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Nutrient Competitive Effects in Chrysanthemum Amended with Flue Gas Desulfurization Gypsum

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Abstract. **Gypsum use in agriculture has a longstanding history, yet there remains a critical need for research to understand better its impact on plant development and plant nutrient availability. This study evaluated the impact of flue gas desulfurization gypsum (FGDG) amendments on the physical and chemical properties of pine bark substrates and the growth and nutrient uptake of chrysanthemum 'Wanda Red'. Pine bark was incorporated with controlled-release fertilizer, micronutrient fertilizer, dolomitic limestone, and varying FGDG rates (0%, 2.5%, 5%, and 10% v:v). Plant growth metrics, including dry weight, canopy volume, and foliar nutrient concentrations, were recorded at bud initiation and peak bloom. Flue gas desulfurization gypsum amendments did not significantly affect plant dry weight at bud initiation, although plants without FGDG had greater canopy volumes. By peak bloom, plants without FGDG exhibited greater dry weights, but no difference in growth indices was observed ($P = 0.8648$). Although the 0% gypsum plants recorded a larger size at bud initiation, there were no differences by full bloom. Foliar nutrient analyses revealed that FGDG amendments influenced nutrient uptake, with notable reductions in nitrogen ($P = 0.0035$) and potassium ($P < 0.0001$) at bud initiation but no significant differences at peak bloom. Conversely, phosphorus and calcium concentrations increased with FGDG amendments, suggesting improved retention and availability. Overall, although FGDG amendments led to reduced uptake of some nutrients and minor delays in bloom, all treatments produced marketable chrysanthemums, indicating that FGDG can be integrated into production practices without compromising plant quality. Further studies are recommended to explore lower gypsum rates and their interactions with nutrient retention and crop demand.**

Container-grown plants are a significant part of the US floriculture industry's wholesale market value of $4.8 billion (USDA 2021). Chrysanthemums (*Chrysanthemum indicum*), a staple fall crop, are the most valuable floriculture container crop, generating $158 million in revenue, marginally greater than poinsettias (USDA 2021). Managing the nutrient needs of chrysanthemums is crucial for optimal growth, with nitrogen, phosphorus, and potassium deficiency occurring at 4.5%, 0.2%, and 3.5% tissue concentration, respectively (Clemson University Regulatory Services 2013). To meet these requirements, chrysanthemum producers often use soluble liquid applied fertilizers at a rate of 250 to 300 ppm N of a 20N–4.4P–16.6K fertilizer, reducing or halting all fertilization 3 weeks before the desired sale date (UMASS Extension 2024). Nitrogen-heavy fertilizer applications are expected during the early stages of chrysanthemum production to support vigorous vegetative growth (MacDonald et al. 2013), whereas phosphorus and potassium are applied more at bud initiation and flowering (Choudhary et al. 2022). However, growers face pressure to avoid excess nitrogen and phosphorus fertilization, as they are linked to eutrophication in aquatic environments (Finlay et al. 2013; Schindler 1974). Therefore, fertilizer recommendations and effects may vary by potting media, container size, and product utilization.

Substrate composition can highly influence fertilization rates. Pine bark, a common substrate component, requires greater fertilization (100 $mg \cdot L^{-1}$ N) to produce chrysanthemums of similar size to those in peat-based substrates (Wright et al. 2008). Although controlled-release fertilizers (CRFs) are effective at mitigating nutrient leaching, sole reliance on CRFs may result in nutrient deficiencies in chrysanthemums due to the extended nutrient release (Catanzaro et al. 1998). Southern Alabama chrysanthemum producers commonly use pine bark–based substrates to reduce water-holding capacity and incorporate CRFs to combat frequent precipitation and saturated root environments, which favor root pathogens and excessive nutrient leaching.

Substrate amendments show promise in improving nutrient retention. For example, combining dolomitic lime with micronutrients in pine bark successfully reduced organophosphate leachate concentrations by 70%, generally from substrate retention by dolomite (Shreckhise et al. 2019). Using CRFs combined with dolomitic lime and micronutrients further reduced leaching (Bilderback et al. 2013). Incorporating activated aluminum into soilless substrates increased the retention of phosphorus and sulfur without impacting plant quality (Abdi et al. 2023). Ferrous sulfide ($FeSO_4$)-amended pine bark was shown to increase phosphorus adsorption without decreasing plant quality, as seen in maples (Shreckhise and Altland 2020, 2022). Depending on bark type, ferrous sulfide applications resulted in iron concentrations between 0.59 and 0.79 $mg \cdot cm^{-3}$ Fe, leading to a quadrupling of phosphorus adsorption in containers compared with an untreated control. Furthermore, the container-grown maples continued to yield marketable plants despite being produced in pine bark containing 0.6 $mg \cdot cm^{-3}$ Fe (Shreckhise and Altland 2022). Other investigations have evaluated the incorporation of gypsum, which can be mined or created synthetically, as an amendment to improve nutrient retention (Dontsova et al. 2005).

