

Multivariate Analysis of Soil Chemical Properties Associated with TSS/TA Ratio and Betalain Concentration in White fleshed Dragon Fruit (*Selenicereus undatus*)

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Abstract

*White fleshed Dragon fruit (*Selenicereus undatus*) quality is primarily assessed using two key traits: sweetness, estimated by the total soluble solids to titratable acidity (TSS/TA) ratio, and pigmentation, measured as betalain concentration. This study examined the association between soil chemical properties and fruit quality (TSS/TA ratio and betalain concentration) in white fleshed dragon fruit across three production sites representing natural soil variability in Bhutan. Thirty fruits were analyzed for TSS, TA, and TSS/TA ratio, and composite soil samples were analyzed for organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), micronutrients (Fe, Mn, Zn, Cu, B), sulphur (S), electrical conductivity (EC), and pH. Correlation and principal component analyses revealed strong interrelationships among soil parameters, indicating multicollinearity and underlying soil chemical gradients. Sweetness (TSS/TA ratio) was strongly promoted by available phosphorus and potassium but reduced by higher soil EC and pH. Betalain concentration declined with increasing nitrogen and organic matter, while copper showed a positive association. Ridge regression confirmed phosphorus and potassium as the strongest drivers of sweetness, whereas nitrogen and organic matter consistently suppressed both sweetness and pigmentation. Threshold analysis demonstrated nonlinear soil–fruit quality responses, including a decline in predicted betalain concentration at higher soil organic matter levels. Multi-response optimization through joint optimal analysis predicted single point optimum soil condition and their optimal range that balance sweetness and pigmentation, characterized by approximate soil chemical values such as pH of 6.9 (range: 6.7–7.0), organic matter of 0.96% (range: 0.90–1.05%), EC of 1.24 dS/m (range: 1.20–1.30 dS/m), phosphorus of 52 mg/kg (range: 50–60 mg/kg), and potassium of 18 mg/kg (range: 16–21 mg/kg). For sweetness-focused production, higher phosphorus (~86 mg/kg; range: 80–90 mg/kg) and potassium (21 mg/kg; range: 20–22 mg/kg) levels were most favorable. In contrast, pigmentation was favored under lower nitrogen and organic matter (0.84%; range: 0.8–0.9%) and slightly alkaline soil conditions (pH 7.6; range: 7.5–7.7). These findings provide soil-based guidance for precision nutrient management, enabling growers to target either sweetness, pigmentation, or balanced fruit quality under naturally variable field conditions.*

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1 Introduction

White flesh dragon fruit (*Selenicereus undatus*, formerly *Hylocereus undatus*), also known as white 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; pigmentation, driven by betalain pigments, and sweetness, determined by the balance of total soluble solids (TSS) and titratable acidity (TA), which together shape coloration 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 are known to influence fruit biochemical composition and metabolite synthesis (Salam et al., 2023). Abiotic factors such as soil pH, organic matter, and micronutrient availability can alter the accumulation of both primary and secondary metabolites. However, specific soil chemical properties and fruit quality relationships in dragon fruit remain inadequately characterized (Mondal & Alam, 2023). Previous studies have reported associations between soil chemical properties and tissue concentrations of nitrogen, phosphorus, and potassium (Islam et al., 2025) yet findings are often inconsistent across environments, highlighting the role of location-specific soil chemical properties in shaping fruit quality. Therefore, multivariate analytical approaches that consider site-level differences are needed to better understand soil chemical properties and 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., 2019). 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 influences of soil chemical parameters on dragon fruit quality.

In Bhutan, white flesh 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). The census reports dragon fruit production without distinguishing flesh color or cultivar type but the growing number of cultivators is undeniable for dragon fruit overall. Although this study focuses on white flesh dragon fruit as this cultivar seems to be widely grown and found at the study sites, this could be used as a baseline for experienced and emerging dragon fruit growers for precise cultivation and management of dragon fruits tailored to the niche market preferences.

There have been no studies evaluating the association between soils chemistry and dragon fruit quality traits in Bhutan, particularly on TSS/TA ratio and betalain concentration. To address this knowledge gap, the present study was designed to investigate the relationships between selected soil chemical parameters (pH, organic matter, available N, P, K, micronutrients, and EC), betalain concentration in three different locations and the TSS/TA ratio in white flesh dragon fruit. By identifying nutrient thresholds and potential trade-offs between sweetness and colour quality, the study aimed to derive joint optimal soil conditions that support balanced fruit quality. The findings were intended to provide context-specific guidance for optimizing fruit quality and supporting sustainable, white fleshed dragon fruit production in Bhutan.

2 Materials and Method

2.1 Experimental Site and Design

Following the approach used in similar agro-ecological studies (Sun et al., 2022), a comparative observational design was used across three sites to examine relationships between soil chemical properties and fruit quality. The inclusion of multiple sites allowed the study to capture natural variability in soil chemical conditions and evaluate how this variability is associated with the fruit TSS/TA ratio and betalain concentration. Consistent with multi-location spatial soil studies (Lee et al., 2023), production site was treated as a fixed factor to account for location-level environmental variation, while soil chemical properties were examined as continuous explanatory variables. First-harvest white fleshed dragon fruits were collected from three representative sites within the subtropical zone of Wangdue Phodrang and Punakha Dzongkhags, Bhutan (Chhogyel & Kumar, 2018). The site characteristics and anthesis-to-harvest climatic conditions are presented in Table 1.

Table 1. Geographic characteristics and average climatic conditions recorded between

Site	Location	Altitude (masl)	Latitude (°N)	Longitude (°E)	T _{max} (°C)	T _{min} (°C)	Rainfall (mm)	Relative Humidity (%)
BAJO	Bajo, Wangdue	1,237	27.49	89.9	30.4	22.14	2.57	77.98
FMCL	Kamichu, Wangdue	822	27.28	90	32.13	21.87	3.84	69.65
CRP	Lobesa, Punakha	1,278	27.52	89.87	31.25	20.27	0.69	76.7

anthesis and harvest at the three study sites.

