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Establishing Leaf Tissue Nutrient Standards and Documenting Nutrient Disorder Symptomology of Greenhouse-Grown Cilantro (*Coriandrum sativum*)

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Abstract

Cilantro (*Coriandrum sativum* L.) is a popular annual culinary herb grown for its leaves or seeds. With the increase in hydroponic herb production in controlled environments, a need exists for leaf tissue nutrient standards specific to this production system. The objective of this study was to develop comprehensive foliar mineral nutrient interpretation ranges for greenhouse-grown cilantro. Cilantro plants were grown in a hydroponic sand culture system to induce and document nutritional disorders. Plants were supplied with a modified Hoagland's solution, which was adjusted to individually add or omit one nutrient per treatment while holding all others constant. Deficiency and toxicity symptoms were photographed, after which the plant tissue was collected to determine plant dry weight and critical tissue nutrient concentrations. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), iron (Fe), and zinc (Zn) deficiencies, as well as B toxicity, were induced. Deficiencies of copper (Cu), manganese (Mn), and molybdenum (Mo) were not observed during the experiment. Additional foliar tissue analysis data (n = 463) were compiled to create nutrient interpretation ranges for 12 essential elements based on a hybrid meta-analysis Sufficiency Range Approach (SRA). This approach defines ranges for deficient, low, sufficient, high, and excessive values. For each element, the optimal distribution was selected according to the lowest Bayesian Information Criterion (BIC) value. A Normal distribution best represented K and S. A Gamma distribution best represented P, Ca, Mn, and Mo, whereas a Weibull distribution best represented N, Mg, B, Cu, Fe, and Zn. These interpretation ranges, along with descriptions of typical symptomology and critical tissue nutrient concentrations, provide useful tools for both diagnosing nutritional disorders and interpreting foliar nutrient analysis results of greenhouse-grown cilantro.

Keywords: coriander; macronutrients; micronutrients; modeling; tissue analysis

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1. Introduction

Coriandrum sativum L., is a popular annual herb grown for its fresh leaves (cilantro) or seeds (coriander) that are used in culinary dishes [1,2]. While traditionally grown in open-field conditions, fluctuating weather patterns, particularly rainfall, can lead to unpredictable yields [3]. Additionally, field cultivation presents a higher risk of biotic stresses, including pest and disease pressures, which can further impact yield and quality. Producing cilantro in a controlled environment can mitigate these challenges by providing consistent and tailored growing conditions that can optimize growth and enable year-round production [4,5]. By optimizing environmental factors such as temperature, light, and nutrient availability, controlled environment systems can improve both the quality and yield of cilantro, making them an increasingly popular production method among commercial growers.

Effective nutrient management is essential in controlled environment systems in order to optimize growth and prevent nutrient disorders. Greenhouse-grown cilantro is reported to have low to moderate fertilizer requirements, with a recommended nitrogen (N) application ranging from 100 to 150 $mg \cdot L^{-1}$ [1]. Owen and Whipker [6] report that insufficient fertility may cause leaf discoloration and stunted growth. In addition, overfertilization can hinder plant growth and cause necrosis of older leaves; therefore, cilantro should be monitored to avoid over- or under-fertilization.

Past studies have evaluated nutrient uptake and specific elemental impacts in cilantro. Donega et al. [7] evaluated the nutrient demands of cilantro and found that potassium (K) and N were absorbed in the highest quantities. Additionally, research on the effects of copper (Cu) deficiency resulted in lower plant dry weight when Cu was limited [8]. Lastly, Currey et al. [9] observed no impact on plant biomass when the electrical conductivity (EC) of the nutrient solution ranged between 0.5 and 4.0 $mS \cdot cm^{-1}$. The study did observe a decrease in calcium (Ca) and magnesium (Mg) tissue concentration as EC increased, in addition to an increase in zinc (Zn) tissue concentration. Various growing systems have also been evaluated for cilantro production in a controlled environment, with hydroponic methods such as the Deep Flow Technique (DFT) [10] and the Nutrient Film Technique (NFT) [11] demonstrating higher water use efficiency.

While comprehensive interpretation ranges have yet to be published for greenhouse-grown cilantro, current foliar mineral nutrient concentration recommendations exist for cilantro based solely on a survey of field-grown plants [12]. With the increase in hydroponic herb production in controlled environments and the use of higher fertilization rates, a need exists for more refined leaf tissue nutrient standards and diagnostic ranges specific to these unique production systems.

Various approaches for evaluating and interpreting leaf tissue analysis data have been utilized to develop leaf tissue nutrient standards for specialty crops, including the Survey Approach (SA) [12], the Critical Value Approach (CVA) [13], the Diagnosis and Recommendation Integrated System (DRIS) [14], and the Sufficiency Range Approach (SRA) [15]. The SA method is commonly used for specialty crops, as it relies on evaluating the tissue nutrient content of healthy-looking plants to determine general leaf tissue nutrient standards. While the SA provides a useful, initial baseline tool when comprehensive interpretation values are not available, it is observational and lacks a research-based connection between nutrient concentrations and plant growth. The CVA establishes a critical threshold and categorizes nutrient concentrations as deficient (below the threshold) or sufficient (above the threshold). This method is effective for determining nutrient deficiencies but does not categorize excessive or toxic nutrient concentrations. The DRIS method is the most extensive method for interpreting tissue concentration and evaluates multiple factors, including yield and nutrient interactions. While the DRIS method provides the most robust analysis,

it requires large datasets that are often not obtainable for specialty crops. Lastly, the SRA defines a broader sufficiency range for each nutrient and distinguishes between low and high concentrations. While it does not account for nutrient interactions, the SRA requires a smaller dataset, making it more applicable to specialty crops.

Evaluation standards do not exist for many culinary herbs grown in controlled environmental conditions. These high-value crops need assessment tools to enable the determination of the nutritional status and diagnosis of problematic situations. With the limited availability of data, new methods are needed for the creation of more robust evaluation standards. A novel approach has been developed by using a hybrid metadata analysis SRA method to establish comprehensive tissue nutrient interpretation ranges for lettuce (*Lactuca sativa* L.) [16] and pentas (*Pentas lanceolata* Forssk.) [17]. By analyzing a dataset of tissue samples based on using both controlled experimental results and grower samples, optimal Normal, Gamma, or Weibel distribution curves were developed, which identified interpretation ranges for deficient, low, sufficient, high, and excessive tissue concentrations. This expansion of the interpretation ranges provided a more robust diagnostic ability for interpreting leaf tissue nutrient concentrations and identifying nutrient disorders. The objectives of this study were to develop a comprehensive symptomology of nutrient disorders and additionally address the need for more refined nutrient interpretation standards for greenhouse-grown cilantro.

2. Materials and Methods

2.1. Plant Material

Cilantro 'Santo' seeds (Johnny's Selected Seeds; Winslow, ME, USA) were sown on 24 January 2024 into top grooved 104-count cell sheets, where each cell measured 3.6 cm tall × 3.4 cm length × 2.3 cm width (Oasis Rootcubes, Oasis Grower Solutions, Kent, OH, USA), with five seeds per cell. Each sheet was placed in a plastic tray, which was grown indoors atop heated mats set to 22 °C. Trays were covered with humidity domes and hand-misted or sub-irrigated to maintain moisture content until germination occurred approximately 10 days later. After germination, seedlings were grown under fluorescent lights (AgroBrite T5 Full Spectrum; Hydrofarm, Petaluma, CA, USA), which provided 17.28 $mol \cdot m^{-2} \cdot d^{-1}$ based on a 24 h photoperiod, and sub-irrigated with tap water for an additional week. Seedlings were grown for three weeks in total.