Gypsum, $CaSO_4(2H_2O)$, provides calcium and sulfur nutrients and enhances ionic bonds (Ekholm et al. 2012). Synthetic gypsum can be harvested as a sustainable byproduct of calcium carbonate scrubbers on coal power plants. This artificial form is called flue gas desulfurization (FGD) gypsum (Brown 2018). Calcium has a competitive relationship with aluminum, manganese, and potassium in soils, which affects their availability (Bossolani et al. 2020; Rhodes et al. 2018). In addition, in the presence of gypsum, the problematic aluminum ion, Al^{3+}, precipitates into the less phytotoxic form, $AlSO^{4+}$ (Zoca and Penn 2017). Gypsum incorporations into pine bark substrates reduced phosphorus leachate in laboratory column tests (Bartley et al. 2023). FGD gypsum reduces dissolved reactive phosphorus in the substrate by 75%, with the most significant reduction occurring when gypsum is incorporated with the container substrate at 15% v/v (Watts et al. 2021). In agricultural applications, FGDG has been applied to tomato crops to lessen instances of blossom end rot while improving fruit size and color (Brown 2018). Similar improvements were also observed in poinsettia, with FGD gypsum-treated plants demonstrating increased shoot growth (Brown 2018). However, overapplication in soil decreased shoot growth in North American ginseng (*Panax quinquefolius* L.), although the issue was not replicated in grain or cabbage. This divergence hints at a

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potential variable maximum threshold by plant species, suggesting increased Ca^{2+} and SO_4^{2+} as an indirect possible cause of plant decline when treated with gypsum, possibly due to nutrient competition (Lee et al. 2010).

Variances in plant growth due to gypsum applications also may stem from antagonistic effects with macro- and micronutrients (Bartley et al. 2023; Ekholm et al. 2012). Gypsum applications in soil increased the mobility and leaching of NH_4–N but had no impact on NO_3–N (Favaretto et al. 2012). Exchangeable potassium decreased at soil depths of 22.5 cm when gypsum was applied at 2 $t{\cdot}ha^{-1}$ (Syed-Omar and Sumner 1991). Hoskins et al. (2014), in a study involving the application of dolomitic lime to a pine bark:sand mixture, reported a competitive dynamic between calcium (Ca^{2+}) and potassium (K^{+}), resulting in the displacement of Ca (Hoskins et al. 2014). In column-leaching experiments with gypsum-amended pine bark, potassium leaching increased significantly 20 d after initiation (Bartley et al. 2023). Both studies point to potential antagonistic effects from gypsum incorporation in container substrates but differ in the displaced element. These studies indicate that nutrient application methods may require alterations when applying gypsum.

The use of gypsum in agriculture has a longstanding history, yet there remains a critical need for research to understand better its impact on plant development and nutrient plant availability. Nutrient antagonistic relationships could affect nutrient availability, requiring changes in fertilization practices when gypsum is applied, particularly in pine bark. This study aimed to quantify potential antagonistic nutrient relationships and their effects on chrysanthemum growth when FGD gypsum is incorporated into the substrate.

