

Influence of Soil Parameters on TSS/TA ratio and Betalain concentration of Dragonfruit (*Hylocereus undatus*)

Nangsel Tshomo and Kuenga Penjor Gyeltshen

Abstract

*Dragon fruit (*Hylocereus undatus*) quality is primarily determined by sweetness, expressed as the total soluble solids to titratable acidity (TSS/TA) ratio, and pigmentation, determined by betalain concentration. This study investigated how soil parameters influence these traits across three production sites in Bhutan. Thirty fruits and composite soil samples were collected and analyzed for physicochemical and nutrient characteristics. Analysis of variance showed significant site effects ($p < 0.001$), with FMCL fruits exhibiting the highest TSS/TA ratio (90.2 ± 19.5), BAJO fruits having the greatest betalain concentration (31.7 ± 11.2 mg/L), and CRP fruits being more acidic. Correlation analysis revealed that the TSS/TA ratio was strongly promoted by available phosphorus ($r = 0.72$) and potassium, but reduced by higher soil electrical conductivity ($r = -0.70$) and pH ($r = -0.52$). Betalain concentration declined with higher nitrogen and organic carbon ($r = -0.46$ and -0.43 , respectively), while copper contributed positively. Ridge regression confirmed phosphorus and potassium as the strongest drivers of sweetness, whereas nitrogen and organic carbon suppressed both sweetness and pigmentation. Threshold analysis demonstrated nonlinear responses, including a decline in betalain concentration beyond 1.5% soil organic carbon and a plateau effect for potassium on sweetness. Multi-response optimization identified joint optimal values that balance both quality traits, providing specific soil parameter targets for growers seeking balanced quality. These findings enable precision soil management tailored to market priorities, with specialized recommendations for maximizing either sweetness or pigmentation, and values for balanced quality optimization.*

Keywords: Dragon Fruit, Soil Parameters, TSS/TA Ratio, Betalain, Nutrient Management

1. Introduction

Dragon fruit (*Hylocereus* spp.), also known as pitaya or pitahaya, is an exotic tropical fruit valued for its vibrant appearance, rich coloration, and organoleptic, nutritional, and therapeutic properties (Franco et al., 2022). Its commercial appeal and market value are largely determined by two key quality parameters; visual quality, driven by betalain pigments, and gustatory quality, determined by the balance of total soluble solids (TSS) and titratable acidity (TA), which together shape sweetness and flavor. The TSS/TA ratio serves as a widely used ripening index in fruits, reflecting the balance between sugars (e.g., glucose and fructose) and acids (Majidi et al., 2011).

Soil chemistry and plant nutrition strongly influence fruit biochemical composition and metabolite synthesis (Salam et al., 2023). Abiotic factors such as soil pH, organic carbon, and trace metals can significantly alter the accumulation of primary and secondary metabolites, yet the specific soil–fruit quality relationships in dragon fruit remain inadequately characterized (Mondal & Alam, 2023). Previous studies suggest links between soil and tissue nitrogen, phosphorus, and potassium concentrations (Islam et al., 2025), but data are inconsistent across environments. These inconsistencies highlight the need for precise, multivariate analyses to understand soil–fruit interactions and guide sustainable nutrient management strategies.

Optimizing soil nutrients for a single fruit quality trait can produce trade-offs with others. Nutrient regimes that enhance sugar accumulation may suppress pigment synthesis, and vice versa (Srivastava & Malhotra, 2014). Meta-analyses of organic and integrated fertilizer practices further reveal that management strategies promoting yield or sweetness may compromise fruit coloration or antioxidant capacity (Yang et al., 2023). These findings highlight the potential and the importance of simultaneously considering both taste-related attributes (TSS/TA ratio) and pigment-related attributes (betalains) when evaluating soil influences on dragon fruit quality.

In Bhutan, dragon fruit cultivation is relatively new but rapidly expanding. According to the Integrated Agriculture and Livestock Census of Bhutan 2025, dragon fruit was cultivated by 3,578 growers, with a total production of 10 MT in 2024, up from 4 MT in 2023 (National Statistical Bureau [NSB], 2025). Despite this growth, no studies have evaluated how Bhutan's soils influence dragon fruit quality traits, especially on TSS/TA ratio and Betalain concentration.

Against this knowledge gap, the present study was designed to investigate how soil parameters (pH, organic carbon, available N, P, K, micronutrients, and EC) affect both betalain concentration and TSS/TA ratio in white-fleshed dragon fruit. By identifying nutrient thresholds, potential trade-offs between visual and gustatory quality and to derive joint optimal values that balance both quality traits for precision nutrient management; this study aims to generate context-specific recommendations for optimizing fruit quality and guiding sustainable dragon fruit production in Bhutan.

2. Materials and Method

2.1. Experimental site

The first harvest of Dragon fruit (*Hylocereus undatus*) used in this study was collected from three sites: (a) Agriculture Research and Development Centre (ARDC), Bajo, (b) Farm Machinery Corporation Limited (FMCL), Kamichu, Wangdue, and (c) Chimipang Royal Project (CRP). These sites are located within the subtropical zone of Wangdue Phodrang and Punakha Dzongkhags, Bhutan (Chhogyel & Kumar, 2018). The ARDC Bajo site is situated at 1,237 masl (27.49°N, 89.90°E), the FMCL Wangdue site at 822 masl (27.28°N, 90.00°E), and the CRP site at 1,278 masl (27.52°N, 89.87°E).

2.2. Data selection

The first harvest of dragon fruits was selected based on an anthesis-to-fruit-set period of 30–33 days. A total of 10 fruits were collected from each site, with only one fruit harvested per randomly selected plant ($n = 30$). Concurrently, soil samples were collected from the selected plants using a hand auger. From each site, 10 topsoil and 10 subsoil samples were collected and combined to form composite samples, resulting in two composite soil samples per site.

