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Multivariate characterization of defoliation traits in sugarcane genotypes: implications for mechanization-oriented breeding in Thailand

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Abstract

Thailand still burns sugarcane because there are no cultivars with natural leaf shedding for mechanized harvesting. This study used multivariate characterization to identify mechanization-supporting defoliation traits in 28 field-grown sugarcane genotypes in Phitsanulok Province between 2020-2022. Defoliation force (DF), self-defoliation rate (SDR), stem and sheath morphology, sheath detachment ease, and cane surface cleanliness were measured. The study found significant genotypic variation ($P \leq 0.001$) and diverse phenotypes. Principal component analysis reduced 13 quantitative traits to four components that explained 70.1% of variance, with DF and SDR as important, inversely related indicators of mechanization readiness. Using hierarchical clustering, genotypes were classified as favorable (CSB08-101, KK07-599, UT12), resistant (CSB07-184, LK92-11), or intermediate (KK3). Sheath morphology traits (LSW, LST, ASR) were found to have a canonical correlation with defoliation ease, and MANOVA confirmed strong genotype effects ($\eta^2 > 0.90$). Correlation networks confirmed SDR, DF, and qualitative indices as valid selection markers. This study presents the first integrated multivariate framework for assessing defoliation in Thai sugarcane germplasm, emphasizing SDR, DF, and sheath architecture as useful indices for breeding cultivars that are compatible with sustainable, mechanized harvesting systems.

Keywords: sugarcane (*Saccharum officinarum* L.), natural defoliation, mechanized harvesting, multivariate analysis, breeding selection indices.

Introduction

Sugarcane (*Saccharum officinarum* L.) is still a major crop in Thailand and other tropical and subtropical areas, supporting rural economies through sugar, bioenergy, and agro-industrial production. Over 1.7 million hectares are under cultivation, contributing to domestic supply and exports (Yingkamhaeng & Vanichsriratana, 2024). Pre-harvest burning, which is still widely practiced, poses serious risks to health, the environment, and soil quality due to particulate and greenhouse gas emissions (Thuayjan et al., 2022; Chaya, 2024). This "wicked problem" emphasizes the need for sustainable green and mechanized harvesting (Silalertruksa et al., 2022).

Natural defoliation traits, including defoliation force (DF), self-defoliation rate (SDR), sheath detachment ease (LSDE), and cane surface cleanliness (CSCS), have a direct impact on harvester efficiency by reducing clogging and residue accumulation (Huang et al., 2018). Defoliation performance is influenced by differences in cell wall enzyme activity, sheath ultrastructure, and abscission zone development, with higher cellulase and pectinase activity resulting in increased leaf shedding (Hu et al., 2022; Hu et al., 2023; Liang et al., 2024). Thai breeding programs prioritize yield and stress tolerance over defoliation despite reducing pre-harvest burning and improving mechanization.

Due to technical and socioeconomic barriers, the adoption of mechanized harvesting remains slow. Burning is faster and cheaper than cultivar adaptation (Da Silva et al., 2021), which damages canes and stumps (Rungmekarat et al., 2023). Cultivars that are incompatible with mechanization limit incentives (Huo et al., 2022; Mohammed et al., 2023).

Multivariate statistical methods analyze complex, interdependent traits. They show trait correlations and genotypes, unlike univariate tests. PCA and MANOVA studies have identified DF and SDR as major determinants of defoliation performance (Huang et al., 2018; Amador-Sacoto et al., 2025), as well as morphological diversity in sugarcane germplasm (Tesfa et al., 2024). However, a comprehensive multivariate evaluation of defoliation traits in Thai sugarcane has not been carried out, particularly in the mechanization-prone lower north.

This study fills three major gaps: (i) unclear relationships between morphological/physiological attributes and defoliation behavior; (ii) no systematic multivariate analysis of Thai germplasm; and (iii) no genotype classification aligned with mechanization readiness. We proposed that DF, SDR, and LSDE can predict mechanization potential and categorize genotypes into functional groups. Field trials were carried out over two seasons (2021-2022) to test trait stability in the face of climatic variability. The goals were to: (i) identify key defoliation traits influencing mechanization suitability, (ii) categorize genotypes into trait-based groups, and (iii) provide selection indices to help Thailand transition from pre-harvest burning to sustainable, mechanized sugarcane production.

