

Article

Foliar Spray of Macronutrient Influences Fruit Quality of Sugar Belle[®] Mandarin Grown in Florida Sandy Soil

Shankar Shrestha ^{1,2,*} , Laura Waldo ¹  and Arnold Schumann ^{1,2,*} 
¹ Citrus Research and Education Center, University of Florida, Lake Alfred, FL 33850, USA

² Department of Soil, Water, and Ecosystem Sciences, University of Florida, Gainesville, FL 32611, USA

* Correspondence: ishankshrestha@gmail.com (S.S.); schumaw@ufl.edu (A.S.)

Abstract: Sugar Belle[®] mandarin is considered tolerant to Huanglongbing (HLB); however, recent reports have raised concerns about its fruit quality, noting issues such as reduced fruit size, thin peel, poor coloration, decreased firmness, and suboptimal juice quality. Two-year field experiments were conducted to improve external and internal fruit characteristics through foliar application of potassium (K) in five-year-old Sugar Belle mandarin grown in Florida sandy soil. The experiment consisted of foliar K supply (17 kg/ha) via Potassium Nitrate (PN, 4.7 kg/ha N), Dipotassium Phosphate (DKP, 12.7 kg/ha P₂O₅), PN with boron (PNB, 0.84 kg/ha B) at different application times (May, July, September), including one-time Gibberellic acid spray (GA@10 mg/L) and control treatments. PN application during July (PN_J) or two applications of PN with B during May and July (PNB_{MJ}) resulted in a larger fruit size (>65 mm). Results showed that PN application before fall (May or July) resulted in a significantly thicker peel (2.3 mm), 1.15 fold more than the control and GA treatment. Fruit puncture resistance force was significantly higher (33.1 N) with GA treatment ($p = 0.07$), followed by PNB_{MJ} (32.6 N). Meanwhile, K spray positively influenced juice qualities and peel color, regardless of application time or source. However, GA treatment significantly reduced juice quality and peel color. These findings highlighted the benefits of foliar K supply as PN to improve fruit qualities in HLB-affected citrus grown in sandy soil.

Keywords: citrus; peel color; peel thickness; potassium nitrate; foliar spray; firmness



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1. Introduction

Huanglongbing (HLB), caused by (*Candidatus Liberibacter asiaticus*) is the most devastating disease threatening citrus production due to its complex nature and resistance to management [1–3]. It severely impairs root function and nutrient uptake, leading to poor tree health, reduced yields, and unmarketable fruit characterized by small size, misshapen form, bitter taste, thick rinds, and dry pithy interiors [4–10]. HLB disrupts nutrient transport by damaging phloem tissues, causing widespread deficiencies in essential nutrients [11]. Nutrient deficiencies exacerbate physiological disorders, impairing nutrient translocation and further stressing nutrient-deprived trees [12,13]. Additionally, the sandy soils in Florida present notable challenges for citrus production due to their well-drained nature, low organic matter and nutrient content, poor nutrient-holding capacity, and high permeability [14,15]. These characteristics often result in nutrient leaching, limiting the efficiency of soil-applied fertilizers, a common practice among citrus growers [16,17]. Consequently, the combined impact of HLB and the inherent challenges of sandy soils threatens the sustainability of Florida's citrus production. Researchers and citrus growers are still looking for strategies to mitigate HLB, but there is no cure to date.

Unfortunately, there are no commercial cultivars, varieties, or scion rootstock combinations with resistance to HLB CLas infection [18,19]. However, in recent years, Sugar Belle® ‘LB8-9’ mandarin hybrid (SB; “Clementine” mandarin × “Minneola” tangelo) has been popular due to apparent HLB tolerance under Florida natural HLB-endemic conditions [20,21]. Sugar Belle® is typically known for its vigor, heavy fruit load, and good juice quality, even under HLB conditions. Nevertheless, recent reports have highlighted a decline in fruit quality, with issues such as low juice total soluble solids (TSS), small fruit size, peel creasing, and increased fruit softness [22]. Florida citrus growers have also faced challenges regarding fruit splitting, damage during harvest and transportation, and problems with fruit peels being ripped off during processing, all of which impact the quality of fresh and processed citrus products. In addition, early-season mandarin fruits are often subjected to poor peel color development due to insufficient low temperatures that are needed to induce chlorophyll degradation and carotenoid accumulation [23,24].

Besides cultivar and climatic issues, imbalanced nutrition in citrus production has been reported to have significant impacts on thin peel size, fruit splitting, poor juice quality, small fruit size, and poor fruit texture [25–27]. Potassium (K) is an essential macronutrient for fruit trees, playing key roles in various biological and physiological processes [28]. It contributes to energy conversion, carbon fixation, and the transport of photosynthetic products, highlighting its importance in regulating fruit quality [29]. Several studies have suggested that potassium fertilization significantly improves fruit quality by enhancing fruit size and peel thickness and reducing the incidence of peel disorders [30–32]. However, excessive K could result in undesirable outcomes, such as thick, rough peel, reduced juice quantity, increased juice acidity, and a decreased brix/acid ratio [33]. Therefore, proper management of K fertilization could enhance the fruit’s external and internal properties, while soil fertilization is an easy method of nutrient application, nutrient uptake can be hindered by poor root systems, particularly in HLB-affected trees and in poor sandy soils with additional stress factors like salinity or drought [34].

Foliar application of minerals has been shown to be more effective in correcting nutrient deficiencies, minimizing soil toxicity, and preventing the fixation of micronutrients in the soil [35,36]. Studies have shown that foliar K application positively influences peel thickness and juice quality [37,38]. It has been found that foliar application of K after flowering increased the fruit size of Valencia oranges and the fruit yield of *Citrus sinensis* cv. Jaffa [39]. This indicates that the timing of K application is crucial, as it affects nutrient uptake, fruit size, and overall fruit quality. Research by Calvert [40] demonstrated that two foliar sprays of potassium nitrate (KNO_3) resulted in higher leaf potassium content compared to more frequent sprays, while late-season applications were less effective in improving fruit size [41]. Boman [42] found positive effects of (KNO_3) applied at key growth stages in Sunburst tangerine. Likewise, a previous study observed that spraying 8% KNO_3 three times produced the highest percentage of large-sized fruits (57–63 mm) in *Clementine* var. *Cadoux* [37]. Sangwan et al. [38] reported that a 2% KNO_3 foliar treatment resulted in the greatest number of large fruits in Kinnow.

