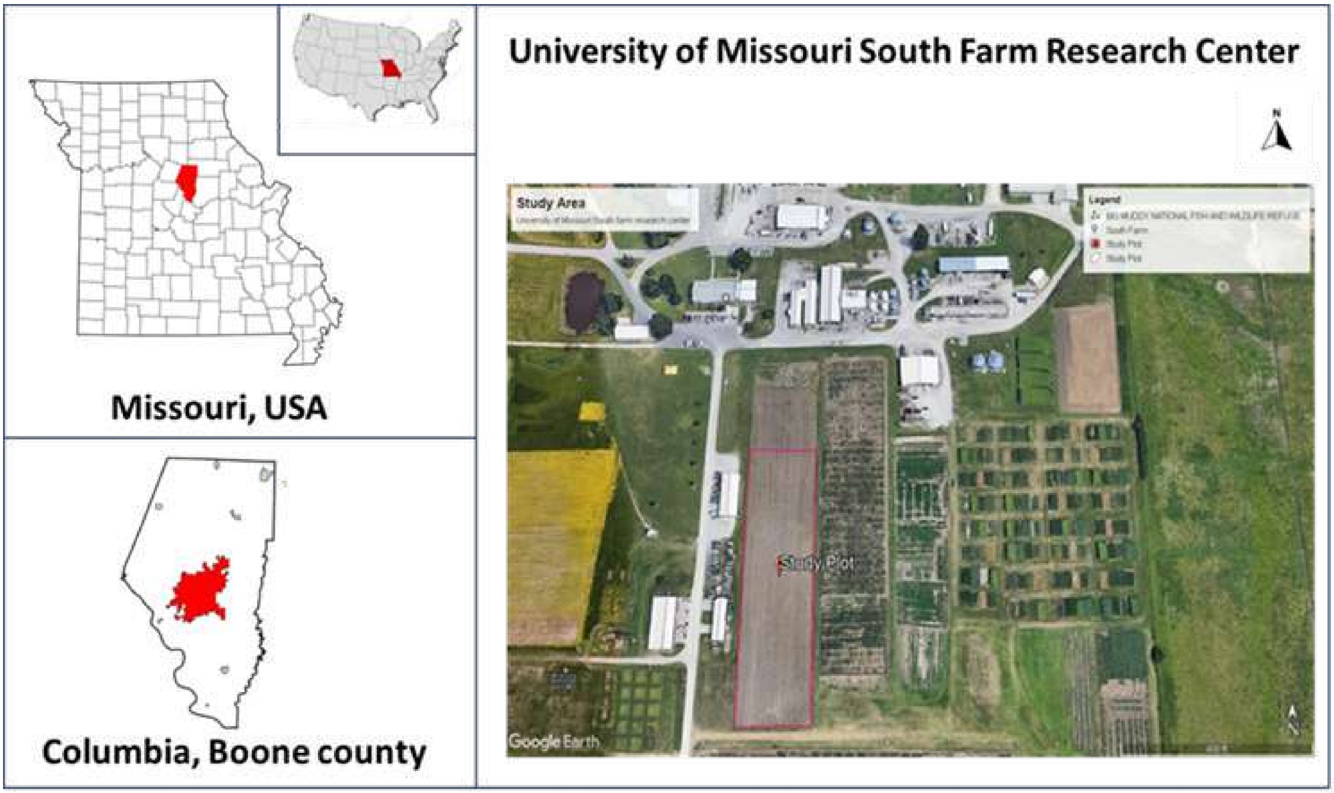

FIGURE 1 | Location of the study site. The rectangle (red) on the right figure shows the location of the plot.

The study design included three replicates for each specific irrigation treatment. The sweet corn hybrids were planted on June 28 via a John Deere 7000 six-row planter. Herbicide (Round-up, Liberty and Lexar) was applied at a rate of $0.02\,g\,m^{-2}$ before planting to control weeds. Seed requirements were estimated based on row length and the recommended plant spacing, resulting in approximately 172,150 seeds being sown per hectare during planting.

To analyse the grain yield, each treatment's water input performance was assessed in relation to the recorded parameters during harvest. The data analysis employed a complete block split-plot design incorporating plot factors such as irrigation treatments and sweet corn varieties. Soil moisture data were continuously collected at 15-min intervals throughout the 2022 growing season.

3 | Data and Methods

3.1 | Data

Crop water use was estimated using PET data from the Missouri Mesonet weather station at Sanborn Field (latitude: 38.942301° N, longitude: 92.320395° W) in Columbia, Missouri. This station, located approximately 5.60 km from the study site, provided data spanning from 2011 to present. These PET data were estimated using the modified Penman-Monteith equation for grass as a reference crop, which combines elements of energy balance and mass transfer to calculate evapotranspiration (Allen et al. 1998). Between July 7 and September 2, 2022, soil volumetric water content (VWC) was measured at 15-min intervals at a depth of 20 cm from 15 VWC sensors (10 Campbell scientific CS616 and 5 Meter ECH_2O 5TM). Soil samples were collected weekly for seven weeks, starting on July 22, 2022, at each sensor location to determine actual gravimetric water content. The irrigation depths, averaged and applied, were recurrently updated over a 5-day cycle until the end of the growing season.

3.2 | Methods

3.2.1 | Crop Water use (CWU)

This study focused on estimating crop water use (CWU) for sweet corn using the modified Penman–Monteith PET method (Allen et al. 1998) because of its precision, adaptability, scientific basis, standardisation and practical utility in agricultural water management.

The crop coefficient approach was employed to estimate sweet corn's CWU. This involves multiplying PET by a crop coefficient (Kc) specific to the crop type and growth stage. The Kc values, obtained from Allen et al. (1998) vary linearly through growth stages.

$$CWU = Kc \times PET \tag{1}$$

where Kc is crop coefficient, PET is potential evapotranspiration (mm)

Erosion factors, represented by the K (Kw and Kf) and T factors in Table 1, measure soil vulnerability to sheet and rill erosion caused by water. The K values range from 0.02 to 0.69 with higher values indicating greater susceptibility to water-induced erosion. The Kw factor represents the entire soil's erodibility, with adjustments for the presence of rock fragments. The Kf factor measures the erodibility of the fine-earth fraction, which includes particles smaller than 2 mm.

TABLE 1 | Physical properties of the experimental plot; source: USDA–Natural Resources Conservation Service–National Cooperative Soil Survey—version 31; August 27, 2024.

	Physical soil properties of the experimental plot													
										Erosion factor				
Soil name	Depth	Sand	Silt	Clay	Moist bulk density	Saturated hydraulic conductivity	Available water capacity	Linear extensibility	Organic matter	Kw	Kf	T	Wind erodibility group	Wind erodibility index
	cm	Pct	Pct	Pct	g/cc	µm/s	cm/cm	Pct	Pct					
Mexico silt loam, 1–4% slopes, eroded	0–18	2–5–10	67–77–83	15–18–27	1.32–1.46	4.00–14.00	0.56–0.61	1.40–3.60	1–4	0.55	0.55	3	5	56
	18–38	5–10–15	50–65–80	15–25–35	1.33–1.43	4.00–14.00	0.46–0.56	1.40–6.10	1–2	0.49	0.49			
	38–86	1–2–5	35–39–49	46–59–60	1.21–1.41	0.01–0.42	0.20–0.30	8–13	0.10–2	0.20	0.20			
	86–107	1–2– 5	58–66–74	25–32–38	1.42–1.46	1.40–4.00	0.41–0.48	2.90–6.60	0.10–0.50	0.43	0.43			
	107–200	3–4–10	52–66–73	24–30–45	1.45–1.51	1.40–4.00	0.41–0.48	2.70–8.40	0.10–0.50	0.49	0.49			

3.2.2 | Irrigation Scheduling

Irrigation scheduling was based on historical PET values, each row's surface area, treatment assumptions and irrigation system efficiency. For the Crop-ET treatment, irrigation was scheduled on the basis of historical PET and a representative Kc (Table 2) over a 5-day period to reflect sweet corn's actual water needs.