2.2. Experiment 1

The seedlings were transplanted on 13 February 2024 into 11.5 cm-diameter (0.8 L) plastic pots containing silica-sand [Millersville #2 (0.8 to 1.2 mm diameter); Southern Products and Silica Co., Hoffman, NC, USA]. Plants were grown in a glass greenhouse in Raleigh, NC (35° N latitude) under ambient light with air temperature setpoints of 22.8 °C (day) and 22.0 °C (night). Fertilizer treatments began immediately, using an automated recirculating irrigation system constructed out of 10.2 cm diameter polyvinylchloride (PVC) pipe (Charlotte Plastics, Charlotte, NC, USA). Fertilizer treatments consisted of a modified Hoagland's solution [18] customized by blending the following individual technical grade salts (Fisher Scientific, Pittsburgh, PA, USA): calcium nitrate tetrahydrate [$Ca(NO_3)_2 \cdot 4H_2O$], potassium nitrate (KNO_3), monopotassium phosphate (KH_2PO_4), magnesium sulfate heptahydrate ($MgSO_4 \cdot 7H_2O$), potassium chloride (KCl), calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$), sodium nitrate ($NaNO_3$), magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$), sodium phosphate monohydrate ($NaH_2PO_4 \cdot H_2O$), sodium sulfate (Na_2SO_4), iron chelated with diethylenetriaminepentaacetic acid (Fe-DTPA), manganese chloride tetrahydrate ($MnCl_2 \cdot 4H_2O$), zinc chloride heptahydrate ($ZnCl_2 \cdot 7H_2O$), copper chloride dihydrate ($CuCl_2 \cdot 2H_2O$), boric acid (H_3BO_3), and sodium molybdate dihydrate

($Na_2MoO_4 \cdot 2H_2O$). Deionized (DI) water was used to formulate all the stock solutions. Disorder treatments were created by omitting one of the elements as outlined in the Table S1 Solution Mixing chart. The boron toxicity treatment was developed by increasing the boron concentration 10× to induce a micronutrient overdose. Irrigation lines were randomly assigned to each treatment before the beginning of the experiment, and eight single plant replicates were installed. Plants were irrigated every 2 h from 06:00 to 18:00. Additional details regarding fertilizer treatments, formulations, fertilizer salts, and the irrigation system are outlined in Barnes et al. [19] and Veazie et al. [20].

2.3. Experiment 1 Data Collection

Plants were photographed and sampled as visual deficiency symptoms appeared, beginning on the third week, 6 March 2024, with N and phosphorus (P)-deficient plants. Four representative plants (n = 4) from each fertilizer treatment were selected, and the most recently matured leaves were sampled for tissue analysis as recommended by Bryson and Mills [12]. The remaining shoots of each plant were also collected to evaluate the total shoot dry mass of each sample. For each sampling date, a set of plants from the control treatment, which received the complete fertilizer solution, was sampled for comparison. The sulfur (S) and Ca deficiency treatments were sampled on 12 March 2024. The K, Mg, and iron (Fe) deficiency treatments, as well as both the boron (B) deficiency and toxicity treatments, were sampled on 20 March 2024. All remaining treatments were asymptomatic and sampled upon termination of the experiment on 10 April 2024, 8 weeks after transplant.

All plant tissue was rinsed in DI water, washed in a 0.5 M HCl solution, then rinsed in deionized water a final time. Immediately after sampling and washing, the tissue was dried at 70 °C for 48 h in a forced-air oven, and the dry mass was weighed and recorded. Total dry mass for each sample was calculated by adding the dry weight of the recently matured leaves to the remainder of the shoot. After drying, the leaf tissue was ground in a grinding mill (Foss Tecator Cyclotec™ 1093 Analytical Instruments, LLC; Golden Valley, MN, USA; <0.5 mm sieve). The ground tissue was then placed in vials and shipped to the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) Application Technology Research Unit (Toledo, OH, USA) for analysis as outlined by Boldt and Altland [21]. To determine foliar N concentration, ≈2.5 mg of plant material was put into tin capsules (EA Consumables, Marlton, NJ, USA) and analyzed with a CHN analyzer (vario MICRO cube; Elementar, Hanau, Germany). To determine all other nutrient concentrations, ≈0.25 g of plant material was combined with 5 mL of nitric acid and heated to 200 °C over 20 min in a programmable microwave (MARS6; CEM Corp., Matthews, NC, USA), and held at 200 °C for an additional 20 min. Once cooled, 1.5 mL of hydrogen peroxide was added, and the samples were reheated to 200 °C and held for another 20 min. Once cooled a final time, 12 mL of ultra-purified water (18 MΩ) was added, and the solutions were filtered (Whatman #2). Finally, a 1.3 mL aliquot of solution was diluted with 8.7 mL of 18 MΩ water and analyzed using inductively coupled plasma-optical emission spectroscopy (ICP-OES; iCAP 6300 Duo, Thermo Electron Corp., Waltham, MA, USA).

2.4. Experiment 1 Data Analysis

Plant dry weight and leaf nutrient concentration data obtained from Experiment 1 were subjected to analysis of variance (ANOVA) using the PROC ANOVA procedure in SAS (version 9.4; SAS Institute, Cary, NC, USA).

2.5. Experiment 2

The second objective of the project was to create refined leaf tissue interpretation ranges for cilantro. Additional foliar tissue analysis data were obtained from university

studies and a public analytical lab (Table 1), which were combined with data obtained from the present deficiency study for a total of 463 samples.

Table 1. Sources of *Coriandrum sativum* leaf tissue nutrient data (n = 463) used to develop tissue nutrient interpretation ranges.

Source	Sample Size	Sample Type	Notes
North Carolina State University	157	Research	Present nutrient deficiency study.
North Carolina State University	130	Research	Unpublished electrical conductivity rate study.
North Carolina Department of Agriculture	95	Diagnostic	Grower submitted samples, unpublished.
Iowa State University	81	Research	Published tissue mineral nutrient concentrations [1].

[1] Currey et al. [9].

Distribution analyses were modeled separately for each element using R (v. 4.4.1; R Foundation for Statistical Computing, Vienna, Austria). Excessive outliers with values greater than what is biologically feasible were removed before further analysis. Normal, Gamma, and Weibull distributions were fit to the data [22–25]. Gamma and Weibull distributions were evaluated due to their ability to more accurately depict right-skewed data, as biological data often does not follow a Normal distribution. *p*-values were calculated based on the Shapiro–Wilk test for normality for Normal and Gamma distributions and the Kolmogorov–Smirnov test for the Weibull distribution. The Bayesian Information Criterion (BIC) was calculated for each distribution, and the optimal distribution for each element was selected based on the lowest BIC value (Table 2).

Table 2. Bayesian Information Criterion (BIC) values for Normal, Gamma, and Weibull distribution models used to develop the sufficiency range approach (SRA) distribution models for each of the 12 essential elements. The lowest BIC value is in bold, indicating the selected model.

Element	BIC Value		
	Normal	Gamma	Weibull
N	1512.87	1701.52	**1496.91**
P	341.52	**157.44**	215.33
K	**1865.07**	1975.81	1880.16
Ca	215.88	**147.62**	262.52
Mg	−237.42	−230.15	**−244.22**
S	**−699.26**	−683.70	−698.65
B	4148.33	4147.32	**4129.85**
Cu	2740.94	2700.90	**2681.44**
Fe	4397.09	4409.82	**4394.69**
Mn	5026.52	**4698.78**	4791.70
Mo	823.31	**581.27**	589.58
Zn	4281.32	4259.51	**4247.32**

Results were illustrated using ggplot2 [26] in R Studio (v. 4.4; Posit, Boston, MA, USA). The Freedman–Diaconis rule [27] was utilized to determine bin width for optimal data visualization. For macronutrients (N, P, K, Ca, Mg, and S), the sufficiency range was defined as the range between the 0.25 and 0.75 quantiles within a 95% confidence interval. The deficient range was based on the values within the 0.025 quantile, and the low range was defined as the area between the 0.025 and the 0.25 quantiles. The excessive range was classified by the right tail (the highest 2.5% of samples), while the high range was determined by the area between 0.75 and 0.975 quantiles. For micronutrients [B, Cu, Fe, manganese (Mn), molybdenum (Mo), and Zn], the cutoff between the deficient and low ranges was defined by the lowest 5% of samples of a 90% confidence interval. Likewise, the

cutoff between the high and excessive ranges was defined by the top 5% of observations within a 90% confidence interval.

3. Results and Discussion

3.1. Macronutrient Disorders

3.1.1. Nitrogen

Symptoms of N deficiency began with overall chlorotic foliage and stunted growth. As symptoms progressed, leaf margins reddened and eventually became necrotic (Figure 1A). Upon sampling, the N-deficient plants had 94% less dry weight than the control plants. The N concentration of the N-deficient plants was 58% lower than the control plants, with N concentrations of 2.50% and 5.92%, respectively (Table 3). The value for control plants falls within the survey range for field-grown cilantro presented by Bryson and Mills [12], which suggested an optimum N concentration between 4.00% and 6.00%.