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 ($n = 30$) subsequently soil samples were collected from the basins of the same plants from which the fruit were harvested through all of the three study sites. Using the hand auger, the first 0cm-15cm (topsoil) and the second 15cm-30cm (subsoil) of soil from the active root zone of each plant were collected. From each study site, ten topsoil samples were collected and combined to form a composite sample; similarly, ten subsoil samples were collected and made into a composite sample. This resulted in six composite soil samples from all three sites.

2.3 Data Collection

2.3.1 Soil analysis

A total of six composite soil samples, comprising topsoil and subsoil from each of the three sites, were analyzed. Organic matter, 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 recognised 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.

2.3.2 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 (Alam et al., 2023).

$$\text{Titrate acid (\%)} = \frac{\text{ml of NaOH (Final reading from the burette)} \times \text{Normality of NaOH (Titrant concentration)} \times \text{Dilution factor (0.1)} \times \text{Equivalent weight of citric acid (0.0064)}}{\text{Volume of analyte (ml)}} \dots(1)$$

2.3.3 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 sorbitol (Chen et al., 2024). A hand-held digital refractometer was used to measure the TSS in Degree Brix (°B) 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).

2.3.4 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.

2.3.5 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 (GNT International B.V, 2010) given below,

$$\text{Betalain Content } \left(\frac{\text{mg}}{\text{L}} \right) = \frac{A_{538}(\text{Absorbance at } 538\text{nm}) \times D.F(\text{Dilution factor}, 0.1) \times MW(550\text{g/mol}) \times 1000}{\epsilon(\text{Coefficient}, 60,000\text{L/mol}) \times l(\text{path length of cuvette}, 1\text{cm})} \dots\dots\dots (2)$$

2.4 Data Analysis

2.4.1 Principal Component Analysis

Principal Component Analysis (PCA) was used as an exploratory multivariate tool to reduce data dimensionality and identify patterns in each study site to understand which soil chemical properties are strongly associated and linked to variations in fruit quality (TSS/TA ratio and betalain concentration).

PCA was conducted using the *prcomp()* function in R statistical software (version [4.4.3]). Prior to PCA, all 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.

PCA loading plots were generated to visualize combinations of soil chemical properties that showed strong association to the variation in fruit quality in all three sites, and represented as principal components. A total of eight principal components were generated, of which the first two principal components (PC1 and PC2) were retained for further interpretation as they explained 84% of the total variance.

PCA score plots were subsequently generated while overlaying fruit quality to visualize the relationship between the white flesh dragon fruit samples along with the components of PC1 and PC2. This whole approach allowed us to narrow down specific major soil chemical parameters which were linked to differences in fruit quality.

2.4.2 Ridge Regression

Ridge Regression is a regularization tool used to address multicollinearity among the predictors (independent) variables and quantify the relationship between independent variables (soil chemical properties) with dependent variables (fruit quality: TSS/TA ratio and betalain concentration). Based on exploratory results from principal component analysis (PCA), the soil chemical parameters that showed strong loading on the principal components associated with fruit quality were retained and further subjected to ridge regression analysis. This screening step of PCA reduced model complexity and focused the analysis on soil variables most strongly associated with variation in fruit quality.

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. Separate ridge regression models were fitted on each dependent variable and 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. Equation (3) describes the ridge regression mathematical model;

$$\hat{\beta}_{ridge} = \arg \min_{\beta} \left\{ \sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^p x_{ij} \beta_j)^2 + \lambda \sum_{j=1}^p \beta_j^2 \right\} \dots\dots\dots (3)$$

Where, y_i represents the fruit quality trait (TSS/TA ratio or betalain concentration) for the white flesh dragon fruit sample i . x_{ij} represents the value of soil parameter j measured for i . β_0 is the intercept and β_j are the regression coefficients estimating the association between soil parameters and the fruit quality trait. n is the number of observations made between fruit and soil and p is the number of soil variables included in the model. λ represents the penalty strength introduced to the coefficients, shrinking predictors toward zero to reduce multicollinearity and stabilize model estimates.

2.4.3 Threshold Joint Optimisation Analysis

Ridge regression allowed for the quantification of soil parameters and their type of association to fruit quality. Threshold analysis was then employed to predict how different levels of soil parameters could affect the fruit quality (TSS/TA ratio and betalain concentration). Non-linear response curves were visualized through this analysis which

revealed optimal values or plateau points where soil parameters are associated with high fruit quality.

Many of the screened-out soil parameters showed tradeoffs to fruit quality, where one trait was boosted and the other trait diminished. Joint Optimisation Analysis was used to derive balanced soil parameter values that simultaneously optimize both TSS/TA ratio and betalain concentration, 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 (4) follows,

$$D_{combined} = \sqrt{D_{betalain} \times D_{TSS/TA}} \dots \dots \dots (4)$$

The joint optimal value was identified as the ideal soil parameters that represent the best compromise between pigmentation and sweetness optimization for white flesh dragon fruits. Optimal ranges were further derived from the predicted response curves by identifying soil parameter values where the predicted response remained within 95% of the maximum predicted value.

3 Results and Discussion

3.1 Descriptive Statistics

Soil chemical properties presented in Table 2 showed the variation in growing conditions from where the fruit samples were collected. Variation in fruit quality traits was examined in relation to these soil chemical parameters.

Table 2. Field-level estimation of soil chemical 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	
	<i>Top</i>	<i>Sub</i>	<i>Top</i>	<i>Sub</i>	<i>Top</i>	<i>Sub</i>
Soil 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 Matter (%)	1.19	1.11	1.42	1.42	1.06	0.84
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(M)	17.75(M)	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.