For Crop-ET treatment

$$Crop - ET\ irrigation(mm) = \frac{\sum CWU\ (5days)}{Irr.\ \ eff.} \quad (2)$$

For PET-based treatment,

$$PET\ irrigation(mm) = \frac{\sum PET\ (5days)}{Irr.\ \ eff.} \quad (3)$$

An irrigation efficiency (Irr. eff.) of 0.90 was assumed for these calculations (Lamm and Rogers 2003).

3.2.3 | Soil Moisture and Soil Available Water

The crop root zone's soil moisture status was monitored via a set of 15 soil VWC sensors (Figure 2). These sensors were placed in one replicate for each treatment with installation depths of 20 cm, where the assumed root majority was located. The data, recorded at 15-min intervals, provided insight into the root zone's moisture dynamics.

To ensure accurate soil moisture measurements, weekly calibrations were conducted by collecting soil samples near each sensor. The samples were taken from the ground surface to a depth of 30 cm to assess the actual moisture content at the depth at which the sensors were buried. A soil probe was driven 30 cm into the soil, and the column of soil between 17.50 cm and 22.50 cm was sampled, stored in a plastic bag and sealed to avoid moisture loss. The moisture content was determined through the gravimetric method involving wet and dry weight calculations with samples that were oven dried at 110 °C for 48 h.

The experiments aimed to ascertain the moisture content limits critical for irrigation management. Undisturbed soil cores were collected at split-plot levels at nine locations (one within each replicate totalising three for each treatment) via aluminium rings measuring 76.2 mm long and 76.2 mm in diameter with a 3.2 mm thick wall (Uhland sampler) at depths of 0–10 cm, 10–20 cm and 20–30 cm from each location.

The soil saturation, an indicator of avoiding overirrigation, was determined by immersing the soil cores in water for 48 h.

TABLE 2 | Crop coefficient per growth stage for sweet corn (Allen et al. 1998).

Initial phase (20 days)	Development phase (25 days)	Mid phase (25 days)	End phase (10 days)
0.30 (constant)	0.30–1.15 (increase)	1.15 (constant)	1.15–1.05 (decrease)

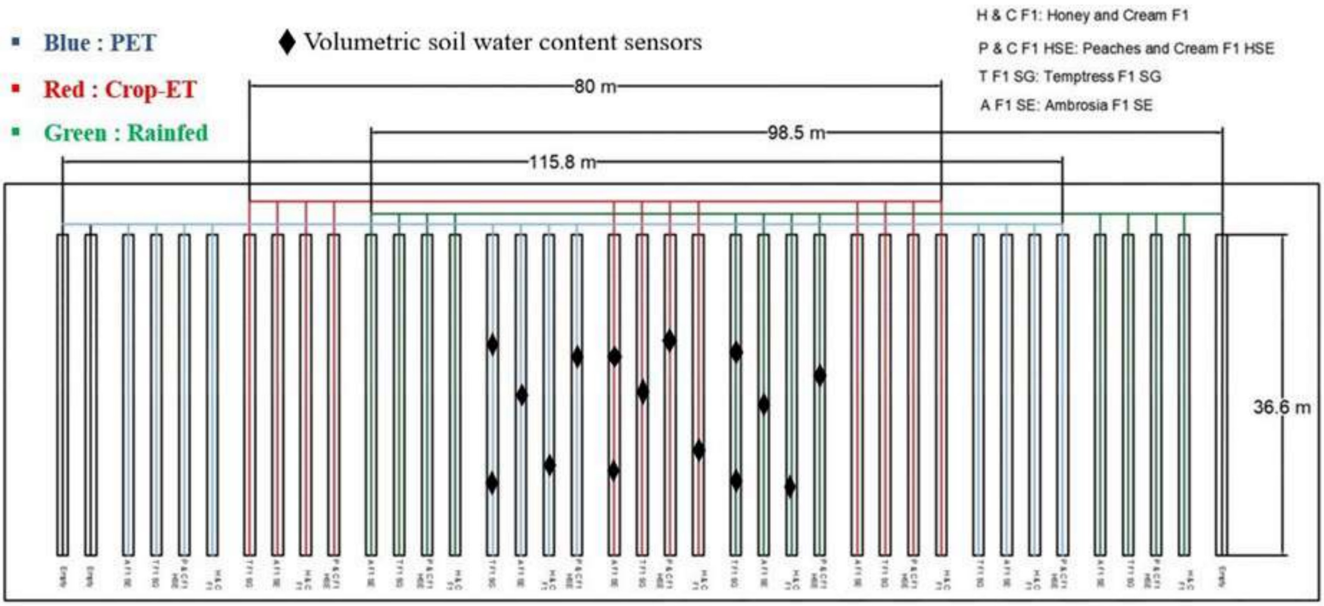

FIGURE 2 | Irrigation system design with the locations of the 15 VWC sensors used during the study. The coloured lines represent the irrigation system, with blue for PET, red for Crop-ET and green for rainfed treatments.

The soil cores were then introduced into pressure chambers to measure field capacity, which represents the soil's water-holding capacity at 33 kPa. Additionally, 100 kPa—the assumed soil water suction at which a tensiometer will lose suction and water will drain out of the ceramic core—was considered the water irrigation threshold during the study. The pressure chambers used were part of the 1600F1 5 Bar Pressure Plate Extractor from Soilmoisture Equipment Corp (United States) for precise measurement of soil water retention between 0 and 500 kPa.

Bulk density was determined at nine different locations spread out over the plot at three depths (0–10 cm, 10–20 cm and 20–30 cm). One sample was collected per replicate using the soil cores mentioned earlier, and bulk density was calculated by determining the ratio of dry weight to volume.

Although VWC was monitored only in the upper 0–20 cm, this zone likely captured the bulk of sweet corn water uptake because most roots are concentrated in the top 0–30 cm: multiple studies report 70–95% of maize/sweet corn roots within this layer, with particularly high densities in the top 10–20 cm (Ahmad et al. 2014). In drip/deficit systems, root systems tend to concentrate near the dripper and show strong vertical gradients in terms of soil moisture, with deeper layers (40–50 cm) often drier and less variable than the surface, which can limit additional deep rooting and extraction (Sampathkumar et al. 2012). Consistent with this, recent sweet corn work under deficit irrigation revealed that 73–80% of the total root length occurred at 0–30 cm, and differences among irrigation treatments largely disappeared below ~40 cm because deeper water remained above field capacity and was not limiting (Singh et al. 2023).

Our treatment effects on soil water dynamics should be interpreted as reflecting the effective root zone where most water uptake occurs. The Management Allowable Depletion (MAD) was assumed to be 0.5 (Allen et al. 1998). Real-time VWC data from soil sensors were used to verify the soil moisture content but were not directly used in irrigation scheduling.

3.2.4 | Harvest and Crop Yield

The harvesting phase commenced on September 5, 2022, and lasted for a week during which time the experimental plot was systematically divided into 108 equal-length segments (i.e., 3 segments from each of the 36 treatments). Various parameters—including the quantity and weight of corn ears, plant height and biomass weight—were thoroughly documented for each sampling unit. Corn ears were collected by hand, weighed and counted. Plant heights were measured with a surveying rod indexed in 0.01-foot units on five randomly chosen plants per segment during harvest, with the averages providing an approximation for the entire segment.

The total aboveground biomass of each segment was systematically harvested by cutting corn plants at ground level and securing them into bundles. These bundles were then weighed using a digital scale with a weight capacity of 2 kg (4.40 lb.) to 300 kg (660 lb.) and a precision of 0.01 kg. Samples were taken from each segment for all considered variables except for sugar content and kernel count and weight. Kernel count determination involved selecting five sweet corn ears from each treatment segment, then counting, cutting and weighing the kernels via a Mettler AJ100 weighing scale with a precision of 0.1 mg. For sugar content, the sweet corn kernels were removed from the ears and placed in sealed plastic bags, where they were manually crushed to extract the juice. Sugar content was measured directly after harvest, and additional samples were frozen for 10 days, thawed and measured again after storage. The extracted juice was transferred into plastic tubes, and a Brix meter was used to measure the sugar concentration in°Brix (Kleinhenz and Bumgarner 2012; Ahmed et al. 2022).