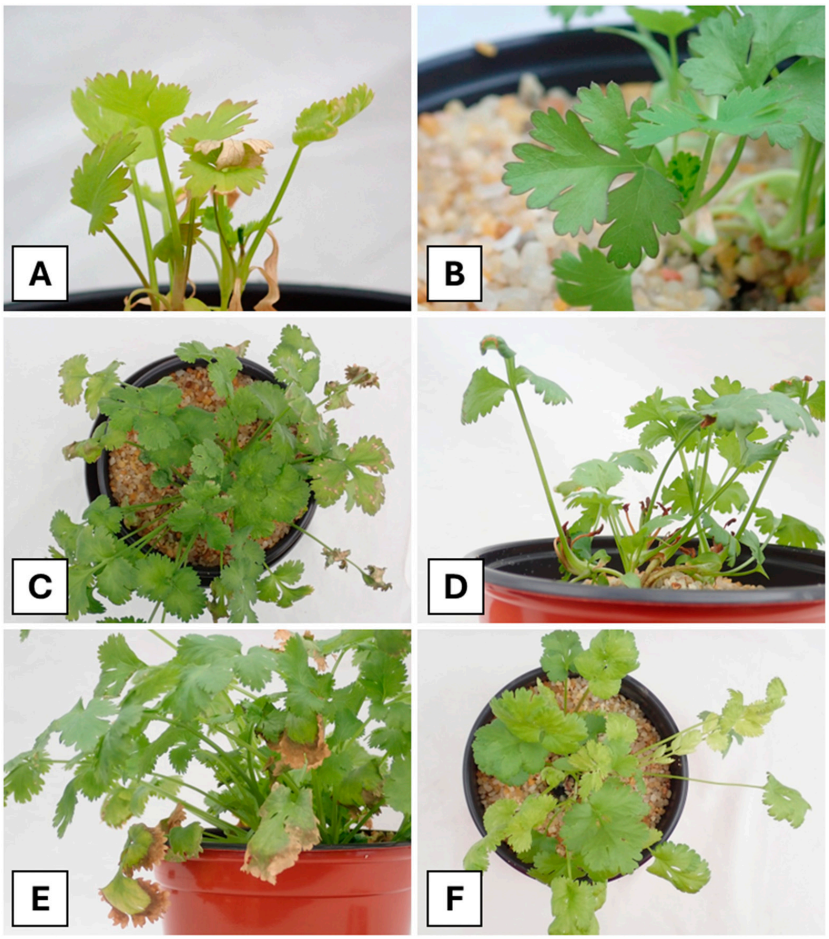


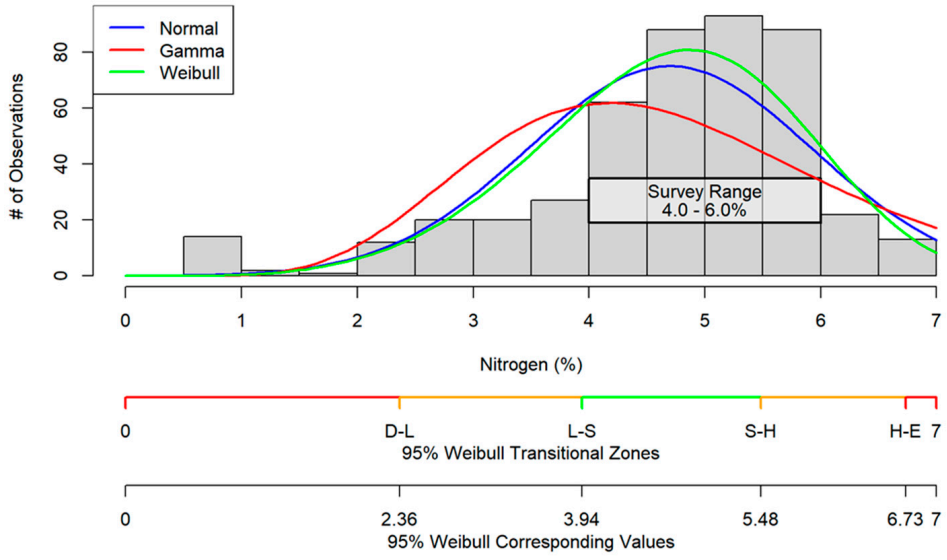
Figure 1. *Coriandrum sativum* 'Santo' visual macronutrient deficiency symptoms. (**A**) Nitrogen-deficient plants exhibited overall chlorotic foliage and stunted growth, with the leaf margins eventually reddening and becoming necrotic. (**B**) Initial symptoms of phosphorus deficiency were stunted growth and faint purpling of the leaf margins. (**C**) Potassium-deficient plants displayed stunted growth and interveinal chlorosis of the most recently matured leaves, coupled with necrotic speckling of the oldest leaves. (**D**) Calcium-deficient plants displayed necrosis of the newest growth and growing tips. Some leaves had a "cupped" appearance due to the death of the growing tip prior to leaf expansion. (**E**) Magnesium-deficient plants exhibited stunted growth and interveinal chlorosis of the older leaves, starting near the leaf margin and progressing inward. (**F**) Sulfur-deficient plants were stunted and had overall light green-yellow foliage, with the newest leaves having the lightest coloration.

Table 3. *Coriandrum sativum* 'Santo' shoot dry weight and tissue nutrient concentration as affected by each nutrient deficiency or toxicity by column.

Treatment	-N	-P	-K	-Ca	-Mg	-S	-B	+B	-Cu	-Fe	-Mn	-Mo	-Zn
	Dry weight (g)												
Complete control	0.82	0.82	4.98	2.07	4.98	2.07	4.98	20.75	4.98	20.75	20.75	20.75	20.75
Disorder	0.05	0.22	3.23	1.01	3.13	1.01	3.08	4.00	16.27	2.67	22.64	19.35	7.31
p-value [1]	***	***	*	**	**	**	NS	*	NS	**	NS	NS	***
	Tissue nutrient concentration												
	(%)						(mg·kg^{-1})						
Element	N	P	K	Ca	Mg	S	-B	+B	Cu	Fe	Mn	Mo	Zn
Complete control	5.92	1.02	6.89	0.71	0.35	0.41	50.31	50.31	4.16	74.63	38.65	2.69	18.80
Disorder	2.50	0.18	0.82	0.27	0.11	0.14	8.06	354.98	0.65	67.56	27.10	0.02	10.37
p-value [1]	***	***	***	***	***	***	**	***	***	NS	NS	***	***
Survey range [2]	4.0–6.0	0.42–0.85	3.8–5.0	0.85–1.25	0.40–0.75	0.22–0.35	25–45	25–45	5–15	55–95	46–80	0.4–1.0	40–70

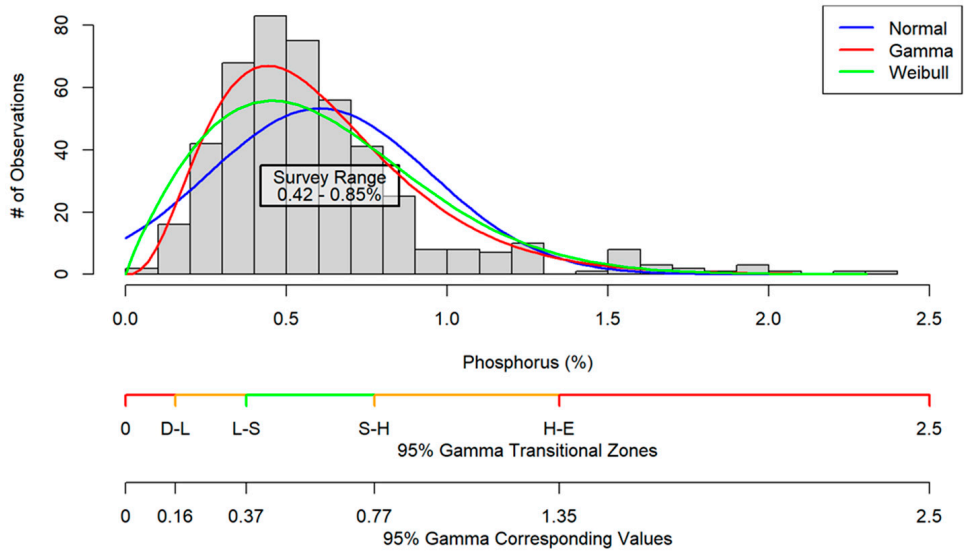
[1] *, **, or *** denotes statistically significant differences between the sample means based on *F* test at $p \leq 0.05$, $p \leq 0.01$, or $p \leq 0.001$, respectively, and NS indicates differences were not significant ($p > 0.05$). Data were presented for each separate element subjected to the disorder treatments. [2] Bryson and Mills [12].

Out of the three models evaluated, a Weibull distribution best fit the N foliar concentration data based on the BIC value and visual fitness (Figure 2a, Table 2). A defined sufficiency range of 3.94% to 5.48% N (Table 4) slightly shifts the previously recommended range of 4.00% to 6.00% N for field-grown cilantro [12]. The deficiency value of 2.36% N for this distribution falls slightly below the 2.50% N tissue concentration observed in Expt. 1 for our N-deficient cilantro plants, although they displayed clear deficiency symptomology. This could be due to young plant age and size at the time of sampling, as tissue values are typically higher in young plants and decline due to the dilution effect as plant mass increases [28].