Soil chemical properties were significantly associated with the TSS/TA ratio, betalain concentration, total soluble solids (TSS, °Brix), and titratable acidity (TA, % citric acid) of white fleshed dragon fruit ($p < 0.001$ for all traits) as shown in Table 3.

Table 3. Mean (\pm SD) values of fruit quality traits (TSS/TA ratio, betalain content, TSS, and TA) of white fleshed dragon fruit measured under different soil chemical conditions.

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

ANOVA p -values and Tukey's HSD test results ($p < 0.05$) are shown. Values are based on ten fruits sample per site.

Environmental factors such as temperature, water availability, and solar radiation are known to influence fruit development and quality (Sundarrajan et al., 2025; Bacelar et al., 2024). In this study, temperature conditions during the anthesis to harvest period were relatively similar across sites, with mean maximum temperatures ranging from 30.4 to 32.1 °C and mean minimum temperatures from 20.3 to 22.1 °C (Table 1). Some differences in rainfall (0.7–3.8 mm) and relative humidity (69.6–78.0%) were observed between sites (Table 1).

When environmental conditions, particularly temperatures show little variation, variation in fruit quality is often attributed to differences in soil chemical properties and nutrient availability (Papadakis et al., 2005; Nie et al., 2025). This has been demonstrated in fruit crops where trees grown under similar climates but on different soils produced fruit with distinct quality characteristics (Papadakis et al., 2005). For dragon fruit specifically, studies have shown that soil nutrient status, particularly potassium, nitrogen, and phosphorus, plays a

key role in determining fruit composition and quality compared to climate (Belbase et al., 2025) better understand the drivers of the observed differences, variation in fruit quality was examined in relation to measured soil chemical parameters.

Higher TSS/TA ratios and TSS values were observed at the FMCL site (TSS/TA: 90.2; TSS: 13.3 °Brix), where soils were characterized by relatively higher phosphorus (67.65–86.25 mg/kg) and potassium availability (topsoil: 20.75 mg/kg). In contrast, fruits from the CRP site, which had comparatively lower phosphorus (14.95–17.75 mg/kg) and potassium (6.15–6.80 mg/kg), exhibited reduced sweetness (TSS/TA: 40.5) and higher acidity (TA: 0.28%). Betalain concentration showed a contrasting trend, with the highest pigment accumulation observed at the BAJO site (31.7 mg/L), where soils exhibited relatively lower nitrogen (subsoil: 137 mg/kg) and organic matter (subsoil: 0.84%). These findings confirm that soil chemical parameters have a strong, measurable influence on dragon fruit quality traits. This is consistent with reports highlighting the role of soil properties in modulating red fleshed dragon fruit composition (Singh et al., 2022), suggesting that similar soil-driven mechanisms could operate in white fleshed varieties.

Sweetness-related traits (TSS/TA ratio and TSS) showed positive associations with soil phosphorus and potassium availability across the study sites. Fruits from the FMCL site, where soils contained relatively higher available phosphorus (67.65–86.25 mg/kg) and potassium (5.10–20.75 mg/kg), exhibited higher TSS/TA ratios (90.2) and TSS (13.3 °Brix). In contrast, the CRP site, characterized by comparatively lower phosphorus (14.95–17.75 mg/kg) and potassium (6.15–6.80 mg/kg), produced fruit with lower TSS/TA ratios (40.5) and elevated titratable acidity (TA: 0.28%). This aligns with previous studies demonstrating that phosphorus and potassium fertilization enhances sugar accumulation and acid balance in dragon fruit (Sahu et al., 2023).

Additionally, betalain concentration exhibited an inverse association with soil nitrogen and organic matter levels across sites. The highest betalain concentration (31.7 mg/L) was recorded at the BAJO site, where soils showed relatively lower nitrogen (137–208 mg/kg) and organic matter (0.84–1.06%). 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; Sadowska-Bartosz & Bartosz, 2021)

3.2 Correlation

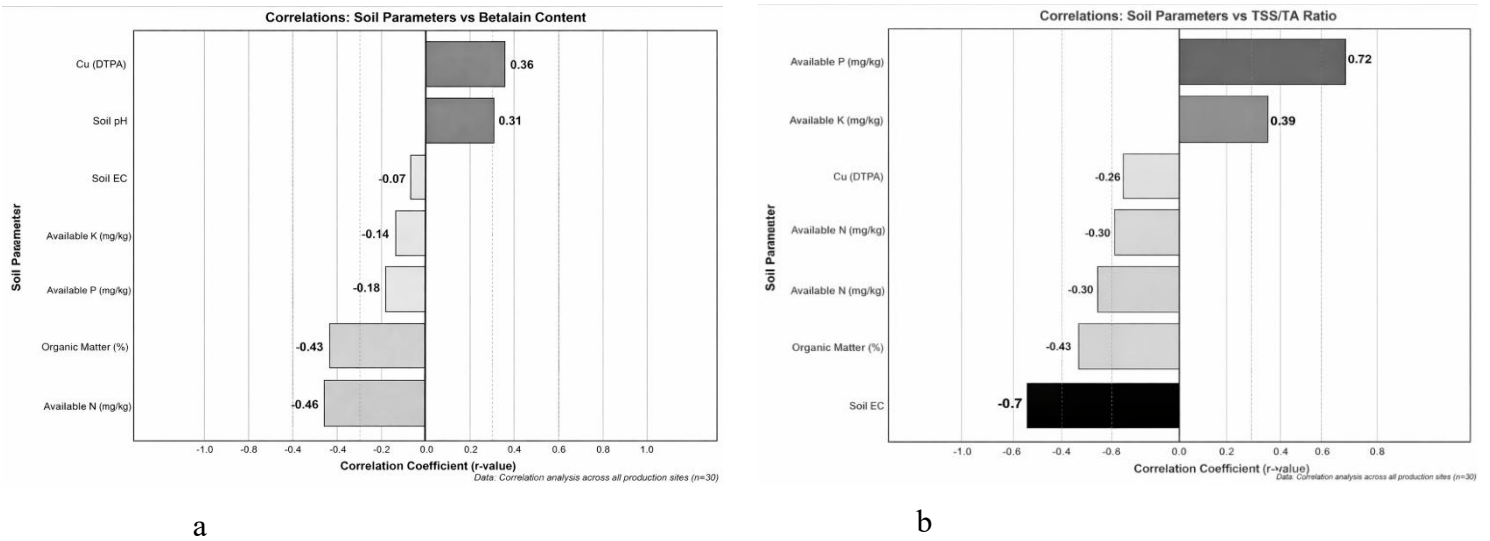


Figure 1. Pearson's correlation coefficients (r-values) between soil chemical parameters and (a) betalain concentration and (b) TSS/TA ratio of white fleshed dragon fruit. Values shown on bars represent correlation coefficients calculated across all samples (n = 30)

