



Foliar Calcium Application Shows Limited Impact on Fruit Calcium and Firmness in Cranberry (*Vaccinium macrocarpon* Ait.)

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Abstract

Calcium is a fundamental macronutrient for plant growth, signaling, and fruit development. High Ca concentration has been associated with improved fruit quality. The objective was to evaluate the effect of foliar calcium applications during pre-bloom and bloom on fruit calcium concentration and fruit quality. In 2022, a research site in Central Wisconsin was used to investigate the effects of calcium chloride (CaCl_2) applications at concentrations of 750 mg L^{-1} , 1500 mg L^{-1} , and 3000 mg L^{-1} on cranberry ‘Stevens’. Treatments were applied at four phenological stages: pre-bloom, 10% bloom, 50% bloom, and 100% bloom. Additional treatments with multiple foliar applications of 1500 mg L^{-1} of CaCl_2 were applied in combinations of four, three, and two of the phenological stages described above, and fruit firmness and Ca content were evaluated at harvest. In 2023, the study was expanded to include two additional experimental sites, another cultivar, and a different Ca fertilizer. In 2022, single foliar Ca applications were ineffective in increasing fruit Ca content. However, multiple applications of 1500 mg L^{-1} CaCl_2 during bloom increased fruit Ca content but without improving firmness. In 2023, multiple applications during bloom had no significant effect on fruit Ca content or firmness across all treatments, cultivars, and sites. These contrasting results suggest that seasonal variation may influence the efficacy of foliar calcium applications in cranberry. Overall, fruit with higher Ca content were firmer during storage. These findings underscore the role of fruit Ca in cranberry quality, providing insights for future studies aimed to enhance cranberry fruit quality.

Keywords Calcium chloride · Calcium uptake · Calcium carbonate · Fruit quality · Postharvest

1 Introduction

Fruit firmness is a key trait in cranberry (*Vaccinium macrocarpon* Ait.) due to the mechanical stress and prolonged submersion of fruit in water during wet harvest, both of which can induce fruit softening (Özgen et al. 2002). Fruit firmness is also critical for producing high-valuable products like sweetened and dried cranberries (SDC) (Díaz-García et al. 2019; López-Moreno et al. 2024). The SDC production is an intensive process in which fruits are slowly frozen for storage, then thawed, cut in half, and exposed to

a high-temperature sugar solution for several hours (Grace et al. 2012). Calcium (Ca) plays a crucial role in maintaining fruit firmness and pulp integrity by forming insoluble pectin that strengthens the cell-to-cell adhesion in the middle lamella, thereby maintaining post-harvest quality (Angeletti et al. 2010; Ejsmentewicz et al. 2015; Lin et al. 2019; Montecchiarini et al. 2021; Ng et al. 2013).

Ca is translocated into fruit via xylem and driven by water potential differentials created by fruit transpiration (Himelrick and McDuffie 1983; Hocking et al. 2016; Montanaro et al. 2010). In cranberry fruits, Ca accumulation is restricted to the early stages of fruit development (Rojas-Barros et al. 2025), similar to other crops such as apple (*Malus domestica* Borkh) (Schlegel and Schönherr 2002) and highbush blueberry (*Vaccinium corymbosum*) (Yang et al. 2020). As fruit matures, physiological and anatomical changes, such as decline in xylem functionality and reduced transpiration, limit further Ca uptake and redistribution into the fruit (Dražeta et al. 2004; Higuchi and Sakuratani 2006; Mazzeo et al. 2013; Montanaro et

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al. 2015; Morandi et al. 2012; Palliotti and Cartechini 2001; Rojas-Barros et al. 2025; Winkler et al. 2021). This restricted movement poses a significant challenge for enhancing fruit Ca uptake during the later stages of development (Blodgett et al. 2002; Vance et al. 2017). Fruit Ca concentration can be increased through soil Ca applications (Hanson and Berkheimer 2004), foliar sprays (Marzouk and Kassem 2011; Neilsen et al. 2005) or dips in Ca solutions after harvest (Hanson et al. 1993; Hernández-Muñoz et al. 2006; Luna-Guzmán and Barrett 2000; Lv et al. 2020; Nguyen et al. 2020). In the case of soil applications, the effectiveness is often limited by the soil chemical and physical properties, plant nutritional status, and the interaction of Ca with other cations such as potassium (K), magnesium (Mg), and ammonium (NH_4) (Doyle et al. 2021; Lötze et al. 2008). Dips of calcium solutions have improved post-storage fruit quality in raspberry (*Rubus idaeus*) (Lv et al. 2020) and highbush blueberry (Hanson et al. 1993), although high concentrations can cause an undesirable salty taste. Therefore, foliar Ca applications are often considered a more efficient method to increase fruit Ca uptake and thus improve fruit quality (Griffith and Einhorn 2023). Nevertheless, the effectiveness of these applications may vary depending on the crop, phenological stage, fertilizer concentration, and number of applications, environmental conditions, among others (Griffith and Einhorn 2023; Huang et al. 2008; Matteo et al. 2024; Vance et al. 2017).

Multiple foliar Ca applications have been shown to effectively increase fruit Ca concentration in apple (Torres et al. 2024), highbush blueberry (Lobos et al. 2021), and sweet cherry (*Prunus avium*) (Matteo et al. 2024). In contrast, foliar Ca applications during late bloom were ineffective in increasing fruit Ca concentration or improving fruit quality in blueberry, strawberry (*Fragaria × ananassa* L.), raspberry, and blackberry (*Rubus* spp.) (Vance et al. 2017). In the only cranberry study of this kind, multiple foliar Ca applications during late bloom did not increase fruit Ca concentration or firmness (Blodgett et al. 2002).