3.2.5 | Statistical Analysis

To assess normality, a Shapiro–Wilk test (Shapiro and Wilk 1965) was applied at 5% significance, revealing that none of the measured parameters adhered to a normal distribution. A visual check of normality (Nuzzo 2019) was further performed through data transformation (log or square root) and histogram plotting, substantiating the non-normal distribution.

Although the split-plot design is suitable for analysing the main and interaction effects between treatments and varieties, it does not address assumptions about data distribution, such as normality, which is critical for statistical tests such as ANOVA. The Shapiro–Wilk test was, therefore, used to check the normality assumption for valid ANOVA results. Welch's ANOVA was used to test the effects of irrigation treatment and sweet corn variety on yield and harvest quality parameters. Welch's ANOVA was selected because preliminary diagnostics indicated heterogeneity of variances (and unequal group sizes in some cases), conditions under which Welch's test provides robust inference without assuming homoscedasticity.

To probe the pairwise differences among treatments and varieties, a Games–Howell post hoc test was conducted, which does not require equal variances or equal sample sizes but still controls the familywise Type I error rate. The Games–Howell results revealed statistically significant differences in biomass, ear weight, plant height and sugar content, providing a clearer picture of how irrigation strategies and genetic differences shape specific performance outcomes.

4 | Results and Discussion

4.1 | Variability in Evapotranspiration

The cumulative PET across crop growth stages (2011–2022) shows year-to-year variability in potential water demand (Figure 3a). In 2022, daily PET values were more variable than during the historical period (2011–2021) as shown in Figure 3b. The cumulative PET for 2022, however, was slightly greater than the historical average (Figure 3c), suggesting stable long-term trends. This consistency supports the use of historical PET data to estimate crop water needs. Table 3 summarises the cumulative PET for 2022 and the 2011–2021 average.

4.2 | Comparison of Cumulative Irrigation Amounts (PET vs. Crop-ET)

The PET-based irrigation resulted in elevated water applications during the initial and development stages (Table 4). This is because PET relies on reference grass evapotranspiration, which overestimates crop needs early in the season when canopy cover is low.

As expected, during the initial stage (Figure 4), PET-based irrigation is ~100 mm, whereas it is ~50 mm under Crop-ET, suggesting that PET tends to overestimate during the early stage. During the development stage, PET-based irrigation reaches ~140 mm, whereas Crop-ET-based irrigation reaches ~80 mm. Again, PET overestimates the crop water requirement, reflecting reliance on atmospheric demand for a reference grass surface rather than the actual crop growth stage. During the middle stage, however, Crop-ET-based irrigation surpasses PET-based irrigation, with Crop-ET at approximately 110 mm and PET at approximately 90 mm. For the final stage, the irrigation amounts are relatively similar, with Crop-ET being slightly greater at approximately 50 mm than at 40 mm for PET.

As expected, in the early growth stages (initial and development), PET-based irrigation leads to overirrigation, but in the later stages (mid- and final), Crop-ET-based irrigation becomes more prominent, suggesting that the actual crop water requirements (Crop-ET) increase during the peak growth periods, whereas PET overestimates the water need earlier on.

4.3 | Soil Water-Holding Capacity and Irrigation Insights

Bulk density (g/cm^3) increases with soil depth, ranging from approximately 1.30 g/cm^3 near the surface (5 cm) to approximately 1.55 g/cm^3 at 25 cm (Figure 5a). Higher bulk densities at greater depths may restrict root penetration and reduce water infiltration, potentially affecting nutrient and water availability during dry periods.

Figure 5b shows the VWC distribution across soil depths under various pressure conditions: 0 kPa (saturation), −33 kPa (field capacity) and −100 kPa (drier soil conditions). At shallower depths (5–10 cm), the VWC values are relatively low under −33 kPa and −100 kPa, indicating that the upper layers retain less moisture under tension. In contrast, the VWC increases with depth across all pressure levels, reaching ~0.35 cm^3/cm^3 at 20–25 cm, suggesting that deeper layers retain more water, likely because of the higher clay content as shown in Table 1.

In this study, irrigation was used to maintain the VWC between field capacity and the irrigation threshold, ensuring optimal water availability. By remaining within the optimal range, the strategy provided adequate moisture while preventing waterlogging or deficit conditions.

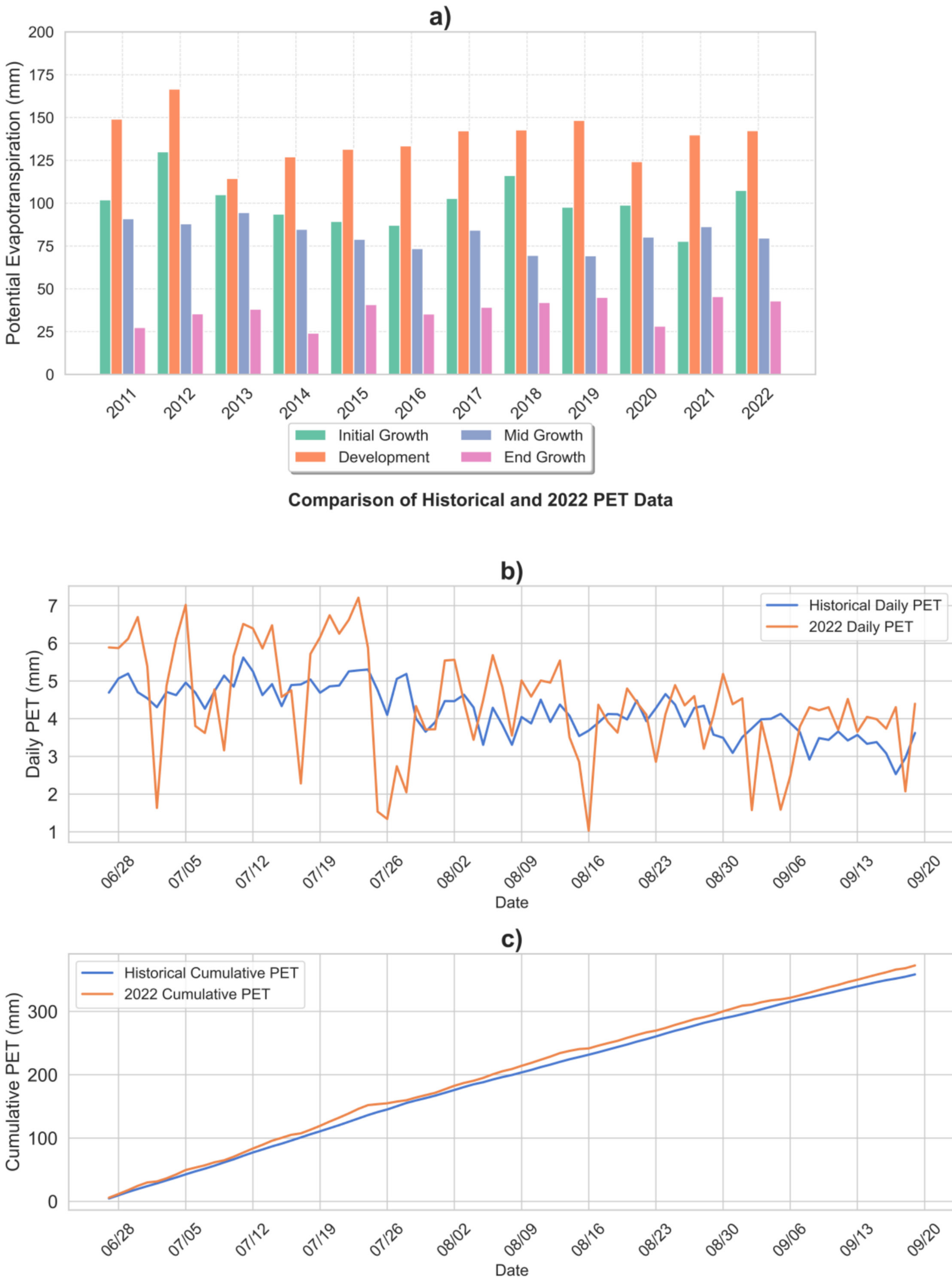

FIGURE 3 | Variability of evapotranspiration. (a) Variability per year and per growth stage. (b) Variability of daily historical average potential evapotranspiration (2011 to 2021) compared to that of the year 2022. (c) Cumulative historical average and year 2022 potential evapotranspiration.

