



Research article

Yield-related traits and biochemical properties of Thai black sugarcane at different harvest ages

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Abstract

Importance of the work: Black sugarcane is a traditional Thai landrace with medicinal and functional food potential; however, its biochemical traits and their relationships to yield attributes remain poorly characterized.

Objectives: To evaluate the phenolics, anthocyanins and antioxidant activity in the juice and bagasse of Thai black sugarcane, to investigate genotypic variation and to examine the relationships between yield traits and bioactive accumulation.

Materials and Methods: A field trial in Kamphaeng Saen, Thailand was conducted in a randomized complete block design using six genotypes (five black sugarcane landraces and Suphanburi 50). Growth and yield traits were recorded during 4–9 mth after transplanting (MAT) and juice and bagasse samples were analyzed for total phenolics, anthocyanins and antioxidant activity.

Results: Black sugarcane had greater values for stalk length, internode number and stalk number per clump, whereas Suphanburi 50 had larger values for stalk diameter, internode length and single-stalk weight. Black sugarcane accumulated higher phenolics (up to 867 µg gallic acid equivalents (GAE)/mL in juice; 4,966 µg GAE/g in bagasse), anthocyanins (14.5 µg/mL in juice, 34 µg/g in bagasse) and antioxidant activity (>400 µg Trolox equivalents (TE)/mL in juice; approximately 3,600–4,100 µg TE/g in bagasse at mid-maturity), while Suphanburi 50 consistently had the highest soluble solids (18.7°Brix). Stalk length and internode number were positively correlated with phenolics, anthocyanins and antioxidant activity, whereas soluble solids were negatively correlated with internode number and stalk number per clump but positively correlated with stalk diameter and single-stalk weight.

Main finding: Thai black sugarcane is a promising source of health-promoting bioactive compounds, particularly when harvested at 8–9 MAT and the identified trait associations should provide guidance for breeding and utilization strategies that integrate biomass productivity with biochemical quality.

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Introduction

Sugarcane (*Saccharum officinarum* L. or *Saccharum* spp.) is an important economic crop in Thailand and other tropical countries, serving as a major raw material for sugar, bioenergy and diverse by-products such as bagasse, which also holds potential in health and material applications (Kerdchan et al., 2020; Srihanam et al., 2021). Fresh black sugarcane, locally known as Thai medicinal sugarcane, is characterized by its dark purple-to-black stalks and is consumed widely, as well as being used in traditional remedies for sore throat, mouth ulcers (oral inflammation) and for general health promotion (Rattanasuk et al., 2024). Other studies have highlighted its potential as a rich source of bioactive compounds, particularly phenolics and anthocyanins, which contribute to antioxidant activity and health benefits (Duarte-Almeida et al., 2006; Kadam et al., 2008; Abbas et al., 2014).

Phenolics and anthocyanins are well-recognized phytochemicals with strong antioxidant properties, capable of reducing oxidative damage and lowering the risk of chronic diseases such as cardiovascular disease, cancer and diabetes (Duarte-Almeida et al., 2006; Kadam et al., 2008). For example, phenolics from sugarcane juice inhibited lipid oxidation in animal brain tissue (Duarte-Almeida et al., 2006), while juice extracts from several cultivars effectively prevented DNA damage and enhanced antioxidant capacity (Abbas et al., 2014). Bagasse, the fibrous by-product of juice extraction, is used primarily as biofuel and pulp material. However, Srihanam et al. (2021) revealed that it still contains high levels of phenolics and flavonoids with considerable antioxidant activity, suggesting opportunities for value-added utilization in food and health industries.

Comparative studies have reported substantial diversity of anthocyanins in sugarcane rind. For example, Rao et al. (2021) identified 43 anthocyanins in purple rind sugarcane, while Zhao et al. (2018) characterized 13 anthocyanins in red and purple cultivars in China. These findings emphasize the strong influence of genotype on the diversity and accumulation of bioactive compounds. In addition, environmental conditions and harvest age play critical roles. For example, in Ethiopia, sugarcane harvested at 15 mth produced the maximum juice yield and sugar content (Urgesa and Keyata, 2021), while in Egypt, 12 mth was reported as the optimal harvest age for yield and juice quality traits such as stalk height, diameter, weight and total soluble solid content (Ali et al., 2022). Furthermore, dark-stalk-colored varieties, including black sugarcane,

consistently had higher phenolic and anthocyanin contents (leading to greater antioxidant activity) than lighter-stalk-color genotypes (Zhao et al., 2018; Rattanasuk et al., 2024). In Brazil, the phenolic profile of sugarcane juice varied with harvest season and processing, with juice collected in September containing higher phenolic levels and antioxidant activity than in other months, while ohmic heating and ultrasound treatments maintained the phenolic contents and color at levels similar to fresh juice (Rodrigues et al., 2021). A recent review summarized flavonoids and phenolic acids across sugarcane and its by-products, highlighting tricetin, apigenin, luteolin, chlorogenic acid, ferulic acid and caffeic acid as common compounds associated with antioxidant effects (Hewawansa et al., 2024). Nevertheless, quantitative comparisons remain challenging due to differences in extraction and analytical methodologies.

Therefore, it is essential to understand the variation in bioactive compounds in the juice and bagasse of black sugarcane (along with the effects of genotype and harvest age) to be able to develop production strategies and to optimize black sugarcane's economic and nutritional potentials. Such knowledge will support the selection of superior genotypes and determine optimal harvest timing, thereby facilitating the development of black sugarcane-based products in agriculture, nutrition and health-related industries. Other studies have demonstrated that black sugarcane possesses health-promoting properties and contains various bioactive compounds (Feng et al., 2014; Zheng et al., 2017; Ban et al., 2025). However, scientific information on Thai black sugarcane remains limited, highlighting the need for further investigation to bridge this knowledge gap. Accordingly, the current study aimed: 1) to evaluate the phenolic content, anthocyanin content and antioxidant activity in the juice and bagasse of Thai black sugarcane; 2) to investigate the variation among black sugarcane genotypes; and 3) to analyze the relationships between yield-related traits and bioactive accumulation.

Materials and Methods

Experimental site and design

A field experiment was conducted April–December 2022 at the Agronomy Research Station, Department of Agronomy, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Nakhon Pathom, Thailand (14.01°N, 99.58°E; 7.25 m above sea level). The soil was classified as sandy

clay loam with the following chemical properties: pH 6.07, electrical conductivity 5.20 dS/m, organic matter 1.24%, available phosphorus 34.34 mg/kg, exchangeable potassium 87.80 mg/kg, calcium 1,785.09 mg/kg, magnesium 186.80 mg/kg and total nitrogen 0.08 mg/kg. During the experimental period, the average temperature range was 23.69–34.22°C and the total rainfall was 1,155.4 mm.

Sugarcane seedlings were established from setts in 5.1 cm × 15.2 cm polyethylene bags and transplanted into the field at 30 d after planting. The experiment was laid out in a randomized complete block design (RCBD) with four replications. Six genotypes were evaluated, consisting of five Thai black sugarcane landraces (Srithep, Ratchaburi, Udon Thani, Dan Makham Tia, Saraburi) obtained from major production areas and the commercial juice variety Suphanburi 50 as a check.