Inconsistent results reported across studies could be explained by the timing of Ca application. Because calcium moves mainly through the xylem and relies on mass flow driven by transpiration, its accumulation in plant tissues, particularly flowers and fruit, largely depends on both environmental conditions and the stage of development (Brüggenwirth et al. 2016; Dražeta et al. 2004; Lang 1990). For example, in raspberry, most Ca accumulation occurs between the immature green and white fruit stages (Dias Da Silva et al. 2024), while in cranberry, Ca accumulates the first 28 days after full bloom (Rojas-Barros et al. 2025). During this phase, the higher density of pores

and trichomes on flowers and young fruit surfaces may further enhance foliar absorption (Saure 2005; Schlegel and Schönherr 2002). However, as fruit develops, the reduction in stomata density and in cuticle thickness likely limit further Ca uptake. Based on this understanding, we hypothesized that pre-bloom and bloom applications of high-concentration foliar Ca fertilizers can enhance fruit Ca content and fruit quality in cranberry. The objective of this study was to evaluate how the timing, number of applications, and concentrations of different Ca fertilizers from pre-bloom to bloom affected fruit Ca content and fruit quality in cranberry.

2 Materials and Methods

2.1 Site Description

In 2022, experiments were conducted at the Wisconsin Cranberry Research Station (WCRS) near Black River Falls, WI (Site 1, 44°11'08.5" N and 90°44'18.7" W), using the cranberry 'Stevens'. In 2023, the study was expanded to include the cranberry 'BG' and two additional sites along with the WCRS. One site was a commercial farm near Necedah, WI (Site 2, 44°12'55.8108"N and 90°4'21.5256"W) and the other was near Tomah, WI (Site 3, 44°03'41"N and 90°24'37"W). The maximum, minimum, and average ambient temperatures from the three study sites during the cranberry growing season in June, July, and August were 27.7 °C, 11.9 °C, and 19.6 °C (Online Resource 1; "NOAA MRCC" 2025). Nutrient levels from cranberry leaf tissue and soil analysis were within adequate levels for fruit production in all three sites (Online Resource 2 and Online Resource 3). Standard commercial and cultural practices for cranberry production were implemented at the research station (Sandler and DeMoranville 2009), including fertilization, pest and insect management, irrigation, winter protection, and sanding of beds every three years for sanitation and rooting of new growth.

2.2 Experimental Treatments

In 2022, two independent experiments were conducted at WCRS using a randomized complete block design (RCBD), with three independent 5-year-old cranberry beds (288 m × 28 m) considered as the blocking factor. The first experiment evaluated the effect of single foliar applications of calcium chloride (CaCl_2 ; 34% Ca) treatments at 750 mg L⁻¹, 1500 mg L⁻¹, and 3000 mg L⁻¹ compared to a water-only control. Each concentration was applied at four different phenological stages: pre-bloom or rough

neck (5 Jun), 10% of bloom (12 Jun), 50% of bloom (17 Jun), and 100% bloom (24 Jun) (Online Resource 4). The second experiment consisted of testing multiple applications of a single concentration of 1500 mg L⁻¹ of CaCl₂ during four (at pre-bloom or rough neck, 10%, 50%, and 100% bloom; Multiple 4), three (10%, 50%, 100% bloom; Multiple 3), and two (50% and 100% bloom; Multiple 2) of the phenological stages described above, plus a water-only control (Online Resource 4). Within each bed, two replicates per treatment were randomly assigned to 14 plots (10 × 10 m), giving a total of 42 plots for each of the four phenological stages.

In 2023, the study was expanded to include ‘BG’ cranberry and two new sites in addition to the WCRS. One site was a commercial farm near Necedah, WI (Site 2, 44°12′55.8108″N and 90°4′21.5256″W), and the other was near Tomah, WI (Site 3, 44°03′41″N 90°24′37″W). For this year, the experimental design was a completely randomized design, consisting of one bed per cultivar. Each bed was divided into 20 plots of 25 m², and each treatment was randomly assigned to four of the 20 plots. The time of application for both cultivars and treatments was at 10% bloom (15 Jun), 50% bloom (22 Jun), and 100% bloom (29 Jun). The Ca fertilizers used were CaCl₂ and Ca carbonate (CaCO₃; 30% Ca) both at a concentration of 750 mg L⁻¹ and 1500 mg L⁻¹ (Online Resource 4). A backpack sprayer with a liquid CO₂ tank was used in both years for spraying 0.02 L per m² which replicated the rates used by cranberry growers for other nutrient foliar applications. The time of the day of each application was between 9:00 a.m. and 12:30 p.m., and all foliar applications included a non-ionic surfactant (Scanner, Loveland Products. Inc.) at a concentration of 4.73 mm L⁻¹.

2.3 Fruit Calcium (Ca) Content

Approximately 50 fruits were randomly collected at harvest from each plot in both years, and samples were oven-dried for 7 days at 80 °C until constant weight. The samples were ground, and 100 mg of fruit was ashed at 450 °C for at least 6 h. The resulting ash was dissolved with 5 ml of 2 N HCl and filtered through a Whatman 541 filter paper into a volumetric flask containing 10 ml of the previously prepared LaCl₃ and HCl solution. The extract was then diluted to a final volume of 50 mL, resulting in a LaCl₃ and HCl solution concentration of 2000 mg L⁻¹ (Özgen and Palta 2005). The Ca concentration was determined using an atomic absorption spectrometer (Varian model Spectraa-20, Varian Associates, Inc., Sunnyvale, CA.), and values were converted to mg of Ca per berry dried weight.