TABLE 3 | Cumulative historical (2011 to 2021) and year 2022 potential evapotranspiration (PET) over the growing season (June 28 to September 5).

Date	6/27	7/7	7/17	7/27	8/6	8/16	8/26	9/5	9/15
Averaged historical PET (mm)	4.69	51.76	101.03	150.26	192.49	231.65	273.29	311.45	346.20
Year 2022 PET (mm)	5.89	57.02	107.48	157.68	200.67	241.57	283.06	319.00	358.01

TABLE 4 | Total irrigation amounts per treatment and average soil VWC at 20 cm depth for the period of July 17 to September 5, 2022.

Treatment	Total irrigation (mm)	Average soil VWC (cm^3/cm^3)
1 (PET)	365	0.36
2 (Crop-ET)	274	0.36
3 (rainfed)	25	0.30

4.4 | Variation in VWC per Irrigation Treatment

Figure 6a,b illustrates water dynamics across different irrigation treatments (PET, Crop-ET and rainfed) in relation to precipitation, evapotranspiration and soil moisture levels. In Figure 6b, the VWC trends indicate that the PET and Crop-ET treatments generally maintain higher VWC values than the rainfed treatment which frequently falls below the water irrigation threshold, indicating limited water availability. Although Crop-ET generally prevents prolonged dry conditions, brief dry periods were observed, particularly on July 27 and August 16. Overall, the soil moisture levels in the Crop-ET treatment remained above the field capacity threshold, which tended toward over-irrigation and reached saturation only after two major rainfall events (Figure 6a).

The rainfed treatment, which relies solely on natural rainfall, frequently fell below the water irrigation threshold (considered at −100 kPa).

4.5 | Crop Performance and Yield

4.5.1 | Number and Weight of Corn Ear

In terms of ear count per hectare (Figure 7a), Crop-ET generally produced the highest counts across varieties, whereas rainfed had the lowest and PET was in between. Peaches and Cream F1 HSE showed the strongest stand performance overall, with medians of approximately 11,300 and 14,000 ears ha^{-1} for PET and Crop-ET, respectively, and the upper values reached ~16,000–18,000 ears ha^{-1}. Ambrosia and H & C were intermediate (typically ~7500 and 9000 ears ha^{-1} and 5000 and 8700 ears ha^{-1} for PET and Crop-ET, respectively), and Temptress was consistently lower, particularly under Crop-ET (~6300 ears ha^{-1}) and rainfed (~5000 ears ha^{-1}).

For the total ear mass (Figure 7b), patterns diverge: Ambrosia had the greatest yield tonnage per hectare under irrigation (medians ~1.30 t ha^{-1} under PET and ~1.70 t ha^{-1} under Crop-ET), indicating larger ears despite only moderate counts. Despite the higher number of kernels per ear, P & C have moderate yield by weight (≈ 0.80 and 1.30 t ha^{-1}, respectively, under PET and Crop-ET), whereas Temptress presents the lowest yield by weight under rainfed (~0.60 t ha^{-1}). Overall, Crop-ET tends to maximize ear numbers, PET is intermediate, and under rainfed, ear numbers are fewer than with irrigation.

Peaches and Cream F1 HSE consistently performed well across all irrigation regimes, particularly under water-limited conditions. The Crop-ET method effectively supports yields for certain varieties including Ambrosia, P & C and H & C. Ambrosia appears more sensitive to water deficits, with notable declines under the rainfed treatments. Peaches and Cream F1 HSE is best when maximising the number of ears harvested, whereas Ambrosia is preferred when prioritising mass yield, underscoring the need to align variety-specific irrigation strategies and cultivars with the intended market outcome.

4.5.2 | Kernel Characteristics and Ear Weight

The average kernel weight varies more by variety than by irrigation as seen in Figure 8a. Temptress is the heaviest (≈ 0.42 g per kernel under PET and rainfed; 0.41 g under Crop-ET), followed by H & C (≈ 0.38–0.39 g across treatments). Ambrosia is intermediate (0.35 g PET; 0.40 g Crop-ET; 0.38 g rainfed), whereas P & C has the lightest kernels (0.32 g PET; 0.33 g under both Crop-ET and rainfed). The treatment effects are modest: within a variety, the range is ≤ 0.05 g per kernel.

Kernels per ear also show a clear varietal ranking (Figure 8b). Ambrosia has the most kernels (600 PET; 550 Crop-ET; 500 rainfed), followed by Temptress (550, 540, 540, respectively), then H & C (500, 490, 490, respectively), and P & C has the fewest (480, 470, 470, respectively). Irrigation mainly shifts counts down from PET to rainfed (e.g., Ambrosia drops ~100 kernels/ear from 600 to 500), but the relative ordering among varieties remains the same.

Overall, kernel count appears to be more responsive to water availability, and the PET treatment generally supports the highest kernel numbers across varieties. Ambrosia displays a strong response to irrigation, particularly regarding kernel count, outperforming the other varieties under both PET and Crop-ET. It even maintains higher kernel counts under rainfed than H & C and P & C, and it is only slightly lower than Temptress.

Ambrosia's average kernel weight, however, decreases under PET, suggesting sensitivity to overirrigation. These findings indicate that while Ambrosia has high yield potential under irrigation, careful management is needed to balance kernel count

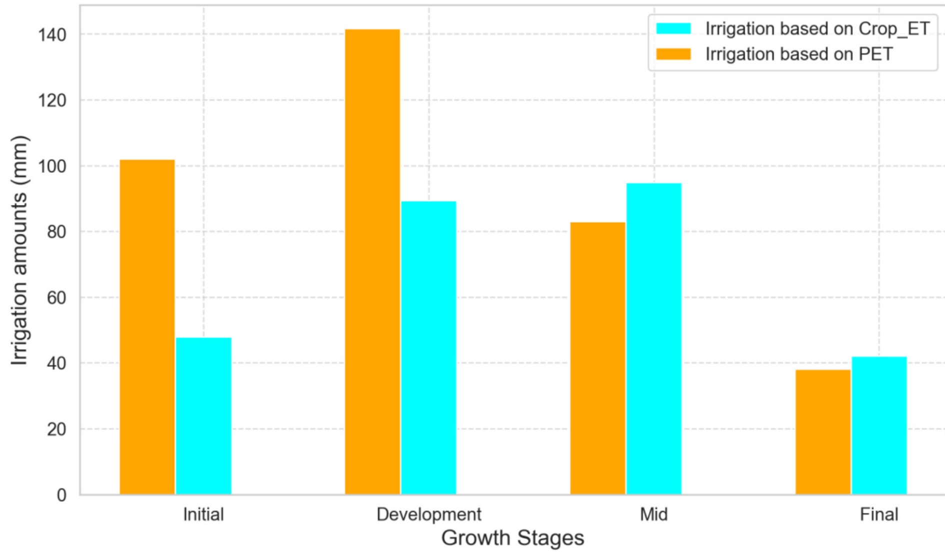

FIGURE 4 | Total irrigation water volume applied per growth stage for the PET and Crop-ET treatments.