Moreover, Alva et al. [34] reported that different sources of K are equally effective for correcting K deficiency; however, they failed to report the possible consequence on fruit quality and peel thickness due to other additional nutrients (like P in mono/di-potassium phosphate). Citrus responses to P fertilization result in higher yield, higher juice content, soluble solid–acid ratio, and decreased rind thickness [43,44]. Although well-balanced P fertilization is necessary for crop and fruit improvement, foliar application of P along with K sources could increase P uptake, which negatively impacts peel thickness, peel coloration, fruit firmness, fruit quality parameters, and also the internal leaf nutrient concentrations [45–47]. Additionally, foliar application of B could contribute to the qualitative

characteristics of fruit firmness, size, and yield [48,49], while there are several publications about the benefits of K spraying on tree and fruit growth, the optimal spraying time and efficacy of K sources are still not well studied with respect to fruit peel thickness, peel color, and fruit quality improvement in HLB-tolerant Sugar Belle[®] mandarin grown in Florida sandy soil. Given the significant role of potassium (K) in fruit quality and the challenges posed by HLB and Florida's sandy soils, we hypothesized that foliar application of K during the cell division stage significantly improves fruit juice quality, peel thickness, fruit size, and firmness in HLB-tolerant mandarin. Therefore, this study aimed to explore the effect of K foliar application timing and fertilizer sources on the external and internal fruit quality of Sugar Belle[®] mandarin grown in Florida's sandy soils.

2. Materials and Methods

2.1. Experimental Site and Soil Type

Field experiments were conducted at the University of Florida, Citrus Research and Education Center, Lake Alfred, Florida (lat. 28.12° N, long. 81.71° W) during 2022 and 2023 in existing 5-year-old Sugar Belle[®] mandarin on UFR 5 rootstock (White 4). The trees were planted at a distance of 6.1 m between tree rows and 3.0 m between trees in the research block. The soil in the experiment site was mapped as Kendrick fine sand series, consisting of well-drained, slowly to moderately permeable soils [50]. The initial soil physicochemical properties of the soil (0–20 cm) at the study site were less than 1% organic matter, a soil pH (H₂O) of 7.8, and a cation exchange capacity (CEC) of 30 meq/kg. The soil exhibited low levels of available nutrients such as N, K, Mg, S, and B; optimal levels of Ca, Mn, Fe, and Cu; and excess P content. The climate of the experimental site is classified as humid subtropical, with the highest rainfall observed between June to October. Two years of daily total annual rainfall, mean, minimum, and maximum temperatures are presented (Figure A1).

2.2. Experimental Design and Foliar Spray Treatments

The experiment was arranged in a randomized complete block design with foliar spray treatments. It included eight treatments varying in potassium (K) sources and foliar application timing; each replicated four times. Supplemental foliar sprays were applied from the fruit cell division stage (May), cell enlargement stage (July), and fruit maturation stage (September) according to treatment allocations (Table 1). The control treatment (T1) did not receive supplemental K foliar fertilization. The T2, Gibberellic acid (GA) treatment was included because sprays of GA during the fall are recommended for reducing preharvest fruit drop in the Hamlin cultivar, which matures at a similar time as Sugar Belle (<https://citrusindustry.net/2022/07/26/its-almost-time-to-spray-gibberellic-acid/>, accessed on 26 July 2022). Other treatments of foliar sprays were K sources, either from Potassium Nitrate (PN; 13-0-45) or Dipotassium Phosphate (DKP; 0-41-54). PN was applied once, twice, thrice, or combined with Boron (B) micronutrient during different fruit growth stages (cell division, enlargement, and maturation).

Since the recommendation of foliar K spray for citrus trees is 9 kg/ha [33], we raised the potassium (as K₂O) rate to 17 kg/ha to increase nutrient uptake due to the dense tree canopy size of Sugar Belle mandarin. The treatments were uniformly sprayed on the tree canopy to the point of runoff (~2 L/tree) while maintaining K₂O concentration of 1.2% from all sources. When foliar K was delivered via either PN or DKP, nutrients N and P (as P₂O₅) were concurrently added at a rate of 4.7 kg/ha or 12.7 kg/ha, respectively. In treatment T8, boron (B) was applied at 0.84 kg/ha from Solubor[®] (US Borax, Boron, CA, USA), combined with the respective treatment. In treatment T2, Gibberellic acid (GA) was applied at a concentration of a.i. 10 mg/L using commercially available GA₃ (ProGibb, Valent BioSciences, Chicago, IL, USA). The pH of the GA solution was adjusted to 6.0 with

citric acid to enhance its effectiveness. Induce[®] (Helena Chemical, Collierville, TN, USA) was added to the spray mixture at 0.125% (v/v) concentration as a wetter and spreader surfactant. All foliar applications were uniformly applied using a Kings skid sprayer (Kings Sprayer, Orlando, FL, USA), ensuring consistent coverage across all experimental plots. Each experimental plot included a net plot of five mature trees flanked by two buffer trees on either side. All trees received granular dry fertilizer supplemented with secondary and micronutrients through soil application, where the base N fertilizer rates were 180 and 200 kg/ha in the years 2022 and 2023, respectively [51]. Soil fertilization was split four times yearly at recommended rates for 5-year-old fruit-bearing trees with a 1:1.25 ratio of N and K fertilizer. Phosphorus fertilization was omitted in both years due to high preexisting soil P availability.

Table 1. Foliar application treatments at different spraying times and sources in Sugar Belle[®] trees grown in Florida sandy soil.

Treatments	Treatment Details	Application Time		
		May	July	September
T1:CT	Control (only soil applied fertilizer)			
T2:GA	Gibberellic Acid application: 10 ppm GA (September)			✓
T3:PN _M	PN—One application during the fruit cell division phase (May)	✓		
T4:PN _J	PN—One application during the cell enlargement phase (July)		✓	
T5:PN _{MJ}	PN—Two applications in May and July	✓	✓	
T6:PN _{MJS}	PN—Three applications in May, July, and September	✓	✓	✓
T7:DKP _{MJS}	DKP—Three applications in May, July, and September	✓	✓	✓
T8:PNB _{MJ}	PN + Boron—Two applications in May and July	✓	✓	

PN = Potassium Nitrate; DKP = Dipotassium phosphate.