2.4 Fruit Firmness and Firmness Loss after Storage

From each plot, 50 fruits were randomly collected at harvest to assess fruit firmness using a Texture Analyzer (TA. XTP-plus Connect, Textural Technologies, Hamilton, MA) with a test speed of 1 mm s⁻¹. Firmness was expressed as the force in grams (g) needed to compress each berry by 20% of its volume (Diaz-Garcia et al. 2019). In both years of the experiment, firmness was evaluated immediately after harvest. In 2023, firmness was also evaluated after one month of storage. Firmness loss after storage was calculated as a percentage using the following equation:

$$\text{Firmness Loss (\%)} = \frac{(\text{Firmness at harvest} - \text{Firmness after storage})}{\text{Firmness at Harvest}} \times 100$$

2.5 Yield and Fruit Weight Loss after Storage

Yield estimation was conducted only in 2023 by harvesting all the fruit in a 0.05 m² area per plot. The harvested fruit was weighed and counted to calculate yield and average berry weight. The berries were then placed in mesh bags and stored at 4 °C for three months. The percentage of fruit weight loss was calculated using the following equation:

$$\text{Fruit Weight Loss (\%)} = \frac{(\text{Weight at harvest} - \text{Weight after storage})}{\text{Weight at Harvest}} \times 100$$

2.6 Statistical Analysis

In 2022, a linear model was used to estimate the single application treatment effect on fruit calcium content and firmness using the following equation:

$$(\hat{Y}_i) = \hat{\beta}_0 + \hat{\beta}_1(x_{1i}) * \hat{\beta}_2(x_{2ii}) + \hat{\beta}_3(x_{3iii}) + \epsilon \quad (1)$$

In which $\hat{Y}_i$ represents the fruit Ca content or firmness, $\hat{\beta}_0$ is the intercept, x_1 is the treatment effect, x_2 is the phenological stage, x_3 is the bed considered as blocking factor (random effect), and ϵ is the error. For the multiple application treatment effect, the phenological stage was removed from the model. In 2023, the linear model described in (1) was slightly modified by removing the blocking factor, and including the cultivar and site interaction effects on the parameters measured using the following equation:

$$(\hat{Y}_i) = \hat{\beta}_0 + \hat{\beta}_1(x_{1i}) * \hat{\beta}_2(x_{2ii}) + \hat{\beta}_3(x_{3iii}) + \hat{\beta}_4(x_4) + \epsilon \quad (2)$$

in which $\hat{Y}_i$ is the response of the measured parameter, $\hat{\beta}_0$ is the intercept, x_1 is the treatment effect, x_2 is the cultivar effect, x_3 is the site effect, x_4 is the interaction between cultivar and site ($x_2 \times x_3$), and ϵ is the error.

An analysis of variance (ANOVA) was performed on every model to test the treatment effect and its interactions on the response variables. Pairwise comparisons were performed using estimated marginal means (EMMs) followed by Tukey's HSD range test with an α -level of 0.05. Assumptions of normality, linearity, and constant variance were assessed using residual vs. fitted plots. In addition, the relationship between fruit firmness and fruit Ca content was studied based on the year of the experiment and cultivar, phenological stage, and site specificity. The data output was generated using RStudio (R Core Team 2025).

3 Results

3.1 Fruit Calcium Content

In 2022, single foliar applications of CaCl_2 at any of the four phenological stages had no effect on average fruit Ca content (Fig. 1; Table 1). However, multiple applications of $1500 \text{ mg L}^{-1} \text{ CaCl}_2$, either three times (at 10%, 50%, and 100% bloom) or twice (at 50% and 100% bloom), increased fruit Ca content by 0.03 mg per berry compared to the control and single-application treatments (Fig. 2A; Table 1).

In 2023, multiple foliar Ca applications at 10%, 50%, and 100% bloom had no effect on average fruit Ca content across sites and cultivars (Fig. 3; Table 1). Across treatments and cultivars, fruit Ca content was higher at site 1 compared to site 2 and 3 (Fig. 3).

3.2 Fruit Firmness and Firmness Loss After Storage

In 2022, single foliar CaCl_2 applications had no effect on average fruit firmness at harvest, regardless of the phenological stage at which they were applied (Fig. 1B; Table 1). Similarly, multiple foliar application treatments of $1500 \text{ mg L}^{-1} \text{ CaCl}_2$ had no impact on firmness (Fig. 2B; Table 1). In 2023, multiple foliar Ca applications increased fruit firmness, but the effect depended on site and cultivar (Table 1). In 'Stevens', fruit treated with 750 mg L^{-1} and $1500 \text{ mg L}^{-1} \text{ CaCO}_3$ had higher firmness compared to the control at site 2 (Fig. 4A). In 'BG', fruit treated with $1500 \text{ mg L}^{-1} \text{ CaCl}_2$ had higher firmness compared to the control also at site 2 (Fig. 4A). Across all treatments, 'Stevens' had firmer fruit than 'BG' (Table 1).

Fruit firmness after storage and firmness loss were only evaluated in 2023. The average firmness after storage was

not affected by foliar Ca applications across sites and cultivars (Fig. 4B; Table 1). However, an interaction between treatment and site was observed, where fruit treated with $750 \text{ mg L}^{-1} \text{ CaCO}_3$ had greater firmness after storage compared to fruit treated with $1500 \text{ mg L}^{-1} \text{ CaCO}_3$ at site 3, though neither treatment differed from the control (data not shown). Regardless of treatment and site, 'Stevens' remained firmer than 'BG' after storage (Fig. 4B; Table 1). Firmness loss after storage was also not affected by foliar Ca application treatments across sites and cultivars (Online Resource 5; Table 1).

3.3 Yield

In 2022, the average yield was not evaluated, as no visible damage from the foliar CaCl_2 application was observed on the vines. However, yield evaluation was included in 2023 to account for any possible negative effect from the treatments. Although no treatment effect on yield was observed, a significant interaction between treatment and site revealed that the application of $750 \text{ mg L}^{-1} \text{ CaCl}_2$ and $1500 \text{ mg L}^{-1} \text{ CaCO}_3$ reduced yield compared to the control at site 3. Additionally, an interaction between site and cultivar indicated that 'BG' had higher yields than 'Stevens' across all sites (Online Resource 6; Table 2).