2.3. Data Collection

- a. Titratable acidity (Citric acid): Dragon fruit contains various organic acids that contribute to its characteristic taste, with citric acid being the predominant acid influencing fruit quality (Xie et al., 2022). Citric acid content was determined using a titrimetric method, specifically the acid–base volumetric analysis (Brima & Abbas, 2014). A standardized 0.1 N sodium hydroxide (NaOH) solution was used as the titrant to quantify the citric acid (Alam et al., 2023; Bengaluru & Karnataka, 2022). Fruit pulp was crushed, and 10 mL of juice was extracted and diluted with 90 mL of distilled water to a total volume of 100 mL. The titrant was added from a burette to the analyte containing 2–3 drops of phenolphthalein, with the endpoint indicated by a persistent pale pink color. Each measurement was

replicated three times per fruit, and the mean value was calculated to minimize experimental bias. The final citric acid concentration was expressed in grams per liter (g/L) using the appropriate calculation formula.

$$\text{Titrate acid (\%)} = \frac{\frac{\text{ml of NaOH (Final reading from the burette)} \times \text{Normality of NaOH (Titrant concentration)}}{\times \text{Dilution factor (0.1)} \times \text{Equivalent weight of citric acid (0.0064)}}}{\text{Volume of analyte (ml)}} \quad (\text{Alam et al., 2023})$$

- b. Total soluble solutes (TSS) and pH: The presence of total soluble solids determines the sweetness of the fruit extract. TSS includes sugars, vitamins, minerals and other soluble substances but majorly consists of sugars such as glucose, fructose and sorbital (Chen et al., 2024). A hand-held digital refractometer was used to measure the TSS in Degree Brix (°Bx) from the fruit extract from the pulp. Along with that the PH of the extract was also measured using the electronic PH meter to determine the flavour of the fruit right after harvest (Budhathoki et al., 2023).
- c. TSS/TA ratio: The TSS/TA ratio was calculated by dividing the total soluble solids (TSS, °Brix) of the fruit juice by its titratable acidity (TA, g/L) for each sample. This ratio was determined for all fruits using the measured values of TSS and TA to quantify the balance between sweetness and acidity.
- d. Betalain content: Frozen fruit peels were removed from the freezer and allowed to thaw at room temperature. The peels were macerated using a blender, and 10 mL of the extract was dissolved in 50 mL of distilled water, following a modified crude extraction method (Fathordoobady et al., 2016; Pratiwi et al., 2025; Woo et al., 2011), with water as the sole solvent at a 1:5 dilution. The solution was shaken for 45 minutes. Subsequently, 1 mL of the supernatant was mixed with 10 mL of distilled water and analyzed using a UV–Visible spectrophotometer at 538 nm. The final betalain concentration was calculated using the standard formula given below,

$$\text{Betalain Content } \left(\frac{\text{mg}}{\text{L}} \right) = \frac{A_{538}(\text{Absorbance at 538nm}) \times D.F(\text{Dilution factor, 0.1}) \times MW(550\text{g/mol}) \times 1000}{\epsilon(\text{Coefficient, 60,000L/mol}) \times l(\text{path length of cuvette, 1cm})}$$

(GNT International B.V, 2010)

- e. Soil analysis: A total of six composite soil samples, comprising topsoil and subsoil from each of the three sites, were analyzed. Macro-nutrients (Nitrogen [N], Phosphorus [P], and Potassium [K]) and micro-nutrients (Boron [B], Iron [Fe], Zinc [Zn], Sulfur [S], Manganese [Mn], and Copper [Cu]) were determined using the Orlab digital soil testing kit (Orlab Instruments Pvt. Ltd., 2025). For micronutrients such as Zn and Cu, both HCl-extractable

and DTPA-extractable forms were measured to assess plant-available concentrations, with DTPA used as it is widely recognized for estimating bioavailable micronutrients in neutral to alkaline soils (Lindsay & Norvell, 1978). Soil pH and electrical conductivity (EC) were measured using a calibrated digital pH meter and EC meter, respectively, with appropriate buffer solutions. Soil pH and electrical conductivity (EC) were measured using a calibrated digital pH meter and EC meter, respectively, with appropriate buffer solutions.

2.4. Data analysis

a. Principal Component Analysis

Principal Component Analysis (PCA) was conducted using the *prcomp()* function in R statistical software (version [4.4.3]). Prior to PCA, the parameters were scaled (centered and divided by the standard deviation) using the *scale()* function to ensure that variables with larger scales did not disproportionately influence the results.

Score plots were generated to visualize the distribution and clustering of samples according to soil type, while loading plots were examined to determine the contribution of each variable to the principal components. Together, these plots were used to interpret the influence of soil parameters on fruit biochemical characteristics.

b. Ridge Regression

Ridge Regression was conducted using the *glmnet()* function in R statistical software (version [4.4.3]). Prior to model fitting, all predictor variables were standardized to a mean of zero and a standard deviation of one to ensure the regularization penalty was applied uniformly. The standardized coefficients from the final models were extracted and analysed to assess the direction, magnitude, and relative importance of each soil parameter's influence on the fruit quality metrics and betalain concentration.

c. Joint Optimisation Analysis

To derive balanced soil parameter values that simultaneously optimize both quality traits, multi-response optimization using the desirability function framework was employed. For each parameter, predicted response curves from ridge regression models for betalain and TSS/TA ratio were merged, normalized to a 0–1 scale, and combined using the geometric mean to calculate a composite desirability score as equation follows,

$$D_{combined} = \sqrt{D_{betalain} \times D_{TSS/TA}}$$

The joint optimal value was identified as the parameter value maximizing this composite score, representing the best compromise between pigment and sweetness optimization.