As shown in Figure 1a, Pearson's correlation analysis revealed that betalain concentration was associated with soil nitrogen and organic matter, both showing moderate negative correlations ($r = -0.46$ and $r = -0.43$, respectively), while available copper exhibited a positive relationship ($r = 0.36$). These correlation coefficients could be linked to higher betalain accumulation under lower nitrogen availability and higher copper levels.

In contrast, the TSS/TA ratio (Figure 1b) 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 ($r = -0.70$), as shown by the corresponding r-values in Figure 1b. Phosphorus exhibited only a weak negative correlation with betalain concentration ($r = -0.18$) as per figure 1a, confirming that its role is largely restricted to sweetness

These correlations provide a mechanistic explanation for variation in fruit quality traits in relation to soil chemical properties, demonstrating that differences in sweetness and pigmentation are driven by underlying soil nutrient availability. The negative relationships between betalain concentration and both nitrogen and organic matter support the plant resource allocation theory, whereby abundant nitrogen promotes vegetative growth at the expense of secondary metabolite production such as betalains (Sadowska-Bartosz & Bartosz,

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 (TSS/TA ratio vs. available P, $r = 0.72$; Fig. 1b), it does not enhance betalain (betalain vs. P, $r = -0.18$; Fig. 1a), which instead is favored by low nitrogen (betalain vs. N, $r = -0.46$; Fig. 1a) and higher copper availability (betalain vs. Cu, $r = 0.36$; Fig. 1a). This creates a fundamental trade-off between maximizing sweetness and visual quality in dragon fruit.

3.3 Principal Component Analysis

In this study, Principal Component Analysis (PCA) was used as an exploratory tool to understand how multiple soil chemical parameters varied together and how these components associate together with the fruit quality. The objective of this tool was to identify which soil parameters that most strongly contributed to the variation in sweetness (TSS/TA ratio) and pigmentation (betalain concentration) under natural field conditions. Because soil variables such as pH, nutrients, and EC are highly interrelated, analysing them individually can hide their combined effects.

The first two principal components (PCs) explained 84.0% of the total variance in soil parameters (PC1: 49.6%; PC2: 34.4; Figure 2), indicating that most soil variability relevant to fruit quality could be summarized along two independent axes. The loadings plot (Figure 2) showed that PC1 was mainly associated with soil available phosphorus and electrical

conductivity, while PC2 was associated with soil pH and available nitrogen. Together, these components represent the dominant soil chemical patterns influencing fruit quality.

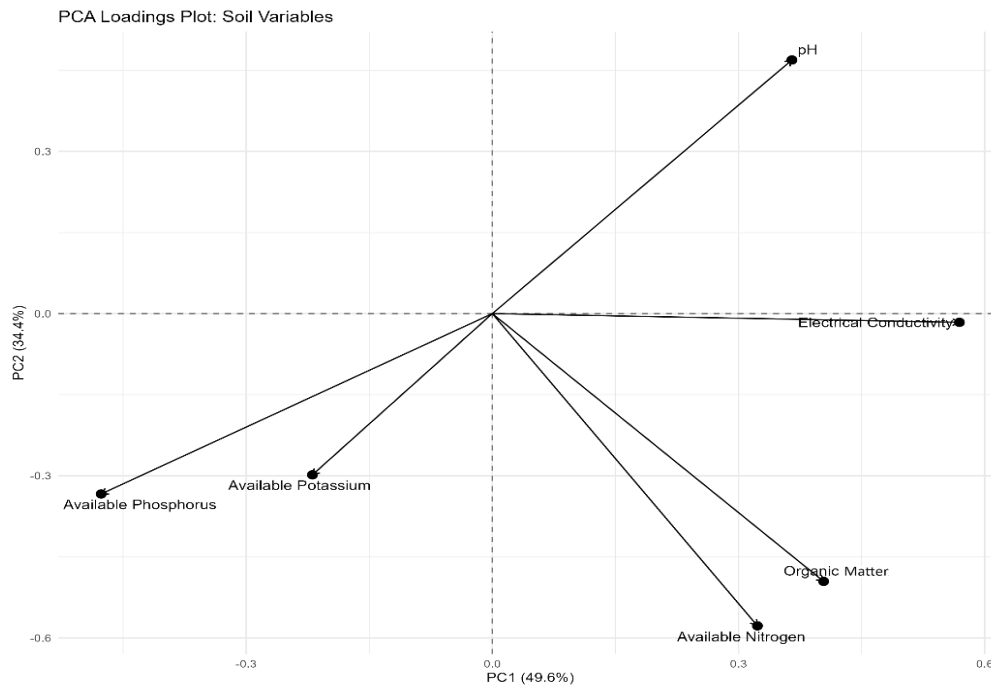


Figure 2. PCA loadings plot of soil parameters. The direction and length of the vectors indicate the contribution and influence of each soil variable on Principal Components 1 and 2.