2.3. Fruit Size, Peel Color, and Fruit Firmness Measurement

Fruit samples (20 matured fruits) were randomly collected on 12 December in 2022 and 2023 from the net plot trees to measure fruit diameter, weight, peel color, firmness, and thickness. Fruit diameter at the equatorial section was measured using a digital caliper with an accuracy of ± 0.02 mm (Husky Tools, Milwaukee, WI, USA). The fresh fruit weight was measured using a digital balance, and the average single fruit weight was calculated by dividing the number of fruits. Fruits were washed in Liquinox detergent (Alconox, Inc., White Plains, NY, USA) and rinsed in distilled water. The washed fruits were photographed with a digital camera for external peel color measurement, and the average peel color was measured using the CIE $L^*a^*b^*$ color system [52]. The component a^* denotes greenness or redness when negative or positive, respectively, and b^* represents the blue or yellow color intensity. L^* indicates lightness (low and high values of 0 to 100 for dark and light. Image segmentation and color channel computations were performed in Keras Tensorflow [53] algorithms developed in a Python 3.11 program using Jupyter Notebook 7 [54,55].

The citrus color index ($CCI = 1000 \times a^* \times / (L^* \times b^*)$) where negative values of CCI mean green, positive values close to zero yellow and high positive values mean reddish-orange [56]. Fruit compression force was measured at the equator of the fruits at room temperature using a computer-controlled texture analyzer. The analyzer was equipped with a flat probe, which compressed the fruit surface at a speed of 2 mm/s. The probe moved downwards and triggered the beginning of measurement when the fruit was detected at 0.1 N force. The compression distance limit was set at 5 mm, and the force required to achieve this compression was recorded in Newtons (N). Fruit puncture

resistance force was measured at the equator and stylar section of the fruit determined with a computer-controlled texture analyzer (Stable Micro Systems Texture Analyzer, Texture Technologies Corp., Surrey, UK) using the methods described in Plaza et al. [57], with slight modifications.

2.4. Peel Thickness and Juice Quality Measurement

Each fruit was carefully cut in half along its polar plane using a sharp knife to ensure a clean and precise cut. The thickness of the rind was then measured using a digital caliper at two distinct points: the stylar end (the end of the fruit opposite the stem) and the equatorial section (midpoint of the fruit's diameter at the cut surface). Fruit juice was extracted from the cut fruits using a commercial citrus juicer (Sunkist Growers, Valencia, CA, USA). The total juice percentage (%) was calculated by dividing the juice mass by the mass of juiced fruits. Total soluble solids (TSS) were determined using a Pocket Brix-Acidity Meter (ATAGO Co. Ltd., Tokyo, Japan) and expressed in °Brix. Titratable acidity (TA) was measured with the same device by analyzing a mixture of 1 mL of juice and 49 mL of deionized water, with acidity quantified using the electroconductivity method and expressed as a percentage (%). The maturity index (MI) was calculated as the ratio of TSS to TA.

2.5. Leaf Sampling for Leaf Parameter Recording and Nutrient Analysis

Twenty-five leaves of 4–6-month-old fully expanded leaves from non-fruiting terminals were randomly collected from all four sides of the trees of each plot to measure leaf morphology, dry matter, and nutrient analysis. The leaf chlorophyll index was measured using a SPAD-502 Chlorophyll meter (Minolta Corporation, Ramsey, NJ, USA). The leaf mass per unit area (LMA) of the sampled leaves was calculated by measuring and dividing the dry mass by the surface area. For leaf surface area estimation, the leaves were scanned in an EPSON flatbed scanner, and the images were analyzed using the ImageJ® software (<https://imagej.net/nih-image/>, National Institutes of Health, Bethesda, MD, USA). Leaf samples were washed in weak detergent solution Liquinox (Alconox, Inc., White Plains, NY, USA) and 5% *v/v* hydrochloric acid, rubbed between the thumb and forefinger, and subsequently rinsed with deionized water to remove debris adhering to the leaf surface [43]. The leaf samples were dried in a convection oven (Thermo Fisher Scientific, Waltham, MA, USA) at 65 °C for 72 h [58] and weighed to determine leaf dry matter biomass. The dried samples were ground with a Mini Thomas Wiley Grinding Mill (Thomas Scientific, Swedesboro, NJ, USA) equipped with a 40-mesh sieve. The processed samples were sent to Waters Agricultural Laboratories, Inc. (Camilla, GA, USA) to determine the elemental concentration of nutrients N, P, K, Ca, Mg, S, Zn, Mn, Fe, Cu, and B.

2.6. Statistical Analysis

All recorded fruit quality attributes and leaf nutrient concentration were analyzed using a linear mixed-effects model ('lmer') to examine the variance between treatment effects across two years (2022 and 2023). Treatments were treated as fixed factors, while the model included replication and year as random factors. Analysis of variance (ANOVA) tables with significant p-values were obtained using the 'anova' function from the 'lmerTest' package to assess the significance of treatment differences. Tukey's Honest Significant Difference (HSD) test was applied for pairwise comparisons of treatment means at a significance level of $\alpha = 0.05$. One-year data of fruit firmness parameters (compaction and puncture force) was analyzed with one-way ANOVA. If necessary, data transformations such as log or Box-Cox were applied to satisfy model assumptions. All statistical analyses were performed in RStudio using R version 4.4.1 [59].

3. Results

3.1. Fruit Size, Peel Thickness, and Firmness

Foliar application of K significantly influenced ($p < 0.05$) the fruit diameter and peel thickness; however, there was no effect on single fruit weight, compression force, and puncture force in the mandarin grown in Florida sandy soil. The result showed that fruit diameter was significantly ($p = 0.048$) increased with K foliar application (either with PN or DKP) compared to control or GA application (Table 2). However, the bigger fruit size was measured in K-applied treatments of PN_J and PNB_{MJ}, i.e., when PN was applied once in July (PN_J) or two applications of PN with B during May and July (PNB_{MJ}) resulting in a significantly larger fruit size. The effect of other foliar K-applied treatments on fruit diameter was comparable with PN_J and PNB_{MJ}.

Table 2. Average fruit diameter (FDM), single fruit weight (SFW), peel thickness, compression force (CF), and puncture force of HLB-tolerant Sugar Belle mandarin as influenced by foliar macronutrient potassium (K) application timing and source, grown in Florida’s sandy soil during 2022 and 2023.

Treatment	FDM (mm)	SFW (g)	Compression Force (N)	Puncture Force (N)	
				Equatorial	Stylar End
T1:CT	62.68 b	151	17.8	25.2	29.3
T2:GA	62.36 b	144	20.3	28.5	33.1
T3:PN _M	64.6 ab	156	18.3	24.6	29.3
T4:PN _J	65.31 a	156	18.6	25.1	29.3
T5:PN _{MJ}	64.41 ab	151	19.0	24.9	31.1
T6:PN _{MJS}	64.37 ab	151	18.4	25.5	29.9
T7:DKP _{MJS}	64.25 ab	155	20.0	26.1	29.3
T8:PNB _{MJ}	65.34 a	156	19.4	27.3	32.6
<i>p</i> -value	0.048 *	NS	NS	0.07	0.07

Different letters in each column and “*” indicate significant differences among treatments based on Tukey’s honest significant difference test ($\alpha < 0.05$). NS = not significantly different. FDM = Fruit Diameter; SFW = single fruit weight; CT = control; GA = Gibberellic acid; PN = Potassium Nitrate; DKP = Dipotassium Phosphate; PNB = PN + Boron; PN_M = PN applied in May; PN_J = PN applied in July; PN_{MJ} = PN applied in May and July; PN_{MJS} = PN applied in May, July, and September; DKP_{MJS} = DKP applied in May, July, and September; PNB_{MJ} = PNB applied in May and July.