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. Nitrogen (**a**) and phosphorus (**b**) foliar concentrations of *Coriandrum sativum* modeled using Normal, Gamma, and Weibull distributions. Interpretation ranges are based on the denoted distribution with four transitional points of deficient to low (D–L), low to sufficient (L–S), sufficient to high (S–H), and high to excessive (H–E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations (n = 463), respectively. Survey ranges from Bryson and Mills [12] are overlayed for reference.

Table 4. *Coriandrum sativum* 'Santo' nutrient distribution interpretation ranges defined from the distribution models, denoting deficient, low, sufficient, high, and excessive foliar elemental concentrations.

Element	Unit	Nutrient Range				
		Deficient	Low	Sufficient	High	Excessive
N	%	<2.36	2.36–3.94	3.94–5.48	5.48–6.73	>6.73
P	%	<0.16	0.16–0.37	0.37–0.77	0.77–1.35	>1.35
K	%	<1.70	1.70–3.64	3.64–6.21	6.21–8.40	>8.40
Ca	%	<0.57	0.57–0.85	0.85–1.23	1.23–1.69	>1.69
Mg	%	<0.15	0.15–0.35	0.35–0.61	0.61–0.87	>0.87
S	%	<0.17	0.17–0.31	0.31–0.47	0.47–0.60	>0.60
B	$mg \cdot kg^{-1}$	<19.68	19.68–39.55	39.55–74.76	74.76–102.14	>102.14
Cu	$mg \cdot kg^{-1}$	<1.79	1.79–4.63	4.63–11.01	11.01–16.84	>16.84
Fe	$mg \cdot kg^{-1}$	<39.04	39.04–71.96	71.96–123.03	123.03–189.71	>189.71
Mn	$mg \cdot kg^{-1}$	<23.36	23.36–46.96	46.96–101.89	101.89–160.23	>160.23
Mo	$mg \cdot kg^{-1}$	-	<0.20	0.20–2.03	2.03–5.48	>5.48
Zn	$mg \cdot kg^{-1}$	<15.97	15.97–34.21	34.21–68.53	68.53–96.32	>96.32

3.1.2. Phosphorus

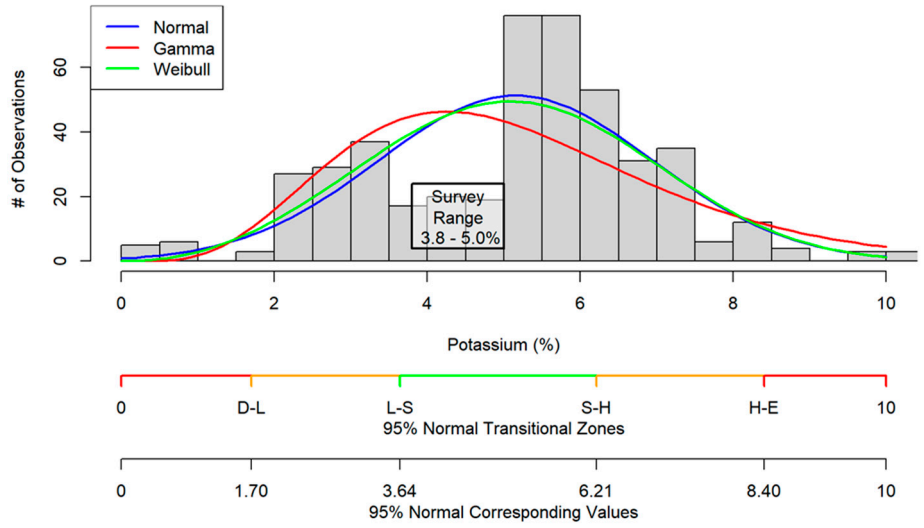
Initial symptoms of P deficiency were stunted growth and faint purpling of leaf margins on lower leaves (Figure 1B). As symptoms progressed, the purpling of the foliage became more prominent, with some leaves becoming entirely purple. The P-deficient plants, upon onset of symptoms, had 73% less dry weight and a P tissue concentration 82% lower than the control plants (Table 3). While the P concentration of the deficient plants (0.22% P) fell below the survey range of 0.42% to 0.85% P presented by Bryson and Mills [12], the control value (0.82% P) was greater than the upper end of their range. Greenhouse-grown plants typically have higher leaf tissue concentrations than their field-grown counterparts because of higher fertilizer applications and optimized cultural practices and environmental conditions [29].

A Gamma distribution had the lowest BIC value and best represented P foliar concentration (Figure 2b, Table 2). The recommended P sufficiency range of 0.37% to 0.77% (Table 4) recommends lower P concentrations than the previously recommended range of 0.42% to 0.85% P [12]. This updated range shifts the lower target value downward, which may encourage lower P applications and help prevent overapplication, thus minimizing potential environmental impacts. The control plants in Expt. 1 had a P concentration above the established sufficiency range, which suggests the P concentration (30.97 mg·L^{-1}) of the modified Hoagland's solution was higher than necessary for cilantro. A deficiency value of 0.16% P was determined, which was similar to the mean P concentration of 0.18% observed in our P-deficient plants. This distribution also established the excessive tissue concentration range as >1.35% P.

3.1.3. Potassium

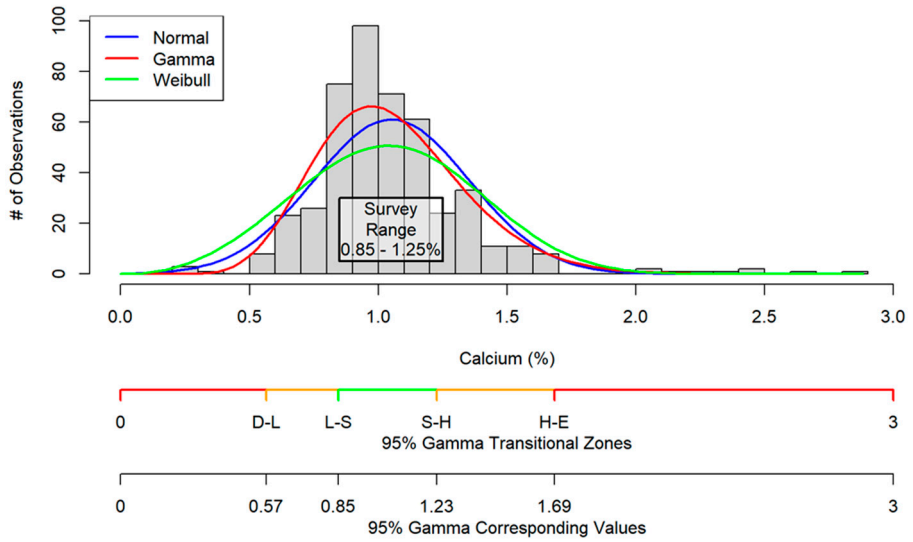
Potassium-deficient plants initially displayed stunted growth, interveinal chlorosis of the most recently matured leaves, and necrotic speckling of the oldest leaves (Figure 1C). Over time, the most recently matured leaves exhibited a downward, cupped orientation. At the time of harvest, the K-deficient plants had 35% less dry weight and a K tissue concentration 88% lower than the control plants (Table 3). As expected, the K concentration of the K-deficient plants (0.82% K) was below the recommended range of 3.80% to 5.00% from Bryson and Mills [12]. The 6.89% K concentration of the control plants was greater than the 5.00% upper value of the K range.

While a K tissue concentration was best represented by a Normal distribution (Figure 3a, Table 2), the visual distribution of data exhibited a low number of samples between 3.50% to 5.00% K. While this is not characteristic of a Normal distribution, the gap represents a difference of about 10 samples, and would likely disappear given a larger set of samples. Based on a Normal distribution, the K sufficiency range of 3.64% to 6.21% (Table 4) broadens the survey range of 3.80% to 5.00% K [12]. While the upper value of the refined range suggests concentrations between 5.0% and 6.21% K to be sufficient, these higher K values likely represent luxury consumption. A larger dataset may decrease the upper value of the sufficiency range. The K deficiency range was determined to be <1.70%, which included the mean K concentration of the K-deficient plants in Expt. 1. Additionally, K tissue concentrations >8.40% were defined as excessive.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Potassium (**a**) and calcium (**b**) foliar concentrations of *Coriandrum sativum* modeled using Normal, Gamma, and Weibull distributions. Interpretation ranges are based on the denoted distribution with four transitional points of deficient to low (D–L), low to sufficient (L–S), sufficient to high (S–H), and high to excessive (H–E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations (n = 463), respectively. The survey ranges from Bryson and Mills [12] are overlayed for reference.

