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Generating Gerbera Foliar Nutrient Interpretation Ranges with a Meta-analysis Sufficiency Range Approach

Patrick Veazie and Hsuan Chen
Department of Horticultural Science, North Carolina State University, 2721 Founders Drive, Raleigh, NC 27695, USA

Kristin Hicks
Agronomic Division, North Carolina Department of Agriculture & Consumer Services, Raleigh, NC 27607, USA

Brian Whipker
Department of Horticultural Science, North Carolina State University, 2721 Founders Drive, Raleigh, NC 27695, USA

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Abstract. **Foliar tissue analysis is an important method for diagnosing nutritional problems in greenhouse crops. Currently, gerbera foliar tissue standards are based on small sample populations and limited rate studies. This study expands prior work and presents a novel approach to creating data-driven nutrient sufficiency ranges of deficient, low, sufficient, high, and excessive, which were not previously available for gerbera. A hybrid meta-analysis sufficiency range approach (SRA) was used to determine the best fit model between Normal, Gamma, and Weibull distributions based on the lowest Bayesian information criteria This study establishes the use of a hybrid-SRA for the creation of refined interpretation ranges of gerbera foliar nutrient analysis results with a higher degree of precision than what is currently available to the greenhouse industry for diagnosing fertility status.**

Gerbera (*Gerbera jamesonii*) is a popular ornamental plant for cut flowers, potted plants, and bedding plants. Previous research has identified nutrient-sufficiency ranges for gerbera using the survey range approach (SA) (Dole and Wilkins 2005; Jeong et al. 2009a). Additional work has established critical nutrient deficiency values and visual nutrient deficiency symptoms (Jeong et al. 2009b). However, limited work has been conducted to determine excessive nutrient ranges.

Foliar tissue analysis standards for most horticultural crops are based on the SA approach, which consists of sampling 25 to 30 "healthy appearing" plants to set a baseline reference for interpreting sufficient ranges in foliar tissue analysis results (Bryson and Mills 2015). This approach was based on collecting 25 to 30 samples of "healthy appearing" plants to provide an approximation of the sufficient range. Although this approach is limited by the small sample size, many commercial diagnostic laboratories use it because of the diverse range of horticultural crops and the limited plant nutrition research available for each species.

Other methods designed to improve the SA have been developed including the critical value approach (Jones and Eck 1973), compositional nutrient diagnosis (Parent and Dafir 1992), diagnosis and recommendation integrated system (DRIS) (Beaufils 1973), and sufficiency range approach (SRA) (Soltanpour et al. 1995). Each of these methods exhibits advantages and limitations for diagnosing foliar leaf tissue samples. For example, the SRA provides an assessment of individual nutrient concentrations (deficient or sufficient) but does not explicitly account for interactions between nutrients that DRIS provides. Although these approaches provide a baseline for creating reference values for specialty crops, the limited sample numbers used can skew the identified values. The SRA method has been widely used to establish recommended leaf tissue ranges, including geranium (*Pelargonium ×hortorum Bailey*) (Krug et al. 2010) and osteospermum (*Osteospermum ecklonis* DC) (Papineau and Krug 2014).

To enhance foliar tissue nutrient interpretation standards for gerbera, refined evaluation ranges were needed for the 11 essential elements commonly analyzed in leaf tissue analysis [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn)]. Previous studies have demonstrated that incorporating larger datasets from both research experiments and grower samples can improve interpretation standards, as shown for lettuce [(*Lactuca sativa*) (Veazie et al. 2024b)] and pentas [(*Pentas lanceolata*) (Veazie et al. 2024a)]. Building on this approach, the objective of this study was to develop robust leaf tissue classification ranges for gerbera using a hybrid SRA method that integrates metadata from controlled research studies and grower samples, providing valuable diagnostic and recommendation tools for commercial growers.

Materials and Methods

Sample collection. Foliar tissue analysis samples were obtained from controlled university research studies conducted across the United States and supplemented with samples from public and commercial analytical laboratories. Leaf tissue samples (n = 985) only included gerberas grown in controlled environments (greenhouses and growth rooms; Table 1) and were analyzed for each study based on procedures cited within the table. With the short production time used with bedding plant production, only one set of foliar nutrient standards for the entire ~60-d production cycle was developed.