3.4 Fruit Weight Loss After Storage

In 2023, foliar Ca application treatments influenced fruit weight loss after storage, but the effect varied by site and cultivar (Online Resource 7; Table 2). In 'Stevens', fruit treated with $1500 \text{ mg L}^{-1} \text{ CaCl}_2$ lost more weight during storage than the control at site 2 (Online Resource 7; Table 2).

3.5 Relationship between Fruit Firmness and Fruit Ca Content

In 2022, a weak positive linear relationship was observed between fruit firmness at harvest and fruit Ca content across single (Online Resource 8, Adjusted $R^2=0.41$) and multiple foliar applications of CaCl_2 (Online Resource 9, Adjusted $R^2=0.35$).

In 2023, a positive linear relationship was found between fruit firmness and fruit Ca content at harvest, but this relationship varied depending on the cultivar and site. In 'Stevens', fruit firmness was positively correlated with fruit Ca content while 'BG' showed a negative relationship between both parameters (Online Resource 10, Adjusted $R^2=0.63$). After storage, fruit firmness was positively associated with fruit Ca content, with a stronger relationship observed in 'Stevens' compared to 'BG' (Online Resource 11, Adjusted

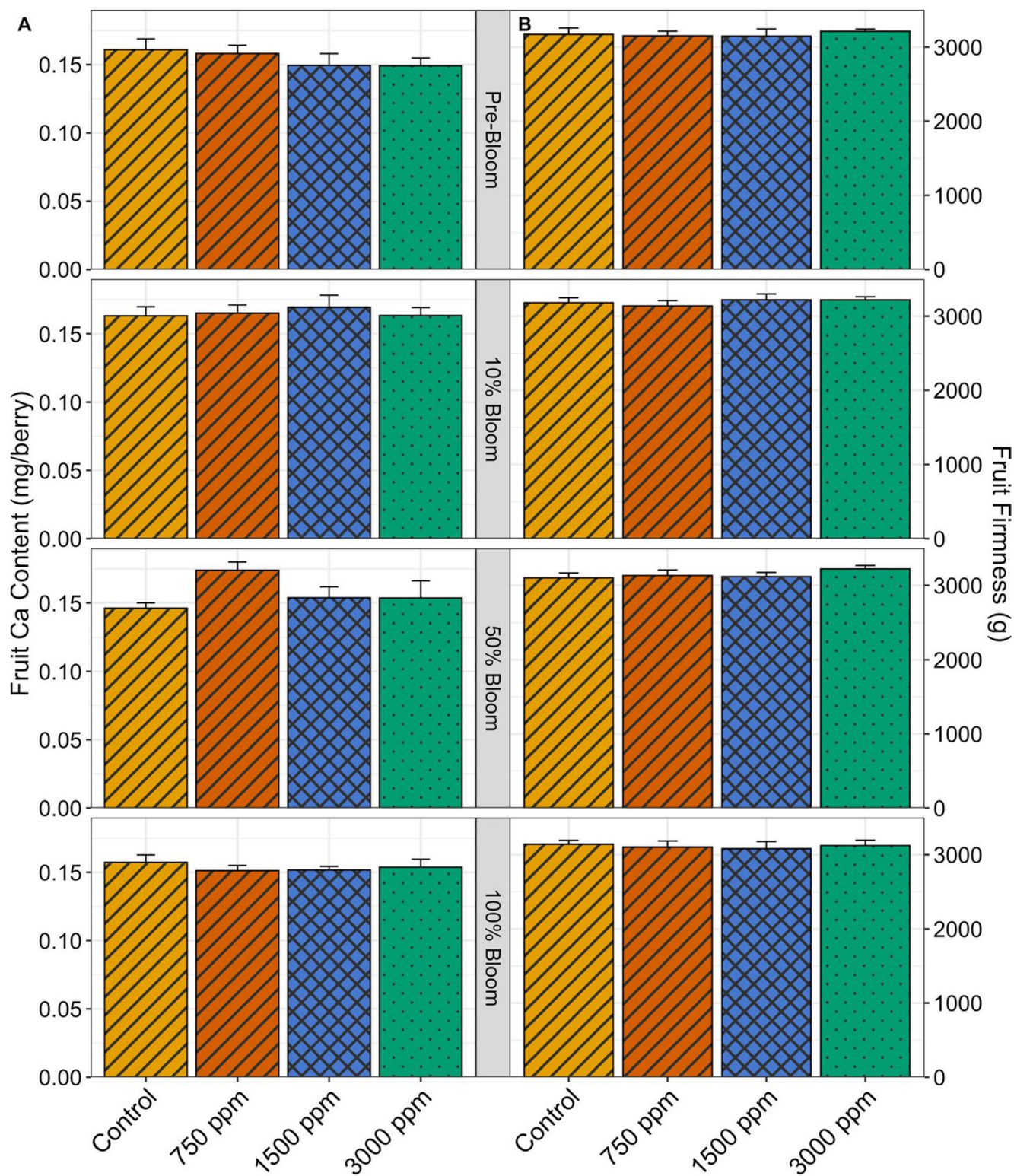


Fig. 1 Effect of single foliar applications of calcium chloride (CaCl_2) on cranberry fruit calcium (Ca) content in mg per berry (A) and fruit firmness in g (B). Treatments were applied at pre-bloom, 10% bloom,

50% bloom, and 100% bloom in ‘Stevens’ produced on the Wisconsin Cranberry Research Station, 2022. Each bar represents the mean of five replicates and error bars denote ± 1 SE

$R^2=0.85$). Additionally, a weak negative linear relationship was found between fruit firmness loss after storage and fruit Ca content (Online Resource 12, Adjusted $R^2=0.3$), indicating that higher fruit Ca content was associated with reduced firmness loss during storage. This relationship appeared more pronounced in ‘BG’ than in ‘Stevens’.