3.1.4. Calcium

Initially, Ca-deficient plants displayed necrosis of the new, unfurled, or unfurling leaves and stems at the growing point. Unfurled leaves exhibited necrosis of the leaf tips, resulting in cupped leaves unable to fully expand (Figure 1D). Calcium-deficient plants were also noticeably stunted, and the dry weight was 51% of the control plants. The Ca concentration of Ca-deficient plants was 62% lower than that of the control plants, with the Ca concentrations being 0.27% and 0.71%, respectively (Table 3). Both these values fell below the suggested range of 0.85% to 1.25% presented by Bryson and Mills [12]. With the control plants receiving 75 mg·L^{-1} Ca, which should be adequate for proper growth, it is uncertain why the Ca concentration of the control plants falls below the recommended sufficiency range. This may be due to lower transpiration rates in a greenhouse environment resulting from the less negative vapor pressure deficit, compared to open field conditions [30], but further research is needed to determine if a higher Ca fertilization rate is necessary for cilantro.

The Gamma distribution was most representative of the Ca tissue data (Figure 3b, Table 2). The recommended sufficiency range of 0.85% to 1.23% Ca (Table 4) supports the survey range recommended by Bryson and Mills [12], with minimal adjustment. The deficiency range of <0.57% was also supported by the mean Ca concentration of the Ca-deficient plants in Expt. 1, which exhibited clear Ca deficiency systems. The established range for excessive Ca concentrations was >1.69% Ca. While Ca can accumulate at higher foliar concentrations without inhibiting plant growth for some species [28], high application rates can inhibit the uptake of other essential elements, particularly K and Mg. Unintentionally high Ca concentrations are most likely to occur in limestone bedrock regions, where high water alkalinity and associated hardness provide additional Ca on top of what may be supplied through fertilizer applications.

3.1.5. Magnesium

Initial symptoms of Mg deficiency were stunted growth and interveinal chlorosis of the older leaves, starting near leaf margins and progressing inward (Figure 1E). As symptoms progressed, some leaves became entirely necrotic. Upon the onset of symptoms, Mg-deficient plants had 37% less dry weight and a 69% lower Mg tissue concentration than the control plants (Table 3). Although the Mg tissue concentrations of the Mg-deficient and control plants (0.11% and 0.35%, respectively) both fell below the suggested range of 0.40% to 0.75% [12], control plants did not display deficiency symptoms.

A Weibull distribution best represented the Mg tissue data (Figure 4a, Table 2). The sufficiency range of 0.35% to 0.61% Mg (Table 4) shifts the previously suggested sufficiency range downward and now includes the Mg concentration of the control plants in Expt. 1. Similarly to Ca, Mg is often present in the tap water in overlying limestone bedrock and may be available at a sufficient concentration, so the need for additional Mg fertilizer provision should be evaluated. Additionally, the deficiency range of <0.15% was corroborated by the mean Mg concentration of the Mg-deficient plants. Magnesium deficiency may occur in cilantro plants if the substrate pH falls below 5.4, as this can inhibit nutrient uptake even when Mg is sufficiently applied [12]. The Weibull distribution also established an excessive range of >0.87% Mg. Above this, uptake of other essential nutrients, particularly Ca and K, can be inhibited [28].

3.1.6. Sulfur

Sulfur-deficient plants were stunted and had overall light green-yellow foliage, with the newest leaves having the lightest coloration (Figure 1F). The deficient plants had 51% less dry weight and a 66% lower S concentration than the control plants (Table 3). The deficient tissue value (0.14% S) was below the recommended range presented by Bryson and Mills [12], which suggested 0.22% to 0.35% S. The control tissue value (0.41% S) was above the upper end of this range.

A Normal distribution yielded the lowest BIC value (Table 2) of the three models evaluated (Figure 4b) and was found to best represent S foliar concentration. The established sufficiency range was defined as 0.31% to 0.47% S (Table 4), which is an upward shift from the previously recommended range of 0.22% to 0.35% [12]. Sulfur deficiency was one of the first nutrient disorders to develop, suggesting that cilantro is sensitive to low S concentrations. The updated sufficiency range reflects these findings and shifts the lower limit of the sufficiency range to avoid low S concentrations. Additionally, the predicted deficiency range for cilantro was <0.17% S, which was corroborated by the mean S concentration of the S-deficient plants in Expt. 1. The boundary between high and excessive S concentration ranges was 0.60%.

3.2. Micronutrient Disorders

3.2.1. Boron

Boron (B)-deficient plants exhibited marginal to interveinal chlorosis of the most recently mature leaves, with some leaf margins having a purple coloration (Figure 5A). The leaves curled downward, and both leaves and stems were thick and brittle to the touch. The newest leaves failed to unfurl, becoming necrotic and eventually abscising.

Despite visual symptoms, dry weights of the B-deficient and control treatments were not statistically different from each other ($p > 0.05$), likely due to sample size (n = 4) and variability among the plants within treatments. The B concentration of the B-deficient plants was 8.06 mg·kg^{-1}, while the control plants had a concentration of 50.31 mg·kg^{-1} (Table 3). The survey range provided by Bryson and Mills [12] suggests 25 to 45 mg·kg^{-1} B.

While the deficient tissue was below this range, the control tissue was above the upper end of the range.

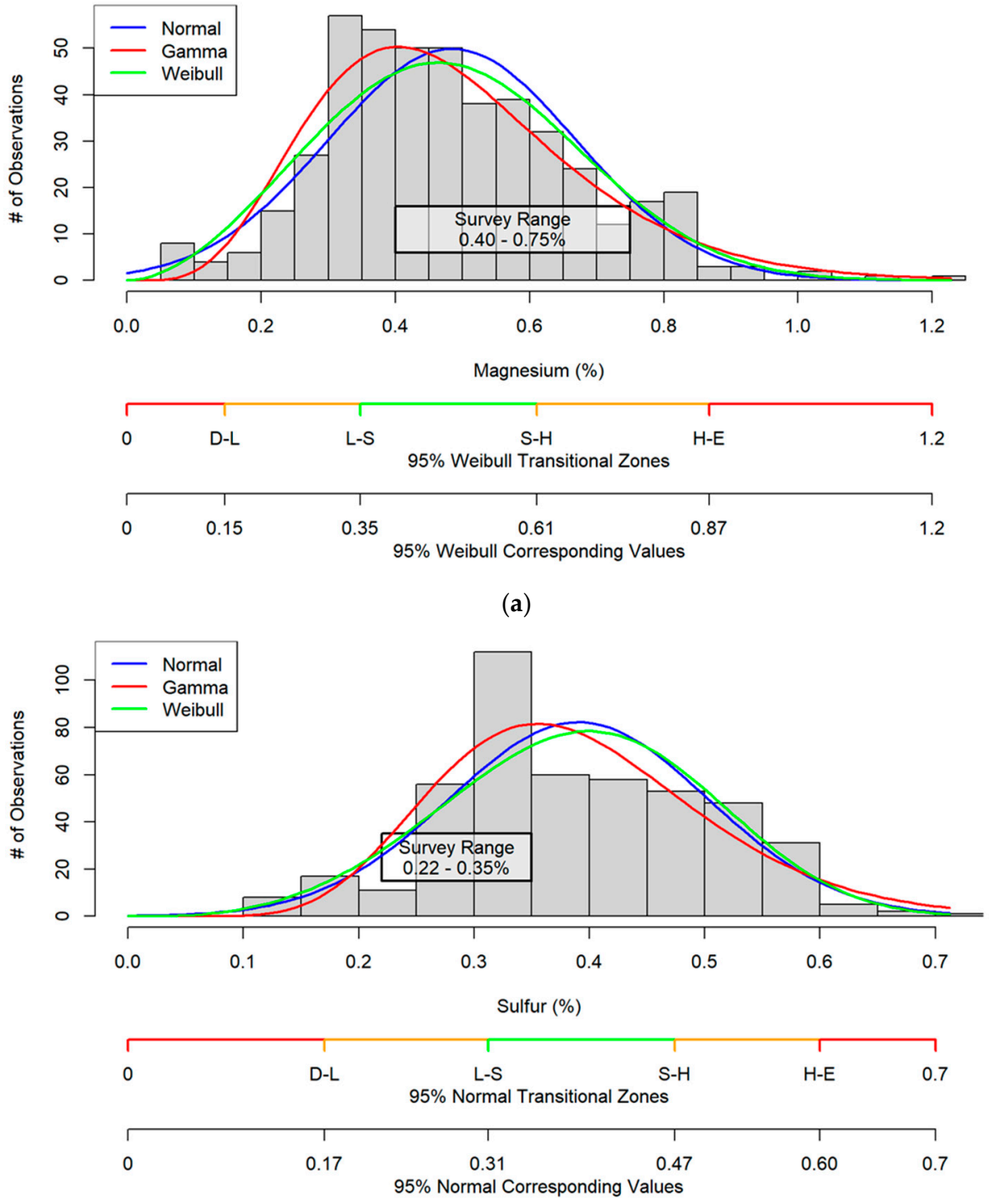


Figure 4. Magnesium (**a**) and sulfur (**b**) foliar concentrations of *Coriandrum sativum* modeled using Normal, Gamma, and Weibull distributions. Interpretation ranges are based on the denoted distribution with four transitional points of deficient to low (D–L), low to sufficient (L–S), sufficient to high (S–H), and high to excessive (H–E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations (n = 463), respectively. Survey ranges from Bryson and Mills [12] are overlayed for reference.