3. Result and Discussion

3.1. Descriptive Statistics

Table 1. Mean values, ANOVA p-values and Tukey's HSD results ($p < 0.05$). for the effect of production site on the physicochemical quality and Betalain content of dragon fruit.

Parameter	Site	Mean $\pm$ SD	F-value	p-value
TSS/TA Ratio	FMCL	90.2 $\pm$ 19.5 ^a	43.21	< 0.001
	CRP	40.5 $\pm$ 9.8 ^c		
	BAJO	59.8 $\pm$ 16.2 ^b		
Betalain (mg/L)	FMCL	17.0 $\pm$ 6.9 ^b	13.41	< 0.001
	CRP	21.2 $\pm$ 9.6 ^b		
	BAJO	31.7 $\pm$ 11.2 ^a		
TSS (°Brix)	FMCL	13.3 $\pm$ 1.1 ^a	35.65	< 0.001
	CRP	10.8 $\pm$ 1.0 ^b		
	BAJO	10.7 $\pm$ 1.3 ^b		
TA (% Citric Acid)	FMCL	0.16 $\pm$ 0.03 ^c	42.61	< 0.001
	CRP	0.28 $\pm$ 0.07 ^a		
	BAJO	0.19 $\pm$ 0.05 ^b		

Table 2. field level estimation of soil physicochemical properties for the topsoil (Top; 0-15 cm) and subsoil (Sub; 15-30 cm) layers across the three study sites (FMCL, CRP, and BAJO)

Parameters	Site					
	FMCL		CRP		BAJO	
Soil	Top	Sub	Top	Sub	Top	Sub
pH	7.15	6.87	7.63	7.28	7.44	7.61
Soil_EC(dS/m)	1.24	1.24	1.68	1.50	1.44	1.30
Organic_Carbon (%)	0.69	0.65	0.83	0.83	0.62	0.49
Nitrogen_(mg/kg)	249.00(M)	222.50(M)	280.00(H)	280.00(H)	208.00(M)	137.00(L)
Phosphorus_(mg/kg)	67.65(vH)	86.25(vH)	14.95(H)	17.75(H)	36.95(vH)	21.9(H)
Potassium_(mg/kg)	20.75(L)	5.10(L)	6.15(L)	6.80(L)	7.70(L)	6.60(L)
Iron_(mg/kg)	0	0	0.33	0	0	0
Manganese_(mg/kg)	0.01	0.01	0.01	0.01	0.01	0.01
Zinc(HCL)_(mg/kg)	0	1.3	2.4	0.2	1.6	1.1
Zinc(DTPA)_(mg/kg)	0	0.6	1.1	0.1	0.7	0.5
Copper(HCL)_(mg/kg)	1.55	0	0	1.06	0	0.56
Copper(DTPA)_(mg/kg)	0	0	0.29	0	0.15	0.43
Sulphur_(mg/kg)	41.17	25.4	31.12	37.66	14.48	31.17
Boron_(mg/kg)	0.36	0.29	0.31	0.01	0.19	0.76

Note: Nutrient status in the soil is expressed as: L = Low, M = Medium, H = High, vH = Very High.

The field-level values of soil properties detailed in Table 2 established the initial conditions for each site. Production site had a significant effect on the TSS/TA ratio, betalain concentration, TSS (°Brix), and TA (% citric acid) of dragon fruit ($p < 0.001$ for all traits; Table 1). Fruits from FMCL exhibited the highest TSS/TA ratio (90.2 ± 19.5), while CRP had the lowest (40.5 ± 9.8). Betalain concentration was significantly greater in BAJO (31.7 ± 11.2 mg/L) compared to FMCL and CRP. Similarly, TSS values were highest in FMCL (13.3 ± 1.1 °Brix), while CRP and BAJO recorded lower values. In contrast, titratable acidity was significantly higher in CRP ($0.28 \pm 0.07\%$) compared to FMCL ($0.16 \pm 0.03\%$). Soil type and the site–soil interaction was not significant for either response ($p > 0.05$).

These findings confirm that environmental and soil conditions exert a strong influence on dragon fruit quality traits, consistent with reports highlighting the role of site-specific factors in modulating red-fleshed dragon fruit composition (Singh et al., 2022) suggesting that similar mechanism might be at play for white fleshed dragon fruits too, as indicated in this study. The superior sweetness observed at FMCL, expressed through the high TSS/TA ratio and TSS values, is attributable to the site's notably high available phosphorus (67.65 mg/kg for top soil and 86.25 mg/kg for sub soil) and potassium (20.75mg/kg for top soil and 5.10 mg/kg for sub soil) levels compared to the rest two sites. This aligns with previous studies demonstrating that phosphorus and potassium fertilization enhances sugar accumulation and related quality attributes in dragon fruit (Sahu et al., 2023). Additionally, the highest betalain concentration at BAJO coincided with the lowest soil nitrogen (208mg/kg for top soil and 137 mg/kg for sub soil) and organic carbon (0.49–0.62 %) levels among the three sites. This negative relationship between nitrogen availability and pigmentation reflects the well-documented role of betalain as stress-responsive secondary metabolites, which are often enhanced under low-nitrogen conditions (Puccinelli et al., 2025; Bartosz et al., 2021).