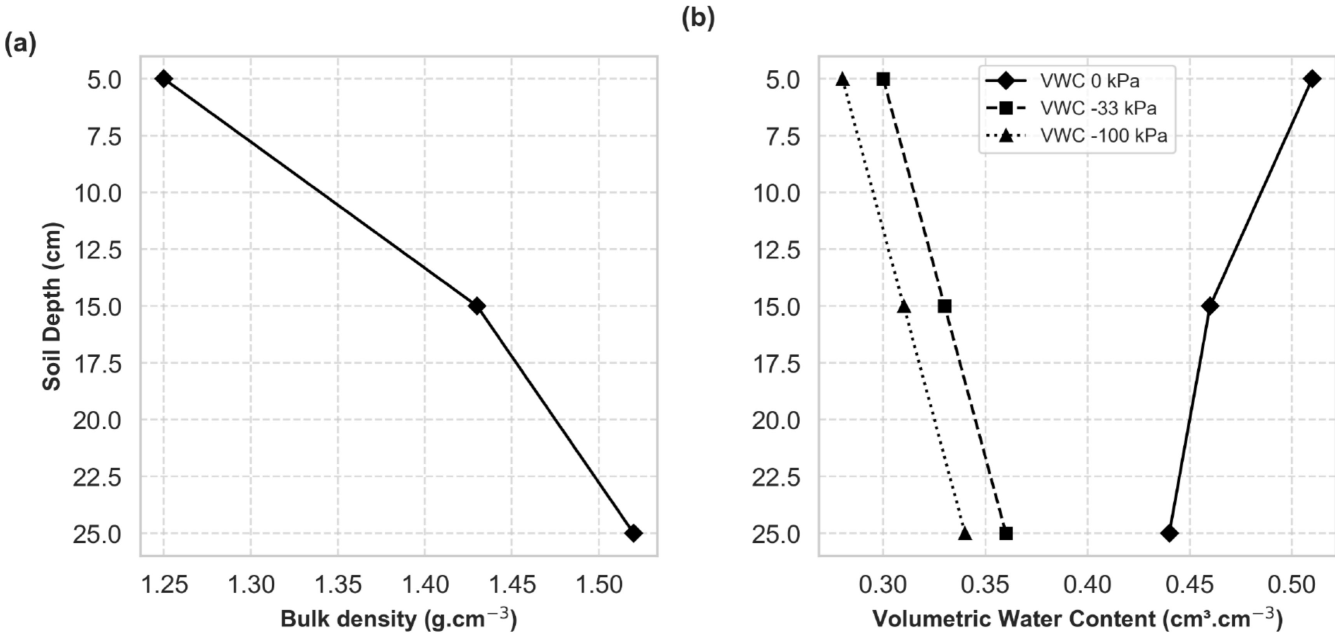

FIGURE 5 | Variations in bulk density (a) and VWC (b) with depth at the study site. The pressure values used in (b) were the pressures used in the laboratory to determine the soil water holding capacity. For VWC 0, no pressure was used, as it is the soil saturation level.

and kernel weight. Therefore, varieties such as Temptress and P & C may be better suited to variable water conditions because of their stable kernel traits across treatments.

4.5.3 | Plant Height and Above-Ground Biomass Analysis

As shown in Figure 9a, total above-ground biomass strongly differed. P & C is consistently the top performer under irrigation, with medians of approximately 4.20 t ha^{-1} for PET and 4.70 t ha^{-1} for Crop-ET, with interquartile ranges of approximately 3.00–5.00 t ha^{-1} and occasionally values above 8 t ha^{-1}. The other varieties cluster much lower: Ambrosia typically centres near 2.00 t ha^{-1} (PET) and 2.40 t ha^{-1} (Crop-ET), Temptress near 1.60 t ha^{-1} (PET) and 2.00 t ha^{-1} (Crop-ET), and H & C approximately 1.70 t ha^{-1} (PET) and 2.20 t ha^{-1} (Crop-ET) across irrigated treatments. Under rainfed, biomass declines for all crops except P & C, which still has a median value of nearly 4.50 t ha^{-1} with a widespread value (~0.50–7.80 t ha^{-1}). The remaining varieties drop to medians near or below 1.00–1.60 t ha^{-1}, underscoring their sensitivity to water deficits.

In Figure 9b, the average plant height mirrors the biomass ranking. P & C is tallest under irrigation, with medians of approximately 1.90 m (PET and Crop-ET), whereas Temptress and H & C follow at ~1.72–1.75 m; Ambrosia is shortest among irrigated plots (~1.65 m). Under rainfed, heights contract overall, but P & C maintains a relatively high median near 1.85m, Temptress is ~1.65m, H & C is approximately 1.60m, and Ambrosia decreases to ~1.5m. Taken together, Figure 9a,b indicates that P & C combines superior height with substantially greater biomass, particularly under irrigation but with notable resilience under rainfed, whereas Ambrosia, Temptress and H & C exhibit lower biomass and shorter plants, with the largest reduction under water limitation.

Collectively, these results confirm that P & C is the most resilient variety in terms of aboveground biomass and plant height across different irrigation strategies. Its ability to maintain productivity under rainfed conditions makes it a promising option for water-limited environments. Ambrosia, while capable of strong performance under full irrigation, shows a marked decline in growth when water is scarce. These findings underscore the importance of matching crop variety to irrigation availability when designing sweet corn production management practices.

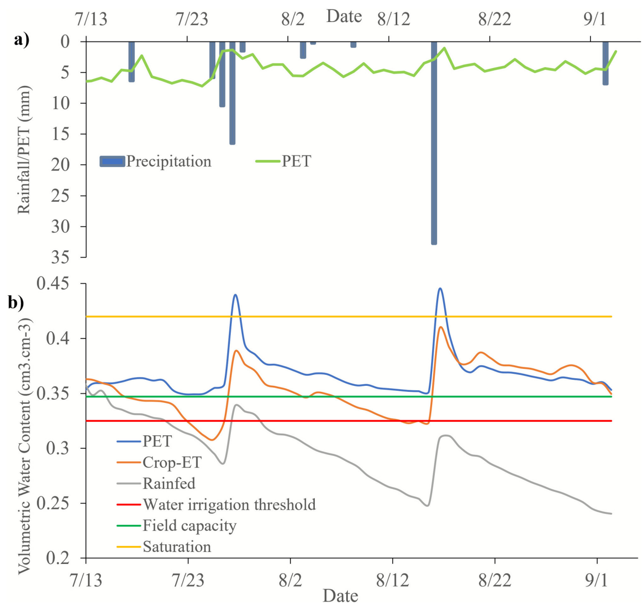

FIGURE 6 | Variations in rainfall and potential evapotranspiration (a) and average soil moisture at a depth of 20cm (b) throughout the growing season across the study site.

4.6 | Sugar Content Variation

Figure 10 illustrates how sugar content varies across irrigation treatments and sweet corn varieties, measured both at harvest and after 10days of freezer storage. At harvest (Figure 10a), P & C presented the highest sugar content across all treatments, confirming its naturally greater sweetness. Ambrosia and Temptress presented similar sugar levels, which were lower than those of P & C but slightly higher than those of H & C.

All the varieties presented relatively similar sugar levels across the three treatments with no drastic differences attributable to irrigation. A slight trend was observed where sugar content was highest under Crop-ET in most varieties. This difference was minor and fell within the error bars; however, indicating that the irrigation treatment did not significantly influence at-harvest sugar content.

Among the varieties, Ambrosia presented greater variability in sugar content at harvest. After 10days of storage at subzero temperatures, a general decline in sugar content was observed across all the varieties (Figure 10b). This was expected as sugars naturally convert to starch over time. Despite the decline, P & C retained relatively high sugar contents compared with those of the other varieties, although the difference became less pronounced after storage. Unexpectedly, for H & C's sugar content after storage increased slightly compared with that at harvest for the PET and rainfed treatments. This could result from the concentration of soluble solids associated with kernel moisture loss.

Similar to the harvest data, the sugar content after storage did not vary significantly across the irrigation treatments. This consistency suggests that the choice of irrigation regime (PET, Crop-ET, or rainfed) had minimal influence on sugar retention during storage. Interestingly, P & C and Temptress resulted in less variation in sugar levels after storage, which may reflect the degree of sugar stability, regardless of irrigation conditions.