Materials and Methods

Nursery-grade pine bark (milled through a 15.9-mm screen) was obtained from Pineywoods Mulch Company (Alex City, AL, USA) on 12 Mar 2021. Particle size analysis was conducted following Bartley et al. (2023). In summary, three oven-dried 0.5-L samples were passed through 12 sieves (12.5, 9.5, 6.3, 3.35, 2, 1.4, 1, 0.5, 0.3, 0.25, 0.15, and 0.106 mm). The sieves were agitated for 5 min using a Ro-Tap device for agitation. Following agitation, the fractional weight retained on each sieve was recorded. The particle size distribution was expressed as a cumulative distribution. The mean particle size of the pine bark was 2.16 mm, with a standard deviation of 0.76 mm. Elemental analysis of the pine bark was determined by Waters Agricultural Laboratories, Inc. (Camilla, GA, USA). The pine bark substrate was composed of 5.25 $g{\cdot}kg^{-1}$ nitrogen (N), 1.58 $g{\cdot}kg^{-1}$ phosphorus (P), 15.79 $g{\cdot}kg^{-1}$ potassium (K), 8.25 $g{\cdot}kg^{-1}$ calcium (Ca), 3.24 $g{\cdot}kg^{-1}$ magnesium (Mg), 2.47 $g{\cdot}kg^{-1}$ sulfur (S), 0.09 $g{\cdot}kg^{-1}$ Boron (B), 0.05 $g{\cdot}kg^{-1}$ zinc (Zn), 0.06 $g{\cdot}kg^{-1}$ manganese (Mn), 0.32 $g{\cdot}kg^{-1}$ iron (Fe), and 0.01 $g{\cdot}kg^{-1}$ copper (Cu).

FGDG was collected from a local coal-fired electrical utility plant (Alabama Power Gaston Generating Plant, Wilsonville, AL, USA). The material was received as a dry fine powder with a pH of ~7. The elemental composition of the FGD gypsum compared with mined gypsum can be found in Table 1.

One day before the initiation of the experiment, the pine bark was amended with 4.75 $kg{\cdot}m^{-3}$ of a commercially available 6-month release CRF (Polyon 19N–2.6P–10K, Harrell's, Lakeland, FL, USA), 0.89 $kg{\cdot}m^{-3}$ granular micronutrient fertilizer (Micromax, Everris, Dublin, OH, USA), and one of four treatment amendments:

1. 4.15 $kg{\cdot}m^{-3}$ dolomitic limestone;
2. 4.15 $kg{\cdot}m^{-3}$ dolomitic limestone and 2.5% (v/v) FGD gypsum;
3. 4.15 $kg{\cdot}m^{-3}$ dolomitic limestone and 5% (v/v) FGD gypsum;
4. 4.15 $kg{\cdot}m^{-3}$ dolomitic limestone and 10% (v/v) FGD gypsum.

From this point forward, each of the four treatments will be referenced by the following: 1) 0% FGDG, 2) 2.5% FGDG, 3) 5% FGDG, and 4) 10% FGDG. All treatment amendments were incorporated into the substrate by machine mixing until the samples were adequately homogenized and stored in plastic bags. The physical characteristics of the substrate were determined using the NCSU Porometer Method (Fonteno et al. 1995). The substrates had a bulk density of 0.21 $g{\cdot}cm^{-3}$, a volumetric water content of 60% ± 3%, and an air-filled porosity of 25% ± 2%.

Chrysanthemum 'Wanda Red' plugs were transplanted on 7 Jul 2022 into 10-L plastic containers, accommodating three plants per container. The desire for a vigorous mid-October blooming plant drove the selection of this cultivar. Each treatment contained 12 replicates. Container placement was randomized on a full sun, nursery pad, and two drip emitters placed in each container for irrigation. Each container was initially hand-watered to container capacity. Irrigation events, each lasting 5 min and releasing 500 mL of water per container, were monitored using remote moisture sensors (Terros 12 sensors with a Meter ZL6 data logger; Meter Group, Pullman, WA, USA). Additional irrigation events were introduced in the afternoons as needed through crop development, with a second event initiated on 15 Aug 2022 and a third event initiated on 21 Sep 2022. Irrigation was controlled to provide uniform leaching for all containers, irrespective of rainfall.

Electrical conductivity (EC) and pH were collected using the Pour Thru method (Wright 1986) at 3, 30, 60, and 85 d after initiation. Additional data were recorded at bud initiation on 7 Sep 2022 (day 55) and peak bloom on 14 Oct 2022 (day 85), including plant volume, fresh weight, dry weight, and foliar nutrient concentrations. Plant volumes were calculated by multiplying plant height and two canopy widths before destructive harvesting. Plants were cut at the substrate level, and fresh weights were recorded. Fifty grams of leaf tissue from each replicant was reserved for tissue nutrient analysis. For tissue analysis, leaves were collected between the fourth and eighth mature leaves below the apical bud. Plant material was air-dried for 1 week at 75 °C before recording dry weights.

Table 1. Elemental composition of flue gas desulfurization gypsum (FGDG), a byproduct of coal-fire electrical utility plants, and mined gypsum.