3.2. Correlation

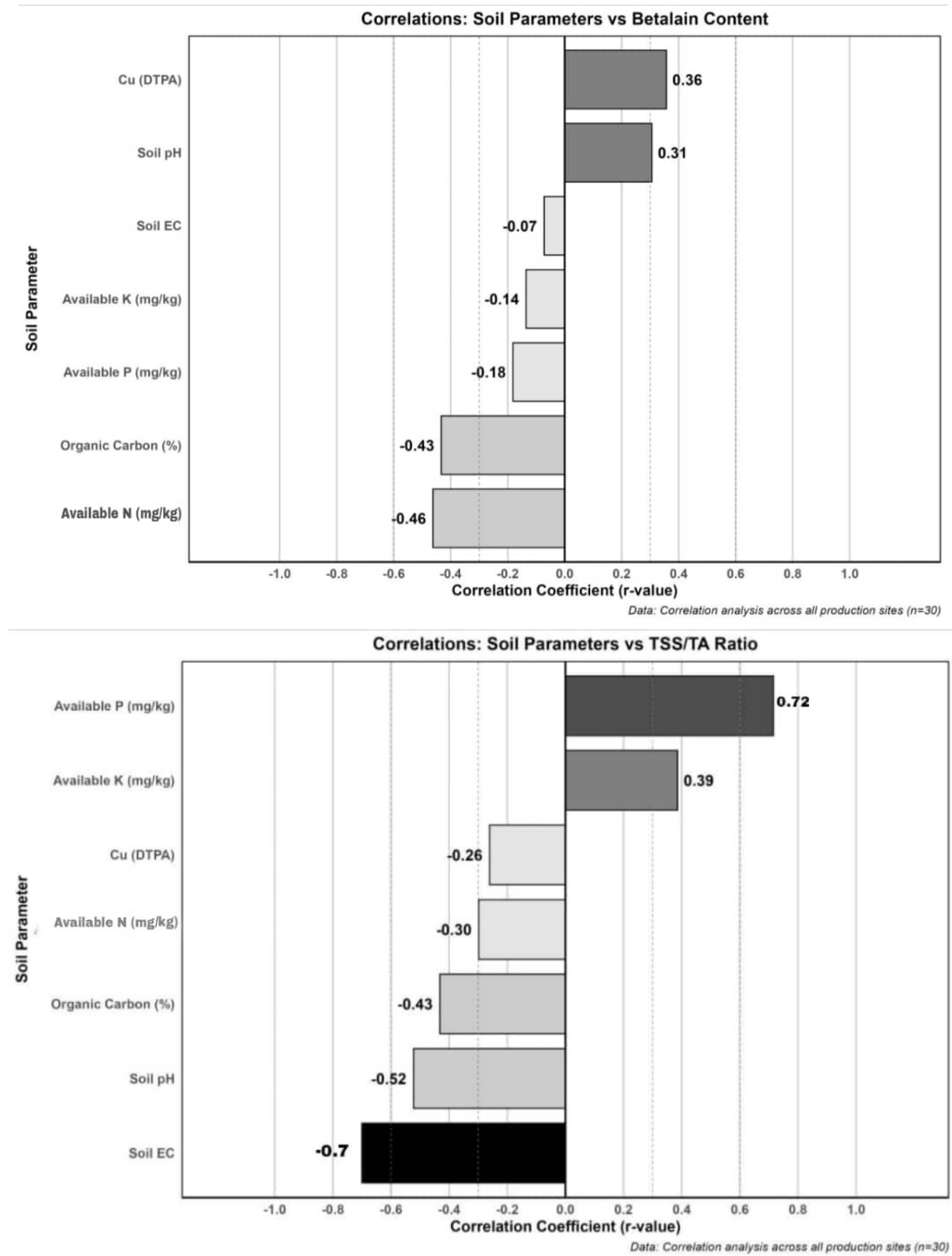


Figure 1. Correlation of soil parameters vs Betalain Content and TSS/TA ratio

As shown in Figure 1, betalain concentration was strongly influenced by soil nitrogen and organic carbon, both showing moderate negative correlations ($r = -0.46$ and $r = -0.43$, respectively), while available copper exhibited a positive relationship ($r = 0.36$). The TSS/TA ratio, on the other hand, showed a very strong positive correlation with available phosphorus ($r = 0.72$), alongside a moderate negative correlation with soil pH ($r = -0.52$) and a very strong negative correlation with soil electrical conductivity ($r = -0.70$). These correlations provide a systematic explanation for the significant site-effects observed in the analysis of variance, indicating that the differences in fruit quality among production sites were driven by these distinct soil chemical properties. Phosphorus showed only a very weak negative correlation with betalain ($r = -0.18$), confirming that its role is largely restricted to sweetness.

The negative relationships between betalain concentration and both nitrogen and organic carbon support the plant resource allocation theory, whereby abundant nitrogen promotes vegetative growth at the expense of secondary metabolite production such as betalains (Bartosz et al., 2021). Also, the positive correlation with copper is scientifically correct, as copper is an essential cofactor for polyphenol oxidases and dioxygenases, key enzymes in betalain biosynthesis (Pratiwi et al., 2025). The strong positive correlation between phosphorus and the TSS/TA ratio reaffirms phosphorus's role in energy transfer (ATP) and sugar metabolism, which are central to fruit sweetness (Sahu et al., 2023). Equally important is the negative effect of soil electrical conductivity, as elevated soluble salts disrupt osmotic balance and water uptake, thereby limiting sugar accumulation and altering acid metabolism. Furthermore, the moderate negative correlation with pH ($r = -0.52$) is consistent with findings in other horticultural crops; for instance, vineyards in alkaline soils showed reduced berry quality, attributed to pH-dependent shifts in nutrient availability that affect sugar and acid metabolism (Li et al., 2024). A similar mechanism may be at play in dragon fruit, where elevated pH could limit the availability of micronutrients essential for these biochemical pathways.

Collectively, these results highlight contrasting nutrient requirements; while high phosphorus supports sweetness, it does not enhance betalain, which instead is favored by low nitrogen and higher copper availability. This creates a fundamental trade-off between maximizing sweetness and visual quality in dragon fruit.