These findings suggest that the variability in sugar content for Ambrosia may pose challenges for uniform quality in commercial production. In contrast, P & C and Temptress may

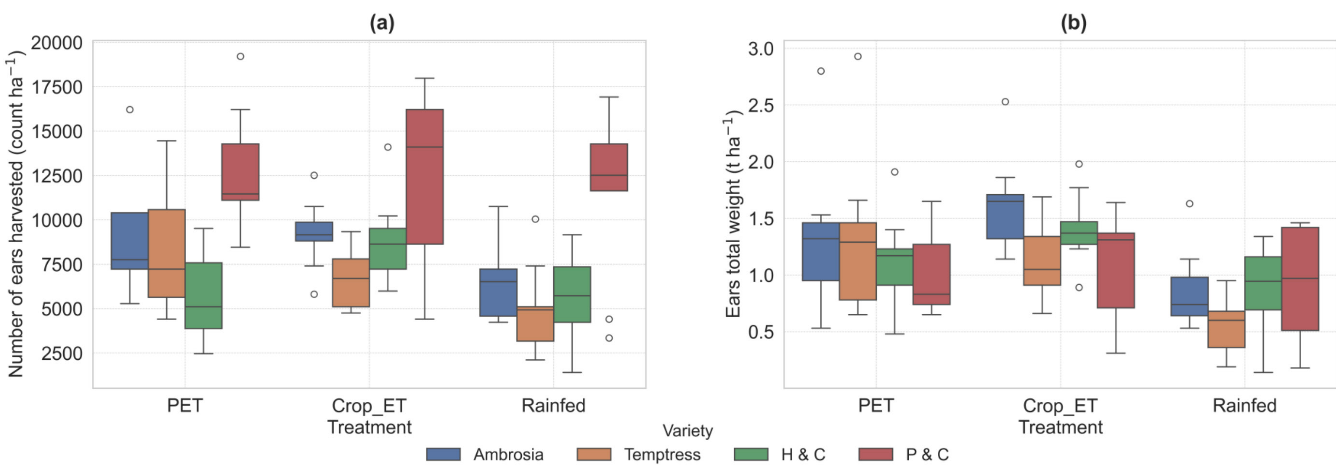

FIGURE 7 | Variability of corn ears harvested on an equivalent hectare area (a) and their total weight, which includes the combined weight of all ears along with the cob (b) per treatment and variety.

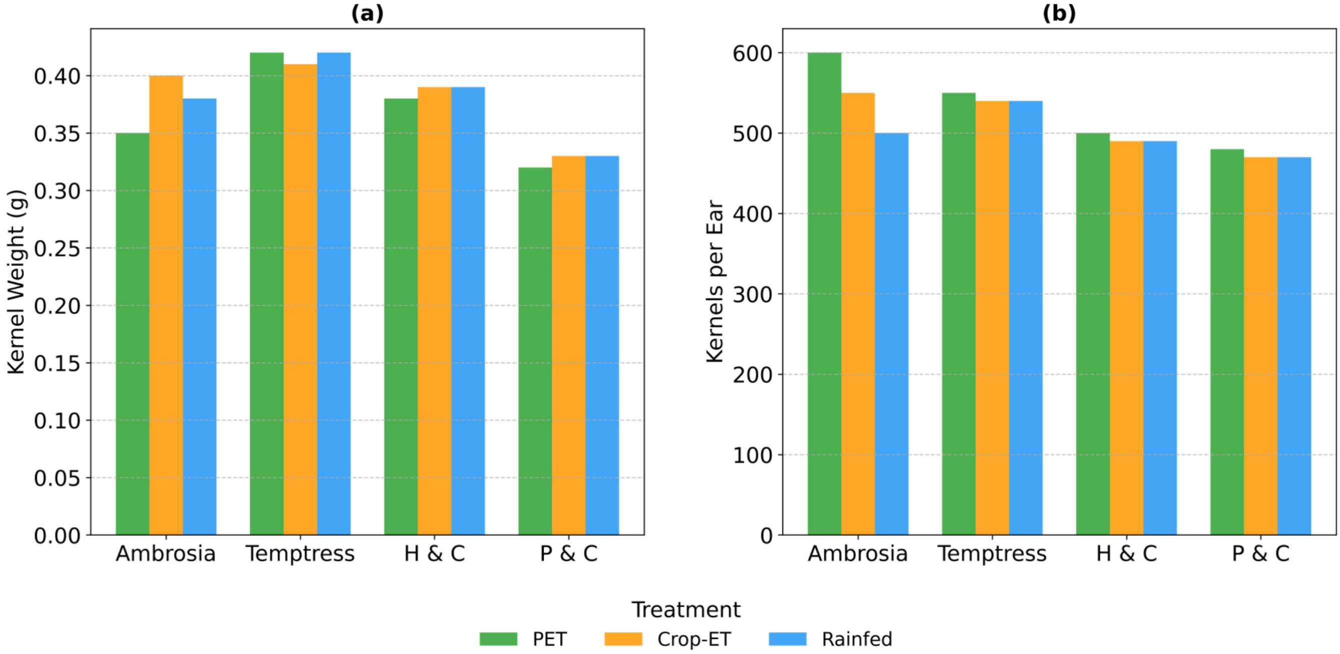

FIGURE 8 | Variability in average kernel weight in grams (a) and the number of kernels per ear (b) per treatment and sweet corn variety.

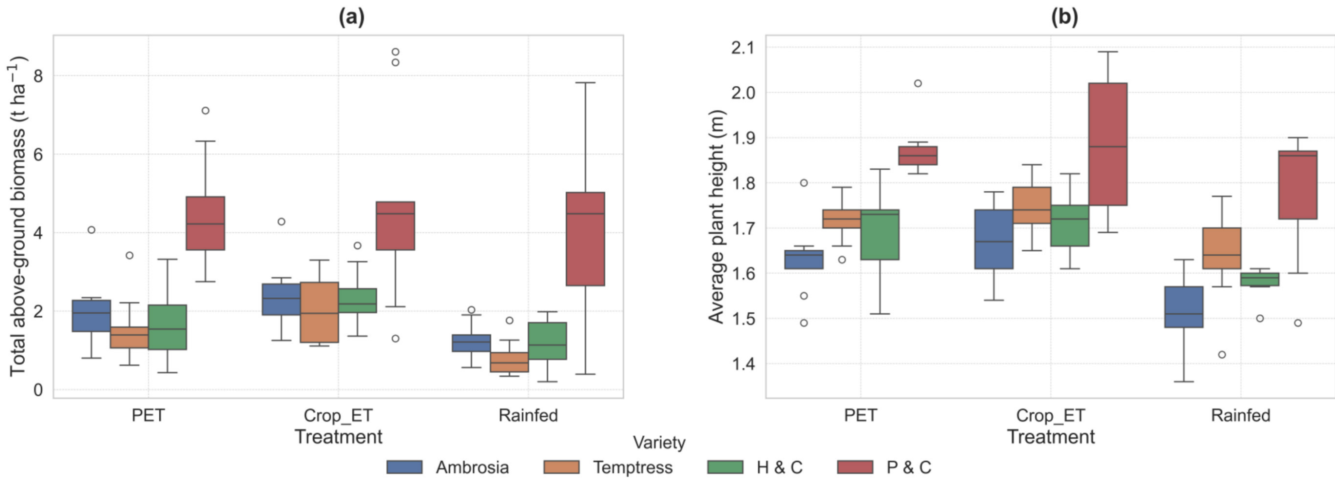

FIGURE 9 | Variability in total aboveground biomass per hectare (a) and plant height (b) per sweet corn variety and per treatment.

offer more consistent sweetness levels, even under variable irrigation or postharvest conditions. These observed varietal differences in sugar loss translate directly to shelf life, sweetness at the point of sale, and therefore market value. Because sweet corn is harvested at high moisture and sugar contents, it respires rapidly; temperature and atmosphere management are the main factors that slow sugar depletion and preserve flavour. Keeping cobs as close as possible to 0 °C and removing field heat quickly (e.g., hydrocooling) slows respiration and helps retain sweetness during distribution, whereas modified/controlled atmospheres (e.g., ~10% O_2/15% CO_2) further limit sugar loss and off-odours when the cold chain is reliable (Becerra-Sanchez and Taylor 2021).