4 Discussion

The study evaluated the effects of different formulations and concentrations of foliar Ca applications on fruit Ca content and quality during pre-bloom and bloom in two cranberry cultivars over two years. In 2022, at least two applications of $1500 \text{ mg L}^{-1} \text{ CaCl}_2$ during bloom were required to increase fruit Ca content in ‘Stevens’, but fruit firmness remained unchanged. In 2023, multiple applications of CaCl_2 and CaCO_3 at various concentrations did not increase fruit Ca content or improve fruit quality in ‘Stevens’ and ‘BG’ across three different experimental sites. Nevertheless, fruit Ca content was positively correlated with fruit firmness after storage.

In 2022, single foliar applications of CaCl_2 from pre-bloom to 100% bloom did not increase fruit Ca content in ‘Stevens’, whereas repeated applications during bloom led to higher fruit Ca accumulation. These results suggest that each individual application delivers a small fraction of Ca to the fruit, and multiple applications increased the likelihood of Ca penetration. For example, studies in apple estimated that for each Ca fertilizer application, only about 5–10 μg of Ca per g of fruit fresh weight penetrates the epidermis of apples (Saure 2005), making repeated

applications necessary to increase fruit Ca concentration. Multiple foliar applications have been favorable in increasing fruit Ca concentration in blueberry (Lobos et al. 2021; Ochmian and Kozos 2015) and sweet cherry (Matteo et al. 2024). In cranberry, previous studies reported that four applications during late bloom failed to increase fruit Ca concentration to reduce fruit rot incidence (Blodgett et al. 2002). Those treatments coincided with a period of rapid cuticle thickening (Rojas-Barros et al. 2025), likely affecting Ca uptake through the epidermis. In our study, foliar Ca treatments were applied a month earlier, during the pre-bloom and bloom periods, and used twice the Ca fertilizer concentration, which may explain the observed increase in fruit Ca content during the first year of the study. Noteworthy, however, is four multiple foliar Ca applications from pre-bloom to 100% bloom tended to numerically reduce fruit Ca content when treated fruit was compared to the other treatments that received fewer applications. This reduction could be explained by an excess of chloride in the tissue that may have reduced stomatal conductance and Ca translocation (Swietlik and Miller 1987). Our results suggest that four applications, including a pre-bloom spray, might negatively affect fruit Ca accumulation in cranberry ‘Stevens’.

In 2023, multiple foliar Ca applications of two different Ca fertilizers at 750 and 1500 mg L^{-1} concentration were again ineffective in increasing fruit Ca content. The inconsistent results may be attributable to seasonal variation like relative humidity (RH), which plays a key role in Ca uptake (Schönherr 2001), as well as differences in the fruit cuticle thickness across years. Ca fertilizers like CaCl_2 penetrate more effectively when their

Table 1 Analysis of variance summary for treatment effects on fruit quality parameters in 2022 and 2023

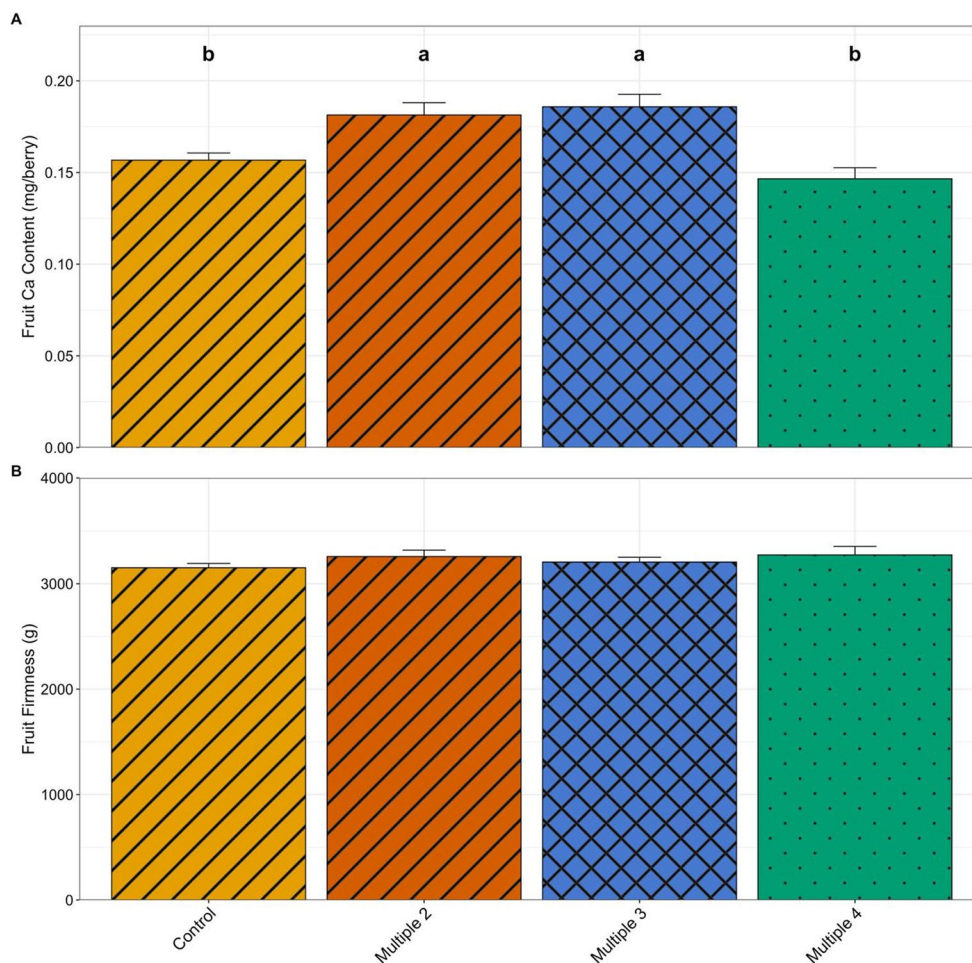
Year	Treatment	Parameter	Source	df	F value	P value
2022	Single Application Treatments	Fruit Calcium Content	Treatment	3	0.82	0.482
			Block	3	0.91	0.405
			Phenological Stage	2	2.40	0.073
			Treatment x Phenological Stage	9	1.08	0.387
			Residuals	78	-	-
		Fruit Firmness	Treatment	3	1.12	0.344
			Block	2	33.52	$<3.12\text{e}^{-11}$
			Phenological Stage	3	1.66	0.181
			Treatment x Phenological Stage	9	0.35	0.951
			Residuals	78	-	-
	Multiple Applications	Fruit Calcium Content	Treatment	3	9.00	<0.001
			Block	2	0.34	0.712
			Residuals	30	-	-
		Fruit Firmness	Treatment	3	1.79	0.168
			Block	2	10.02	<0.001
			Residuals	30	-	-