Plots consisted of six rows, each 15 m in length, with 1.5 m between rows and 0.5 m between hills. Carbofuran granules (3% active ingredient; FMC AG; Bangkok, Thailand) were applied at transplanting for insect control. Compound fertilizer (15–15–15, N–P₂O₅–K₂O) was applied at 312.5 kg/ha twice—first, immediately after transplanting and then at 4 mth after transplanting (MAT). Furrow irrigation was supplied immediately after transplanting, every 10–15 d during the 1–4 MAT period and every 20–30 d thereafter until harvest, with adjustments made based on weather and soil moisture. Weeds were controlled based on hand hoeing at 2 MAT and 4 MAT. No serious outbreaks of pests or diseases were observed, so no additional pesticide applications were required.

Data collection of yield-related traits

Yield-related traits were recorded during 4–9 MAT. Data consisted of stalk length, stalk diameter, internode length, number of internodes per stalk, number of stalks per clump and single-stalk weight. Plants were harvested by cutting at ground level, removing leaf sheaths and topping at the last visible dry leaf sheath. Four clumps were harvested randomly per plot to record total fresh weight and 10 stalks were selected randomly to measure morphological traits and to analyze juice quality.

Juice and bagasse preparation

Each juice sample (0.5 mL aliquot) was extracted with 1.0 mL of 70% ethanol or acidified ethanol (prepared by mixing 95% ethanol 85 mL with 1 N HCl 15 mL). The extracts were centrifuged at 10,000 revolutions per minute for 10 min at 4°C and the supernatants were collected for analysis. For dried

bagasse samples, 0.2 g of ground material was extracted with 9 mL of 70% ethanol (acidified ethanol was used specifically for anthocyanin determination). Each mixture was vortexed, sonicated in an ultrasonic bath for 30 min, passed through Whatman No. 1 filter paper, with each filtrate adjusted to a final volume of 10 mL.

Determination of total phenolic content

The total phenolic content was determined using the Folin-Ciocalteu method (Mohd-Esa et al., 2010). Aliquots of 0.2 mL extracted were mixed with 1.0 mL 10% Folin-Ciocalteu reagent and 0.8 mL 7.5% Na₂CO₃, incubated at room temperature for 30 min, after which the absorbance was read at 765 nm. The results were expressed as micrograms of gallic acid equivalents (GAE) per gram dry weight (DW) for bagasse and per milliliter for juice.

Determination of anthocyanin content

The anthocyanin content was measured using the pH differential method (Lee et al., 2005). Aliquots of 0.5 mL extract were diluted with 0.5 mL KCl buffer (pH 1.0) and CH₃COONa buffer (pH 4.5), incubated at room temperature for 30 min, after which the absorbance was measured in micrograms per milliliter at 520 nm (A₅₂₀) and 700 nm (A₇₀₀). Concentrations were calculated as cyanidin-3-glucoside equivalents, using Equation 1:

$$\text{Anthocyanin} = A \times 449.2 \times \text{DF} \times 10^3 / 26,900$$

(cyanidin-3-glucoside equivalent) (1)

where $A = (A_{520} - A_{700})_{\text{pH } 1.0} - (A_{520} - A_{700})_{\text{pH } 4.5}$, 449.2 is the molecular weight of cyanidin-3-glucoside, DF is the dilution factor and 26,900 is the molar absorptivity of cyanidin-3-glucoside.

Determination of antioxidant activity

The antioxidant activity was analyzed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay (Sittisart et al., 2020). A sample of the extracted solution (100 µL) was mixed with 100 µL of 0.2 mM DPPH solution in microplates, incubated in the dark for 30 min, after which the absorbance was read at 517 nm using a microplate reader. The percentage of DPPH inhibition was calculated using Equation 2:

$$\text{Percentage DPPH inhibition} = (A_{\text{Control}} - A_{\text{Sample}}) / A_{\text{Control}} \times 100$$

(2)

where A_{control} is the absorbance of the DPPH solution mixed with the solvent used for sample dissolution and A_{sample} is the absorbance of the DPPH solution mixed with the sample extract. The percentage inhibition values were compared with a Trolox standard curve (0–50 $\mu\text{g/mL}$; $y = 4.7903x$, coefficient of determination = 0.995). The results were expressed as micrograms Trolox equivalents (TE) per gram DW for bagasse and per milliliter for juice.

Statistical analysis

The data were analyzed using analysis of variance according to a RCBD separately for each harvest age and mean comparisons were conducted using the least significant difference test. Since no anthocyanin was detected in Suphanburi 50 during the early growth stages (4–7 MAT), this variety was excluded from the anthocyanin analysis for those harvest ages. The mean $\pm$ SD were calculated for each genotype at each harvest age. Pearson's correlation coefficients (r) were computed to evaluate the relationships between yield-related traits and bioactive parameters (total phenolic content, anthocyanin content and antioxidant activity, with latter based on DPPH assay). All statistical analyses were performed using the Statistix 8 software (version 8.0; Analytical Software; Tallahassee, FL, USA). Statistical significant was set at $p < 0.05$ for significant differences and $p < 0.01$ for highly significant differences.

Results

Yield-related traits of black sugarcane

Significant differences in yield-related traits were observed between black sugarcane genotypes and the commercial variety Suphanburi 50 during 4–9 MAT (Figs. 1–3). The stalk length of the black sugarcane increased rapidly during 4–6 MAT and continued to increase more gradually, reaching approximately 320–360 cm by 7–8 MAT, before slightly declining at 9 MAT (Fig. 1a). In contrast, Suphanburi 50 remained consistently shorter across the observation period, increasing from about 80 cm at 4 MAT to only around 260 cm by 8–9 MAT (Fig. 1a). The stalk diameter showed the opposite trend, with Suphanburi 50 producing consistently thicker stalks (generally 20–30 mm) than the black sugarcane (mostly 14–19 mm) throughout 4–9 MAT (Fig. 1b). Overall, genotypic differences were evident at all sampling times, indicating superior stalk elongation in the black sugarcane, whereas Suphanburi 50 showed a clear advantage in stalk thickening.

The internode length of the black sugarcane remained relatively stable across 4–9 MAT, generally in the range of approximately 8–11 cm, with only minor temporal fluctuations (Fig. 2a). In contrast, Suphanburi 50 produced consistently longer internodes from 5 MAT onward, increasing to around 12–15 cm and peaking at about 7 MAT before declining slightly toward 9 MAT. The number of internodes per stalk increased markedly with plant age in the black sugarcane, rising from about 20–22 internodes at 4 MAT to approximately 35–42 internodes by 7 MAT, followed by a slight decrease or stabilization at 8–9 MAT (approximately 30–35 internodes), as shown in Fig. 2b. Conversely, Suphanburi 50 maintained substantially fewer internodes throughout the period, remaining near 12–15 internodes up to 7 MAT and increasing only modestly to around 20–22 internodes by 9 MAT. Overall, based on these results, the black sugarcane produced a greater number of internodes, primarily through enhanced node formation, whereas Suphanburi 50 had longer internodes but fewer nodes per stalk.