Results

Phenotypic variation in stem, leaf, and defoliation traits

All traits showed significant genotypic variation ($P \leq 0.001$), confirming the broad phenotypic diversity of the 28 sugarcane genotypes (Supplementary Tables S1-S3). The number of internodes, stem diameter, and sheath rupture geometry varied greatly, indicating distinct structural mechanics influencing the ease of detachment. The self-defoliation rate (SDR) varied between 13% and 36%, while the detachment force (MDF) varied more than twice as much across genotypes. Shannon diversity indices also indicated a wide range of qualitative traits, including leaf senescence and sheath persistence. These findings provide a phenotypic foundation for subsequent multivariate analyses.

Principal component analysis (PCA)

Thirteen quantitative traits were reduced to four principal components that explained 70.1% of the total variance (Table 4). PC1 (27.7%) represented defoliation traits, positively loaded for DF (0.403) and MDF (0.165), but negatively loaded for SDR (-0.445), SDN (-0.442), LSR (-0.348), and ASR (-0.285), distinguishing tight-sheath, high-resistance genotypes from easily shed ones. PC3 (9.5%) had stalk strength (SD 0.526) and sheath structure (LSW -0.538), while PC2 (13.9%) had biomass traits (MDF 0.566, NDLN 0.383, SD 0.366).

The biplot (Figure 1) classified genotypes into three groups: resistant (LK92-11, CSB07-184) with high DF and low SDR, favorable (CSB08-101, KK07-599, UT12) with low DF and high SDR, and intermediate (KK3). Some, such as CSB10-89 and KKU99-03, diverged along PC2 due to high leaf biomass (GLW, SLW, NDLN), implying that excess canopy may impede mechanized harvesting despite high defoliation potential.

Overall, SDR and DF were the best predictors of mechanization suitability, whereas biomass traits influenced residue management and harvest efficiency.

Agglomerative hierarchical clustering (AHC)

Ward's clustering of the 28 genotypes using SDR, SDN, and DF resulted in three clusters (Figure 2). Cluster 1 (favorable) had SDR of 32.9 ± 0.3% and DF of 14.3 ± 0.1 N (CSB08-101, KK07-599, UT 12). Cluster 2 (resistant) had SDR 18.4 ± 0.6% and DF 23.2 ± 0.1 N (CSB07-184, CSB10-458, and TBy28-0348). Cluster 3 (intermediate) consisted of KK3 and other commercial cultivars with moderate SDR (22.8 ± 0.3%) and DF (18.6 ± 0.1 N). These separations prove SDR, SDN, and DF are good selection indices for mechanization-ready genotypes.

Multivariate analysis of variance (MANOVA)

MANOVA confirmed highly significant genotype effects (Wilks' $\lambda = 0$; $P < 0.001$; Pillai's trace = 6.96; $P < 0.001$) with very large effect sizes ($\eta^2 > 0.90$; Table 5). Variation extended beyond individual traits like SDR and DF to correlated complexes that include stem, leaf, and defoliation characteristics. These strong multivariate signals indicate that defoliation traits are interdependent and genetically regulated, justifying the use of multivariate approaches (PCA, CCA, AHC) for accurate characterization. Agreement among multiple MANOVA tests reinforced result reliability and the necessity of multivariate frameworks for breeding focused on mechanization traits.

Clustered heatmap

The correlation heatmap in Figure 4 revealed that stem, leaf, and defoliation traits were all highly correlated. The significant negative correlations shown by SDR and SDN with DF ($r = -0.72$) and MDF ($r = -0.68$) confirmed that genotypes with higher natural shedding require less detachment force. The presence of a distinct, moderately linked module ($r > 0.60$) composed of biomass traits (GLW, SLW, and NDLN) suggests that high biomass does not always translate into easier defoliation. As fast, field-based mechanization suitability measures, LSDE and CSCS correlated positively with SDR. The combined quantitative and qualitative correlations connect structure, biomass, and defoliation efficiency, and SDR, DF, and qualitative scores serve as useful indicators for selecting genotypes suitable for mechanized harvesting.

Discussion

This study found significant genetic variation in sugarcane defoliation traits, which affect stem and sheath morphology and mechanization suitability. Self-defoliation rate (SDR), self-defoliating number (SDN), and defoliation force (DF) were consistently identified as key predictors, demonstrating the trade-off between natural leaf shedding and mechanical resistance. These findings support previous research on the role of leaf-sheath adherence in harvestability (Huang et al., 2018) and extend it by combining quantitative descriptors like stalk diameter, sheath thickness, and rupture angle with qualitative field proxies to provide a comprehensive selection framework (Misra et al., 2020; Liang et al., 2024).