Table 1 (continued)

Year	Treatment	Parameter	Source	df	F value	P value
2023	Multiple Applications	Yield	Treatment	4	0.44	0.782
			Cultivar	1	172.08	$<2.2\text{e}^{-16}$
			Site	2	6.53	0.002
			Treatment x Cultivar	4	0.48	0.752
			Treatment x Site	8	2.01	0.054
			Cultivar x Site	2	4.11	0.020
			Treatment x Cultivar x Site	8	0.38	0.927
			Residuals	90	-	-
		Fruit Calcium Content	Treatment	4	0.75	0.559
			Cultivar	1	1.70	0.196
			Site	2	80.98	$<2.20\text{e}^{-16}$
			Treatment x Cultivar	4	1.14	0.344
			Treatment x Site	8	0.84	0.566
			Cultivar x Site	2	18.80	$<1.50\text{e}^{-08}$
			Treatment x Cultivar x Site	8	1.13	0.352
			Residuals	90	-	-
		Fruit Firmness at Harvest	Treatment	4	3.10	0.019
			Cultivar	1	85.92	$<9.47\text{e}^{-15}$
			Site	2	24.94	$<2.42\text{e}^{-09}$
			Treatment x Cultivar	4	2.28	0.067
			Treatment x Site	8	1.39	0.213
			Cultivar x Site	2	23.35	$<6.80\text{e}^{-09}$
			Treatment x Cultivar x Site	8	4.87	$<5.18\text{e}^{-05}$
			Residuals	90	-	-
		Fruit Firmness at Storage	Treatment	4	0.62	0.652
			Cultivar	1	290.69	$<2.2\text{e}^{-16}$
			Site	2	38.01	1.08e^{-12}
			Treatment x Cultivar	4	0.84	0.504
			Treatment x Site	8	2.73	0.010
			Cultivar x Site	2	35.57	$<4.14\text{e}^{-12}$
			Treatment x Cultivar x Site	8	0.95	0.480
			Residuals	90	-	-
		Firmness loss after storage	Treatment	4	1.45	0.224
			Cultivar	1	16.19	0.0001
			Site	2	0.37	0.690
			Treatment x Cultivar	4	2.25	0.069
			Treatment x Site	8	1.85	0.076
			Cultivar x Site	2	2.66	0.075
			Treatment x Cultivar x Site	8	1.8832	0.072
			Residuals	90	-	-
		Fruit weight loss	Treatment	4	3.26	0.015
			Cultivar	1	0.88	0.351
			Site	2	0.20	0.823
			Treatment x Cultivar	4	4.71	0.002
			Treatment x Site	8	0.74	0.656
			Cultivar x Site	2	4.37	0.015
			Treatment x Cultivar x Site	8	1.09	0.375
			Residuals	90	-	-

The p value <0.05 using are significant different at $\alpha=0.05$

Fig. 2 Effect of multiple foliar applications of 1500 mg L⁻¹ of calcium chloride (CaCl₂) on cranberry fruit calcium (Ca) content in mg per berry (**A**) and fruit firmness in g (**B**). Treatments were applied at 50% and 100% bloom (Multiple 2), at 10%, 50% and 100% bloom (Multiple 3), and at pre-bloom, 10%, 50%, and 100% bloom (Multiple 4) in ‘Stevens’ produced on the Wisconsin Cranberry Research Station, 2022. Each bar represents the mean of five replicates and error bars denote ± 1 SE. Bars presented with the same letter are not different at $P < 0.05$ using Tukey’s HSD range test



point of deliquescence is lower than the RH, allowing them to absorb moisture and dissolve on the fruit surface (Schönherr 2001; Winkler and Knoche 2021). In apples, RH above 50% increases the rate of CaCl₂ penetration through the fruit cuticle (Schönherr 2001). Although RH was not recorded in our study, 2023 received less precipitation than 2022 during the period of foliar Ca applications (“NOAA MRCC” 2025). This may have reduced RH and limited fruit Ca uptake for both fertilizers. In addition, fruit cuticle permeability may have also influenced absorption, as a three-year study in cranberries found year-to-year variations in cuticle thickness within the same cultivars (Stevens 1932). Notably, these variations in cuticle thickness were not correlated with air temperature, and RH was not recorded in the study, leaving open the possibility that RH or other environmental factors influenced the differences observed.

While these results explain variability in Ca uptake, they also provide context for firmness outcomes. In 2022, although multiple foliar applications of CaCl₂ increased

fruit Ca content, they did not increase fruit firmness at harvest. Similar findings were reported in highbush blueberry where higher fruit Ca concentration did not increase fruit firmness (Hanson and Berkheimer 2004; Ochmian and Kozos 2015). This discrepancy could reflect a minimal impact of increased fruit Ca content on firmness, or it may indicate that any potential effect of higher Ca levels was not yet detectable at harvest. In our 2022 data, fruit firmness at harvest showed only a weak correlation with Ca content when data were pooled, consistent with results in strawberry, blueberry, blackberry, and raspberry (Vance et al. 2017). In some cases, the positive effect on fruit firmness by foliar Ca applications and dips in CaCl₂ solutions has only been observed after storage, as reported in highbush blueberry (Angeletti et al. 2010) and raspberry (Lv et al. 2020).