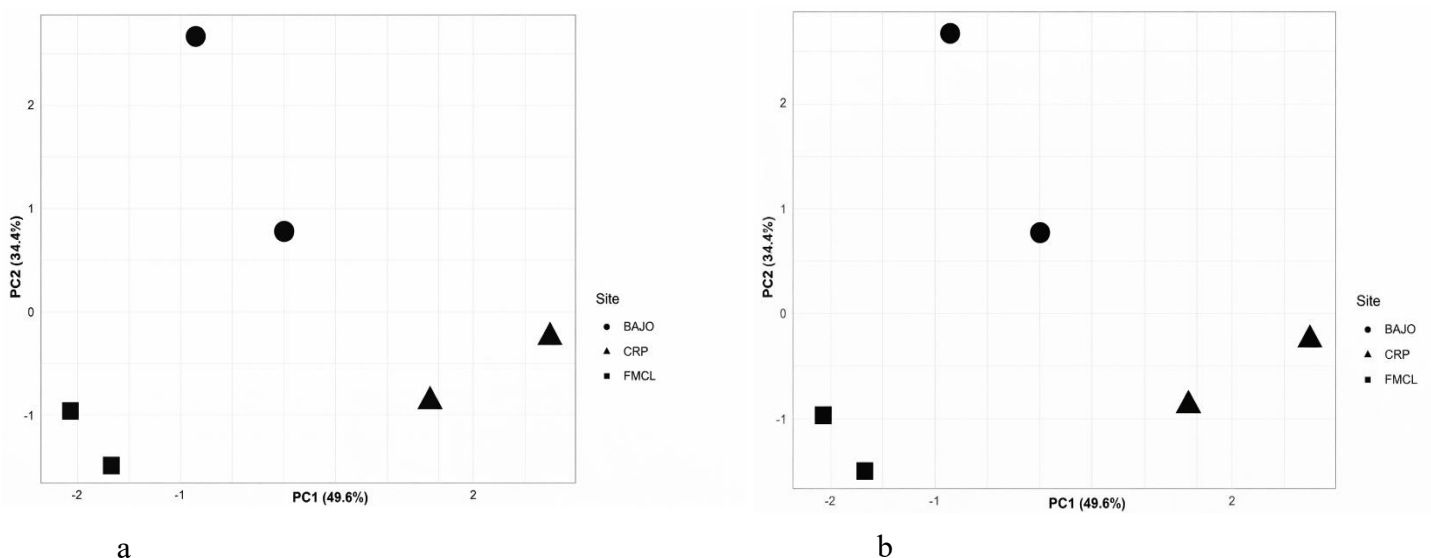


Figure 3. PCA scores plots showing how samples are distributed along PC1 and PC2 based on soil chemical properties. Different symbols represent the production sites used to capture

natural soil variability. Graph (a) shows the distribution of samples in relation to betalain concentration, and graph (b) shows the distribution in relation to the TSS/TA ratio

The PCA scores plot (Figure 3) visualized how white fleshed dragon fruit samples clustered along these gradients and how this clustering related to fruit quality traits. For betalain concentration (Graph 3a), separation was mostly present along PC2, with BAJO samples clearly distinct from CRP and FMCL. This indicates that lower nitrogen availability and favorable soil pH, the primary contributors to PC2, were the main drivers of differences in fruit pigmentation. In contrast; as per graph 3b. separation based on the TSS/TA ratio (sweetness) occurred mostly along PC1, with FMCL and BAJO positioned on the high-phosphorus, low EC end of the axis and CRP on the opposite end. This demonstrates that phosphorus availability and electrical conductivity were the principal soil factors associated with variation in fruit sweetness.

Consistent with its established use in agronomy (Jolliffe & Cadima, 2016), PCA in this study enhanced the results by revealing a clear soil-based trade-off between sweetness and pigmentation. Soil conditions favouring high betalain concentration were associated with the nitrogen pH gradient (PC2), whereas conditions promoting a high TSS/TA ratio aligned with the phosphorus EC gradient (PC1). This separation indicates that the observed differences in fruit quality across production sites corresponded closely to the underlying soil chemical properties

3.4 Ridge Regression

Several soil chemical properties were found to be moderately to strongly correlated to each other through correlation and PCA that was done earlier which suggested multicollinearity. Specifically, there was a strong covariation between soil nitrogen and organic matter and a positive correlation between phosphorus and potassium. The pH and electrical conductivity of the soil also varied in relation to the availability of nutrients. Ridge regression was used to quantify the contribution of each soil parameter to the TSS/TA ratio and betalain concentration while taking multicollinearity into account, as these interrelationships can mask the individual contribution of predictors if other standard multiple regression is used.

Ridge Regression was applied to identify the soil parameters most strongly associated with variation in fruit quality, specifically sweetness (TSS/TA ratio) and pigmentation (betalain concentration), while accounting for multicollinearity. This eliminated the instability brought

on by correlated predictors and allowed for the quantification of the contributions of each soil parameter to fruit quality.

The standardized ridge regression coefficients (Table 4) revealed that different soil parameters were associated with sweetness and pigmentation. For betalain concentration, organic matter (-2.23) and available nitrogen (-2.04) showed the strongest negative associations, indicating that higher levels of these parameters were linked with reduced pigment accumulation. In contrast, soil pH showed a moderate positive association (+1.42), suggesting that more alkaline soil conditions favor betalain synthesis. Available phosphorus showed a weak coefficient (-0.90), indicating a limited role in determining pigment concentration.

Table 4. 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 Matter	-2.23	-4.3
Electrical Conductivity	0.11	-1.98
Available Nitrogen	-2.04	-1.9
Available Phosphorus	-0.9	11.44
Available Potassium	-0.37	4.13

For the TSS/TA ratio (sweetness), available phosphorus had the largest positive standardized coefficient (+11.44), which was higher than all other predictors in the model (Table 4). This clearly indicates that phosphorus was the most influential soil parameter associated with sweetness, with potassium as the secondary contributor (+4.13). Organic matter again showed a strong negative association (-4.30), highlighting its suppressive influence on both sweetness and pigmentation. Electrical conductivity exhibited a negative coefficient (-1.98), consistent with reduced sugar accumulation under higher salinity conditions.