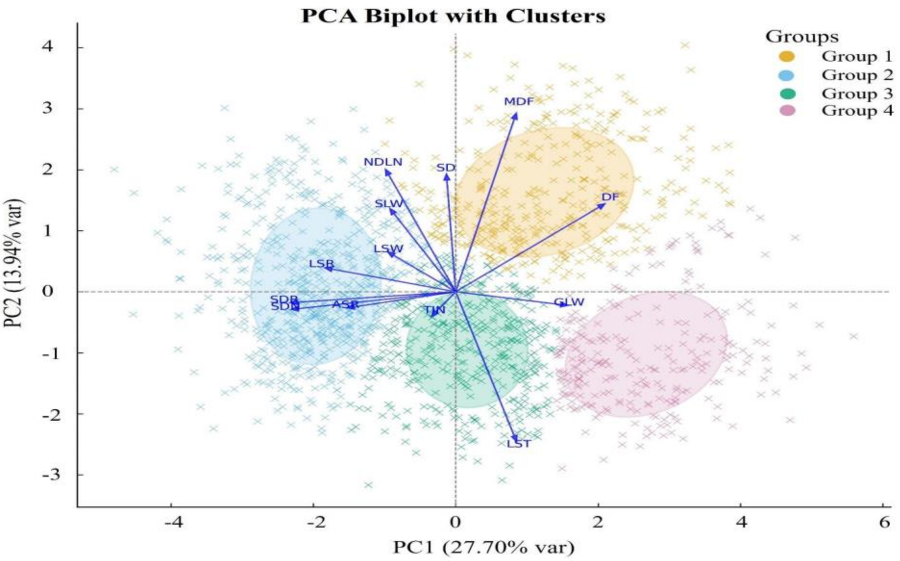
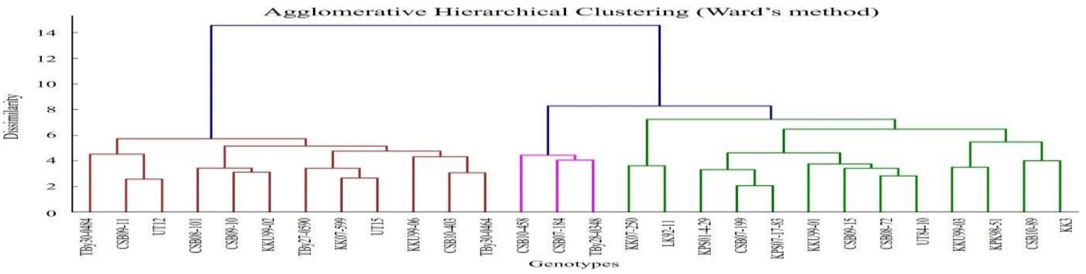


Fig. 1. Principal component analysis (PCA) biplot of sugarcane genotypes based on stem, leaf, and defoliation traits (combined across two years, 2021–2022). Vectors indicate trait loadings, while colored ellipses represent four distinct genotype clusters identified by hierarchical clustering on principal components (HCPC). PC1 and PC2 explained 27.70% and 13.94% of the total variance, respectively.



Cluster 1 (Brown)	Cluster 2 (Pink)	Cluster 3 (Green)
SDR: 32.88 ± 0.29	SDR: 18.42 ± 0.59	SDR: 22.83 ± 0.30
SDN: 8.26 ± 0.08	SDN: 4.62 ± 0.15	SDN: 5.90 ± 0.08
DF: 14.27 ± 0.09	DF: 23.22 ± 0.14	DF: 18.55 ± 0.10
Genotypes: CSB08-101, CSB09-10, CSB09-11, CSB10-403, KK07-599, KKU99-02, KKU99-06, TBy27-0590, TBy30-0464, TBy30-0484, UT12, UT15	Genotypes: CSB07-184, CSB10-458, TBy28-0348	Genotypes: CSB07-199, CSB08-72, CSB09-15, CSB10-89, KK07-250, KK3, KKU99-01, KKU99-03, KPK98-51, KPS01-4-29, KPS07-17-83, LK92-11, UT84-10

Fig. 2. Agglomerative hierarchical clustering (AHC) dendrogram of 28 sugarcane genotypes using Ward's method and Euclidean distance (combined across two years, 2021–2022). The grouping was based on three key defoliation-related traits; stalk dry matter ratio (SDR), stalk dry matter (SDN), and detachment force (DF). Genotypes were clustered into three groups (Cluster 1 = brown, Cluster 2 = pink, Cluster 3 = green), each showing distinct patterns of natural defoliation. Mean values (±SE) of SDR, SDN, and DF are presented for each cluster, together with the list of genotypes comprising the respective groups.