Fruit firmness after storage was considered only in 2023. That year, fruit from ‘Stevens’ treated with 750 and 1500 mg L⁻¹ CaCO₃ had higher firmness at harvest than the control, but the effect varied by site and cultivar

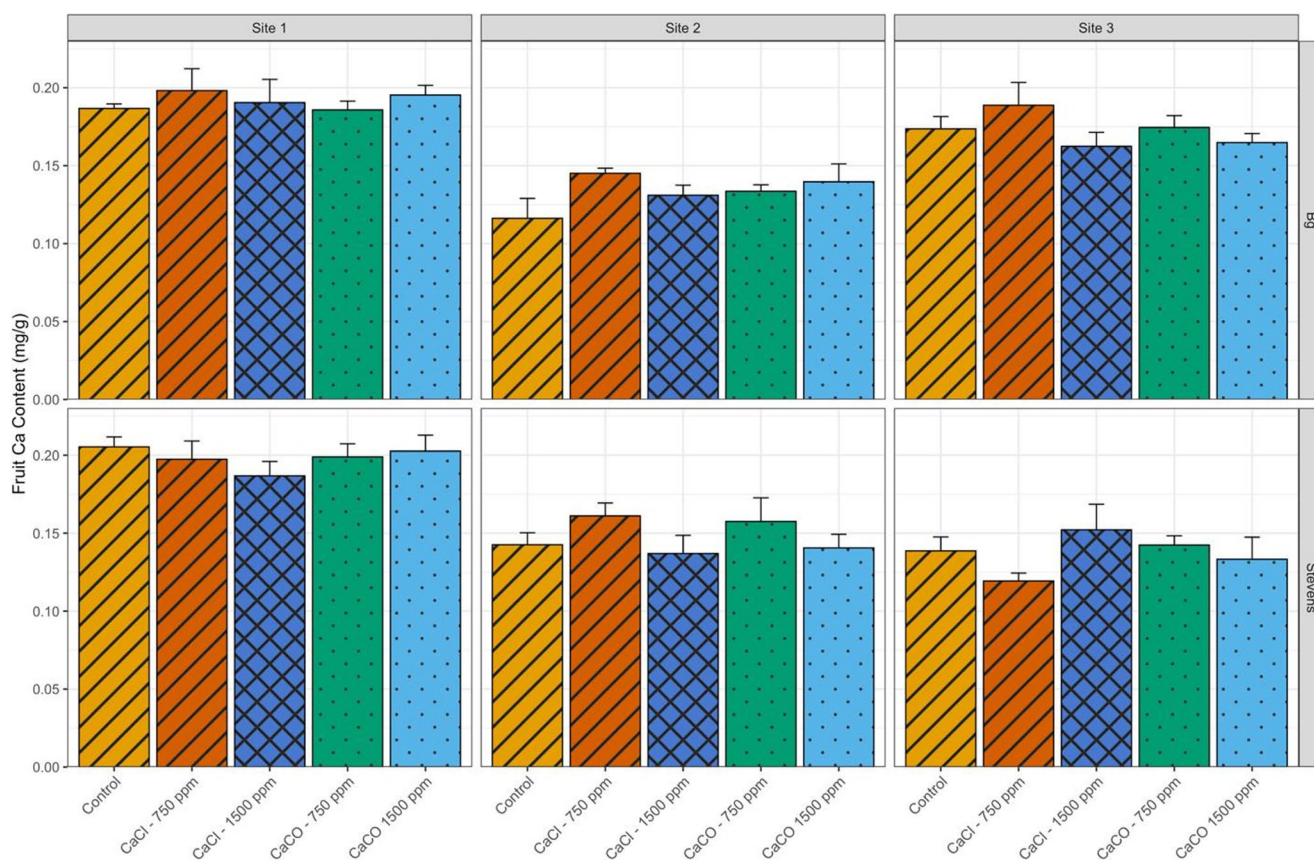


Fig. 3 Effect of foliar calcium treatments (calcium chloride, CaCl_2 ; calcium carbonate, CaCO_3) on cranberry fruit calcium (Ca) content in mg per berry. Treatments were applied at 10% bloom, 50% bloom,

and 100% bloom in ‘Stevens’ and ‘BG’ cranberries produced on three sites in central Wisconsin, 2023. Each bar represents the mean of five replicates and error bars denote ± 1 SE

and was not associated with higher Ca content. However, when data were pooled across treatments and sites, a positive correlation between firmness and Ca content after storage emerged. Across cultivars, firmness loss during storage was negatively correlated with Ca content. These findings suggest that Ca may help maintain cell wall integrity during storage, potentially by reducing pectin solubilization, as observed in blueberry (Angeletti et al. 2010; Liu et al. 2019).

Firmness loss during storage can result from dehydration and changes in cell wall components (Montecchiarini et al. 2021; Ng et al. 2013; Vicente et al. 2007). In this study, weight loss was not associated with firmness loss (data not shown), suggesting that changes in pectin and hemicellulose solubilization may have been more important (Vicente et al. 2007). In blueberry, firmness retention during storage has been linked to delayed pectin solubilization in the middle lamella, a process reduced by higher Ca content (Angeletti et al. 2010; Liu et al. 2019). Our results suggest that Ca may

play a similar role in maintaining cranberry fruit cell wall integrity during storage.