To further examine whether these relationships were linear across the observed range, nonlinear response patterns were explored using threshold analysis (Figure 4 and 5). For betalain concentration (Figure 4), organic matter (Figure 4b) exhibited a nonlinear negative relationship, with predicted betalain levels decreasing progressively at higher organic matter

contents. Soil pH (Figure 4c) showed a positive response across the observed range, indicating increased betalain concentration under more alkaline soil conditions. In contrast, available phosphorus (Figure 4d) and potassium (Figure 4e) displayed higher betalain concentration occurring at intermediate nutrient levels.

For the TSS/TA ratio (Figure 5), available phosphorus (Figure 5d) showed a strong positive response, reinforcing its role as the dominant soil parameter associated with fruit sweetness. Potassium (Figure 5e) exhibited a nonlinear response, with reduced TSS/TA values at intermediate concentrations. Electrical conductivity (Figure 5a) showed a clear negative trend, while organic matter (Figure 5b) displayed a nonlinear response with a mid-range optimum. Soil pH (Figure 5c) showed a weak to moderate negative association with the TSS/TA ratio, consistent with the ridge regression results.

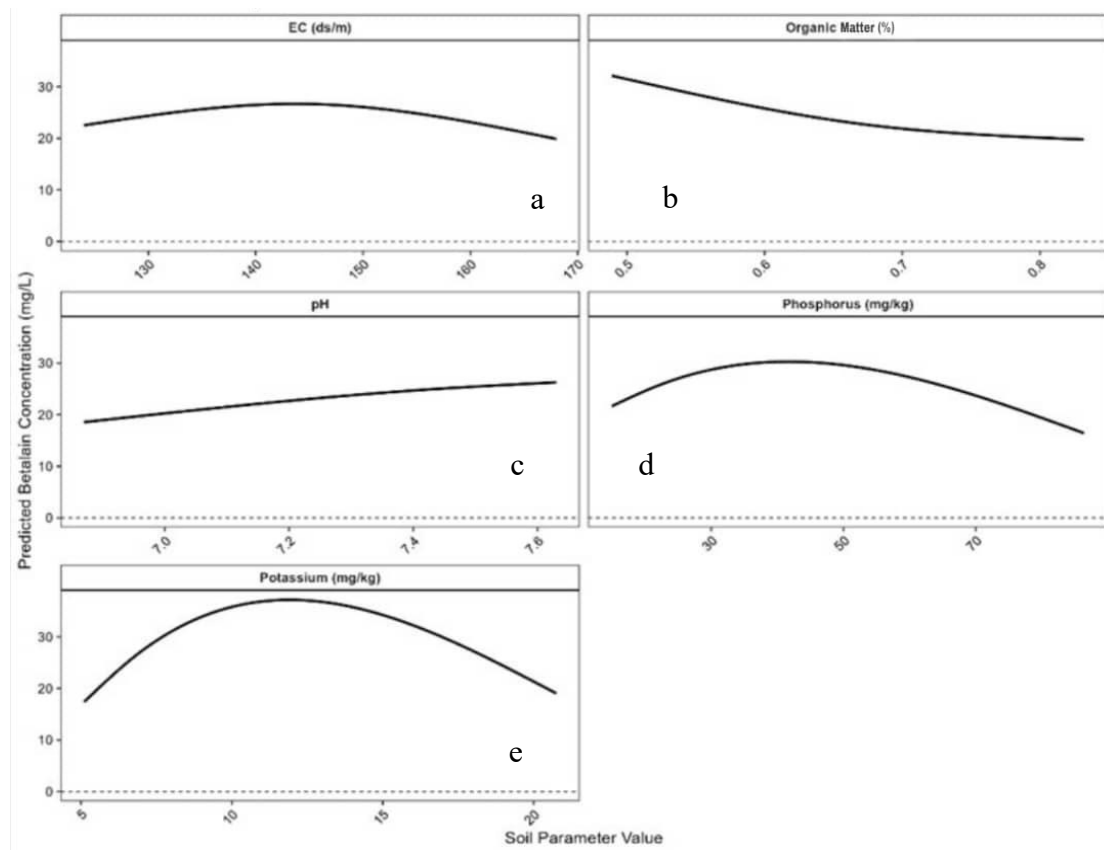


Figure 4. Threshold analysis for Betalain Concentration

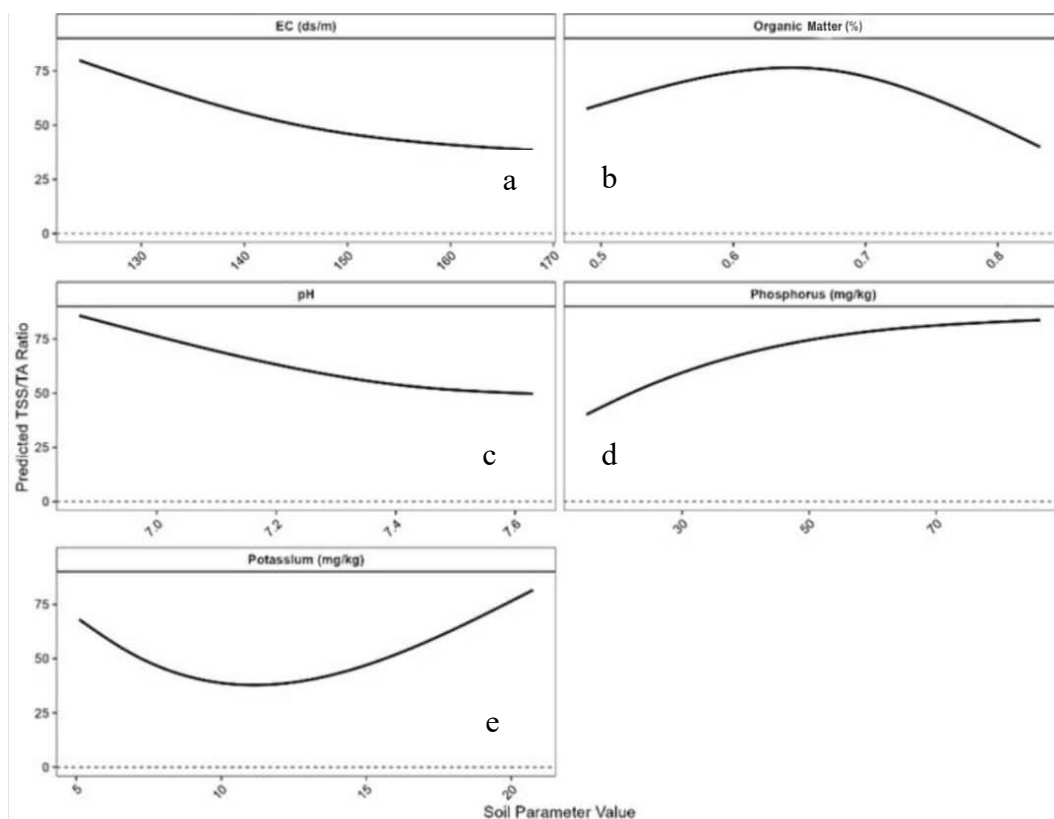


Figure 5. Threshold analysis for TSS/TA ratio

To further complement the threshold analysis, optimal soil parameter values in relation to betalain concentration and TSS/TA ratio were identified and summarized in Table 5. These values were derived from the model-predicted nonlinear response curves (Figure 4 and 5) and represent the soil parameter values at which the predicted response for each quality trait was highest within the observed data range along with their corresponding optimal ranges.

Table 5. Optimal soil parameter values and ranges derived from threshold analysis for maximizing betalain concentration and TSS/TA ratio in white fleshed dragon fruit

Parameters	Betalain		TSS/TA Ratio	
	Optimal value	Optimal Range	Optimal Value	Optimal Range
pH	7.63	7.5-7.7	6.87	6.7-6.9
Organic Matter (%)	0.84	0.8-0.9	1.1	1.0-1.1
EC (dS/m)	1.43	1.4-1.5	1.24	1.2-1.3
Phosphorus (mg/kg)	41.7	40-45	86.35	80-90
Potassium (mg/kg)	11.91	10-12	20.75	20-22

As shown in Table 5, betalain concentration was associated with higher soil pH (7.63; range: 7.5–7.7), whereas the TSS/TA ratio peaked at a slightly lower pH (6.87; range: 6.7–6.9). Organic matter showed low optimal values for both traits, with 0.84% (range: 0.8–0.9%) for betalain concentration and 1.1% (range: 1.0–1.1%) for the TSS/TA ratio, indicating that increased organic matter levels were consistently associated with reduced fruit quality across sites. Available phosphorus and potassium exhibited substantially higher optimal values for sweetness (86.35 mg/kg P and 20.75 mg/kg K; ranges: 80–90 mg/kg and 20–22 mg/kg, respectively) compared with pigmentation (41.70 mg/kg P and 11.91 mg/kg K; ranges: 40–45 mg/kg and 10–12 mg/kg, respectively), further reinforcing their stronger influence on the TSS/TA ratio than on betalain.