3.3. Principal Component Analysis

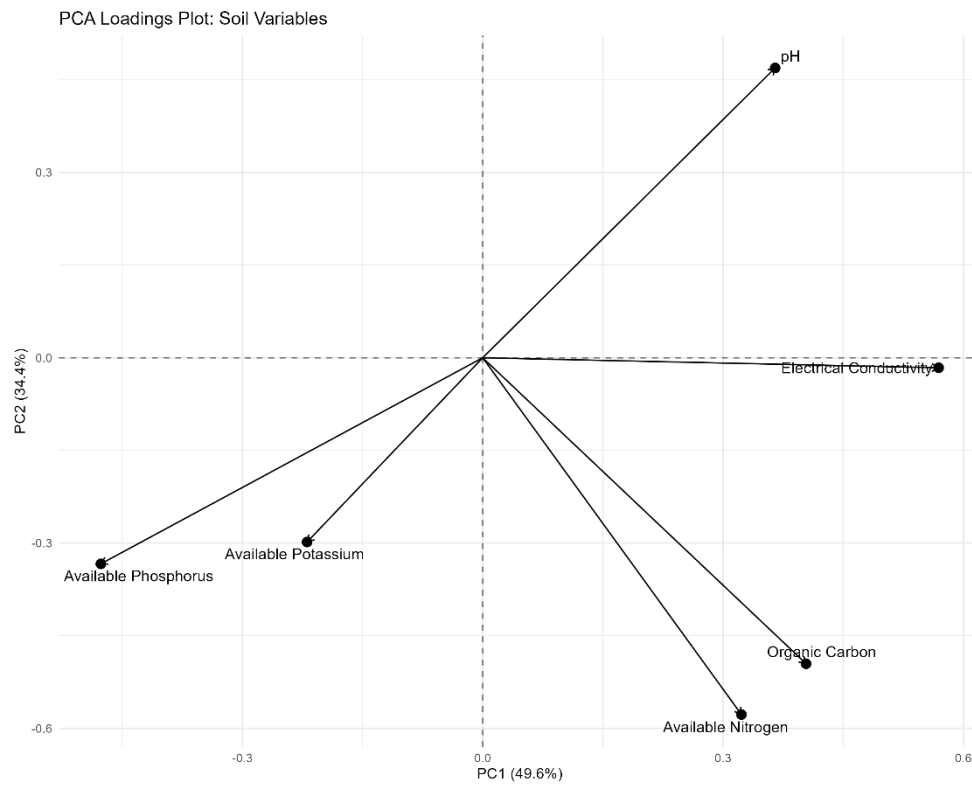


Figure 2. PCA loadings plot of soil parameters. The direction and length of the vectors indicate the contribution and influence of each soil variable on Principal Components 1 and 2.