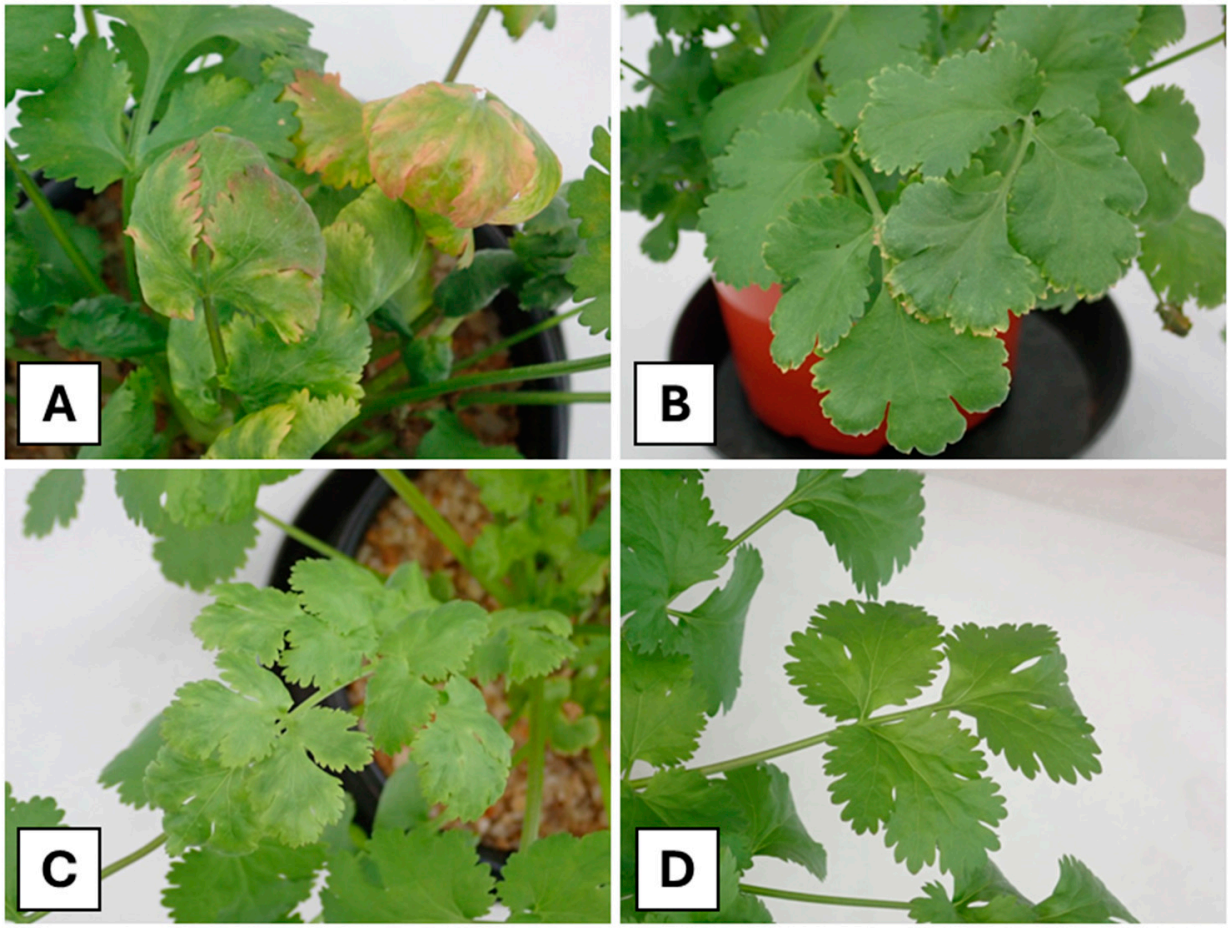


Figure 5. *Coriandrum sativum* 'Santo' visual micronutrient deficiency and toxicity symptoms. (**A**) Recently matured leaves of boron-deficient plants exhibited marginal chlorosis and a "cupped" appearance, with newer leaves and stems becoming thick and brittle. (**B**) Plants receiving the boron-toxicity treatment exhibited marginal chlorosis of the older leaves, which quickly turned into necrosis. (**C**) Iron-deficient plants exhibited interveinal chlorosis of the recently mature leaves. (**D**) Control plant.

Plants receiving the B-toxicity treatment exhibited marginal chlorosis, which turned into necrosis on older leaves (Figure 5B). Eventually, the newest leaves also became necrotic before expanding and unfurling. Upon sampling, the B-toxicity plants had 20% less dry weight than the control plants. The B tissue concentrations for the B-toxicity and control plants were 354.98 mg·kg^{-1} and 50.31 mg·kg^{-1}, respectively (Table 3). Both tissue values were greater than the aforementioned survey range provided by Bryson and Mills [12].

A Weibull distribution best represented foliar B concentration (Figure 6a, Table 2). The established sufficiency range was 39.6 to 74.8 mg·kg^{-1} B (Table 4), which significantly shifts upward the recommended survey range provided by Bryson and Mills [12]. This suggests a higher B concentration is necessary for sufficient growth in greenhouse environments. This was corroborated by the control plants, which had a mean foliar B concentration of 50.31 mg·kg^{-1} in Expt. 1. The recommended deficiency range of <19.68 mg·kg^{-1} was also supported by the B concentration of the B-deficient plants, which displayed clear deficiency symptoms. Lastly, the excessive range was determined to be >102.14 mg·kg^{-1}, above which toxicity symptoms may occur.

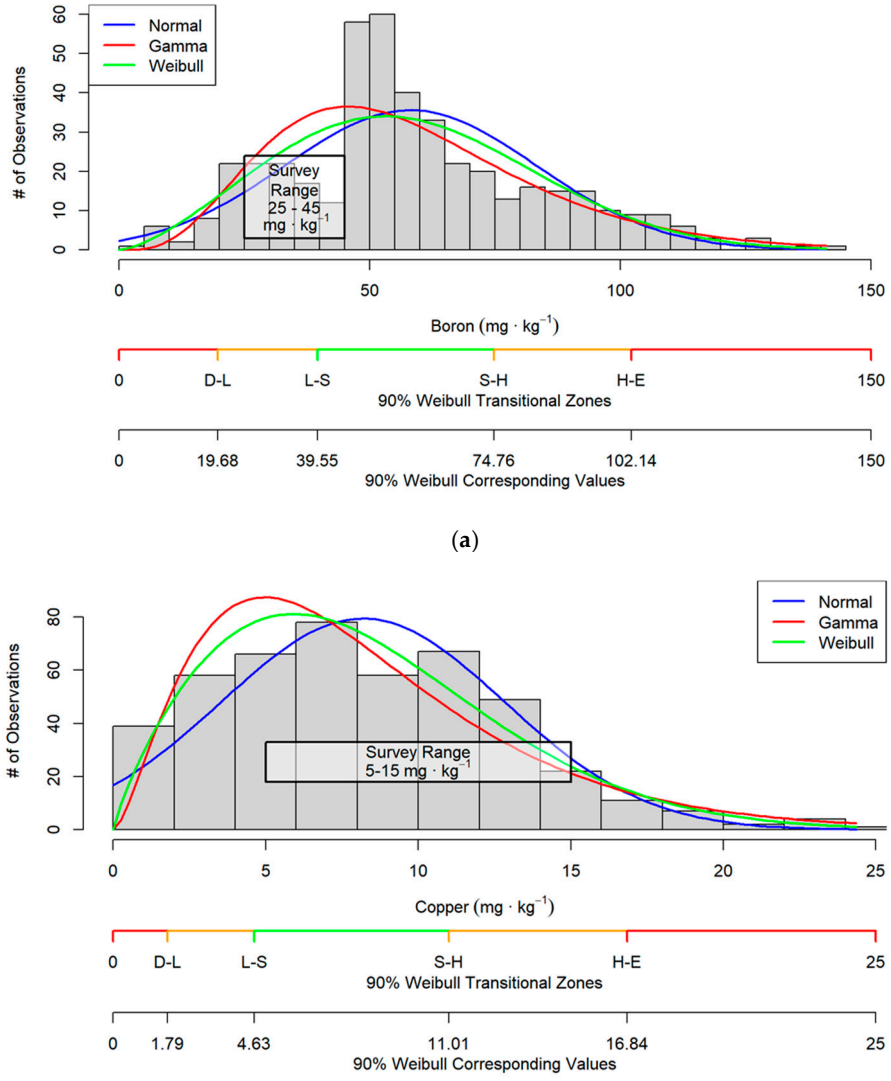


Figure 6. Boron (**a**) and copper (**b**) foliar concentrations of *Coriandrum sativum* modeled using Normal, Gamma, and Weibull distributions. Interpretation ranges are based on the denoted distribution with four transitional points of deficient to low (D–L), low to sufficient (L–S), sufficient to high (S–H), and high to excessive (H–E), which correspond to 5%, 25%, 75%, and 95% of sample observations (n = 463), respectively. The survey ranges from Bryson and Mills [12] are overlayed for reference.