Multivariate analyses revealed the structural basis of variation: genotypes with high SDR and low DF differ sharply from resistant types, resulting in distinct harvestability syndromes. This pattern is consistent with observations in cereals such as maize and sorghum, where leaf shedding and stalk strength define mechanical adaptability (Baye et al., 2022; Parra et al., 2025). In sugarcane, sheath architecture, rather than discrete abscission zones, determines defoliation ease via thickness, rupture angle, and surface coverage (Mou et al., 2013; Liang et al., 2024). These morphological indicators thus serve as useful, quick field screening tools for breeding programs in resource-constrained environments (Furbank et al., 2019; Khadka et al., 2020).

Cluster analysis classified genotypes as favorable, resistant, or intermediate, resulting in clear breeding implications. Favorable genotypes (e.g., CSB08-101, KK07-599) exhibited high SDR and low DF, a rare phenotype among commercial checks such as KK3. Resistant genotypes reflect long-standing traditional ideotypes, whereas intermediates have the potential for gradual improvement. Mechanization traits have historically been undervalued in yield and disease resistance, as shown by similar groupings in Brazilian and Indian germplasm (Huang et al., 2018).

The findings are also consistent with sustainability goals. Genotypes with high self-defoliation capacity provide a biological solution to reduce pre-harvest burning and support Thailand's "No-Burn" and Bio-Circular-Green (BCG) initiatives (Keil et al., 2020; Krishnapriya et al., 2024). Selecting such cultivars improves harvester efficiency, lowers labor costs, and reduces environmental impact (Wang et al., 2023; Lin et al., 2024; Pan et al., 2024).

Table 1. Origin, genotype, parentage, and harvesting time (months after planting, MAP) for 28 sugarcane genotypes, including one with intermediate defoliation tolerance (KK3) and another with low tolerance (LK92-11).

Origin[a]	Genotype name	Parentage	Maturity class (MAP)[d]
OCSB	CSB07-184	Kps98-024 × Kps01-8-8	Medium
OCSB	CSB07-199	Kps98-024 × Kps01-8-8	Medium
OCSB	CSB08-101	K98-291 × U-Thong 4	Medium
OCSB	CSB08-72	K98-291 × U-Thong 4	Late
OCSB	CSB09-10	K99-72 × K88-82	Medium
OCSB	CSB09-11	K99-72 × K88-82	Early–Medium
OCSB	CSB09-15	K99-72 × K88-82	Late
OCSB	CSB10-403	M13-58 × K84-365	Medium
OCSB	CSB10-458	Q79 × E-heaw	Medium
OCSB	CSB10-89	K83-74 × ROC 1	Late
OCSB	KPK98-51	K84-200 × K92-165	Medium
KKFCRC	KK07-250	KK1 selfed	Early–Medium
KKFCRC	KK07-599	90-2-043 × U-Thong 6	Medium
KKU	KKU99-01	K83-74 × H59-3755	Late
KKU	KKU99-02	U-Thong 1 × Chai-nat 1	Medium
KKU	KKU99-03	UT1 × Chai-nat 1	Medium
KKU	KKU99-06	B43-62 × Chai-nat 1	Medium
KU	KPS01-4-29	KPS94-13 × KPS98-2-081	Medium
KU	KPS07-17-83	KPS94-13 × K84-200	Medium
KU	TBy27-0590	K84-200 × U-Thong 1	Medium
KU	TBy28-0348	U-Thong 4 × TBy20-1300	Medium
KU	TBy30-0464	TBy26-1255 × LK92-11	Medium
KU	TBy30-0484	TBy26-1255 × LK92-11	Medium
SPFCRC	U-Thong 12, UT12	SPR80 × U-Thong 3	Medium
SPFCRC	U-Thong 15, UT15	U-Thong 12 selfed	Early–Medium
SPFCRC	U-Thong 84-10, UT84-10	97-2-535 × 94-2-128	Medium
KKFCRC	*Khon Khen 3, KK3* [b]	85-2-352 × K84-200	Early–Medium
OCSB	*LK92-11* [c]	K84-200 × E-heaw	Medium

[a] KU: Kasetsart University Kamphaeng Saen Campus, KKU: Khon Kaen University, KKFCRC: Khon Kaen Field Crops Research Center, SPFCRC: Suphan Buri Field Crops Research Center, and OCSB: Office of Cane and Sugar Board.