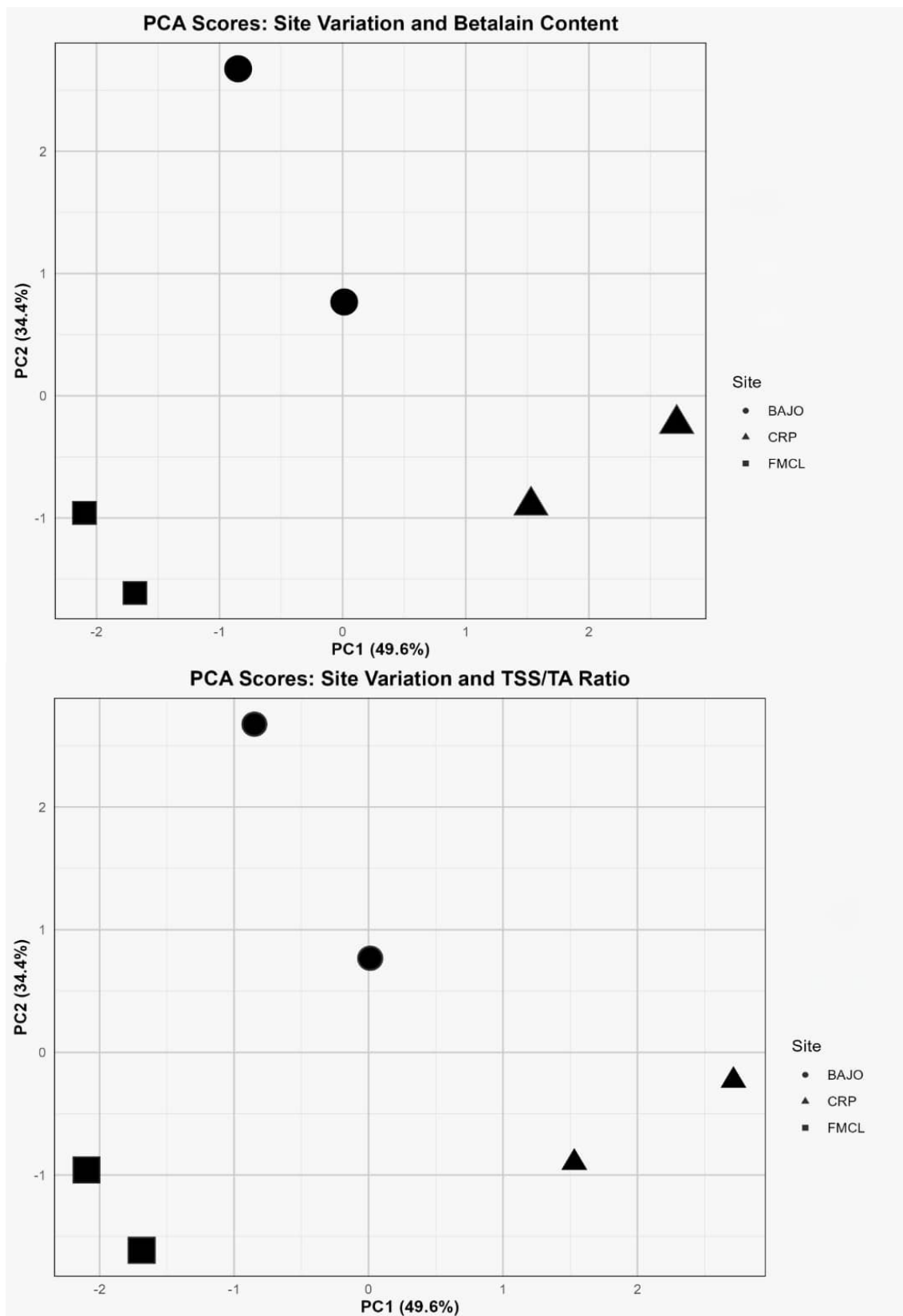


Figure 3. PCA scores plot across sites and betalain content and TSS/TA ratio

Principal Component Analysis (PCA) was performed to reduce the dimensionality of the soil dataset and visualize the underlying structure differentiating the production sites. The first two principal components (PCs) explained 84.0% of the total variance in soil parameters (PC1: 49.6%; PC2: 34.4%). The loadings plot (Fig. 2) revealed that PC1 was strongly influenced by soil available phosphorus (negative loading) and electrical conductivity (positive loading), while PC2 was characterized by soil pH (positive loading) and available nitrogen (negative loading).

The PCA scores plots (Fig.3) visualized the separation of sites (BAJO, CRP, FMCL) based on these soil characteristics and their relation to fruit quality. For betalain concentration, clustering was more pronounced along PC2, with BAJO distinct from CRP and FMCL. This indicates that soil pH and available nitrogen, the key contributors to PC2, were the main factors differentiating sites in terms of fruit color. As for the TSS/TA ratio (an indicator of sweetness), sites separated clearly along PC1; BAJO and FMCL on the positive side and CRP on the negative. This separation demonstrates that electrical conductivity and available phosphorus, the main drivers of PC1, strongly influenced differences in fruit sweetness.

This application of PCA is supported by its established use in agronomy to illustrate complex trait correlations and trade-offs among nutrient management strategies (Jolliffe & Cadima, 2016). In this study, it effectively reveals the intrinsic soil-based trade-off in dragon fruit cultivation between sweetness (TSS/TA) and color (betalain). The clear separation along different principal axes demonstrates that this fundamental compromise is embedded within the growing environment, where soil factors favoring high betalain concentration are distinct from those favoring a high TSS/TA ratio.

3.4. Ridge Regression

Table 3. Ridge regression results showing the effects of soil parameters on Betalain concentration and TSS/TA ratio

Soil Parameter	Betalain Concentration	TSS/TA Ratio
pH	1.42	-1.06
Organic Carbon	-2.23	-4.3
Electrical Conductivity	0.11	-1.98
Available Nitrogen	-2.04	-1.9
Available Phosphorus	-0.9	11.44