Overall, the irrigation strategy does not significantly impact the sugar content at harvest or after storage. Varietal traits play a more dominant role. For producers focused on sweetness, selecting a high-sugar variety such as Ambrosia can be beneficial, although its variability should be considered. For those prioritising consistency in sugar levels, P & C or Temptress may offer more predictable outcomes across different water availability scenarios. The relatively high sugar levels of P & C at harvest may be attributed to physiological adaptations and stress responses that increase sugar metabolism. Supersweet corn varieties such as Ambrosia, which likely carry the sh2 (shrunken-2) gene, tend to accumulate more soluble sugars because of the increased activity of enzymes such as sucrose phosphate synthase (SPS) and acid invertase during grain filling. This leads to increased sucrose synthesis and retention (Fucheng et al. 2014). Transcriptomic evidence also suggests that sweet corn varieties with elevated sugar levels exhibit upregulation of genes related to carbohydrate metabolism and sugar transport, particularly under environmental stress conditions (Chen et al. 2022).

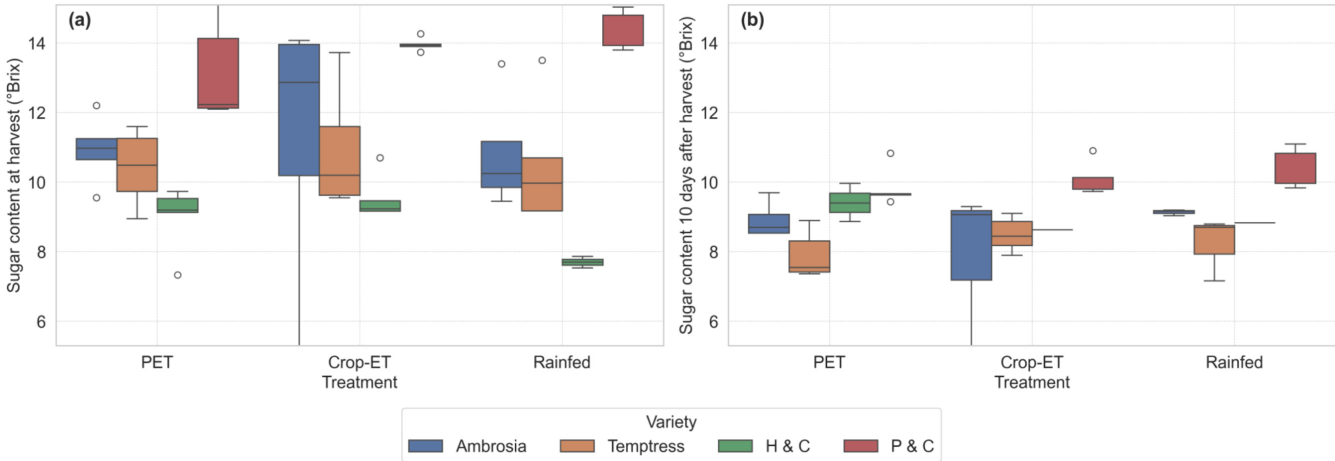

FIGURE 10 | Variation in sugar content per sweet corn variety and per irrigation treatment at harvest (a) and after 10 days of storage in the freezer (b). Brix percentage quantifies the sugar concentration in a liquid solution, denoting the grams of sucrose present in 100 g of the solution or the percentage of sucrose by mass.

TABLE 5 | Pairwise comparisons of irrigation treatments and sweet corn varieties based on Tukey HSD post hoc tests (only statistically significant differences at a significance level of 0.05 are reported in the table).

	Comparison groups (A vs. B)			95% Confidence interval (CI)	
Parameter	**A**	**B**	**Mean difference**	**Low**	**High**
			Treatment		
Total ears weigh per hectare	Crop-ET	Rainfed	0.51	0.31	0.71
	PET	Rainfed	0.40	0.17	0.63
Average plant height	Crop-ET	Rainfed	0.13	0.06	0.19
	PET	Rainfed	0.10	0.04	0.16
			Variety		
Number of ears per hectare	P & C	Temptress	5638.94	3627.44	7650.44
	H & C	P & C	−5398.65	−7440.70	−3356.60
	Ambrosia	P & C	−4126.33	−6096.44	−2156.22
Average plant height	Ambrosia	P & C	−0.25	−0.31	−0.18
	H & C	P & C	−0.17	−0.24	−0.11
	P & C	Temptress	0.15	0.09	0.21
	Ambrosia	Temptress	−0.10	−0.15	−0.04
Total above ground biomass per hectare	P & C	Temptress	2.90	2.03	3.78
	H & C	P & C	−2.58	−3.46	−1.70
	Ambrosia	P & C	−2.50	−3.38	−1.62
Sweetness (at harvest)	H & C	P & C	−4.79	−5.82	−3.77
	P & C	Temptress	3.19	1.99	4.40
	Ambrosia	P & C	−2.81	−4.64	−0.98
	H & C	Temptress	−1.60	−2.86	−0.34
	Ambrosia	H & C	1.99	0.12	3.85
Sweetness (10 days after harvest)	P & C	Temptress	1.97	1.35	2.58

Despite being stored at temperatures below 0 °C for 10 days after harvest, Ambrosia—like the other supersweet corn varieties that carry the sh2 (shrunken-2) gene—presented a noticeable decline in sugar content. This trend aligns with previous studies, which have shown that supersweet corn degrades sugars faster after harvest than varieties with the su (sugary) or se (sugary enhancer) genes do (Wang et al. 2023; Ashoknarayanan et al. 2025). Although subzero storage slows metabolic processes such as sugar-to-starch conversion and senescence, it does not completely halt metabolic processes such as sugar-to-starch conversion and senescence. Fang et al. (2023) emphasized that proper preharvest and postharvest handling, including low-temperature storage, can delay sucrose loss but cannot prevent it entirely. Modified-atmosphere packaging further slows respiration and limits sugar loss. Processors and distributors should thus trial pack designs according to genotype and lane conditions to optimize sweetness and shelf-life.

These findings reinforce the idea that while Ambrosia's sweetness is genetically and metabolically driven, its sugars are more susceptible to post-harvest degradation, especially compared with varieties with su or se backgrounds. Moreover, varieties such as P & C and Temptress may provide greater consistency across both irrigation treatments and post-harvest storage periods because of their slower sugar degradation and potentially more stable metabolic profile.

4.7 | Statistical Analysis of Harvest Variables

The measured harvest variables displayed non-normal distributions and heterogeneous variances, which posed challenges for conventional statistical analysis. To address these issues, a model incorporating both irrigation treatment and variety as factors was applied. This model demonstrated superior performance by capturing the interaction effects and complexities inherent in the data, providing a more nuanced understanding of the outcomes.

The Games–Howell post hoc test results shown in Table 5 reveal statistically significant effects of both irrigation treatment and variety on sweet corn performance. Compared with both the PET and Crop-ET treatments, the rainfed conditions were consistently associated with reduced aboveground biomass, ear weight and plant height, confirming the detrimental effects of water limitation on crop growth and yield. Among the varieties, P & C outperformed all others across multiple traits. It presented the highest biomass production, ear count and sugar content, both at harvest and after 10 days of storage, demonstrating resilience under various irrigation conditions.

In contrast, Temptress and H & C underperformed across several key traits including lower biomass and ear yields. Interestingly, Ambrosia was also found to be significantly shorter in height, suggesting that distinct morphological characteristics may influence its growth and water-use efficiency. These differences highlight how varietal traits can interact with irrigation strategies to shape overall crop performance.

The collective results emphasize the combined influence of irrigation management and varietal selection on sweet corn productivity and quality. The consistent superiority of P & C underscores the importance of genetic adaptability, whereas the poorer performance of other varieties under rainfed conditions confirms the need to match crop types to water availability.