The stalk number per clump in the black sugarcane was consistently higher than in Suphanburi 50 across 4–9 MAT, remaining relatively stable at approximately 5.5–7.5 stalks/clump, with Sri Thep and Udon Thani generally maintaining the highest tiller numbers (Fig. 3a). In contrast, Suphanburi 50 produced fewer stalks, typically around 4.0–4.9 stalks/clump, with the differences among genotypes being significant at most sampling times, except at 8 MAT when the genotype effect was not significant. Single-stalk weight showed an opposite pattern (Fig. 3b). Suphanburi 50 exhibited a pronounced increase in single-stalk weight with age, rising from values comparable to the black sugarcane at 4 MAT to clearly higher weights from 5 MAT onward, exceeding 1.0 kg/stalk at 7–9 MAT and peaking at approximately 1.5 kg/stalk at 8 MAT. In comparison, the black sugarcane maintained lower single-stalk weights throughout the period, generally within approximately 0.5–0.85 kg/stalk, with only modest changes over time. Overall, based on these results, the black sugarcane achieved greater stalk productivity per clump, primarily via higher stalk number, whereas Suphanburi 50 had greater biomass allocation per stalk, as reflected by its superior single-stalk weight.

Overall, these findings indicated that the black sugarcane possessed advantages in stalk length and stooling capacity, while thicker stalks, longer internodes and heavier single-stalk weight characterized Suphanburi 50. These contrasting traits reflected the distinct yield potential of the black sugarcane landraces compared to the commercial variety.

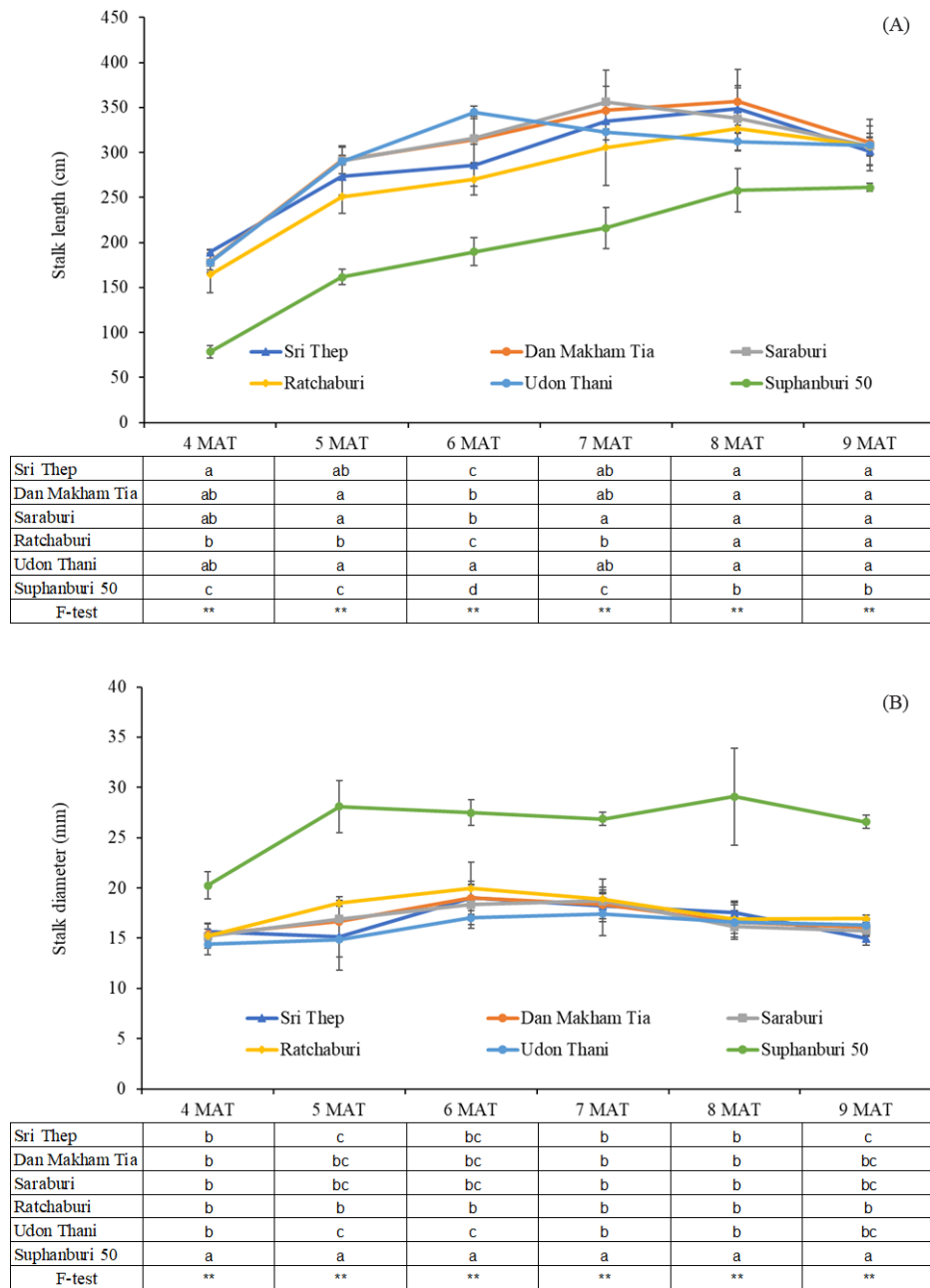


Fig. 1 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): (A) stalk length; (B) stalk diameter. Error bars indicate $\pm$ SD; different lowercase letters in tables indicate significant differences among genotypes within same month; * significant at $p < 0.05$ and ** significant at $p < 0.01$.