Peel thickness was significantly influenced by foliar K applied treatments compared to the control and the GA-applied treatment. Peel thickness measured at the stylar end of the fruit (base-end) increased significantly ($p < 0.01$) with PN-applied treatments compared to GA and DKP-applied treatments. The result showed that one-time application of PN either in May (PN_M) or July (PN_J) had a significantly higher peel thickness of 2.29 mm. In contrast, peel thickness was compromised significantly with GA, DKP_{MJS}, and PNB_{MJ} treatments, which indicated that even one-time application of GA, three-time application of DKP or two-time PN with B application reduced the peel thickness (Figure 1).

The fruit firmness refers to peel puncture, and fruit compression force was measured at harvest, where the treatment effect was not significantly different ($p > 0.05$). However, GA application treatment ($p = 0.07$) resulted in a significantly higher puncture resistance force (28.5 N) at the equatorial or stylar section compared to other treatments. No significant difference in fruit puncture force was found; however, PNB-applied treatment resulted in 11% higher puncture force than other K-applied treatments and controls. These findings suggest that foliar application of potassium consistently (across two years of experiments) enhances fruit diameter, puncture resistance force, and peel thickness, although the timing and source of application play a critical role and require careful consideration.

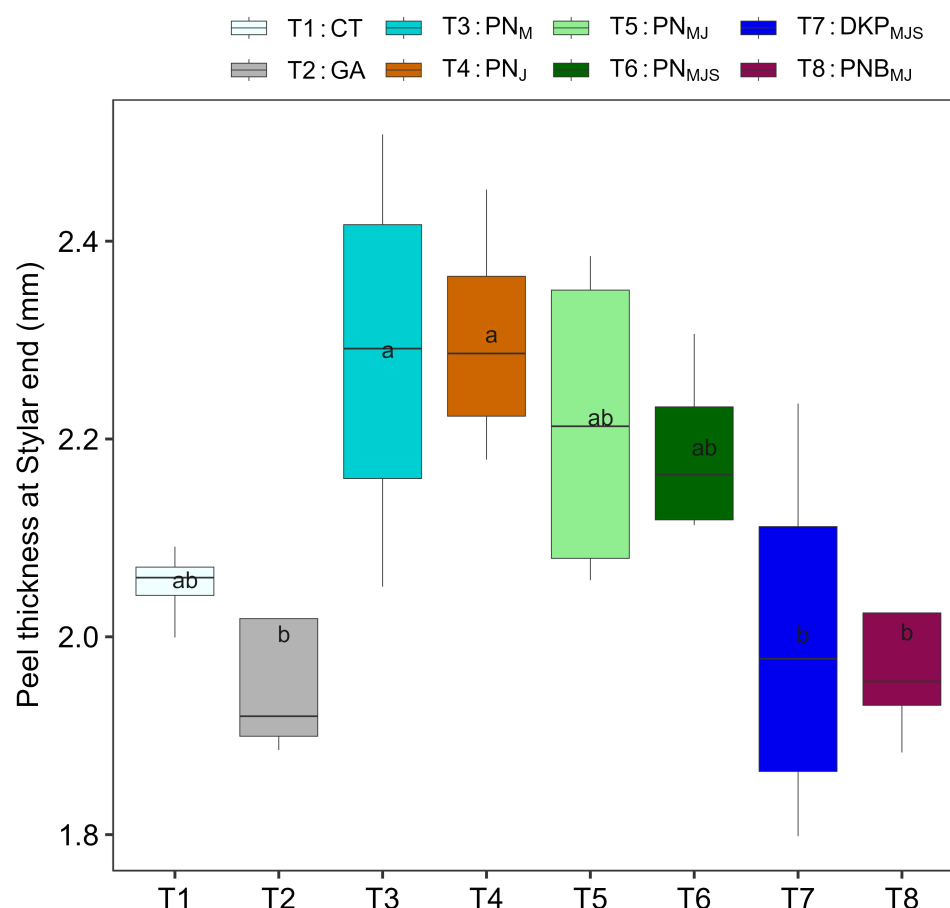


Figure 1. Peel thickness measured at the styler base end of Sugar Belle[®] mandarin as affected by foliar macronutrient application treatments grown in Florida sandy soils. CT = control, GA = Gibberellic acid; PN = Potassium Nitrate; DKP = Dipotassium Phosphate; PNB = PN + B; PN_M = PN applied in May; PN_J = PN applied in July; PN_{MJ} = PN applied in May and July; PN_{MJS} = PN applied in May, July, and September; DKP_{MJS} = DKP applied in May, July and September; PNB_{MJ} = PNB applied in May and July. Different letters in the boxplot indicate significant differences among treatments based on Tukey's honest significant difference test ($\alpha < 0.05$).

3.2. Peel Color and Juice Quality

Foliar K application treatments did not influence fruit external peel color attributes (CIELAB a^* , b^* , and CCI) of HLB-tolerant Sugar Belle mandarin but significantly differed with GA-treated treatment. The peel color a^* (greenish to reddish) and b^* (bluish to yellowish) values were significantly ($p < 0.01$) lower in GA treatment than in other treatments, indicating that GA application significantly compromised peel color development (Figure 2; Table 3). Although there was no significant difference among the foliar K-applied (PN or DKP) treatments in a^* value, treatments PN_{MJ} and PNB_{MJ} resulted in comparatively higher values than the control treatment (1.05 folds) and GA application (2.32 folds). With respect to peel b^* color value, K-applied treatments PN_{MJS} and PNB_{MJ} significantly had higher values of 52.4 and 52.2, respectively, relative to GA treatment (49.5). In addition, CCI color values were significantly decreased by GA application ($p < 0.001$); however, there was no difference with foliar K application compared to control (Table 3). Peel color b^* value was also higher in two times PN applied (PN_{MJ}) or PN with B treatments (PNB_{MJ}). Based on the peel color attributes, GA application significantly compromised the peel color break (chlorophyll degradation process).