In conclusion, incorporating both treatment and variety effects into the statistical model allowed for more comprehensive data analysis. The findings underscore that irrigation alone does not determine performance; varietal choice also plays a critical role in shaping how crops respond to environmental and management factors.

5 | Conclusion

This study revealed that irrigation strategy and genotype jointly shape sweet corn performance, but genetics dominate quality outcomes. As expected, Crop-ET scheduling better aligns water application with crop demand than does PET—reducing early-season overirrigation and generally producing the highest ear counts—while rainfed conditions decrease yields. Across traits, P & C was the most resilient and productive (biomass, height, ear number), especially under water limitation, whereas Ambrosia produced heavier ears under irrigation but was more sensitive under rainfed conditions. Kernel weight varied mainly by variety, not by irrigation, and kernel number decreased with reduced water. Irrigation had little effect on sugar content at harvest or after storage, and all varieties lost sweetness during frozen storage. Given the heteroscedastic data, Welch's ANOVA and Games–Howell tests confirmed these patterns. In practice, Crop-ET is the preferred scheduling approach, and variety choice should match market goals: P & C for consistent yield and stature under variable water, Ambrosia when maximising mass yield under reliable irrigation, and Temptress/H & C where moderate performance with stable kernel traits is acceptable. The VWC was only monitored at 0–20 cm, a depth that likely captures the majority of crop water uptake. Nevertheless, deeper horizons may contribute to prolonged drought or practices that promote deeper rooting. Although the yield and quality results in this study represent only a single year, inter-year variability was accounted for by utilising a 10-year data for potential evapotranspiration. Further, the experimental design incorporated three replicates per irrigation treatment, with each treatment subdivided into smaller units which provided adequate samples for statistical analysis. This robust structure adequately captured the variability across irrigation types and sweet corn varieties, allowing for reliable conclusions to be drawn. Future work should include additional validation and extend moisture and root profiling to ≥ 60 cm.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data and computer codes used to generate the figures can be requested from the corresponding author. Reasonable accommodation for such requests will be entertained.

References

Ahmad, A., A. Fares, N. V. Hue, et al. 2014. "Root Distribution of Sweet Corn (*Zea mays*) as Affected by Manure Types, Rates and Frequency of Applications." *Journal of Animal & Plant Sciences* 24, no. 2: 592–599.

Ahmed, M., G. Ahmed Taha, K. Ibrahim, M. Mohamed, and H. Z. Elabedeen. 2022. "Evaluation of Digital Brixmeter Performance for Brix Measurement In Raw Sugar Solution." *JES. Journal of Engineering Sciences* 50, no. 3: 1–10. https://doi.org/10.21608/jesaun.2022.115375.1108.

Allen, R. G., L. S. Pereira, and D. Raes. 1998. "Crop Evapotranspiration (Guidelines for Computing Crop Water Requirements)." Irrigation and Drainage Paper No. 56 Rome, Italy.

Ashoknarayanan, S., R. Umarani, C. Vanitha, et al. 2025. "Rapid Depletion of Total Sugars in Stored Sweet Corn Seeds Limits Shelf Life." *Plant Science Today* 12, no. 1. https://doi.org/10.14719/pst.6141.

Becerra-Sanchez, F., and G. Taylor. 2021. "Reducing Post-Harvest Losses and Improving Quality in Sweet Corn (*Zea mays* L.): Challenges and Solutions for Less Food Waste and Improved Food Security." *Food Energy Secur* 10 no. 3. https://doi.org/10.1002/fes3.277.

Camp, C. R. 1998. "Subsurface Drip Irrigation a Review." *American Society of Agricultural Engineers* 41, no. 5: 1353–1367.

Chen, B., S. Feng, J. Hou, et al. 2022. "Genome-Wide Transcriptome Analysis Revealing the Genes Related to Sugar Metabolism in Kernels of Sweet Corn." *Metabolites* 12, no. 12: 1254. https://doi.org/10.3390/metabo12121254.

Dieter, C. A., M. A. Maupin, R. R. Harris, et al. 2018. *Water Availability and Use Science Program Estimated use of Water in the United States in 2015*. Reston.

Erdal, Ş., M. Pamukçu, O. Savur, and M. Tezel. 2011. "Evaluation of Developed Standard Sweet Corn (*Zea mays sacharata* L.) Hybrids for Fresh Yield, Yield Components and Quality Parameters." *Turkish Journal of Field Crops* 16, no. 2: 153–156.

Erwin, A. T. 1951. "Sweet Corn: Mutant or Historic Species?" *Economic Botany* 5: 302–306.

Fang, R., G. Lv, X. Zhang, J. Chen, X. Chen, and B. Wang. 2023. "Preharvest 24-Epibrassinolide Treatment Prolongs Harvest Duration and Shelf Life in Sweet Corn." *Food Chemistry: Molecular Sciences* 7: 100179. https://doi.org/10.1016/j.fochms.2023.100179.

Fucheng, Z., L. Jing Liquan, W. G. Dalei, and L. Weiping. 2014. "Dynamic Change of Sugar Components Accumulation and Enzyme Activity Associated With Sucrose Metabolism During Grain Filling of Super Sweet Corn." *Journal of Nuclear Agricultural Sciences* 28, no. 12: 2230–2237. https://doi.org/10.11869/j.issn.100-8551.2014.12.2230.

Kleinhenz, M. D., and N. R. Bumgarner. 2012. *Using°Brix as an Indicator of Vegetable Quality: An Overview of the Practice, HYG-1650-12*. Ohio State University.

Lamm, F. R. 2005. "SDI for Conserving Water in Corn Production." In *World Water Congress 2005: Impacts of Global Climate Change - Proceedings of the 2005*, 557. World Water and Environmental Resources Congress.

Lamm, F. R., H. L. Manges, L. R. Stone, et al. 1998. "Water Requirement of Subsurface Drip-Irrigated Corn in Northwest Kansas." *Transactions of the ASAE* 38, no. 2: 441–448.

Lamm, F. R., and D. H. Rogers. 2003. *Design Considerations for Subsurface Drip Irrigation (SDI) Systems*. Manhattan.

NASS. 2022. *Crop Production 2021*. Summary: USDA, National Agricultural Statistics Service.

Nuzzo, R. L. 2019. "Histograms: A Useful Data Analysis Visualization." *PM and R* 11, no. 3: 309–312. https://doi.org/10.1002/pmrj.12145.

Sampathkumar, T., B. J. Pandian, and S. Mahimairaja. 2012. "Soil Moisture Distribution and Root Characters as Influenced by Deficit Irrigation Through Drip System in Cotton-Maize Cropping Sequence." *Agricultural Water Management* 103: 43–53. https://doi.org/10.1016/j.agwat.2011.10.016.

Shapiro, S. S., and A. M. B. Wilk. 1965. "An Analysis of Variance Test for Normality (Complete Samples)." *Biometrika* 52, no. 3/4: 591–611.

Singh, M., S. Singh, S. Deb, and G. Ritchie. 2023. "Root Distribution, Soil Water Depletion, and Water Productivity of Sweet Corn Under Deficit Irrigation and Biochar Application." *Agricultural Water Management* 279: 108192. https://doi.org/10.1016/j.agwat.2023.108192.

Soussa, H., and H. K. Soussa. 2010. "Effects of Drip Irrigation Water Amount on Crop Yield, Productivity and Efficiency of Water Use in Desert Regions in Egypt." *Nile Basin Water Science& Engineering Journal* 3, no. 2.

Tracy, W. F. 1993. "Sweet Corn." In *Genetic Improvement of Vegetable Crops*, 777–807. Elsevier.

Wang, J., Q. Yang, J. Han, et al. 2023. "Effect of Nicosulfuron on Dynamic Changes in the Starch-Sugar Interconversion in Sweet Maize (*Zea mays* L.)." *Environmental Science and Pollution Research* 30, no. 21: 59606–59620. https://doi.org/10.1007/s11356-023-26766-z.