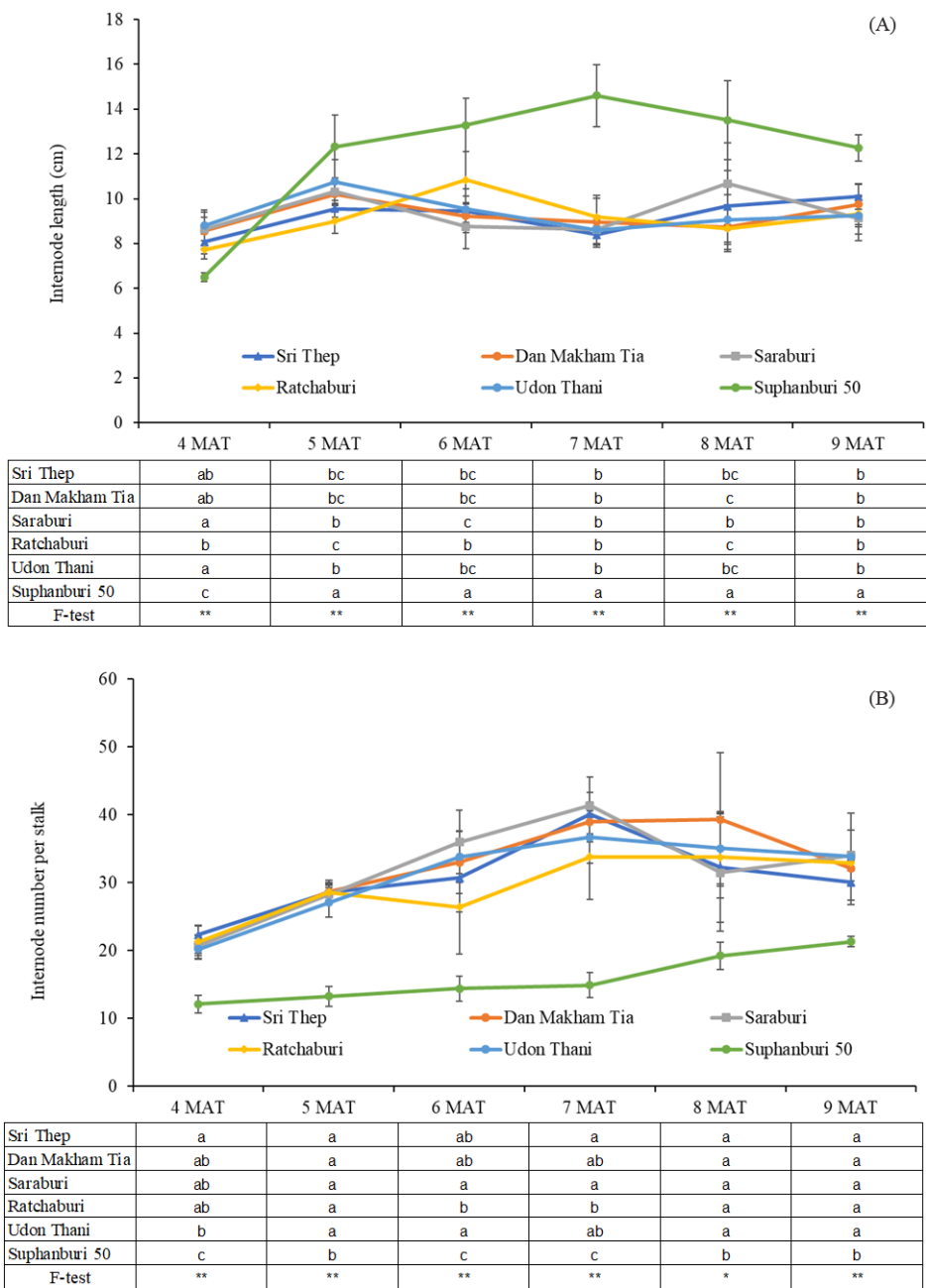


Fig. 2 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): (A) internode length; (B) number of internodes. Error bars indicate $\pm$ SD; different lowercase letters in tables indicate significant differences among genotypes within same month; * significant at $p < 0.05$ and ** significant at $p < 0.01$.

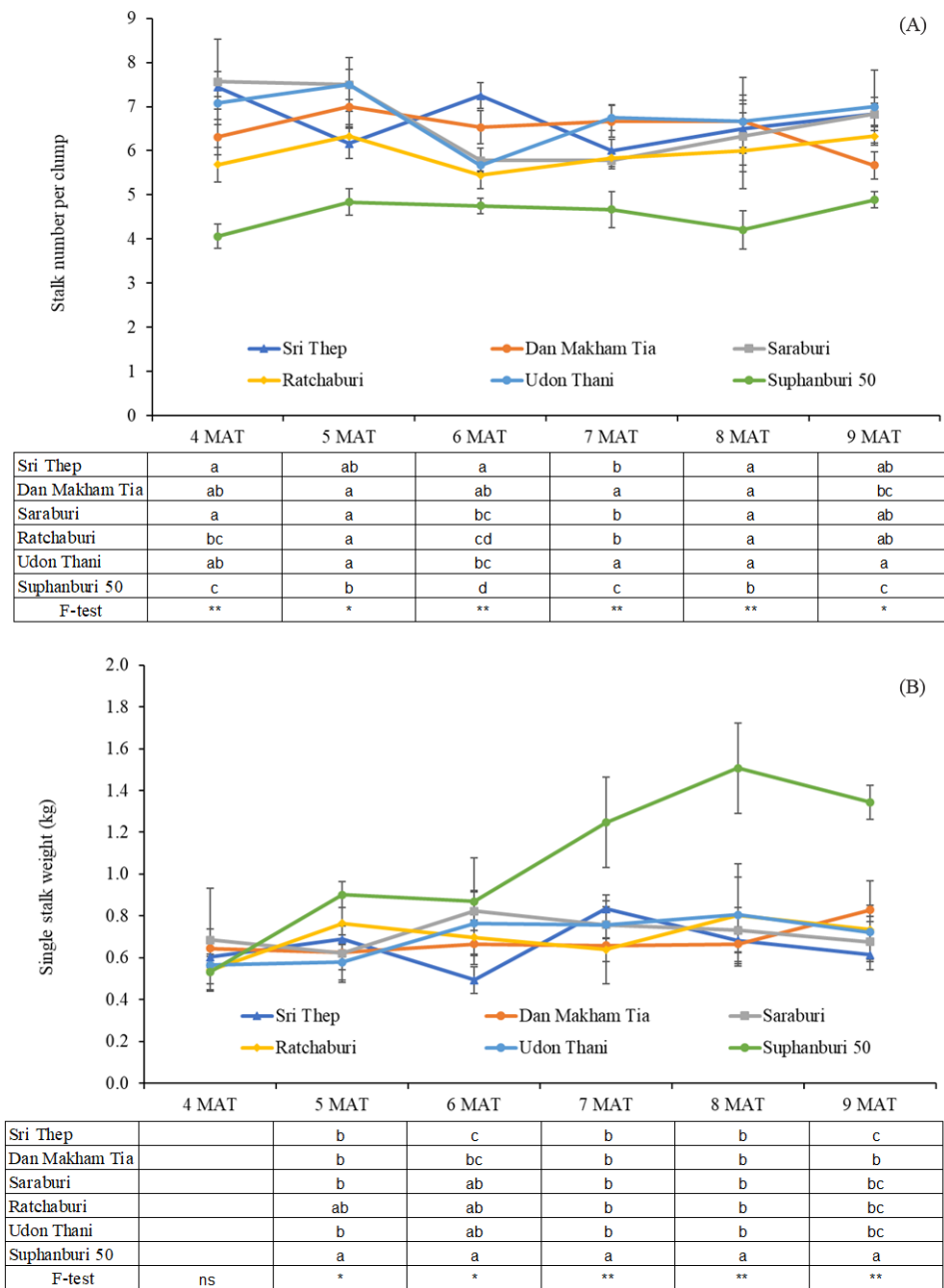


Fig. 3 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): (A) stalk number per clump; (B) single-stalk weight. Error bars indicate $\pm$ SD; different lowercase letters in tables indicate significant differences among genotypes within same month; * significant at $p < 0.05$ and ** significant at $p < 0.01$.

Chemical composition and antioxidant properties of juice and bagasse

Significant differences in biochemical composition were detected among black sugarcane genotypes and Suphanburi 50 across harvest ages, in both the juice and bagasse fractions. In juice, black sugarcane consistently showed higher phenolic concentrations than Suphanburi 50 and increased with maturity, rising from ~300–350 µg GAE/mL at 4 MAT to ~600–700 µg GAE/mL at 9 MAT (Fig. 4a). Dan Makham Tia exhibited the strongest late-stage increase, reaching the highest value at 9 MAT (~850–900

µg GAE/mL), whereas Suphanburi 50 remained markedly lower throughout (~170–380 µg GAE/mL) with only a modest increase at 9 MAT (Fig. 4a). In bagasse, phenolic concentrations were substantially higher than in juice and remained high in black sugarcane across 4–9 MAT, generally >4,000 µg GAE/g and peaking around 5 and 8 MAT (~5,000–5,600 µg GAE/g) (Fig. 4b). Suphanburi 50 consistently recorded the lowest bagasse phenolics (~2,000–2,800 µg GAE/g) and tended to decline toward late maturity. These findings indicate that both genotype and harvest age strongly influence the accumulation of bioactive compounds in black sugarcane, particularly in the bagasse fraction.