Element	FGDG[i]	Mined gypsum[ii]
Calcium	21.9%	24.5%
Sulfur	16.7%	16.1%
Nitrogen	Not determined	Not determined
Phosphorous	22.3 ppm	30 ppm
Potassium	<0.1 ppm	3600 ppm
Magnesium	150 ppm	26,900 ppm
Boron	12 ppm	99 ppm
Copper	23 ppm	<0.60 ppm
Iron	327 ppm	3800 ppm
Manganese	3 ppm	225 ppm
Nickel	NA	<0.6 ppm
Zinc	<0.1 ppm	8.7 ppm
Mercury	<0.26 ppm	<0.26 ppm

[i] FGDG collected from Alabama Power Gaston Plant in Wilsonville, AL, USA.
[ii] Composition of mined gypsum (Dontsova et al. 2005).

Foliar testing was conducted by the Auburn Soil, Water, and Forage Laboratory (Auburn, AL, USA). Foliar concentrations for N, P, K, Ca, S, Mg, Cu, and Zn were recorded. Nutrient concentrations were considered deficient at thresholds suggested by Clemson University (Table 2; Clemson University Regulatory Services 2013). The effects of gypsum, rate, and the gypsum × rate interaction on dry weight, plant volume, and foliar nutrient concentrations were analyzed via analysis of variance with the PROC Glimmix procedure in SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Means were separated using Tukey's honestly significant difference at a 5% alpha level.

Results and Discussion

EC and pH. The leachate EC was influenced by the interaction between substrate treatment and time ($P = 0.0003$). Individually, treatment and time influenced leachate EC ($P < 0.0001$). Notably, the EC levels of leachate increased proportionally with rates of gypsum, consistently observed throughout

Table 2. Foliar nutrient concentration sufficiency levels for chrysanthemum production.

Nutrient	Sufficiency range[i]
Nitrogen (%)	4.50–6.00
Phosphorus (%)	0.2–1.10
Potassium (%)	3.50–10.00
Calcium (%)	0.50–4.60
Magnesium (%)	0.14–1.50
Copper (ppm)	5–50
Zinc (ppm)	7–35

[i] Nutrient foliar concentration sufficiency range suggested by Clemson University Regulatory Services (2013).

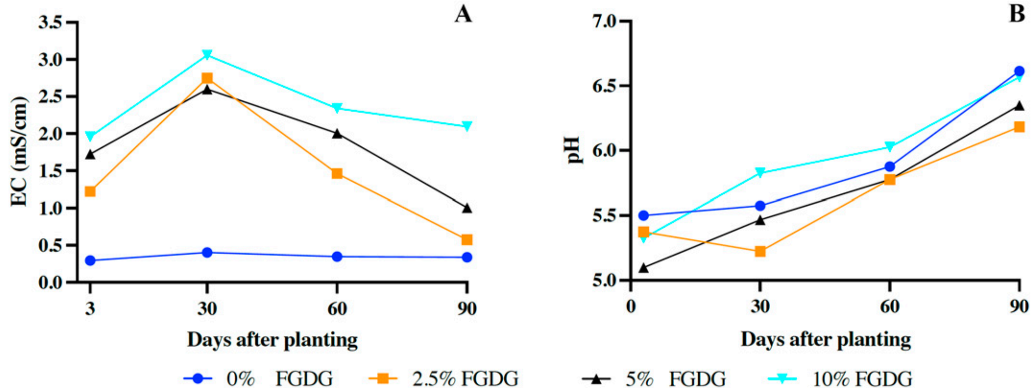

Fig. 1. Substrate electrical conductivity (EC) (**A**) and pH (**B**) 3, 30, 60, and 85 d after planting on chrysanthemum 'Wanda Red' with increasing rates of flue gas desulfurization gypsum (FGDG) amended in the substrate.

the study (Fig. 1A). Peak EC levels were registered 30 d after planting (DAP). Specifically, mean EC levels of 3.1 ± 0.2 $mS \cdot cm^{-1}$ were recorded in substrates containing 10% FGDG at 30 DAP, while treatments with 2.5% and 5% FGDG exhibited mean EC levels of 2.7 ± 0.2 and 2.5 ± 0.2 $mS \cdot cm^{-1}$, respectively, at the same interval. However, by the study's conclusion, EC levels had notably decreased from their peak values. At 85 DAP, mean EC levels of 2.3 ± 0.2 $mS \cdot cm^{-1}$, 1.0 ± 0.2 $mS \cdot cm^{-1}$, and 0.6 ± 0.2 $mS \cdot cm^{-1}$ were recorded in substrates containing 10%, 5%, and 2.5% FGDG, respectively. All gypsum-amended treatments exhibited greater leachate EC than 0% FGDG, which averaged 0.3 ± 0.1 $mS \cdot cm^{-1}$ throughout the study and never exceeded 0.5 $mS \cdot cm^{-1}$.