[b] Khon Khen 3 (KK3) exhibited intermediate tolerance to natural defoliation. [c] LK92-11 exhibited low tolerance to natural defoliation (i.e., leaves remained tightly attached). [d] Maturity classes: Early = 10–11 MAP, Medium = 12–13 MAP, Late = 14–15 MAP, “Early–Medium” indicates a harvest window spanning 10–13 MAP depending on site-year.

Table 2. Qualitative defoliation traits of sugarcane genotypes and scoring methods.

Trait	Abbreviation	Description	Scoring (1–5)	Measurement Method / Unit
Leaf Senescence Pattern	LSP	Degree and distribution of leaf drying across the canopy	1 = minimal drying, 2 = mild drying, 3 = moderate drying, 4 = extensive drying, 5 = complete drying	Visual assessment of whole plant
Leaf Color at Senescence	LCS	Predominant leaf color at shedding	1 = green, 2 = green-yellow, 3 = yellow, 4 = yellow-brown, 5 = dark brown	Visual observation of blade & sheath
Leaf Sheath Detachment Ease	LSDE	Ease of sheath detachment from stalk	1 = very difficult, 2 = difficult, 3 = moderate, 4 = easy, 5 = very easy	Manual detachment test
Cane Surface Cleanliness	CSCS	Degree of stalk cleanliness after leaf drop	1 = heavily covered, 2 = moderately covered, 3 = partially clean, 4 = mostly clean, 5 = completely clean	Visual inspection
Persistence of Leaf Sheath Layers	PLSL	Number and compactness of retained sheath layers	1 = very thick, 2 = thick, 3 = moderate, 4 = few, 5 = minimal/none	Count and visual assessment

While two-year data increased reliability, a single-site design may not fully capture genotype-environment interactions. Environmental factors like temperature, humidity, and fertility affect leaf senescence and shedding. Future multi-location trials are required to validate the identified indices. The genetic basis of these traits warrants further investigation using transcriptomic and genomic tools (Li et al., 2016; Wu et al., 2025), which could speed up molecular breeding for mechanization-compatible cultivars.

To summarize, sugarcane defoliation is a multivariate phenomenon influenced by both structural and physiological factors. Ideal ideotypes for mechanized harvesting have high SDR, low DF, and favorable sheath morphology, providing selection indices for "no-burn" sugarcane production.

Table 3. Quantitative defoliation traits of sugarcane genotypes and measurement methods.

Trait	Abbreviation	Description	Unit / Method
Total internode number	TIN	Internodes from soil to dewlap leaf	count per plant
Stem diameter	SD	Diameter at mid-stalk	cm, digital caliper
Length of Sheath Ruptured	LSR	Length of detached sheath	cm, caliper
Angle of Sheath Ruptured	ASR	Angle between ruptured sheath and stalk	°, digital protractor
Leaf sheath width	LSW	Maximum sheath width	cm, caliper
Leaf sheath thickness	LST	Sheath thickness	mm, micrometer
Green leaf weight	GLW	Fresh weight of green leaves	g, digital balance
Senescent leaf weight	SLW	Fresh weight of senescent leaves	g, digital balance
Number of Dead Leaf Nodes	NDLN	Total nodes with senescent leaves	count per plant
Defoliation force	DF	Force required to detach leaves	N, push–pull tester
Mean defoliation force	MDF	Average DF per genotype	N, calculated
Self-defoliating number	SDN	Naturally detached leaves	count per plant
Self-defoliating rate	SDR	% naturally detached leaves	%, SDR = (SDN/TIN) × 100

Table 4. Principal component loadings of 13 quantitative traits contributing to variation in natural defoliation of 28 sugarcane genotypes (combined across two years, 2021–2022).