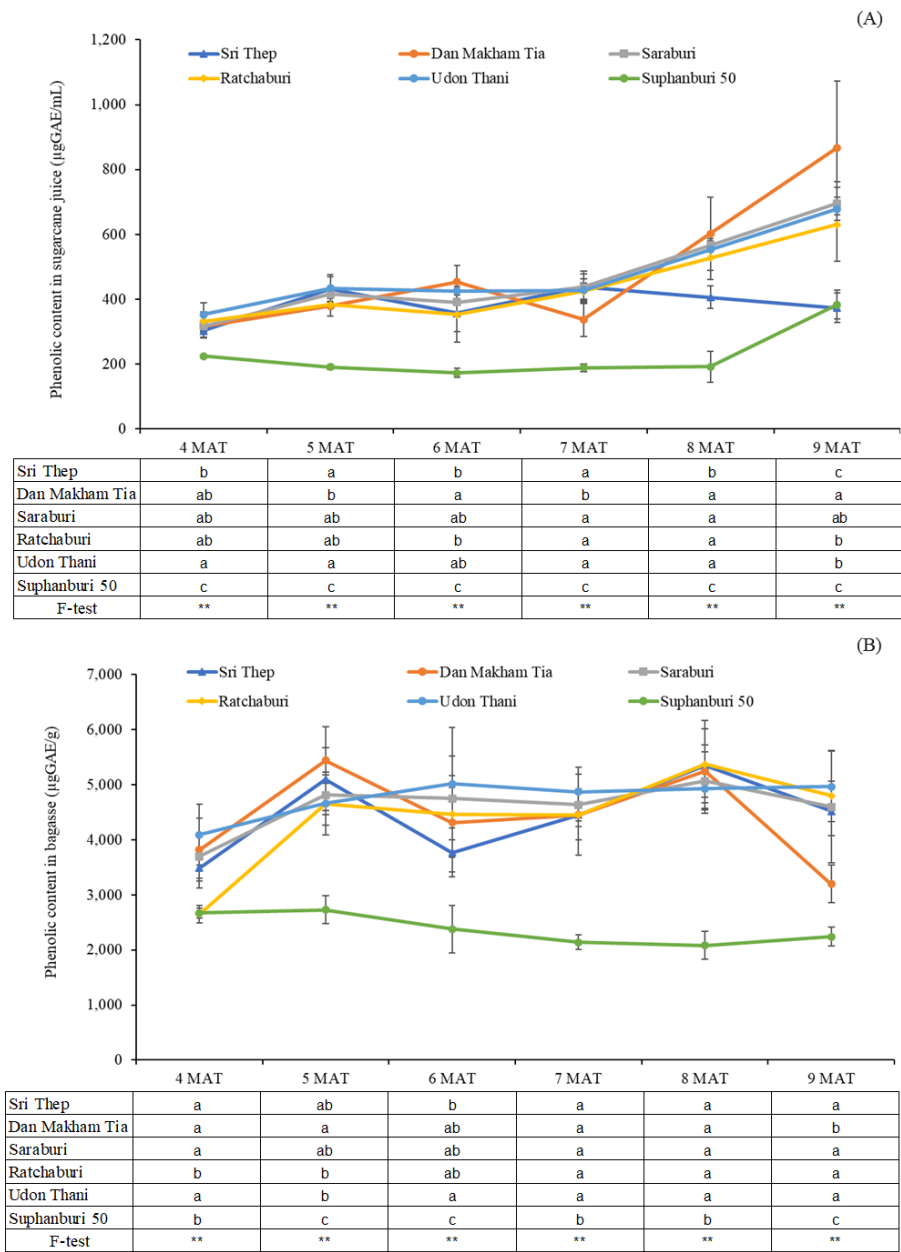


Fig. 4 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): (A) phenolic content in juice; (B) phenolic content in bagasse. Error bars indicate ± SD; different lowercase letters in tables indicate significant differences among genotypes within same month. * significant at $p < 0.05$ and ** significant at $p < 0.01$.

The anthocyanin content varied among genotypes and harvest ages in both the juice and bagasse (Fig. 5). Specifically, the anthocyanin content in the juice of the black sugarcane increased sharply from 4 to 5 MAT (approximately 4–6 to approximately 8–11 $\mu\text{g/mL}$) and then fluctuated within approximately 7–15 $\mu\text{g/mL}$. notably, in the Saraburi variety, the anthocyanin content peaked at 7 MAT (approximately 14–15 $\mu\text{g/mL}$), with several genotypes reaching approximately 11–12 $\mu\text{g/mL}$ at 9 MAT (Fig. 5a). In contrast, Suphanburi 50 had no detectable anthocyanins at 4–7 MAT and only trace levels at 8–9 MAT (~ 1 –2 $\mu\text{g/mL}$). In the bagasse, the anthocyanin concentrations were much higher

than in the juice and increased markedly toward late maturity. Black sugarcane rose from approximately 5–18 $\mu\text{g/g}$ at 4–5 MAT to a clear maximum at 8 MAT (approximately 25–30 $\mu\text{g/g}$), with Saraburi being the highest at 9 MAT (approximately 34 $\mu\text{g/g}$), as shown in Fig. 5b. In contrast, Suphanburi 50 had minimal accumulation, with very low values at 8–9 MAT (approximately 3–5 $\mu\text{g/g}$) and no detectable anthocyanins at earlier stages. Overall, based on these results, both genotype and harvest maturity strongly affected anthocyanin accumulation, particularly in the juice fraction at early to mid-maturity and in the bagasse fraction at later stages.