The elevated EC values observed in FGDG treatments stemmed from the dissolution of soluble gypsum, particularly Ca, S, and Mg (Bartley et al. 2023). Interestingly, These EC levels align closely with those reported in laboratory column experiments with similar treatments. Notably, FGDG-treated plants appeared to have a greater residual effect on EC than the findings of Bartley et al. (2023). The levels in all FGDG-amended treatments experienced an initial increase from 3 DAP to 30 DAP before going downward. Notably, FGDG-amended treatments exhibited greater residual activity compared with findings from controlled other assessments (Bartley et al. 2023; Watts et al. 2021). Although leachate ECs in 2.5% FGDG treatments were significantly higher than 0% FGDG at 85 DAP ($P <$ 0.0001), they had notably decreased from the peak recorded levels of 2.7 $mS \cdot cm^{-1}$, indicating near exhaustion of the gypsum amendment. Factors such as irrigation, precipitation, and leachate fraction may have influenced the efficacy of FGDG in this relatively extended evaluation period. Rainfall totaling 20.6 cm over 25 d during July and August was recorded, potentially affecting gypsum dissolution. Irrigation was infrequently applied during the initial 60 DAP, potentially contributing to the prolonged activity of gypsum amendments compared with daily irrigation in laboratory studies.

No significant differences in leachate pH were observed from treatment × time interactions ($P = 0.5044$). Individually, both treatment ($P = 0.0039$) and time ($P < 0.0001$) influenced pH. A positive trend in pH was evident over the experiment's duration (Fig. 1B). Across all substrate treatments, pH levels increased by ~1 unit over 85 d, aligning closely with values reported by Bartley et al. (2023) in a pine bark substrate and falling within ranges recommended for chrysanthemum production. Although no significant pH change was observed, it is noteworthy that residual $CaCO_3$ in FGDG has been associated with elevated substrate pH (Bartley et al. 2023), with the $CaCO_3$ content of the FGDG used in this study measured at 7.8% ($g \cdot g^{-1}$).

Weight and growth indices. Dry weights were affected by a treatment × development stage interaction (Table 3). During bud initiation, no differences in dry weights were noted across treatments ($P = 0.8648$). Despite similar canopy masses, as estimated by growth indices, canopy size exhibited a significant increase in plants without gypsum amendment compared with those treated with 5% FGDG (Table 4). At bud initiation, dry weights of plants treated with 2.5% and 5% FGDG were comparable to those without gypsum. At peak bloom, plants without gypsum amendment demonstrated dry weights 14% to 17% greater than those receiving FGDG amendments. Although significant differences in dry weights were evident, no disparities in growth indices were observed across treatments at peak bloom.

Overall, FGDG amendments resulted in reductions in both chrysanthemum weight and size; however, the timing of these differences varied according to the plant's developmental stage. Detecting these differences through observation alone proved challenging, as all treatments yielded plants of marketable quality. Although the quality of plants was not compromised by FGDG amendments, a delay in bloom opening (color cracking) of 3 to 5 d was observed in plants treated with FGDG. In the absence of significant visual defects, the similarities in chrysanthemum growth suggest that FGDG amendments should not impact the value of the product for growers.

Foliar nutrient concentrations. Foliar N tissue concentrations were affected by a treatment × development stage interaction ($P <$ 0.0001; Table 3). At the bud initiation development stage, 0% FGDG chrysanthemums contained greater N concentrations than those receiving 5% and 10% FGDG. Mean foliar N concentrations at bud initiation decreased with increasing FGDG amendment rates, with 0% FGDG containing 3.05% N, 2.5% FGDG containing 2.75% N, 5% FGDG containing 2.70% N, and 10% FGDG containing 2.59% N. Yet, by peak bloom, no differences in foliar N concentrations were recorded (Fig. 2A). Mean foliar N concentrations at peak bloom ranged between 1.73% N and 1.89% N across all treatments with increasing FGDG amendment rates, with 0% FGDG containing 3.05% N, 2.5% FGDG containing 2.75% N, 5% FGDG