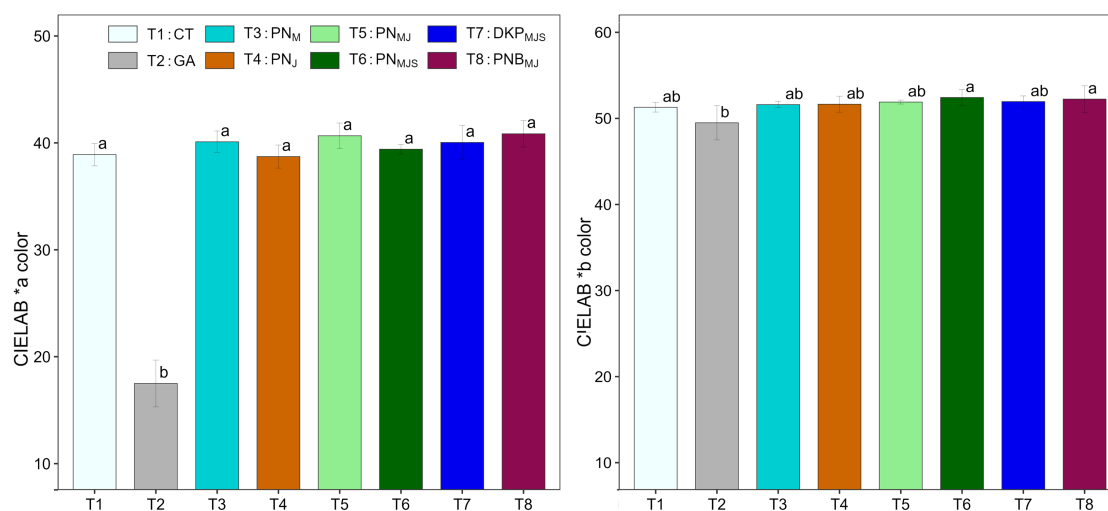


Figure 2. External fruit peel color a^* and b^* of Sugar Belle® mandarin as affected by foliar macronutrient application treatments grown in Florida sandy soils. CT = control, GA = Gibberellic acid; PN = Potassium Nitrate; DKP = Dipotassium Phosphate; PNB = PN + B; PN_M = PN applied in May; PN_J = PN applied in July; PN_{MJ} = PN applied in May and July; PN_{MJS} = PN applied in May, July, and September; DKP_{MJS} = DKP applied in May, July and September; PNB_{MJ} = PNB applied in May and July. Different letters in the barplot indicate significant differences among treatments based on Tukey's honest significant difference test ($\alpha < 0.05$).

Table 3. Average fruit peel color attributes of HLB-tolerant Sugar Belle mandarin as influenced by foliar macronutrient potassium (K) application timing and source, grown in Florida's sandy soil during 2022 and 2023.

Treatment	CIELAB L*	CIELAB a*	CIELAB b*	CCI
T1:CT	46.8	38.9 a	51.3 ab	16.0 a
T2:GA	48.1	17.5 b	49.5 b	7.4 b
T3:PN _M	47.1	40.1 a	51.6 ab	16.3 a
T4:PN _J	47.4	38.7 a	51.6 ab	15.7 a
T5:PN _{MJ}	47.3	40.7 a	51.9 ab	16.4 a
T6:PN _{MJS}	48.0	39.4 a	52.4 a	15.5 a
T7:DKP _{MJS}	47.7	40 a	52 ab	16.0 a
T8:PNB _{MJ}	47.7	40.9 a	52.2 a	16.3 a
<i>p</i> -value	NS	<0.01 **	0.02 *	<0.01 **

Different letters in each column indicate significant differences among treatments based on Tukey's honest significant difference test ($\alpha < 0.05$). ** and *** in the last row indicate the significant difference at $p < 0.05$ and $p < 0.01$, respectively. NS = not significantly different. CT = control, GA = Gibberellic acid; PN = Potassium Nitrate; DKP = Dipotassium Phosphate; PNB = PN + Boron; PN_M = PN applied in May; PN_J = PN applied in July; PN_{MJ} = PN applied in May and July; PN_{MJS} = PN applied in May, July, and September; DKP_{MJS} = DKP applied in May, July and September; PNB_{MJ} = PNB applied in May and July.

Foliar application treatments significantly influenced fruit juice composition. K application from PN or DKP significantly increased total soluble solids (TSS) content; however, GA-applied treatment reduced the TSS content by more than 10% (Table 4). Treatment PN_M had a higher TSS content of 11.9, followed by DKP_{MJS}, PNB_{MJ}, PN_J, and PN_{MJS} of 11.74, 11.68, 11.65, and 11.53, respectively, which was at par with control and PN_{MJ}. The titratable acidity (TA) was not significantly influenced by foliar spray treatments, while MI was reduced significantly ($p = 0.07$) with the GA-applied treatment. Comparatively, three-time foliar application (May, July, and September) of K from PN or DKP resulted in higher MI of 14.61 and 14.62, respectively, followed by K applied treatment PN_M (14.42) and PN_J (14.27). Two years of pooled results, fruit juice quality, especially TSS and MI, were consistently improved with K application regardless of K source (PN or DKP), but need to consider appropriate application time to yield better quality fruit.

Table 4. The average fruit juice composition of HLB-tolerant Sugar Belle mandarin was influenced by the timing and source of foliar macronutrient potassium (K) application, grown in Florida’s sandy soil during 2022 and 2023.

Treatment	Juice (%)	TSS (brix)	TA (%)	MI
T1:CT	45.8	11.34 ab	0.80	14.26
T2:GA	46.9	10.51 b	0.81	13.05
T3:PN _M	45.0	11.90 a	0.83	14.42
T4:PN _J	47.4	11.65 a	0.82	14.27
T5:PN _{MJ}	45.2	11.53 ab	0.82	14.09
T6:PN _{MJS}	47.7	11.58 a	0.80	14.61
T7:DKP _{MJS}	44.8	11.74 a	0.81	14.62
T8:PNB _{MJ}	45.1	11.68 a	0.84	14.10
<i>p</i> -value	NS	<0.01 **	NS	0.071

Different letters in each column indicate significant differences among treatments based on Tukey’s honest significant difference test ($\alpha < 0.05$). “**” in the last row indicates the significant difference at $p < 0.01$. NS = not significantly different. TSS = total soluble solids; TA = titratable acidity; MI = maturity index; CT = control, GA = Gibberellic acid; PN = Potassium Nitrate; DKP = Dipotassium Phosphate; PNB = PN + Boron; PN_M = PN applied in May; PN_J = PN applied in July; PN_{MJ} = PN applied in May and July; PN_{MJS} = PN applied in May, July, and September; DKP_{MJS} = DKP applied in May, July and September; PNB_{MJ} = PNB applied in May and July.