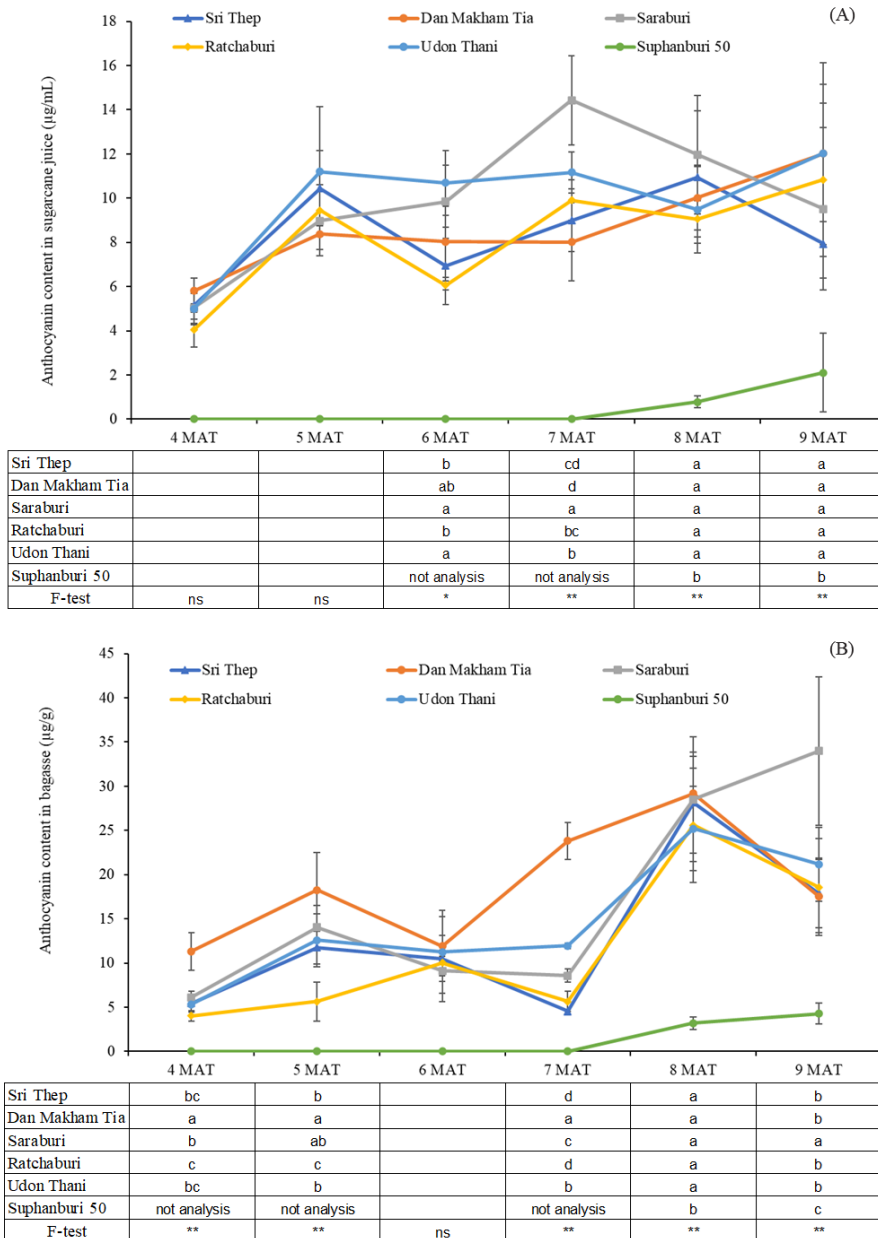


Fig. 5 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): (A) anthocyanin content in juice; (B) anthocyanin content in bagasse. Error bars indicate $\pm$ SD; different lowercase letters in tables indicate significant differences among genotypes within same month; * significant at $p < 0.05$ and ** significant at $p < 0.01$.

The antioxidant activity differed significantly among genotypes across harvest ages in both the juice and bagasse (Fig. 6). In the juice, black sugarcane consistently exceeded Suphanburi 50 and the activity increased with maturity, rising from approximately 100–160 µg TE/mL at 4 MAT to approximately 220–270 µg TE/mL by 7 MAT and reaching approximately 380–420 µg TE/mL at 9 MAT, particularly in the Ratchaburi and Dan Makham Tia samples (Fig. 6a). Suphanburi 50 remained very low at early stages (<30 µg TE/mL at 4–6 MAT) and increased to only approximately 200 µg TE/mL

by 9 MAT. In the bagasse, the antioxidant activity was much higher and peaked at mid-maturity; black sugarcane increased from approximately 1,800–2,700 µg TE/g at 4 MAT to approximately 3,600–4,100 µg TE/g at 5 MAT, then remained at approximately 3,000–3,600 µg TE/g through 9 MAT (Fig. 6b). Suphanburi 50 had consistently the lowest values (approximately 1,400–2,300 µg TE/g), with a pronounced decline at 8 MAT. Overall, the black sugarcane had superior antioxidant capacity in both fractions, with juice activity maximized at late maturity and bagasse activity at mid-maturity.

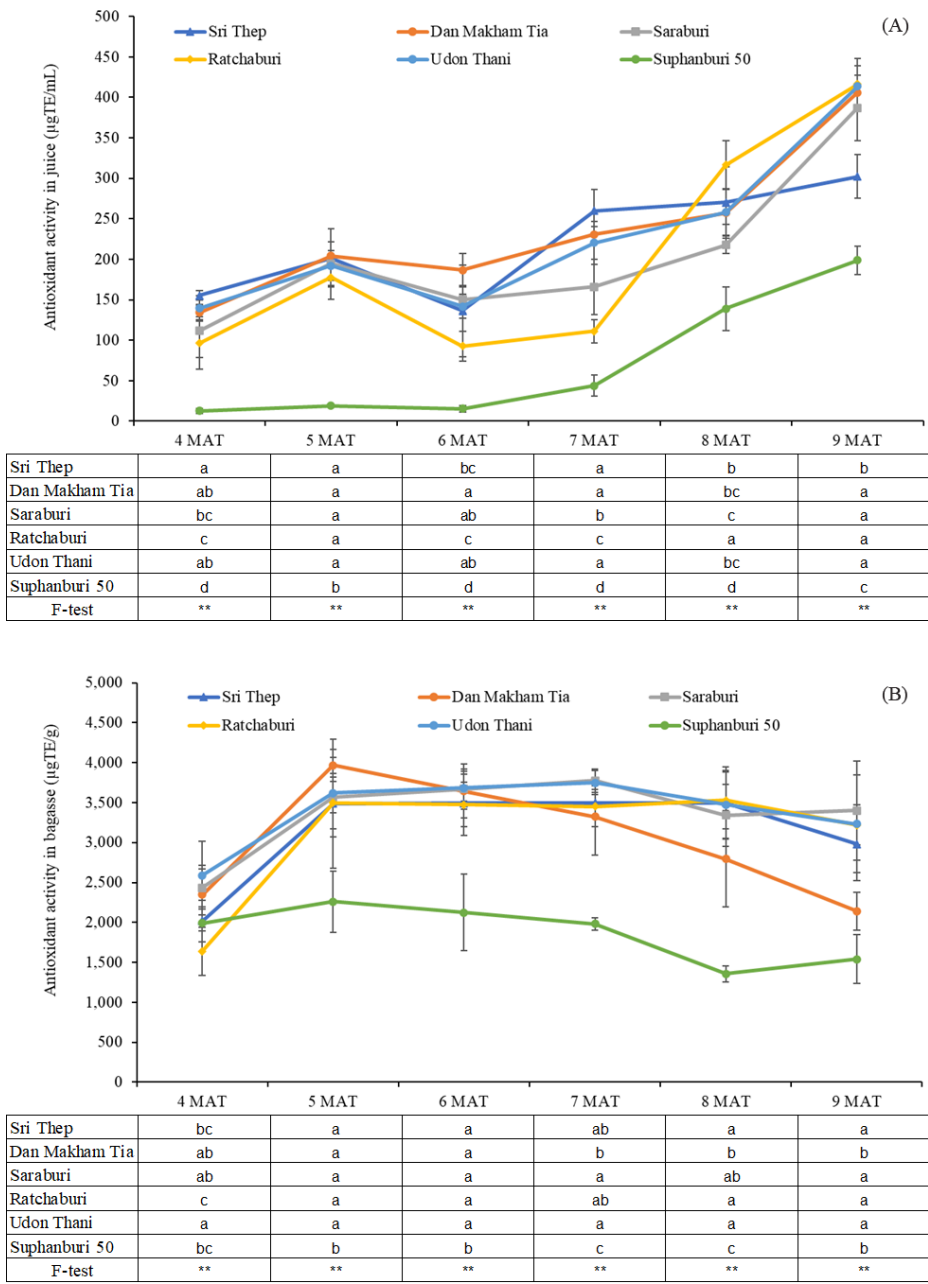


Fig. 6 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): (A) antioxidant content in juice; (B) antioxidant content in bagasse. Error bars indicate ± SD. different lowercase letters in tables indicate significant differences among genotypes within same month. * significant at $p < 0.05$ and ** significant at $p < 0.01$.