From the trait-specific optimal value and range (table 5) and by identifying overlapping soil parameters where both sweetness and pigment colour were favourable, the joint optimal value and range were derived, representing balanced soil conditions for both fruit quality (betalain and TSS/TA ratio) rather than maximising each trait. The values are presented in Table 6.

Table 6. Joint optimal soil parameter values derived from threshold analysis for maximizing betalain concentration and TSS/TA ratio in white fleshed dragon fruit.

Parameters	Joint Optimal Value	Joint Optimal Range
pH	6.87	6.7-7.0
Organic Matter (%)	0.96	0.90-1.05
EC (dS/m)	1.24	1.20-1.30
Phosphorus (mg/kg)	51.73	50-60
Potassium (mg/kg)	17.87	16-21

As per Table 6, the joint optimal pH was 6.87 (range: 6.7–7.0), where sweetness was favoured while maintaining acceptable pigmentation. The joint optimal organic matter level was 0.96% (range: 0.90–1.05%), confirming that low organic matter levels were consistently associated with improved overall fruit quality. For phosphorus and potassium, the joint optimal values were 51.73 mg/kg (range: 50–60 mg/kg) and 17.87 mg/kg (range: 16–21 mg/kg), respectively, representing intermediate levels that support both sweetness and pigmentation. Electrical conductivity showed a joint optimal value of 1.24 dS/m (range:

1.20–1.30 dS/m), indicating that lower to moderate salinity levels were favorable for overall fruit quality.

Overall, the joint optimal analysis shows that soil conditions that maximise betalain concentration do not fully coincide with those that maximise sweetness. By integrating trait-specific optimal values across study sites, this approach identifies soil parameter ranges that balance colour and sweetness in white fleshed dragon fruit under natural field variability.

3.5 Practical Application and Management Implications

The ridge regression, threshold and joint optimal 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 white fleshed dragon fruit.

For growers targeting balanced quality, the joint optimal values indicate maintaining pH at 6.87 (range: 6.7–7.0), organic matter at 0.96% (range: 0.90–1.05%), EC at 1.24 dS/m (range: 1.20–1.30 dS/m), phosphorus at 51.73 mg/kg (range: 50–60 mg/kg), and potassium at 17.87 mg/kg (range: 16–21 mg/kg). These values maximize both betalain content and the TSS/TA ratio. None of the white flesh dragon fruits grown on the study sites have the hypothetical optimal balanced quality of both sweetness and coloration as the fruits grown in BAJO and CRP showed higher coloration in fruits in trade off with sweetness and the fruits grown in FMCL showed the highest sweetness but had low coloration.