Quantitative traits	Principal component (PC)		
	1st PC	2nd PC	3rd PC
Total internode number (TIN)	-0.055	-0.066	-0.193
Stem diameter (SD)	-0.025	0.366	**0.526**
Length of sheath ruptured (LSR)	-0.348	0.074	-0.125
Angle of sheath ruptured (ASR)	-0.285	-0.05	0.128
Leaf sheath width (LSW)	-0.175	0.12	**-0.538**
Leaf sheath thickness (LST)	0.164	**-0.472**	0.043
Green leaf weight (GLW)	0.295	-0.042	-0.334
Senescent leaf weight (SLW)	-0.174	0.256	-0.242
Number of dry leaves (NDLN)	-0.188	0.383	0.287
Defoliation force (DF)	**0.403**	0.277	-0.151
Mean defoliation force (MDF)	0.165	**0.566**	-0.241
Sheath dry number (SDN)	**-0.442**	-0.055	-0.142
Sheath dry rate (SDR)	**-0.445**	-0.034	-0.097
Characteristic root	*3.60*	*1.81*	*1.23*
Contribution rate (%)	*27.70*	*13.94*	*9.45*
Cumulative contribution rate (%)	*27.70*	*41.63*	*51.09*
Factor weight	*0.54*	*0.27*	*0.19*

Values represent loadings of each trait on the first three principal components (PC1–PC3). Bold values ≥ |0.40| indicate traits with strong contributions to the respective component. Characteristic root refers to eigenvalues, with factor weights representing the proportion of variance explained by each component. Contribution rate indicates the percentage of total variance explained by individual components, while cumulative contribution rate denotes the accumulated variance across successive components.

Table 5. Multivariate analysis of variance (MANOVA) test statistics for genotype effects across stem, leaf, and defoliation trait sets in sugarcane (combined across two years, 2021–2022).

Test statistic	Statistic value	Num DF	Den DF	F-value	Pr > F	Partial η^2
Wilks' lambda	0	351	19,305.54	1,625.9	<0.001	0.94
Pillai's trace	6.96	351	21,476.00	70.5	<0.001	0.92
Hotelling–Lawley trace	1.34×10^{13}	351	14,024.46	6.27×10^{13}	<0.001	0.93
Roy's greatest root	1.34×10^{13}	27	1,652.00	8.23×10^{14}	<0.001	0.93

Values represent multivariate test statistics including Wilks' lambda, Pillai's trace, Hotelling–Lawley trace, and Roy's greatest root. Reported are statistic values, numerator and denominator degrees of freedom (Num DF and Den DF), approximate F-values, significance levels (*Pr* > *F*), and effect size (Partial η^2). All tests indicated highly significant multivariate differences among genotypes ($P < 0.001$), with large effect sizes ($\eta^2 > 0.90$).

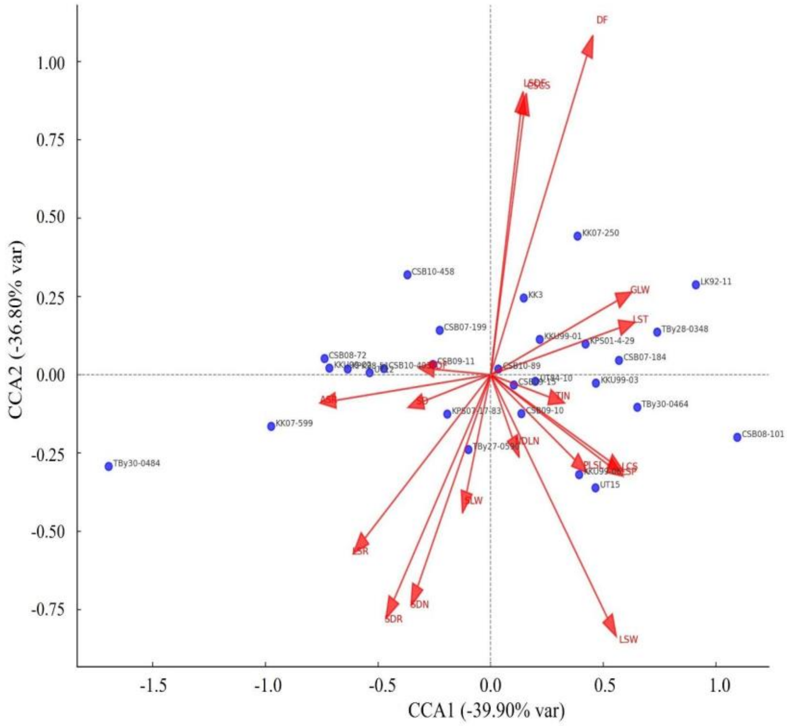


Figure 3. Canonical correlation analysis (CCA) biplot of 28 sugarcane genotypes (combined across two years, 2021–2022). Blue points represent genotypes, and red arrows represent trait vectors. CCA1 and CCA2 explained 39.90% and 36.80% of the variation, respectively. Trait vectors indicate the direction and strength of associations with phenotypic characteristics, highlighting the contribution of stem, leaf, and defoliation traits (e.g., GLW, LSW, LST, NDLN, MDF, SDN, SDR, DF) to overall variation.