Table 3. Analysis of variance for the effects of fertilizer treatments on the development of *Chrysanthemum indicum* for the studied traits.[i]

		P values								
Source of variation	df[ii]	Dry wt	Foliar nitrogen	Foliar phosphorus	Foliar potassium	Foliar calcium	Foliar magnesium	Foliar sulfur	Foliar copper	Foliar zinc
A: Rate	3	<0.0001	0.0128	<0.0001	<0.0001	<0.0001	<0.0001	0.0010	0.2520	0.0777
B: Stage	1	<0.0001	<0.0001	0.0018	<0.0001	<0.0001	<0.0001	<0.0001	0.0061	<0.0001
A × B	7	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1048	<0.0001

[i] Treatment effects were analyzed using PROC Glimmix in SAS 9.4 (SAS Institute, Cary, NC, USA).
[ii] df = degrees of freedom.

Table 4. Chrysanthemum dry weight and volume at bloom initiation and peak bloom amended with of flue gas desulfurization gypsum (FGDG).

	Dry wt (g)		Growth indices (cm^3)	
Treatments[i]	Bud initiation[i]	Peak bloom[iii]	Bud initiation	Peak bloom
0% FGDG	422.4 ns[iv]	549.3 a	146 a	181 ns
2.5% FGDG	423.6	462.3 b	131 ab	175
5% FGDG	416.1	465.7 b	128 b	165
10% FGDG	425.4	476.4 b	130 ab	172

[i] Increasing rates of FGDG were mixed with a 3:1 pinebark:peat soilless substrate on a volume basis. Treatments included a 0%, 2.5%, 5%, and 10% FGDG rates.

[ii] The date for bud initiation was 7 Sep 2022. Bud initiation marked the end of vegetative growth, where nutrients usage focused on forming reproductive structures.

[iii] The date for peak bloom was 25 Oct 2022. The date was determined when plants passed a 75% of canopy in bloom threshold. Peak bloom was determined (i.e., greater than 75% of canopy in bloom).

[iv] Data were analyzed using PROC Glimmix and subsequent means were compared using the Tukey's honestly significant difference ($P \leq 0.05$). Means within a column with the same letter do not significantly differ from each other and use of "ns" signifies no significant differences.

containing 2.70% N, and 10% FGDG containing 2.59% N. Regardless of developmental stage or treatments, chrysanthemum foliar N concentrations failed to reach the recommended 4.5% to 6% foliar N range. Incorporating gypsum into the substrate may necessitate greater N fertilizer rates commiserate with the rate of gypsum amendment, which reduced N uptake at bud initiation. Although the rate of N supplied in this study was insufficient, marketable chrysanthemums were produced.

P tissue concentrations were unaffected by FGDG treatments at bud initiation ($P = 0.204$), but treatment differences in P uptake were observed at peak bloom ($P < 0.001$). Mean foliar P concentrations at bud initiation ranged between 0.34% and 0.40% P across all treatments. At peak bloom, chrysanthemum plants produced in FGDG-amended substrates had a mean foliar P concentration of 0.36%, 38% higher than those produced without FGDG (Fig. 2B). Increasing the rate of FGDG amendment beyond 2.5% (v:v) did not improve P uptake at peak bloom. Gypsum-amended substrates have reported reduced P leaching by 45% to 75% in pine bark and peat substrates (Bartley et al. 2023; Watts et al. 2021). Treatments of FGDG likely extended the accessibility of P for plant uptake, resulting in greater foliar P concentrations later in the production cycle. Although differences in P uptake were observed, all foliar P concentrations fell within the recommended range of 0.2% to 1.1% recommended range.

Soilless substrates used in the floriculture and nursery industry have limited P-holding capacity (Henry et al. 2018; Marconi and Nelson 1984; Whipker 2014). In controlled systems P can be applied when needed however outdoor grown chrysanthemums are not produced with such precision. Previous studies have shown that liming agents can lead to P precipitation or adsorption of P ions (Argo and Biernbaum 1996a, 1996b). Argo and Biernbaum (1996a) found that the amount of soluble P decreased as the amount of liming agent added to peat-based substrates increased. Shreckhise et al. (2019) observed similar results in a pine bark substrate, attributing these reductions to the formation of $CaHPO_4$ or CaH_5O_6P precipitates. Similarly, reductions in P leaching due to FGDG amendments may be caused by the formation of Ca–P complexes. Because only orthophosphates are available for plant uptake, P bound in Ca–P complexes may be unavailable during critical stages of plant development, potentially reducing plant vigor. However, the results from this study do not indicate that P availability was diminished in any capacity. Instead, these data suggest that P fertilizer applications may be reduced in gypsum-amended substrates.