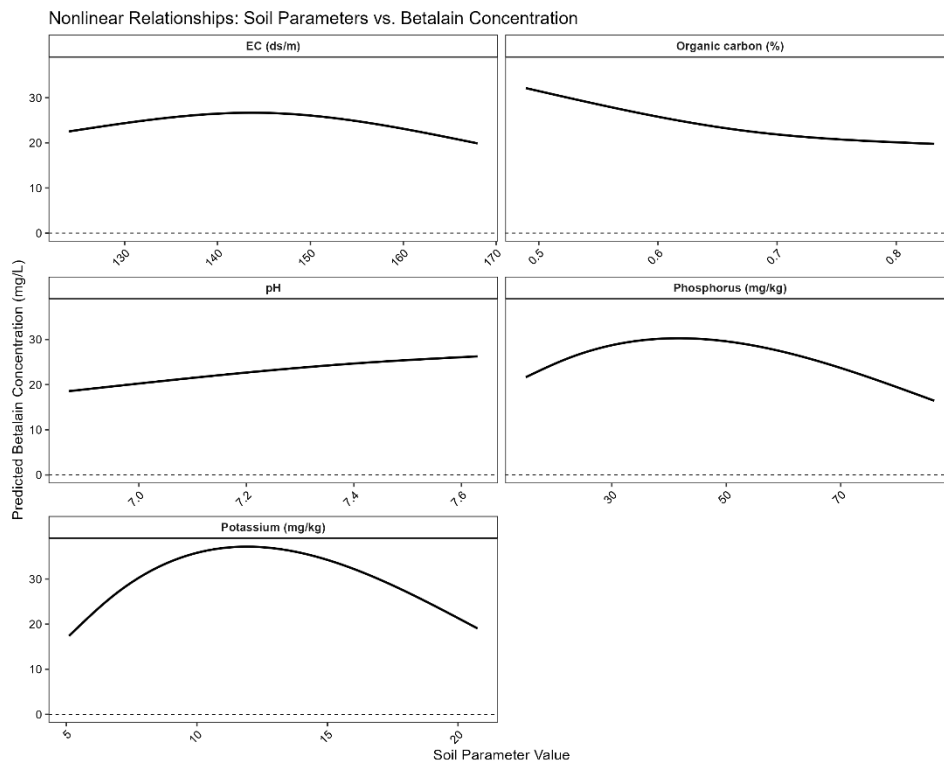


Figure 4. Threshold analysis for Betalain concentration

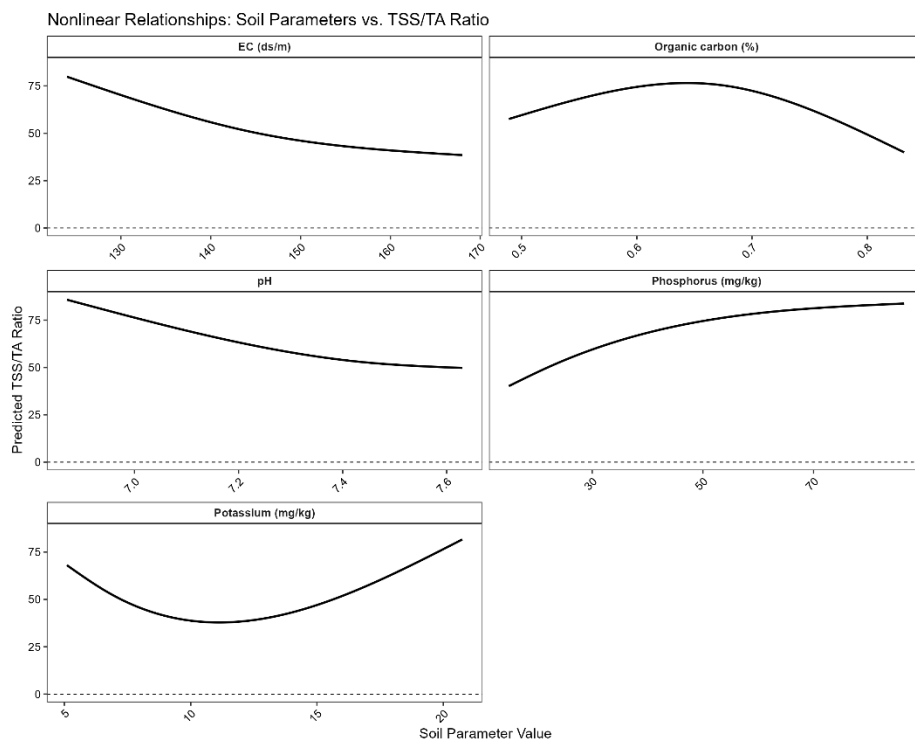


Figure 5. Threshold analysis for TSS/TA ratio

A ridge regression analysis, a multivariate technique designed to control for multicollinearity (Rathod & Sable, 2021; Trusova et al., 2020), was done to isolate the independent effects of soil predictors on fruit quality and rigorously quantify the trade-offs suggested by earlier analyses. The results, focusing on the most influential parameters (Table 3), reveal distinct drivers for betalain concentration and the TSS/TA ratio. For betalain concentration, organic carbon (−2.23) and available nitrogen (−2.04) were the strongest negative predictors, while soil pH had a moderate positive effect (+1.42). Available phosphorus showed only a weak negative coefficient (−0.9), confirming that it exerts little influence on betalain compared to the dominant roles of nitrogen and organic carbon. In contrast, for the TSS/TA ratio, phosphorus was by far the strongest positive driver (+11.44), with potassium as an important secondary contributor (+4.13). Organic carbon again acted as a strong negative predictor (−4.30), highlighting its suppressive effect on both sweetness and pigmentation.

The standardized coefficients highlight that available phosphorus was the significant driver of sweetness, with potassium as a key secondary contributor. To top it off, soil organic carbon exerted a strong negative effect on both quality parameters, and available nitrogen's negative relationship with betalain is consistent with findings in other crops where high nitrogen favors vegetative growth over secondary metabolite production (Yu et al., 2024). The positive effect of soil pH on betalain (coefficient: 1.42) aligns with reports that alkaline conditions influence micronutrient availability critical for pigment biosynthesis (Rathod & Sable, 2021). Furthermore, the model confirmed the significant negative impact of electrical conductivity on the TSS/TA ratio (coefficient: -1.98), supporting prior evidence that salinity stress can impair sugar accumulation (Yang et al., 2019).

The ridge regression model was further studied to illustrate the nonlinear dynamics governing the soil–fruit quality relationship through a threshold analysis. The resulting threshold plots (Figs. 4 & 5) visually confirm that the influence of soil parameters is characterized by complex responses, including thresholds, plateaus, and saturating effects, rather than simple linearity.

For betalain concentration (Fig. 4), the relationship with soil organic carbon was particularly revealing, exhibiting a distinct threshold effect. The predicted betalain concentration remained stable until organic carbon reached approximately 1.5%, after which it declined sharply. This indicates that exceeding this carbon threshold is directly detrimental to pigment accumulation. In contrast, soil pH demonstrated a saturating positive effect, with betalain content increasing up to a pH of approximately 7.5 and plateauing thereafter, suggesting no further benefit from

additional alkalinity. As indicated by their relatively flat response curves, available phosphorus and potassium exhibited only minor influences, aligning with the regression coefficients.

For the TSS/TA ratio (Fig. 5), the nonlinear relationships underscored the dominance of specific nutrients. Available phosphorus displayed a strong, nearly linear positive relationship, confirming its role as the primary driver of fruit sweetness. The effect of available potassium was also positive but nonlinear, increasing initially before reaching a clear plateau, indicating a point of diminishing returns for potassium fertilization. Organic carbon exerted a steady negative influence, directly contrasting its threshold effect on betalain. Electrical conductivity (EC) showed a negative trend, while soil pH had a negligible effect, consistent with the regression model.

To further complement and solidify the threshold analysis, the optimal soil parameter values corresponding to maximum betalain concentration and TSS/TA ratio are summarized in Table 4. These values highlight a specific value within which the pigment accumulation and sweetness are maximized.

Table 4. Optimal soil parameter values derived from threshold analysis for maximizing betalain concentration and TSS/TA ratio in white-fleshed dragon fruit.

Parameters	Optimal Betalain Values	Optimal TSS/TA Ratio Values	Joint Optimal Value
pH	7.63	6.87	6.87
Organic carbon (%)	0.49	0.64	0.56
EC (ds/m)	1.43	1.24	1.24
Phosphorus (mg/kg)	41.70	86.35	51.73
Potassium (mg/kg)	11.91	20.75	17.87

As per Table 4, pH of 7.63 is optimal for betalain production, while a slightly more acidic pH of 6.87 favors a higher TSS/TA ratio. The joint optimal pH of 6.87 aligns with the TSS/TA requirement, suggesting acidity takes priority for overall quality. Similarly, the optimal phosphorus level for sweetness (86.35 mg/kg) is more than double the level required for color (41.70 mg/kg), directly reflecting the strong positive relationship seen in the threshold plot. The compromise value of 51.73 mg/kg represents a balanced approach that supports both quality parameters. Most critically, the optimal organic carbon level is low for both quality parameters (0.49% for betalain and 0.64% for TSS/TA), with a joint optimal of 0.56% firmly supporting the finding that levels exceeding ~1.5% are detrimental to overall fruit quality.