3.2.2. Copper

Plants that were not supplied with Cu appeared asymptomatic upon experiment termination. Despite a lack of visual symptoms, plants that did not receive Cu had a Cu foliar concentration 84% lower than the control plants, with Cu concentrations of 0.65 mg·kg^{-1} and 4.16 mg·kg^{-1}, respectively (Table 3). Both values were below the suggested range of 5 to 15 mg·kg^{-1} determined by Bryson and Mills [12]. The dry weights between the -Cu treatment (0 mg·L^{-1} Cu) and the control treatment were also not statistically different ($p > 0.05$).

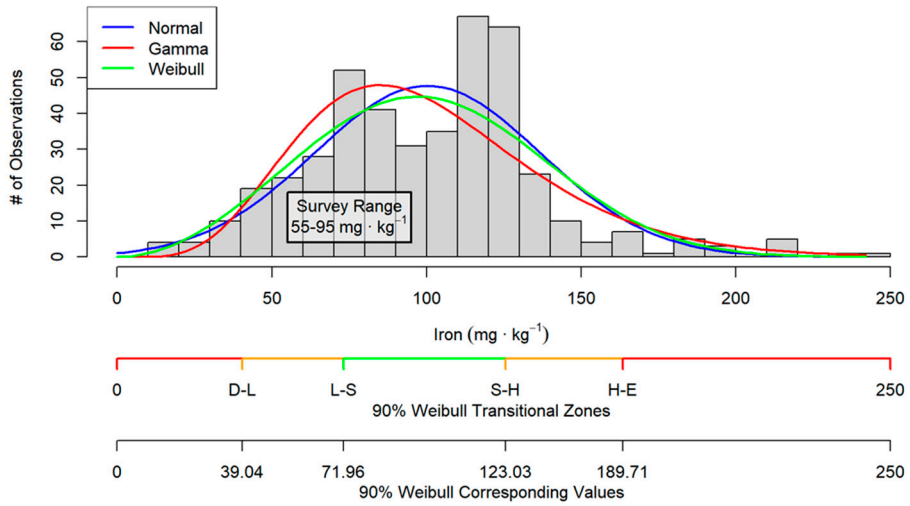
A Weibull distribution was most representative of Cu foliar concentrations (Figure 6b, Table 2). The model suggests a sufficiency range between 4.6 and 11.0 mg·kg^{-1} Cu (Table 4). This narrows the range provided by Bryson and Mills [12], which suggested an upper sufficiency value of 15 mg·kg^{-1} Cu. The foliar Cu concentration of the control plants fell just below the sufficiency range, which could have been due to the high N supply impeding Cu translocation [28]. Plants from the Cu deficiency treatment fell within the

newly established deficiency range, which was <1.79 mg·kg^{-1} Cu, even though no visual symptoms were present. Due to a lack of symptoms, despite low and deficient tissue values, further research is needed to examine the Cu deficiency value in cilantro. Lastly, the boundary value between high and excessive ranges was 16.84 mg·kg^{-1} Cu. Excessive Cu can result in Cu toxicity and may impede the uptake of N, P, Zn, Fe, and Mo [31].

3.2.3. Iron

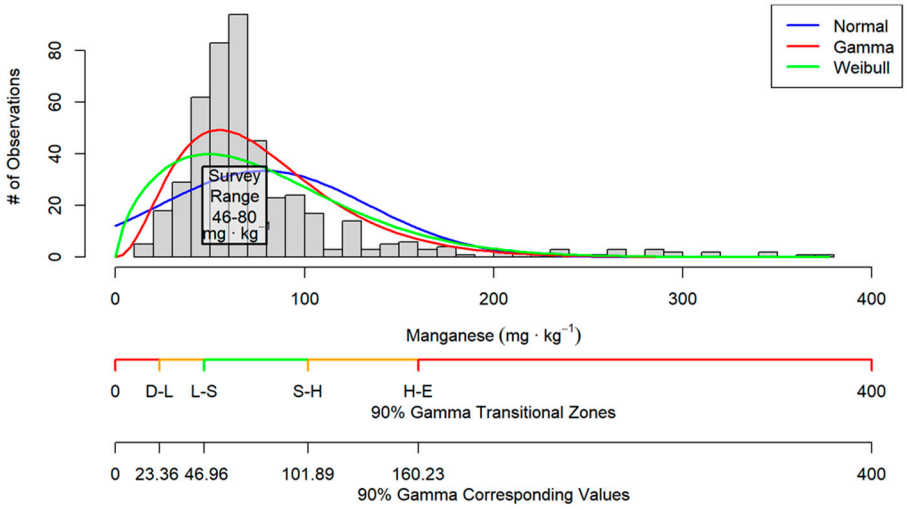
The primary symptom of Fe deficiency was interveinal chlorosis of the most recently matured leaves (Figure 5C). The Fe-deficient plants had 46% less dry weight than the control plants. However, the tissue Fe concentrations of the deficient and control plants were not statistically different ($p > 0.05$); the foliar Fe concentration of the deficient and control plants was 67.56 mg·kg^{-1} and 74.63 mg·kg^{-1}, respectively (Table 3). Although Fe deficiency symptoms were observed, the foliar Fe concentration of the Fe-deficient plants was within the survey range presented by Bryson and Mills [12], which suggested a range of 55 to 95 mg·kg^{-1} Fe. The discrepancy between Fe-deficiency symptoms and tissue concentrations may be due to Fe precipitation in the apoplasm of the leaves, where it is not physiologically available to the plant but is detected during destructive analysis [28].

The Weibull model had the lowest BIC value of the three models evaluated (Table 2) and best represented Fe foliar concentrations (Figure 7a). The recommended sufficiency range was 72.0 to 123.0 mg·kg^{-1} Fe (Table 4), which increased the previously recommended range and suggests a higher Fe concentration is required for greenhouse-grown cilantro. This may explain why cilantro plants with an Fe concentration of 67.56 mg·kg^{-1} displayed visual deficiency symptoms in Expt. 1, despite falling within the previously recommended range provided by Bryson and Mills [12]. The established deficient and excessive ranges were defined as <39.04 mg·kg^{-1} Fe and >189.71 mg·kg^{-1} Fe, respectively. At a high substrate or hydroponic nutrient solution pH, Fe deficiency can be induced due to an inhibition of Fe uptake, despite supplying an adequate concentration [6]. While the Weibull model best represents the data, the visual distribution of data reflects a low number of samples with Fe concentrations between 35 mg·kg^{-1} and 45 mg·kg^{-1}. Because Fe availability and uptake is driven by pH [28], we hypothesize that the emergence of two populations of data may be due to varying forms of Fe application. The use of Fe chelates can enhance Fe availability at a higher pH, thus resulting in plants with higher Fe content.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. Iron (**a**) and manganese (**b**) foliar concentrations of *Coriandrum sativum* modeled using Normal, Gamma, and Weibull distributions. Interpretation ranges are based on the denoted distribution with four transitional points of deficient to low (D–L), low to sufficient (L–S), sufficient to high (S–H), and high to excessive (H–E), which correspond to 5%, 25%, 75%, and 95% of sample observations (n = 463), respectively. The survey ranges from Bryson and Mills [12] are overlayed for reference.

3.2.4. Manganese

After 8 weeks of treatment, plants that were not supplied with Mn did not exhibit any visual deficiency symptoms. Additionally, the dry weight and foliar Mn concentration of plants from the Mn deficiency treatment (0 mg·kg^{-1} Mn) were not significantly different than that of the control plants. The foliar Mn concentrations for plants from the Mn deficiency treatment and the control treatment were 27.10 mg·kg^{-1} and 38.65 mg·kg^{-1}, respectively (Table 3). Both fell below the survey range of 46 to 80 mg·kg^{-1} [12], although none of the plants had any deficiency symptoms.