For sweetness-focused markets (TSS/TA ratio), phosphorus was identified to be the main key driver with optimal level being 86 mg/kg (range: 80–90 mg/kg) and potassium, with its optimum value being 21 mg/kg (range: 20–22 mg/kg) was the second key driver. Organic matter should be maintained at 1.1% (range: 1.0–1.1%) and EC around 1.24 dS/m (range: 1.20–1.30 dS/m). The white flesh dragon fruits grown at the FMCL farm best represents this scenario having the highest TSS/TA ratio among the three study sites due to the soil chemical conditions of the farm being similar to the hypothetical values which compromises the coloration but accentuates the sweetness.

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 matter. A target of 0.84% (range: 0.8–0.9%) is optimal. Unlike sweetness, betalain production benefits from slightly alkaline conditions with pH of 7.6 (range: 7.5–7.7) and has a much lower phosphorus requirement of 42 mg/kg (range: 40–45 mg/kg). Ridge regression and threshold analysis consistently showed that lower nitrogen

enhanced betalain accumulation indicating that excessive dose of nitrogen should be avoided if betalain is to be enhanced. The white flesh dragon fruits grown at CRP and BAJO best explains and represents this scenario having higher betalain values and matching similar soil conditions which favors coloration but comprises sweetness.

This shows that the main trade-off between sweetness and color is not only about nutrients competing with each other, but moreover about certain response thresholds. To achieve balanced fruit quality, it is important to keep key soil parameters within their optimal ranges instead of simply maximizing them.

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 analysis was based on three study sites within a single region of Bhutan. As a result, the findings represent soil-driven relationships observed under local field conditions and may not fully reflect responses under different climates, soil types, or dragon fruit cultivars. Although average climate data during anthesis to harvest period was documented, these variables were not included in regression due to minimal variability among sites. Future studies should incorporate a large number of sites to more explicitly partition soil and climatic effects. In addition, interpretation of the results was constrained by the limited availability of peer-reviewed literature specifically addressing soil chemical parameters–quality relationships in dragon fruit (*Hylocereus* spp.). Also, the influence of soil physical properties on white fleshed dragon fruit quality was not assessed in this study, as the experimental design focused on chemical soil variability thus, conclusions are restricted to soil chemical drivers of fruit quality.

These results fulfil 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 improved sweetness, whereas nitrogen and organic matter reduced both sweetness and pigmentation. Soil pH had a positive effect on betalain concentration up to a saturation point. The nonlinear responses revealed an inherent trade-off between quality traits. Increasing phosphorus and potassium to maximize sweetness tended to reduce colour intensity, while soil conditions that favoured pigment development often compromised sweetness. The joint optimal values therefore provide a scientifically grounded compromise for growers aiming to achieve balanced fruit quality.

Overall, these findings offer clear, context-specific guidance for nutrient management in Bhutan's white fleshed dragon fruit production. While maximizing both sweetness and colour simultaneously remains challenging, precision soil management based on joint optimal values provides a practical pathway to improve overall fruit quality under natural field conditions.

4 Conclusion

To conclude, this study showed that soil chemical parameters are key determinants of dragon fruit quality, influencing both sweetness (TSS/TA ratio) and pigmentation (betalain concentration). Through correlation, principal component analysis, ridge regression, and threshold analysis, soil parameters with strong effects on fruit quality were identified. The results reveal a fundamental trade-off: soil conditions that enhance sweetness tend to reduce pigmentation, whereas conditions that favor pigment accumulation often compromise sweetness. These findings also highlight the need for prior analysis of soil chemical parameters which is crucial for high quality white fleshed dragon fruit cultivation, as optimal soil conditions could be accurately managed to achieve desired fruit quality traits.

To address this trade-off, joint optimal values and ranges for soil chemical parameters, including soil pH (6.87; range: 6.7–7.0), organic matter (0.96%; range: 0.90–1.05%), electrical conductivity (1.24 dS/m; range: 1.20–1.30 dS/m), phosphorus (51.73 mg/kg; range: 50–60 mg/kg), and potassium (17.87 mg/kg; range: 16–21 mg/kg), were derived. These values represent soil conditions under which both sweetness and pigmentation are favorable, rather than maximizing either trait individually. This approach provides a scientifically grounded compromise for overall fruit quality.

These findings offer guided implications for growers where the trait-specific optimal values can be used to target niche markets that emphasise either sweetness, as seen in the white flesh dragon fruits produced at FMCL study site or visual appeal, as seen in the fruits produced by BAJO and CRP study sites, while joint optimal soil ranges and values can guide production toward balanced fruit quality. Together, these results provide an evidence-based framework for precision soil nutrient management in white fleshed dragon fruit cultivation.

The soil chemical compositions at the study sites reflected these quality differences. The FMCL site exhibited approximate available soil nitrogen at 249–225 mg/kg, phosphorus at 67.65–86.25 mg/kg, potassium at 5.10–20.75 and soil pH ranging from 6.87 to 7.15. The CRP site had approximate available soil nitrogen of 280 mg/kg, phosphorus at 14.95–17.75 mg/kg, potassium at 6.15–6.80 mg/kg and soil pH ranging from 7.28 to 7.63. The BAJO site

displayed approximate available soil nitrogen at 137–208 mg/kg, phosphorus at 21.90–36.95 mg/kg, potassium at 6.60–7.70 mg/kg and soil pH ranging from 7.44 to 7.61.

Future studies should validate these soil quality relationships across different regions, soil types, and dragon fruit cultivars, and assess the economic implications of adopting specialised versus balanced soil management strategies.

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6 Authors' contribution statement

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 analysing, interpreting, and visualising the data and drafting the manuscript. Kuenga Penjor Gyeltshen performed the biochemical analysis and data collection.

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