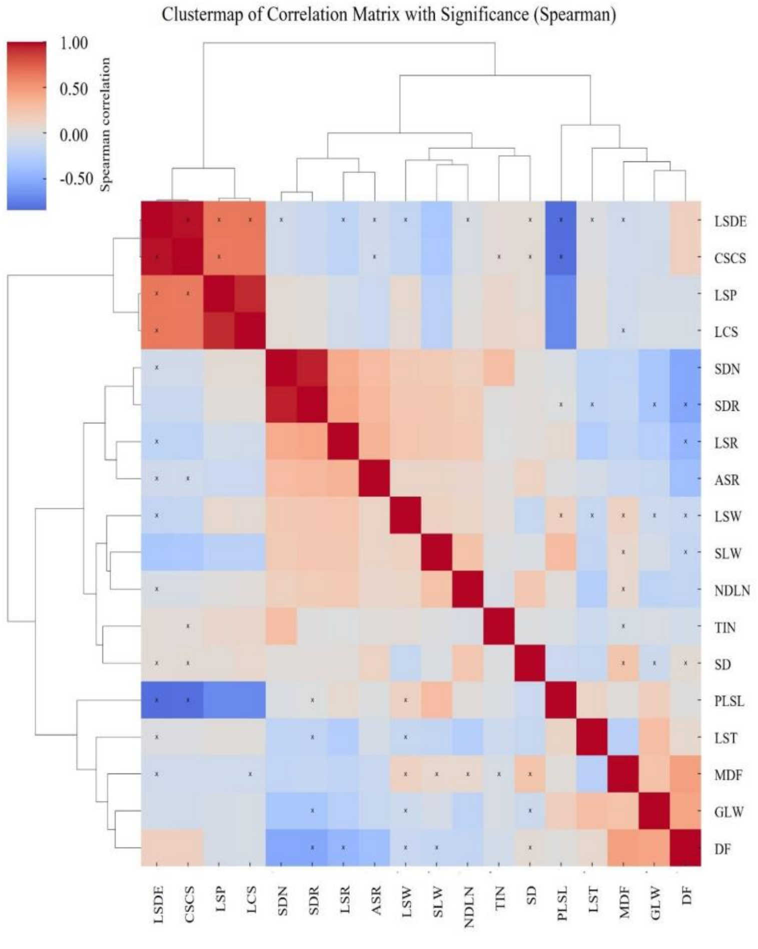


Figure 4. Clustered heatmap of Spearman correlation coefficients among stem, leaf, and defoliation traits of sugarcane genotypes (combined across two years, 2021–2022). Hierarchical clustering was applied to group correlated traits, with the color scale indicating the strength and direction of correlation (red = positive, blue = negative). Asterisks (×) indicate significant correlations at P ≤ 0.05.

Materials and Methods

Plant materials, field experiments, and experimental design

Field experiments were conducted in the Bang Rakam district of Phitsanulok Province, Thailand (16°38′16″N, 100°09′42″E; 48 m a.s.l.), a key sugarcane region with rapid mechanization. The site has average temperatures of 35.1 °C (max) and 22.3 °C (min), an annual rainfall of 1,250 mm, and sandy clay loam soil (pH 6.2, organic matter 1.3%). Between October 2020 and December 2022, 1,186 mm of rain fell, which was supplemented by irrigation to support establishment. Using flow meters and an automated weather station, rainfall and irrigation were tracked.

The natural defoliation diversity of twenty-eight sugarcane genotypes, sourced from national research centers, Khon Kaen University, and Kasetsart University, was assessed (Table 1). Mechanization references were two commercial checks: LK92-11 (low defoliation) and KK3 (intermediate). The randomized complete block design (RCBD) trial comprised four replications. To reduce edge effects and automate processes, each 96 m^2 plot had six 10-m rows separated by 1.6 m.