Taken together, these findings indicate that the effectiveness of foliar Ca applications in cranberry depends strongly on environmental conditions, particularly RH, fruit developmental stage, and cuticle properties. While multiple applications can enhance Ca content under favorable conditions, excessive sprays or suboptimal timing may be counterproductive. Future work should explore the mechanisms of Ca penetration, the influence of cuticle traits, the optimal frequency and fertilizer concentration for foliar Ca in cranberry, as well as the role of Ca in cranberry fruit quality.

5 Conclusions

The effectiveness of foliar calcium (Ca) applications in increasing fruit Ca content varied between years and did not improve fruit firmness at harvest or after storage in both

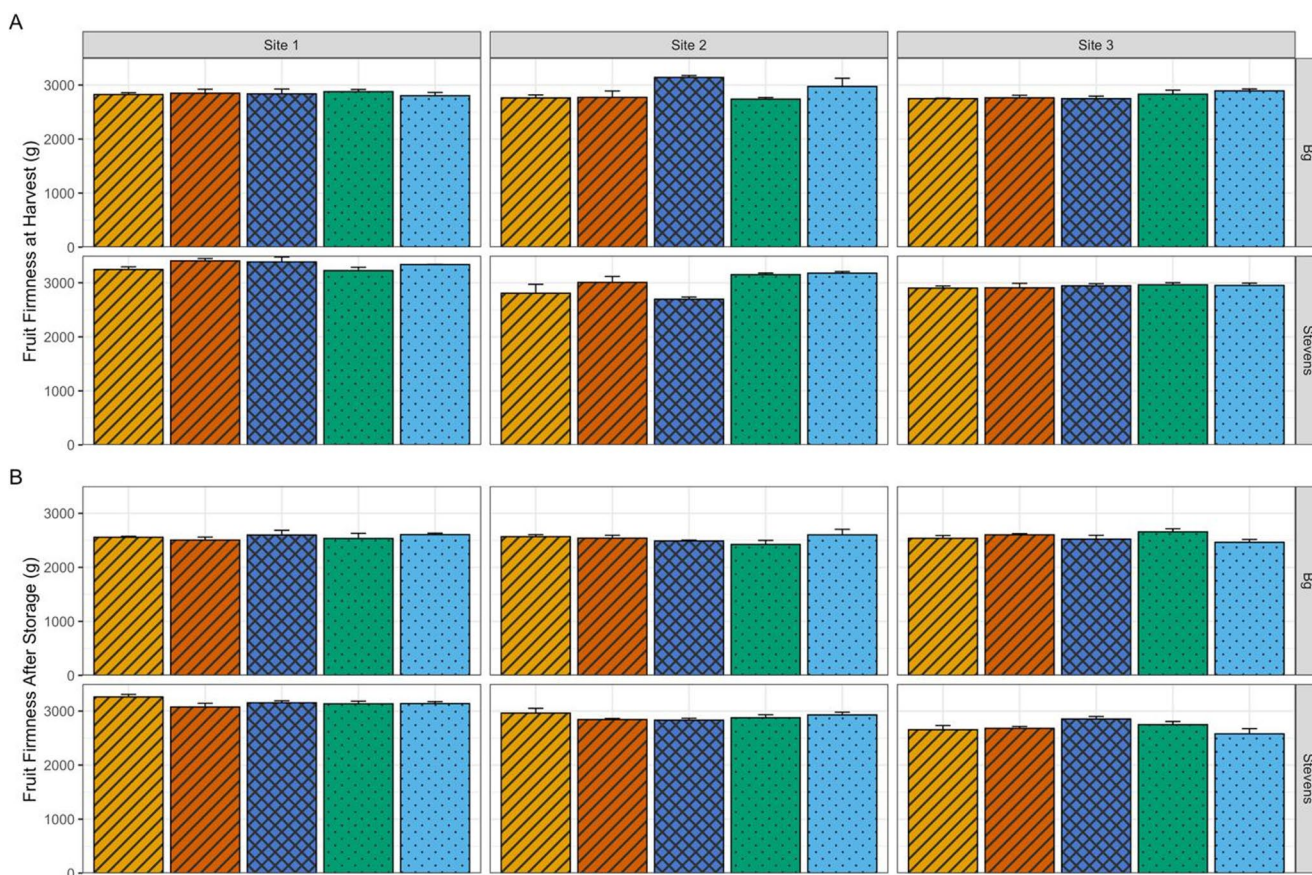


Fig. 4 Effect of foliar calcium treatments (calcium chloride, CaCl_2 ; calcium carbonate, CaCO_3) on cranberry fruit firmness (g) at harvest **A**) and after storage **B**). Treatments were applied at 10% bloom, 50%

bloom, and 100% bloom in ‘Stevens’ and ‘BG’ cranberries produced on three sites in central Wisconsin, 2023. Each bar represents the mean of five replicates and error bars denote ± 1 SE

‘Stevens’ and ‘BG’ cranberries. The challenges of using foliar Ca applications to increase Ca content and firmness are well documented, and this study was no exception. Despite these results, fruit Ca content remains relevant for quality and firmness retention during storage. Future research should explore mechanisms of Ca uptake by cranberry fruit or other more efficient ways of increasing fruit Ca content such as breeding for cultivars with higher fruit Ca translocation, or the potential use of plant growth regulators such as abscisic acid or biostimulants enhancing Ca uptake and translocation into cranberry fruits.

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Ann Workmaster, Juan Zalapa, and Pedro Rojas-Barros. Experiment execution and data collection were carried out by Pedro Rojas-Barros. Data analysis/interpretation and manuscript writing were done by Amaya Atucha, Beth Ann Workmaster, and Pedro Rojas-Barros.

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Data Availability The data that support the findings of this study are available at GitHub (<https://github.com/rojasbarros>).

Code Availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent for publication Not applicable.

Consent to participate Not applicable.

Conflict of interest The authors declare that they have no conflicts of interest.

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