Foliar K tissue concentrations were affected by a treatment × development stage interaction ($P < 0.001$). At bud initiation, 0% FGDG chrysanthemums had greater K foliar concentrations, 3.26%, than those amended with FGDG (Fig. 2C). Amendments of FGDG reduced K uptake by 42% on average at bud initiation. No differences in foliar K concentrations were observed across FGDG amendment rates at bud initiation, with 2.5% FGDG containing 2.3% K, 5% FGDG containing 1.91% K, and 10% FGDG containing 2.19% K. At peak bloom, reductions in foliar K concentrations were observed across all treatments. The most significant decrease in foliar K concentration occurred in 0% FGDG substrates, decreasing from 3.26% to 1.92% in 5 weeks. No differences in foliar K concentrations were observed at peak bloom ($P = 0.354$). Mean foliar K concentrations at peak bloom ranged between 1.64% K and 1.92% K across all treatments. Similar to trends observed in N, foliar K concentrations in this study failed to reach the recommended 3.5% minimum K concentration. Gypsum had a more significant effect on plant K uptake than N, where K and N uptake were reduced by 34.5% and 10.3%, respectively, in

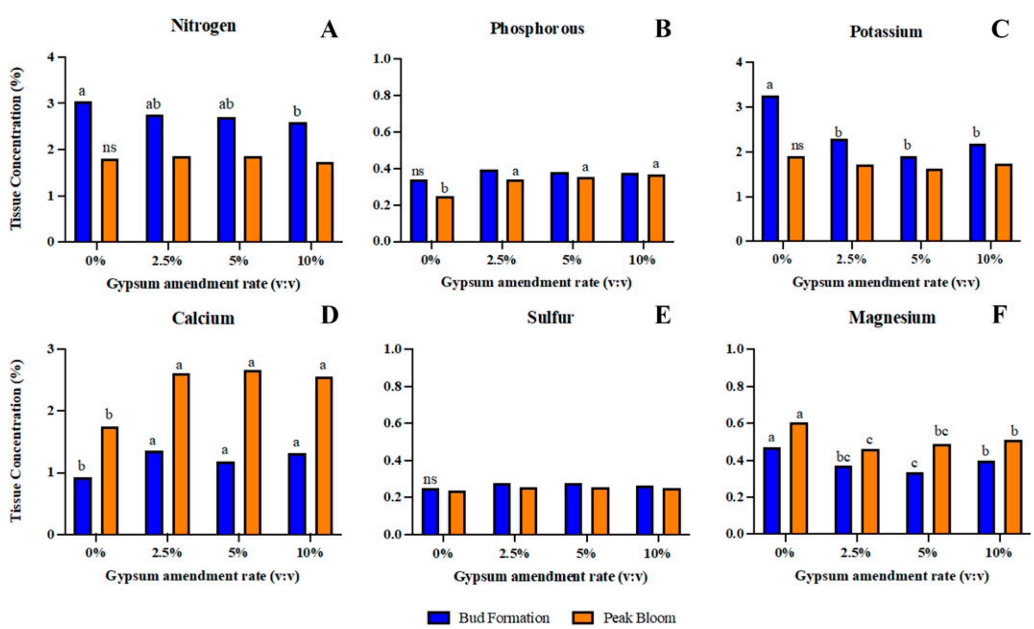

Fig. 2. Comparison of chrysanthemum nutrient tissue concentration between bud formation and peak bloom: (**A**) nitrogen, (**B**) phosphorous, (**C**) potassium, (**D**) calcium, (**E**) magnesium, and (**F**) sulfur. Data were analyzed using a one-way analysis of variance and subsequent means were compared using the Tukey's honestly significant difference ($P \leq 0.05$). Means within an individual graph with the same letter do not significantly differ from each other.

plants treated with 2.5% FGDG at bud initiation. However, both K and N foliar concentrations were similarly deficient at peak bloom for all treatments. Brown and Pokorny (1977) reported that K applied to a pine bark substrate was adsorbed by the bark, though unevenly distributed. However, antagonistic relationships between Ca and K have been reported in similar substrates (Bartley et al. 2023; Hoskins et al. 2014). Bartley et al. (2023) reported that K leaching increased by 31% in a pine bark substrate amended with 2.5% FGDG and by 45% with a 10% FGDG amendment after 45 d. Hoskins et al. (2014) found that the reverse antagonistic effect was also possible with K, applied as potassium nitrate (KNO_3) and monopotassium phosphate (KH_2PO_4), displacing Ca and Mg. Mined gypsum, rather than FGDG, may contain large amounts of K, potentially alleviating concerns related to K availability (Dontsova et al. 2005).