3.3. Leaf Size, SPAD, and Nutrient Concentration

Based on two years of data, leaf parameters, and nutrient composition were not significantly influenced by foliar application treatments in HLB-tolerant Sugar Belle mandarin grown in sandy soil. Neither the leaf SPAD chlorophyll nor leaf mass per area (LMA) was affected, even with the application of GA and K foliar treatments. This was likely due to the limited amount of nutrients and GA supplied, which may not have been sufficient to influence vigorously growing trees. Similarly, all leaf nutrient concentrations except for leaf B showed no significant differences in response to the foliar application treatments (Table A1). Despite multiple foliar applications of PN (potassium and nitrogen) and DKP (potassium and phosphorus) throughout the growing season, no significant increase in leaf nutrient concentration was observed. This suggests that foliar K applications did not substantially enhance nutrient reserves, potentially preventing negative impacts on fruit ripening, juice quality, and peel coloration at higher concentrations. The lack of significant differences in leaf nutrient concentrations at harvest may indicate the plant’s active translocation of nutrients from leaves to support fruit development, above-ground growth, or root activity. However, leaf boron (B) concentration was significantly higher in the foliar B-spray treatment with PN. Leaf B levels reached 186 mg/kg in the B-applied treatment (PNB_{MJ}), reflecting the efficiency of foliar application. This elevated leaf B concentration underscored boron’s limited mobility within plant systems, as it remains primarily in the leaf tissue where it is applied rather than translocating to other plant parts. Overall, these results suggested that foliar applications were largely ineffective in improving leaf nutrient levels, possibly with no negative effects observed on fruit ripening, juice quality, or peel coloration.

4. Discussion

The results of this study demonstrated that foliar application of potassium (K) significantly influenced fruit diameter and peel thickness of Sugar Belle mandarin grown in Florida’s sandy soil (Table 2). These findings align with previous research showing that K application enhances fruit size and peel thickness in citrus [32,60–62]. Foliar K application is significantly more effective and facilitates faster nutrient uptake, enhancing fruit growth benefits compared to soil-applied fertilizers [36,40]. The larger fruit size of mandarin is generally desirable for yielding and bringing higher prices. Our study revealed that an increase in fruit diameter, especially in treatments where Potassium Nitrate (PN) was applied once

in July (PN_J) or twice in May and July with B (PNB_{MJ}), suggested that the time, frequency, and source of K application influenced fruit growth. Foliar supplementation of K and B plays a crucial role in fruit growth with synchronizing K and B uptake. Nasir et al. [63] and Zekri and Obreza [33] reported that the supply of K promotes the synthesis of carbohydrates, regulates several enzymatic functions, and maintains cell extensibility that significantly affects fruit growth and development. Previous studies supported greater mobility of assimilated K to the developing fruit, which acts as a potent metabolic sink [64,65]. The study on grapefruits with foliar K supply during fall was less effective in average fruit size [41] but increased fruit size when K was applied before fall [61]. Additionally, nutrient B application supports fruit setting, carbohydrate transportation, and nutrient uptake efficiencies, increasing fruit size [66–68]. Our results were supported by Saleh and El-Monem [69], who stated that foliar K and B produce higher fruit sets and larger fruit sizes in mango and ‘Kinnow’ mandarin, respectively. On the other hand, repeated applications of PN and DKP would increase the concentration of N and P, respectively, along with K supply, which could negatively impact fruit growth and partition the nutrients toward vegetative growth instead of fruit development. Although several studies supported the fruit size increment with K fertilization, higher N and P negatively impacted fruit growth and development due to higher fruit set and canopy volume growth [44,70,71].

Regarding the peel thickness of Sugar Belle mandarin grown in Florida sandy soil, the study revealed that the foliar application of K improved the peel thickness; however, application time, source, and micronutrient integration impacted peel growth. The result is consistent with earlier studies that reported improved peel quality with K supply [25,37,60,61,71,72]. The increased peel thickness in treatments with a one-time PN application in May or July (PN_M and PN_J) highlights the efficient K uptake when applied at the right time that enhances fruit peel expansion and protection, possibly due to its role in strengthening cell walls [41,73]. High K application could increase leaf nutrient concentration and negatively impact the peel thickness (Table A2). This effect was especially evident at the stylar end of the fruit; however, no significant differences were noted in the equatorial section, suggesting that the impact of K on peel thickness may be location-specific within the fruit. In contrast, frequent foliar K applied either from PN, DKP, or additional B did not enhance the peel thickness of Sugar Belle®, suggesting that not all K sources and multiple applications were effective. In contrast, excessive or poorly timed K foliar application may be detrimental. Frequent K supply through PN and DKP also resulted in more N and P uptake that perhaps counteract peel expansion [43,71].

Shahzad et al. [32] reported that the puncture resistance force was significantly higher when potassium (K) was applied with boron (B) compared to the control, suggesting that this application may improve fruit resistance to handling stresses—an important factor for postharvest handling and storage. Correlation results illustrated the positive response with leaf K and B concentration (Table A2). A similar trend was observed in our study, where fruit puncture force was higher with GA and K+B application. However, the results were not statistically significant, possibly due to the small fraction of the nutrient supply.

The uniform and appealing color of mandarin is among the driving preferences for consumer purchase decisions [74,75]. The findings highlighted that foliar K application treatments did not influence change in fruit peel color attributes of mandarin, specifically the parameters of CIELAB a*, b*, and CCI, regardless of different K sources and application time. However, past studies reported that higher leaf nutrient concentration accumulation during ripening stages delays or inhibits peel chlorophyll degradation [76,77]. Despite the strong correlation between fruit color parameters and leaf nutrient concentrations (N, P, and K), surprisingly, the foliar application of PN and DKP had an insignificant effect regardless of application time and source (Table A3). These results are aligned with previous

research demonstrating that fruit nutrients such as N, P, and K could be partitioned into growing parts during maturation and perhaps peel color break with favorable weather conditions and ethylene phytohormone production [78,79]. Comparatively, foliar K treatments, particularly those with the combination of boron (PNB_{MJ}), were associated with more vibrant fruit color indexes, which could indicate enhanced physiological processes linked to fruit ripening and maturation. The synergistic effect of K and B could be linked to their role in enzyme activation and photosynthesis regulation, as these nutrients are essential for maintaining healthy fruit development and improving coloration throughout the maturation stages [32]. Nevertheless, the significant reduction in green-to-red (a*) and blue-to-yellow (b*) gradient values observed with the GA treatment suggested that Gibberellic acid (GA) application may inhibit the color break process. The suppression of color break in citrus fruit by GA has been documented in other studies, where GA was shown to delay the color transition during fruit maturation, possibly due to its effects on ethylene biosynthesis [80,81]. The present study exhibited that GA application negatively affected the peel color attributes, which are crucial for marketability, especially for fresh fruit sales. The reductions in chroma and CCI values reported in the GA treatment further emphasize the detrimental effect of GA on fruit coloration. These indices, which measure color intensity and saturation, are essential in determining the visual appeal of citrus fruits. Overall, GA treatment significantly compromised peel coloration, but foliar K application did not impact color breaks. The results of this study suggested that foliar K application, particularly when combined with boron, can positively influence fruit peel color attributes.