The total soluble solids (TSS) contents in the juice differed significantly among genotypes across harvest ages (Fig. 7). Suphanburi 50 had consistent and substantially higher TSS contents than any of the black sugarcane genotypes throughout 4–9 MAT, increasing steadily from approximately 6°Brix at 4 MAT to approximately 19°Brix at 9 MAT. In contrast, the TSS contents in black sugarcane remained low and relatively stable over time, generally in the range from approximately 3–5°Brix, with only minor increases toward late maturity, with the differences among black the sugarcane genotypes being small compared to the clear separation from Suphanburi 50.

Correlations among yield-related traits and biochemical properties

Significant correlations were observed between yield-related traits and biochemical properties (phenolics, anthocyanins, antioxidant activity, total soluble solids) in the juice and bagasse of the black sugarcane and the check variety Suphanburi 50 (Table 1, Table 2, Table 3).

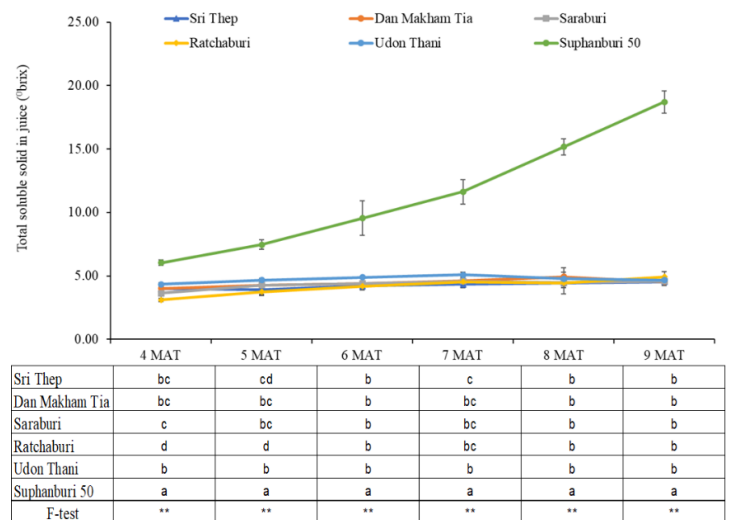


Fig. 7 Black sugarcane and the comparative genotype Suphanburi 50, measured at 4–9 months after transplanting (MAT): total soluble solids contents in juice. Error bars indicate $\pm$ SD; different lowercase letters in tables indicate significant differences among genotypes within same month; * significant at $p < 0.05$ and ** significant at $p < 0.01$.

Table 1 Pearson correlation coefficients among yield-related traits of black sugarcane and comparative genotype across harvest ages ($n = 36$)

	Stalk diameter	Internode length	Internode number	Stalk number	Single stalk weight
Stalk length	-0.26	-0.04	0.90 **	0.32	0.02
Stalk diameter		0.75 **	-0.50 **	-0.76 **	0.77 **
Internode length			-0.42 *	-0.42 *	0.72 **
Internode number				0.44 **	-0.25
Stalk number					-0.62 **

* significant at $p < 0.05$; ** significant at $p < 0.01$.

Table 2 Pearson correlation coefficients among phenolic content, anthocyanin content, antioxidant activity and total soluble solids in juice and bagasse of black sugarcane and comparative genotype at different harvest ages ($n = 36$).

		Sugarcane juice			Sugarcane bagasse		
		Anthocyanin	Antioxidant activity	Total soluble solid	Phenolic	Anthocyanin	Antioxidant activity
Juice	Phenolic	0.64 **	0.81 **	-0.21	0.32	0.62 **	0.20
	Anthocyanin		0.48 **	-0.53 **	0.75 **	0.49 **	0.72 **
	Antioxidant activity			-0.05	0.30	0.67 **	0.13
	Total soluble solids				-0.60 **	-0.24	-0.54 **
Bagasse	Phenolic					0.58 **	0.87 **
	Anthocyanin						0.35 *

* significant at $p < 0.05$; ** significant at $p < 0.01$.

Table 3 Pearson correlation coefficients among yield-related traits, phenolic, anthocyanin content, antioxidant activity and total soluble solids in juice and bagasse of black sugarcane and the comparative genotype across genotypes and harvested ages ($n = 36$).

		Sugarcane juice				Sugarcane bagasse		
		Phenolic content	Anthocyanin content	Antioxidant activity	Total soluble solids	Phenolic content	Anthocyanin content	Antioxidant activity
Stalk length		0.61 **	0.70 **	0.64 **	-0.17	0.69 **	0.56 **	0.69 **
Stalk diameter		-0.55 **	-0.47 **	-0.49 **	0.82 **	-0.69 **	-0.33 *	-0.49 **
Internode length		-0.33 *	-0.32	-0.25	0.71 **	-0.45 **	-0.06	-0.32
Internode number		0.66 **	0.77 **	0.65 **	-0.44 **	0.77 **	0.48 **	0.74 **
Stalk number		0.37 *	0.24	0.44 **	-0.62 **	0.63 **	0.28	0.52 **
Single stalk weight		-0.21	-0.37 *	-0.09	0.88 **	-0.51 **	-0.21	-0.46 **

* significant at $p < 0.05$; ** significant at $p < 0.01$.

For relationships among yield-related traits (Table 1), stalk length was strongly and positively correlated with the number of internodes ($r = 0.90^{**}$). Stalk diameter was positively associated with internode length ($r = 0.75^{**}$) and single-stalk weight ($r = 0.77^{**}$) but negatively correlated with the number of internodes ($r = -0.50^{**}$) and stalk number per clump ($r = -0.76^{**}$). Internode length was positively related to single-stalk weight ($r = 0.72^{**}$) but negatively associated with internode number and stalk number per clump. Stalk number per clump had a significant negative correlation with single-stalk weight ($r = -0.62^{**}$).

For relationships among the biochemical traits (Table 2), the phenolic content in the juice was positively correlated with anthocyanins ($r = 0.64^{**}$) and antioxidant activity ($r = 0.81^{**}$). Anthocyanins were positively associated with antioxidant activity ($r = 0.48^{**}$) but negatively correlated with TSS ($r = -0.53^{**}$). Cross-tissue comparisons revealed that phenolics and anthocyanins in the juice were positively correlated with their counterparts in the bagasse, as well as with bagasse antioxidant activity. Notably, the phenolic content in the bagasse was strongly correlated with antioxidant activity ($r = 0.87^{**}$).

The relationships between yield-related traits and biochemical traits (Table 3) showed that stalk length and internode number were positively associated with bioactive traits in both fractions. Stalk length correlated with the juice phenolics, anthocyanins and antioxidant activity (r range = 0.61^{**} – 0.70^{**}) and with the bagasse phenolics, anthocyanins and antioxidant activity (r range = 0.56^{**} – 0.69^{**}). Internode number had the strongest positive relationships, particularly with the juice anthocyanins ($r = 0.77^{**}$) and with the bagasse phenolics ($r = 0.77^{**}$) and the bagasse antioxidant activity ($r = 0.74^{**}$). In contrast, stalk diameter and single-stalk weight were strongly and positively correlated with TSS ($r = 0.82^{**}$ and 0.88^{**} , respectively) but were negatively related to phenolics or anthocyanins, or both. Stalk diameter was negatively correlated with the juice phenolics ($r = -0.55^{**}$), juice anthocyanins ($r = -0.47^{**}$) and the bagasse phenolics ($r = -0.69^{**}$), while single-stalk weight was negatively associated with the juice anthocyanins ($r = -0.37^{*}$) and the bagasse phenolics ($r = -0.51^{**}$).