Ca tissue concentrations were affected by FGDG treatments at bud initiation ($P < 0.0001$) and at peak bloom ($P < 0.0001$). At bud initiation, plants receiving FGDG amendments had a mean foliar Ca concentration of 1.29%, 34% lower than those receiving 0% FGDG (Fig. 2D). At peak bloom, the mean foliar Ca concentration in plants grown in FGDG-amended substrates was 2.61%, which was 47% higher than those grown without FGDG. Increasing the rate of FGDG amendment above 2.5% (v:v) did not improve Ca uptake at either developmental stage.

Sulfur tissue concentrations were unaffected by FGDG treatments at bud initiation ($P = 0.056$) and at peak bloom ($P = 0.0628$). Sulfur tissue concentration differed by developmental stage ($P < 0.0001$), averaging 0.27% at bud initiation and 0.25% at peak bloom (Fig. 2E). Sulfates, such as ammonium sulfate or iron sulfate, are known to reduce and stabilize the pH of soilless container substrates over the long term (Cacini et al. 2021). However, significant sulfur additions did not affect pH in this study. This may be because of the high levels of calcium carbonate in the tested FGDG effectively countering the effects of sulfur oxidation.

Magnesium concentration was affected by developmental stage ($P < 0.0001$) and amendment ($P < 0.0001$). Similar to Ca uptake, Mg foliar concentrations increased from bud initiation to peak bloom across all treatments, with each showing a 30% to 55% increase in foliar Mg (Fig. 2F). Mg uptake was 24% higher in plants receiving 0% FGDG than gypsum-amended plants at bud initiation and 22% higher at peak bloom. All FGDG-amended treatments were similar at bud initiation, ranging from 0.33% to 0.40%. Similarly, no differences in foliar Mg concentrations were observed across FGDG amendment rates at peak bloom, with 2.5% FGDG containing 0.46% Mg, 5% FGDG containing 0.49% Mg, and 10% FGDG containing 0.51% Mg. Mg concentrations have been demonstrated to correlate strongly with Ca concentrations (Shreckhise et al. 2019). However, the data suggest that FGDG applications reduced Mg uptake, as the high concentrations of Ca provided by FGDG potentially decreased the plant's uptake of the similar divalent cation.

Cu and Zn foliar concentrations were affected by the developmental stage of the chrysanthemums ($P = 0.0061$ and $P < 0.0001$, respectively). At peak bloom, regardless of treatment, chrysanthemum plants had a mean foliar Cu concentration of 18 ppm, 41% higher than plants at bud initiation. Similarly, chrysanthemum plants had a mean foliar Zn concentration of 170 ppm at peak bloom, double the concentration recorded at bud initiation. Gypsum incorporation has not demonstrated increased Cu concentrations within leaf tissue in sugarcane (Widiarso et al. 2017). Like studies investigating soil applications, gypsum did not affect the availability of either Cu or Zn within soilless horticultural substrates (Xu et al. 2014).

Conclusions

Nutrient uptake results revealed that FGDG amendments affected foliar concentrations of several key nutrients. Specifically, N and K concentrations were reduced at bud initiation but showed no significant differences by peak bloom. Reduced availability of N and K may have resulted in differences in plant dry weight by peak bloom. However, chrysanthemum canopy size was not different across treatments at peak bloom. Mg uptake was also reduced, likely due to competitive interactions with the high calcium levels from FGDG. Conversely, P and Ca concentrations increased with FGDG amendments, suggesting improved retention and availability of these nutrients after 99 d of production. Benefits from FGDG were observed in plants treated with the lowest gypsum rate, 2.5% FGDG. Future studies should investigate lower rates of gypsum amendment and P fertilizer to understand the interactions among P retention, gypsum rates, and crop demand. Reducing the volume of FGDG applied to the substrate may also mitigate nutrient competitive effects with key nutrients. Despite some reductions in nutrient uptake and minor delays in bloom development, all FGDG-amended treatments produced chrysanthemums of marketable quality, indicating that the use of gypsum can be integrated into production practices without compromising plant quality.

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