Crop management

Before planting, 0–60 cm soil samples were analyzed. Fields were ploughed to 30 cm and limed (250 kg ha^{-1}) to adjust pH to ~6.5, with 5 t ha^{-1} of farmyard manure added. Fertilizer was applied in two stages: a basal 120:60:60 kg NPK ha^{-1} before planting (urea, TSP, MOP) and 80 kg N ha^{-1} top-dressed at 90 days. Furrow irrigation-maintained soil near field capacity, triggered at –30 to –40 kPa using tensiometers (Allen et al., 1998). Irrigation frequency was reduced during maturation to simulate harvest conditions. Atrazine (1.5 kg a.i. ha^{-1}) and interrow cultivation were used to control weeds. Pests and diseases were controlled in accordance with regional regulations.

Phenotypic observations and trait characterization

Defoliation traits were recorded across two consecutive seasons (2021–2022) during early maturation (October–December), corresponding with the regional harvest window. Fifteen plants per replication (60 per genotype) were sampled. Observations were taken at 9 and 12 months after planting, following DUS guidelines (Crop Guidelines, 2005) and protocols by Huang et al. (2018) and Liang et al. (2024). Both quantitative and qualitative traits relevant to mechanized harvesting were assessed.

(1) Quantitative traits

Measured traits (Table 2) included: total internode number (TIN), stem diameter (SD), sheath rupture length (LSR), sheath rupture angle (ASR), leaf sheath width (LSW), and thickness (LST). Biomass traits comprised green leaf weight (GLW), senescent leaf weight (SLW), and number of dead leaf nodes (NDLN). Defoliation force (DF) was measured with a digital push–pull tester (Imada DS2-50N, Japan), and mean detachment force (MDF) was calculated per genotype.

(2) Qualitative traits

Visual scoring (Table 3) covered self-defoliating number (SDN), self-defoliation rate (SDR = SDN/TIN × 100), leaf senescence pattern (LSP), leaf color at senescence (LCS), leaf sheath detachment ease (LSDE), cane surface cleanliness (CSCS), and persistence of leaf sheath layers (PLSL), all rated on a 1–5 scale indicating degree or ease of detachment.

Data analysis

Coefficients of variation (CV%), standard errors (SE), and trait means were computed. Genomic differences were detected using Duncan's Multiple Range Test (P ≤ 0.05) and one-way ANOVA (SAS v9.4, Cary, NC, USA). Using the Shannon index $[H' = -\sum_{i=1}^{n} p_i \ln(p_i)]$ (Konopiński, 2020), which was calculated in R v4.3.1, qualitative trait diversity was estimated. Greater genotypic trait variability is indicated by higher H' values.

Multivariate analyses

Using eigenvalues >1 and a cumulative variance threshold of ≥70%, Principal Component Analysis (PCA) was conducted on 13 quantitative traits (TIN, SD, LSR, ASR, LSW, LST, GLW, SLW, NDLN, DF, MDF, SDN, and SDR). Agglomerative Hierarchical Clustering (AHC) employs Euclidean distance groupings and Ward's method, with bootstrap resampling and cophenetic correlations confirming the cluster robustness. Canonical correlation analysis was used to investigate the relationships between defoliation traits and stem/leaf morphology. To estimate effect sizes beyond univariate comparisons, genotype effects were tested using Wilks' λ, Pillai's trace, Hotelling-Lawley trace, Roy's greatest root, and partial η^2 in multivariate analysis of variance (MANOVA).

Conclusions

To evaluate defoliation traits in Thai sugarcane germplasm, this two-year field study develops the first multivariate framework. Along with sheath morphology, self-defoliation rate (SDR), self-defoliating number (SDN), and defoliation force (DF) demonstrated a high degree of reliability in determining the suitability of mechanization. Multivariate analyses, using KK3 as an intermediate benchmark, clearly separated resistant types from favorable genotypes (low DF, high SDR). In support of Thailand's "No-Burn" and Bio-Circular-Green (BCG) efforts toward sustainable mechanized harvesting, these indices offer useful resources for breeding self-defoliating cultivars, even though more multi-location validation is required.

Statement of contributions

Conceptualization: AW, SC; Methodology: AW, PB; Investigation: AW, SC, PB; Data curation: AW, PB; Formal analysis: AW; Visualization: AW; Writing – original draft: AW; Writing – review and editing: AW, SC; Supervision: AW; Funding acquisition: AW; Project administration: AW. All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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