Of the three models, a Gamma distribution best represented Mn foliar concentrations (Figure 7b, Table 2). A recommended sufficiency range of 47.0 to 101.9 mg·kg^{-1} Mn (Table 4) expands the survey range, which previously had an upper boundary of 80 mg·kg^{-1}. The established deficiency range of <23.36 mg·kg^{-1} Mn is slightly lower than the mean Mn foliar concentration of the plants in Expt. 1 grown under Mn-deficient conditions. While this deficiency range provides a guideline for growers, visual deficiency symptoms were not induced to support this critical deficiency value. The distribution also defined Mn foliar concentrations >160.23 mg·kg^{-1} to be excessive. While an excessive Mn concentration can result in toxicity, it can also induce deficiencies of Ca and Mg [28].

3.2.5. Molybdenum

Plants not supplied with Mo did not exhibit visual deficiency symptoms during the experiment. However, there was a significant difference in foliar Mo concentration between plants from the Mo deficiency treatment (0 mg·kg^{-1} Mo) and the control treatment. Plants from the Mo deficiency treatment had a foliar concentration of 0.02 mg·kg^{-1} Mo, whereas the control had a concentration of 2.69 mg·kg^{-1} Mo (Table 3). Both values fell outside the suggested range 0.40 to 1.00 mg·kg^{-1} reported by Bryson and Mills [12]. The dry weights of the two treatments were not statistically different ($p > 0.05$).

The foliar Mo interpretation ranges were determined using a smaller sample size (n = 286) because a subset of the tissue analysis data did not include Mo tissue concentrations. Further, Mo concentrations that fell below the detection limit were assigned a

concentration of 0.01 mg·kg^{-1} Mo for analysis purposes. A Gamma distribution had the lowest BIC value and best represented foliar Mo concentrations (Figure 8a, Table 2). Based on this distribution, the suggested sufficiency range is 0.06 to 1.47 mg·kg^{-1} Mo (Table 4), which expands the survey range provided by Bryson and Mills [12]. Due to a lack of visual deficiency symptoms in Expt. 1 and numerous very low Mo concentration values, a deficiency value could not be established. As a result, the deficiency and low bins were combined, and the value for the deficient/low range was <0.06 mg·kg^{-1} Mo. Although some crops are highly sensitive to Mo deficiency, the present study indicated that cilantro was not significantly affected by low Mo levels. This distribution established 4.92 mg·kg^{-1} Mo as the boundary between high and excessive concentrations. While Mo toxicity is relatively rare, many crops, such as French marigold (*Tagetes patula* L.) do not show Mo toxicity symptoms until much higher concentrations, with reports indicating symptoms at 5010 mg·kg^{-1} [32]. Although Mo toxicity has not been observed in cilantro, further research is needed to determine if the upper limit for Mo is higher than currently reported. While the Gamma distribution was deemed the best fit, the high level of variation among samples suggests further refinement would be advantageous. A larger sample size may address these issues and provide a more representative distribution.

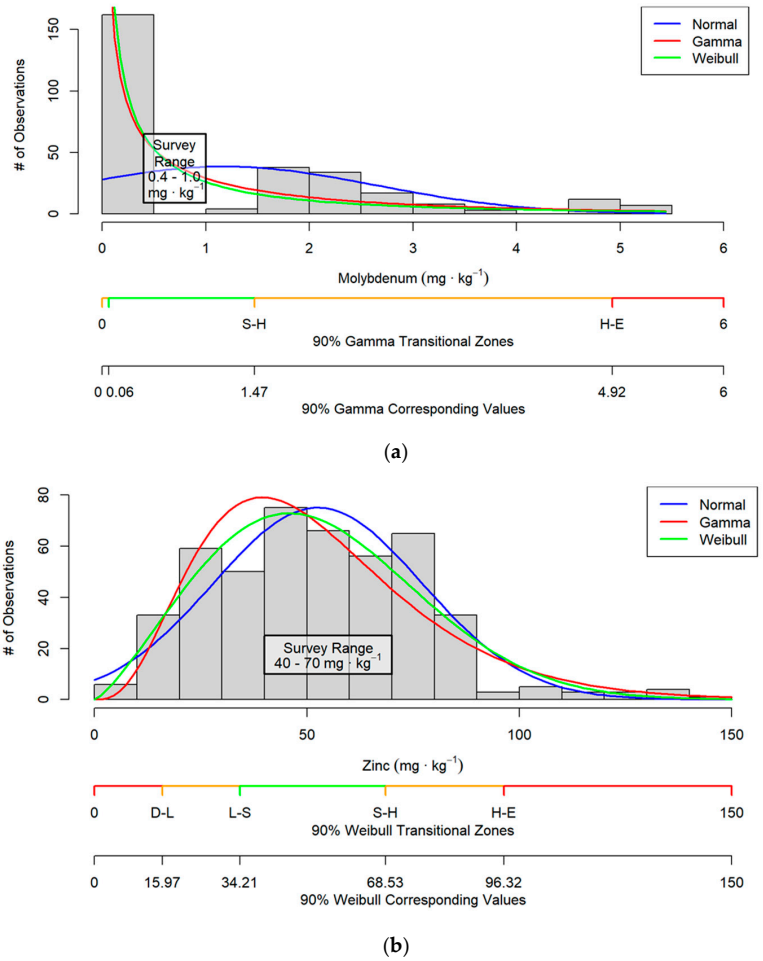


Figure 8. Molybdenum (**a**) and zinc (**b**) foliar concentrations of *Coriandrum sativum* modeled using Normal, Gamma, and Weibull distributions. Interpretation ranges are based on the denoted distribution with four transitional points of deficient to low (D–L), low to sufficient (L–S), sufficient to high (S–H), and high to excessive (H–E), which correspond to 5%, 25%, 75%, and 95% of sample observations; n = 286 and n = 463, respectively. For Mo, the deficient and low ranges were combined, creating one low range corresponding to the lowest 30% of sample observations. The survey ranges from Bryson and Mills [12] are overlayed for reference.

3.2.6. Zinc

The only visual symptom exhibited by the Zn-deficient plants was noticeable stunted growth. Leaf coloration was similar between the Zn-deficient treatment and the control. The Zn-deficient plants had 65% less dry weight than the control plants. Tissue analysis revealed that the Zn-deficient plants had a Zn concentration of 10.37 mg·kg^{-1}, while the control plants had a concentration of 18.80 mg·kg^{-1} (Table 3). Both Zn concentration values were below the range of 40 to 70 mg·kg^{-1} suggested by Bryson and Mills [12].

Out of the three models tested, a Weibull model yielded the smallest BIC value and thus best represented Zn foliar concentrations (Figure 8b). The recommended sufficiency range of 34.2 to 68.5 mg·kg^{-1} Zn (Table 4) expands the recommendation provided by Bryson and Mills [12]. Based on this model, the deficiency range fell below 15.97 mg·kg^{-1} Zn, while the excessive range was established as above 96.32 mg·kg^{-1} Zn. It is worth noting that while the control plants had a mean Zn concentration of 18.80 mg·kg^{-1}, which would have placed them in the low Zn range, they did not exhibit any visual deficiency symptoms.

4. Conclusions

This research provides the first documented photographs, descriptions of symptoms, and tissue concentrations for all observed nutrient disorders, which will aid growers in identifying the nutrient problems of greenhouse-grown cilantro. Refined foliar nutrient interpretation ranges were needed for greenhouse-grown cilantro. By expanding upon the hybrid SRA method, foliar nutrient interpretation ranges were defined for deficient, low, sufficient, high, and excessive tissue concentrations. These expanded interpretation ranges will enable growers to evaluate foliar tissue concentrations that fall above or below the sufficiency range. This information greatly expands the diagnostic ability of cilantro growers. Collectively, these documented deficiencies and toxicity symptoms and comprehensive interpretation ranges will provide important guidelines for classifying and diagnosing nutritional disorders of cilantro.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15179266/s1, Table S1. Nutrient disorder solution mixing recipe based on 100 liters of fertilizer.

Author Contributions: Conceptualization, B.W. and D.C.; methodology, B.W. and D.C.; software, P.V., B.W. and D.C.; validation, B.W. and D.C.; formal analysis, P.V., B.W. and D.C.; investigation, B.W. and D.C.; resources, B.W. and D.C.; data curation, J.B., C.C., N.F., K.W., K.H., B.W. and D.C.; writing—original draft preparation, B.W. and D.C.; writing—review and editing, B.W., J.B., C.C., N.F., K.W., P.V., and K.H.; visualization, D.C.; supervision, B.W.; project administration, B.W. and D.C.; funding acquisition, B.W. All authors have read and agreed to the published version of the manuscript.

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