These nonlinear patterns are critical for moving beyond qualitative assessments to precise nutrient management. The stark contrast in how organic carbon affects betalain (threshold-driven decline) versus the TSS/TA ratio (consistent negative effect) quantifies the inherent trade-off. Interestingly, while previous studies in other fruit crops including dragonfruit have reported positive associations between organic matter and sweetness (Ye et al., 2022; Karunakaran et al., 2025), the present findings indicate that a soil with high organic carbon (>1.5%) is suboptimal for both color and sweetness in white-fleshed dragon fruit. A moderate carbon level may favor pigment retention but still compromises sweetness, highlighting the crop- and site-specific nature of these relationships. Similarly, the saturating effect of pH on betalain and the plateau for potassium on TSS/TA define optimal ranges beyond which resource inputs become inefficient.

3.5. Practical Application and Management Implications

The ridge regression and threshold analysis indicate the need to move away from a one-size-fits-all fertilization approach toward precision management, tailored to the specific market niche of dragon fruit.

For growers targeting balanced quality, the joint optimal values provide scientifically-derived compromise targets: maintain pH at 6.87, organic carbon at 0.56%, EC at 1.24 dS/m, phosphorus at 51.73 mg/kg, and potassium at 17.87 mg/kg. These values represent the mathematical optimum for simultaneously maximizing both betalain content and TSS/TA ratio.

For Sweetness-focused markets (TSS/TA ratio), Phosphorus was identified to be the main key driver with optimal level being 86 mg/kg and Potassium, with its optimum value being 21 mg/kg was the second key driver. Organic carbon should be maintained at 0.64% and EC around 1.24 dS/m.

For Visual-appeal markets (higher pigmentation), Focus should be given on secondary metabolites and maintaining low vegetative growth. This is done through keeping low soil nitrogen and controlling organic carbon, which threshold analysis identifies as levels exceeding 1.5% of OC trigger a sharp decline in betalain concentration. A target of 0.49% is optimal. Unlike sweetness, betalain production benefits from slightly alkaline conditions with pH of 7.6 and has a much lower phosphorus requirement of 42 mg/kg.

This demonstrates that the fundamental trade-off between sweetness and colour is not merely a competition between nutrients but is also governed by specific response thresholds. Consequently, achieving balanced fruit quality requires maintaining key soil parameters within their optimal, nonlinear windows rather than pursuing their maximum level. This insight presents a clear challenge for balanced quality maximization but provides a scientific basis for developing precision agriculture strategies tailored to dragon fruit cultivation.

While this study provides a thorough analysis of the influence of soil parameters on TSS/TA ratio and betalain concentration in dragon fruit, its scope and certain limitations should be considered. The findings are based on three distinct production sites within a specific region of Bhutan, which provides valuable insights but may not capture the variations in results that could be found across different geographies, climates, and dragon fruit cultivars. Furthermore, the interpretation of these soil-fruit quality relationships was challenged by a scarcity of existing peer-reviewed literature specifically on dragon fruit (*Hylocereus* spp.).

These results fulfill the study's objective by demonstrating how soil parameters influence dragon fruit quality, revealing critical nutrient thresholds, and providing joint optimal values to balance competing quality traits. Phosphorus and potassium consistently enhanced sweetness, nitrogen and organic carbon suppressed both traits, and pH positively affected betalain up to a saturating point. Nonlinear responses highlighted inherent trade-offs; maximizing sweetness through high P and K reduced colour intensity, while conditions favoring pigment development compromised sweetness. Crucially, the joint optimal values provide a scientifically-grounded compromise for growers seeking balanced quality. These findings offer clear, context-specific guidance for nutrient management, enabling farmers in Bhutan to strategically target either specialized market traits or optimized overall quality. Overall, this research demonstrates that while simultaneous maximization of both sweetness and colour remains challenging, precision management using joint optimal values offers a practical pathway

4. Conclusion

In conclusion, this study demonstrates that soil parameters are critical determinants of dragon fruit quality, influencing both sweetness (TSS/TA ratio) and pigmentation (betalain concentration). Utilizing ridge regression and threshold analysis, specific optimal ranges for individual quality traits were quantified, revealing a fundamental trade-off: soil conditions that favor increased sweetness tend to reduce pigmentation, and vice versa.

Importantly, joint optimal values were computed to maximize overall fruit quality. These joint optima provide a data-driven framework for growers aiming to achieve a balanced profile in both sweetness and color. Consequently, soil management for dragon fruit cultivation need not be constrained by these optimal values. Farmers can strategically use the individual value to target niche markets emphasizing either sweetness or pigmentation, or apply the joint optima to produce fruit with a balanced, high-quality profile. Future studies should aim to validate these soil–quality relationships across additional regions and cultivars and assess the economic implications of adopting specialized versus balanced management strategies.

5. Acknowledgement

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6. Authors Contribution

Nangsel Tshomo and Kuenga Penjor Gyeltshen were involved in the study's conceptualization and protocol design of the manuscript. Nangsel Tshomo was primarily responsible for analyzing, interpreting, visualizing the data and drafting the manuscript, with assistance from Kuenga Penjor Gyeltshen. Kuenga Penjor Gyeltshen performed the biochemical analysis and data collection, with assistance from Nangsel Tshomo.

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