Based on these results, stalk length and internode number played important roles in the accumulation of phenolics, anthocyanins and antioxidant capacity, while stalk diameter and single-stalk weight were more closely associated with TSS. This pattern reflected a trade-off between the physical yield attributes and biochemical qualities of sugarcane.

Discussion

This study revealed clear differences in yield-related traits between the black sugarcane genotypes and the commercial variety (Suphanburi 50). The black sugarcane had greater stalk length, internode number and stalk number per clump, whereas Suphanburi 50 had the highest stalk diameter, internode length and single-stalk weight. These contrasting traits reflected underlying genetic differences that determine plant architecture and utilization potential (Jannoo et al., 2017). The morphological profile of the black sugarcane suggested a stronger potential for biomass-oriented utilization, whereas Suphanburi 50 would be better suited for fresh juice beverages and sugar production (Moore, 2005; Jackson, 2005).

Furthermore, the biochemical analyses demonstrated that the black sugarcane accumulated significantly higher levels of phenolics, anthocyanins and antioxidant activity than Suphanburi 50 in both the juice and bagasse. Generally, the sugarcane varieties Dan Makham Tia and Udon Thani were among the higher levels of phenolic compounds and antioxidant activity in the juice, particularly at later maturity. At the same time, Saraburi had prominent anthocyanin accumulation, peaking around mid-to-late maturity. Across harvest ages, the rankings among the black sugarcane genotypes varied, indicating a clear genotype $\times$ maturity influence on bioactive accumulation. In the bagasse, the black sugarcane genotypes consistently produced higher phenolic, anthocyanin and antioxidant activity than Suphanburi 50, with peaks varying depending on harvest age, whereas Suphanburi 50 remained comparatively low. These findings were consistent with other reports that indicated, generally, that dark-colored or landrace sugarcane genotypes had higher phenolic and anthocyanin levels than commercial cultivars (Zhang et al., 2020; Singh et al., 2022). Such bioactive compounds are strongly linked to antioxidant activity and human health benefits (Li et al., 2022; de Oliveira et al., 2023).

In contrast, Suphanburi 50 consistently had the highest TSS values, reflecting its superior sugar quality. This trend corresponded with commercial breeding objectives that have prioritized sugar yield over the enhancement of secondary metabolites (Moore, 2005; Jannoo et al., 2017).

Overall, the black sugarcane genotypes had a strong capacity to accumulate phenolic compounds, anthocyanins and antioxidant activity, with the highest levels generally observed in juice at late maturity (8–9 MAT). In contrast, the commercial variety Suphanburi 50 was characterized by a higher sugar

content (TSS) but substantially lower concentrations of these bioactive compounds, highlighting distinct biochemical profiles between the materials and supporting the potential of the black sugarcane as a source of health-promoting compounds when harvested at an appropriate maturity stage. Notably, the maturity effects differed among the fractions, with the juice phenolics, anthocyanins and antioxidant activity generally increasing toward 8–9 MAT, whereas the bagasse antioxidant activity peaked at mid-maturity (around 5 MAT) and then stabilized or declined, with the bagasse anthocyanin having a pronounced maximum around 8 MAT. Similar maturity-associated increases in phenolics and anthocyanins have been reported in sugarcane and other crops (Wu et al., 2016; Huang et al., 2021).

The correlation analysis revealed significant associations between yield-related traits and bioactive compounds, suggesting a physiological linkage between structural growth and secondary metabolisms in sugarcane. Stalk length and internode number were positively correlated with phenolic, anthocyanin and antioxidant activity in both the juice and bagasse, indicating that genotypes with taller stalks and more internodes tended to accumulate greater amounts of bioactive compounds. In contrast, stalk diameter and single-stalk weight were negatively correlated with these compounds but positively associated with TSS, implying that thicker and heavier canes allocated more carbon toward sucrose synthesis rather than secondary metabolite production.

These findings indicated a metabolic trade-off between carbohydrate accumulation and secondary metabolite biosynthesis (Dixon and Paiva, 1995; Taiz and Zeiger, 2015), consistent with reports in other crops where increased sugar accumulation coincided with a reduction in phenolic or antioxidant contents (Kumar et al., 2019; Ashraf et al., 2021). Therefore, while the black sugarcane genotypes displayed superior potential for phenolic and anthocyanin accumulation, high-yielding varieties, such as Suphanburi 50, prioritize assimilate partitioning toward sucrose deposition, resulting in higher TSS but lower bioactive compound levels.

Evidence from recent sugarcane studies under flooding stress has highlighted the consistent relationships between growth traits, yield and quality. Root dry weight had strong positive correlations with total biomass traits, while the number of adventitious roots was associated with tolerance indices (Maitreemitr et al., 2023). Likewise, cane height and stalk number were positively correlated with cane yield and CCS yield in both plant and ratoon crops (Teinseree et al., 2024). Together, these findings indicate that key morphological traits

are reliable indicators of productivity and quality and can be exploited effectively in sugarcane breeding programs.

In breeding programs, yield-related traits, such as stalk length, internode number and stalk number, can be used as criteria for enhancing bioactive compound accumulation. This aligns with reports that morphological traits could be integrated into phenotypic screening or marker-assisted selection to improve nutritional quality and resilience (Henry and Kole, 2010; Racedo et al., 2016). Conversely, commercial sugarcane cultivars, such as Suphanburi 50, which prioritize sucrose accumulation, represent contrasting breeding objectives. The strategic integration of complementary traits, including high sugar content from commercial cultivars and enhanced bioactive or stress-tolerant characteristics from traditional landraces, provides a promising approach for developing new cultivars that can strengthen sugar industries, expand functional food applications and improve environmental resilience.

Overall, the current study confirmed that black sugarcane has strong potential as a valuable source of phenolics and anthocyanins, which are closely associated with antioxidant activity. Its integration into functional food and nutraceutical applications could diversify utilization beyond conventional juice and sugarcane products. Furthermore, Suphanburi 50, which is widely used for fresh sugarcane juice as a beverage due to its high TSS, remains well-suited for juice-based commercialization. Bridging these contrasting qualities through targeted breeding could contribute to the development of dual-purpose sugarcane cultivars that combine high juice sweetness and quality with enhanced bioactive compound accumulation.

This study revealed distinct differences between Thai black sugarcane and Suphanburi 50 in both yield-related traits and biochemical composition. The black sugarcane had greater stalk length, more internodes and a higher number of stalks per clump, indicating its potential for high biomass production. In contrast, Suphanburi 50 had thicker stalks, longer internodes and heavier single-stalk weight, reflecting its superiority in sugar quality (higher TSS). Biochemically, the black sugarcane accumulated significantly higher levels of phenolics, anthocyanins and antioxidant activity than Suphanburi 50, whereas the latter recorded the highest TSS. Furthermore, correlation analysis demonstrated that stalk length and internode number were positively associated with bioactive compounds and antioxidant capacity, while TSS was negatively correlated with stalk number and internode number but positively associated with stalk diameter and single-stalk weight. These findings underscore the potential

of black sugarcane as a valuable source of health-promoting phytochemicals for functional food and nutraceutical applications and provide a foundation for breeding strategies that integrate both biomass productivity and biochemical quality in sugarcane improvement programs.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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