This study demonstrated the significant influence of foliar application treatments on the fruit juice composition of mandarin, with particular emphasis on total soluble solids (TSS) and maturity index (MI). The findings aligned with previous studies that have emphasized the importance of potassium (K) in fruit quality by enhancing TSS content [60,63,82]. The application of K, whether from Potassium Nitrate (PN) or Dipotassium Phosphate (DKP), resulted in a significant increase in TSS, where the PN_M treatment yielded the highest TSS content. This result was supported by prior research indicating that macronutrients (N, P, K) are a key nutrient in regulating the sugar accumulation in fruits, particularly when applied at the right time and amount [31,44]. The results of our correlation analysis showed that leaf N and fruit TSS ($r = 0.48$) were significant, possibly with higher N uptake with PN (Table A3). Interestingly, the relationship between leaf nutrient content and P and K was negative, which might be possible nutrient distribution towards fruits and growing parts [44]. Additionally, the additional B application also increased the TSS content of Mandarin when combined with PN [44]. Interestingly, titratable acidity (TA) and MI did not show significant change with foliar K treatments. On the other hand, the application of Gibberellic acid (GA) had a detrimental effect on TSS, reducing its content by more than 10%. The reduced TSS and MI with GA application could be attributed to the hormonal imbalance induced by GA, which might have altered the natural accumulation of sugars during fruit maturation [83,84]. Over two years, the consistent improvement in TSS and MI with K application, regardless of the source (PN or DKP), underscored the reliability of K as a key determinant of fruit juice quality.

Adequate mineral nutrient is a prerequisite for ensuring high yield, fruit quality, and tree health [85]. Foliar spray is regarded as a credible method to acquire a rapid response of nutrient supply, especially when soil and stress conditions limit the uptake of elements by roots during the growth periods [36,86]. However, the results of this study showed that foliar nutrient application did not significantly affect the leaf mineral content of HLB-tolerant mandarin grown in sandy soils except for micronutrient B. These findings are consistent with previous studies indicating that foliar applications of macronutrients, although beneficial in some contexts, may not always be retained in the leaves, especially

in nutrient-deficient or stress-prone systems such as those affected by HLB [39]. Uptake of nutrients could probably be distributed toward the growing roots, canopy, new flush, and fruit growth for being vigorous growing and highly productive characteristics of Sugar Belle mandarin [20]. However, contrasting results were reported that K application via PN and DKP significantly increased the leaf P and K content [39,41,87]. Leaf nutrient analysis of B concentration was significantly higher after B-applied with PN treatment (PNB_{MJ}) compared to the rest of the treatments. The results align with those described by Ullah et al. [68], where leaf boron is known as phloem immobile within plant systems, which causes it to accumulate in the leaf tissue where it is applied rather than being translocated to other parts of the plant. This result also suggests that foliar B applications effectively boost leaf B levels, but their impact may be localized and not significantly alter broader nutrient dynamics within the plant. In terms of macronutrient concentrations, the foliar treatments did not elevate nitrogen (N), phosphorus (P), or potassium (K) levels beyond the lower end of the critical nutrient concentration range for Florida citrus (CNCFC), even with multiple applications. This reflects no potential impact on fruit quality and attributes due to foliar micronutrient supplementation, where leaf macronutrient concentration is often negatively correlated with fruit TSS, color indexes, fruit size, etc. Notably, despite a slight increase in leaf N and K concentrations in specific treatments, these changes did not impact overall nutrient balance or fruit quality.

5. Conclusions

The present study demonstrated that potassium (K) foliar application time and source significantly improved fruit quality attributes in Sugar Belle mandarin grown in Florida sandy soil. The trees treated with a one-time foliar application of K via Potassium Nitrate (PN_J) during July or two applications of PN with B (PNB_{MJ}) during May and July resulted in larger fruit sizes. The peel thickness could be increased with one-time K fertilization through PN before the fall season (PN_M or PN_J). However, GA treatment had significantly compromised fruit juice quality and peel color development. Interestingly, there was no change in leaf nutrient concentration as affected by K fertilization except on the B-treated plot. No effect on nutrient composition avoids the potential consequence of higher nutrient content on the fruit's external and internal qualities. These findings underscore the benefits of foliar K nutrient application on fruit quality with one to two applications of PN during May and July with PN source in HLB-affected citrus and suggest that further research on the timing, concentration, and combination of treatments is needed to optimize fruit quality and improve nutrient uptake in these conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

HLB	Huanglongbing
TSS	Total Soluble Solids
TA	Titrateable Acidity
MI	Maturity Index
GA	Gibberellic Acid
PN	Potassium Nitrate
DKP	Dipotassium Phosphate

Appendix A

Table A1. Average leaf nutrient concentration on HLB-tolerant Sugar Belle mandarin as influenced by foliar macronutrient potassium (K) application timing and source, grown in Florida’s sandy soil during 2022 and 2023.

TRT	B %	P %	K %	Ca %	Mg %	S %	Mn mg/kg	Zn mg/kg	Cu mg/kg	Fe mg/kg	B mg/kg
T1:CT	2.16	0.12	0.96	2.85	0.34	0.34	32.3	9.5	8.4	47	119 b
T2:GA	2.24	0.12	1.10	2.75	0.32	0.30	34.6	11.0	9.6	49	131 b
T3:PN _M	2.25	0.12	0.97	2.78	0.33	0.35	38.8	11.5	8.3	54	132 b
T4:PN _J	2.26	0.11	0.99	2.87	0.33	0.32	33.3	10.9	7.5	47	118 b
T5:PN _{MJ}	2.21	0.12	1.01	2.71	0.34	0.33	39.8	13.4	7.8	54	124 b
T6:PN _{MJS}	2.27	0.11	1.01	2.85	0.32	0.32	36.0	11.3	8.8	50	118 b
T7:DKP _{MJS}	2.26	0.12	1.12	2.64	0.33	0.34	36.3	13.1	8.1	54	117 b
T8:PNB _{MJ}	2.24	0.12	1.03	2.74	0.32	0.30	39.8	12.3	7.0	52	186 a
<i>p</i> -value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	<0.01 **

Different letters in each column indicate significant differences among treatments based on Tukey’s honest significant difference test ($\alpha < 0.05$). “**” in the last row indicates the significant difference at $p < 0.01$. NS = not significantly different. CT = control, GA = Gibberellic acid; PN = Potassium Nitrate; DKP = Dipotassium Phosphate; PNB = PN + Boron; PN_M = PN applied in May; PN_J = PN applied in July; PN_{MJ} = PN applied in May and July; PN_{MJS} = PN applied in May, July, and September; DKP_{MJS} = DKP applied in May, July, and September; PNB_{MJ} = PNB applied in May and July.

Table A2. Overall Pearson’s correlation (r-value) between physical characteristics of fruit measurements and leaf nutrients (N, P, K, and B) of Sugar Belle mandarin grown in Florida’s sandy soil during 2022 and 2023.

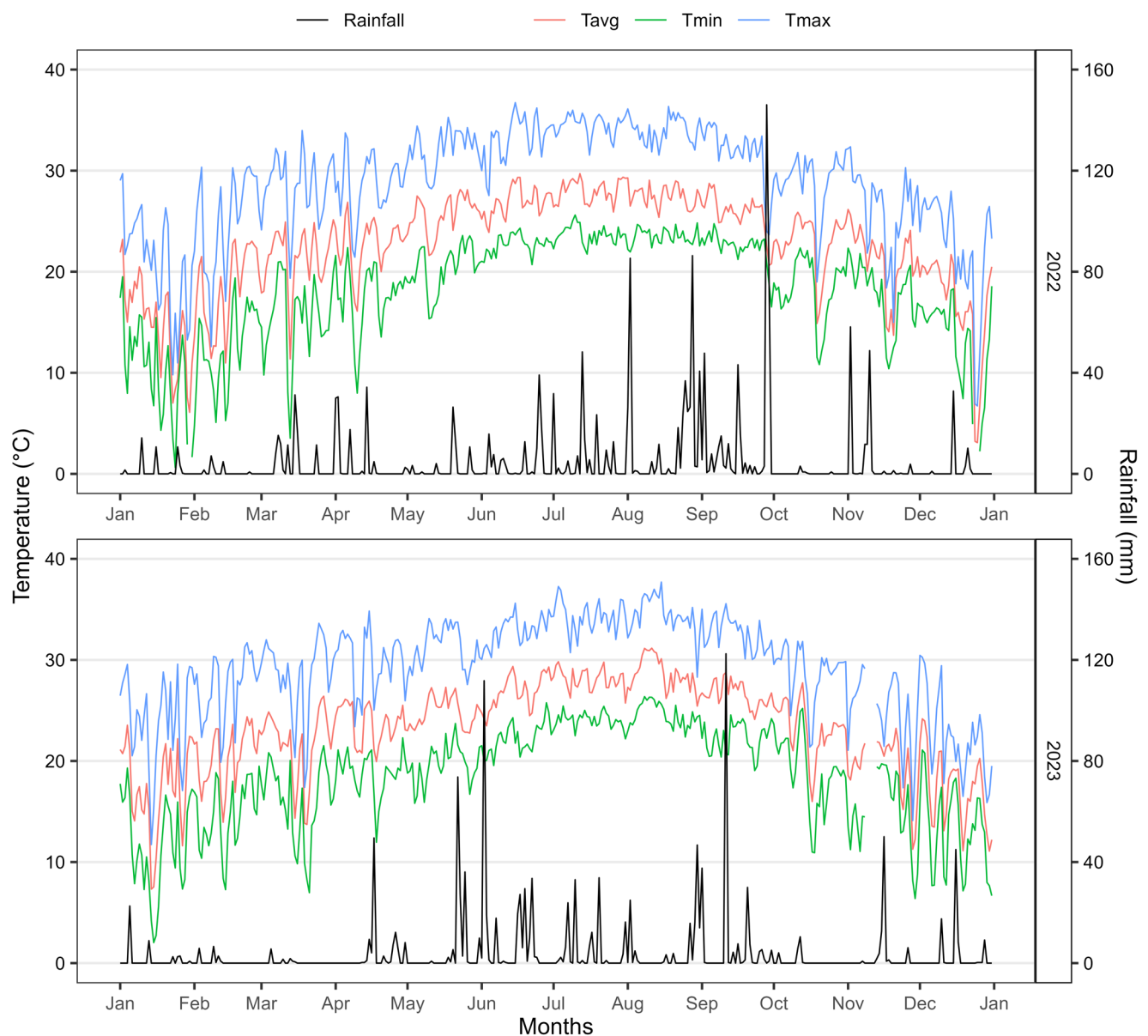
Fruit Parameter	N	P	K	B
Single fruit weight	0.62 *	−0.29 *	−0.22	−0.20
Fruit diameter	0.63 *	−0.27 *	−0.23	−0.12
Peel thickness at the stylar section	0.02	−0.14	−0.28 *	−0.25 *
Peel thickness at the equatorial section	0.34 *	−0.13	−0.01	−0.16
Compression Force	0.11	−0.21	0.14	−0.16
Puncture Force at the equatorial section	0.01	0.01	0.16	0.10
Puncture Force at the stylar section	0.17	0.10	0.10	0.28

** symbol denotes significant correlations at $p < 0.05$.

Table A3. Overall Pearson's correlation analysis (r-value) between peel color, juice quality, and leaf nutrients (N, P, K, and B) of Sugar Belle grown in Florida's sandy soil during 2022 and 2023.

Fruit Color and Juice Parameter	N	P	K	B
CIE L*	0.60 *	−0.30 *	−0.12	−0.14
CIE a*	0.46 *	−0.22	−0.30 *	−0.13
CIE b*	0.68 *	−0.33 *	−0.26 *	−0.19
CCI	0.19	−0.08	−0.25 *	−0.06
Juice %	−0.32 *	0.10	0.05	−0.06
TSS	0.48 *	−0.29 *	−0.32 *	−0.26 *
TA	−0.33 *	0.10	−0.08	−0.05
MI	0.65 *	−0.30 *	−0.19	−0.15

*/ symbol denotes significant correlations at $p < 0.05$.

**Figure A1.** Weather conditions of the study sites were measured for 2 years by FAWN-UF, Lake Alfred. Tavg = average mean daily temperature, Tmin = minimum mean daily temperature; Tmax = maximum mean daily temperature.

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