Nutrient distribution statistical analysis. Distribution analyzes were conducted using R-Studio (v. 4.1.1; R Foundation for Statistical

Table 1. Sources of gerbera leaf tissue nutrient data (n = 985) used in the development of the hybrid meta-analysis sufficiency range approach (SRA) distribution model.

Source	Sample size	Sample type	Notes/citation
North Carolina State University	75	Research[i]	Unpublished electrical conductivity rate and nutrient deficiency studies.
North Carolina State University	39	Research[ii]	Published nutrient deficiency studies.
North Carolina State University	108	Research[iii]	Published electrical conductivity rate studies.
North Carolina Grower Samples	464	Predictive[iv]	Samples collected from normally growing plants in commercial greenhouses, unpublished.
North Carolina Dept of Agriculture	299	Diagnostic[iv]	Samples collected from diagnostic analysis at commercial laboratory.

Citations for leaf tissue analysis methods used for data.
[i] Lab testing procedures used are reported in Jeong et al. (2009b).
[ii] Jeong et al. (2009a).
[iii] Jeong et al. (2009b).
[iv] Lab testing procedures used are reported in Veazie et al. (2024a).

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P.V. is the corresponding author. E-mail: phveazie@ncsu.edu.

Table 2. Comparison of Bayesian information criterion (BIC) values for normal, gamma, and Weibull distribution models used in the development of the hybrid meta-analysis sufficiency range approach distribution model for each of the 11 elements in gerbera. The selected models with the lowest BIC values were bolded.

	BIC Values		
Element	Normal	Gamma	Weibull
N	2,638.41	2,714.04	**2,625.38**
P	−932.98	−928.78	**−947.87**
K	2,388.62	2,630.92	**2,424.46**
Ca	573.96	**573.81**	590.77
Mg	−802.46	**−1,085.15**	−853.75
S	−2693.49	**−2,734.33**	−2,601.35
Fe	12,823.67	**11,946.28**	12,000.48
B	7,634.23	**7,276.95**	7,553.81
Mn	11,474.75	**11,159.21**	11,209.23
Zn	8,988.26	**8,847.17**	8,909.78
Cu	5,440.90	5,251.35	**5,249.07**

Computing, Vienna, Austria). Each element was modeled independently, and extremely excessive outliers (greater than biologically feasible or a significant break in the population) were removed before further analysis. Data were fit to normal, gamma, and Weibull distributions, and the three statistical distributions were compared (Cera et al. 2022; Mhango et al. 2021; Slaton et al. 2021; Weibull 1951). Corresponding *P* values describing the fitness of the data into the statistical distributions were calculated based on the Shapiro–Wilk test for normality (normal and gamma distributions) or the Kolmogorov–Smirnov test (Weibull distribution). The optimal distribution was selected based on the lowest Bayesian information criterion (BIC) value and visual fitness (Table 2). Results were illustrated using ggplot2 (Wickham 2011) in R. For macronutrients (N, P, K, Ca, Mg, and S), the deficiency range was established based on the left tail of a 95% distribution (lowest 2.5% of the samples that contained >40 observations), the low range corresponded to the region between the lowest 2.5% of the observations and the 0.25 quantile, the sufficiency range was the area between the 0.25 and 0.75 quantiles, the high range corresponded to the region between the 0.75 quantiles and the highest 2.5% of the observations, and the excessive range was based on the right tail of a 95% distribution (highest 2.5% of the samples which contained >40 observations). For micronutrients (B, Cu, Fe, Mn, and Zn), the deficiency range was established based on the left tail of a 90% distribution (lowest 5% of the samples), the low range corresponded to the region between the lowest 5% of the observations and the 0.25 quantile, the high range corresponded to the region between the 0.75 quantile and the highest 5% of the observations, and the excessive range was based on the right tail of a 90% distribution (highest 5% of the distribution).

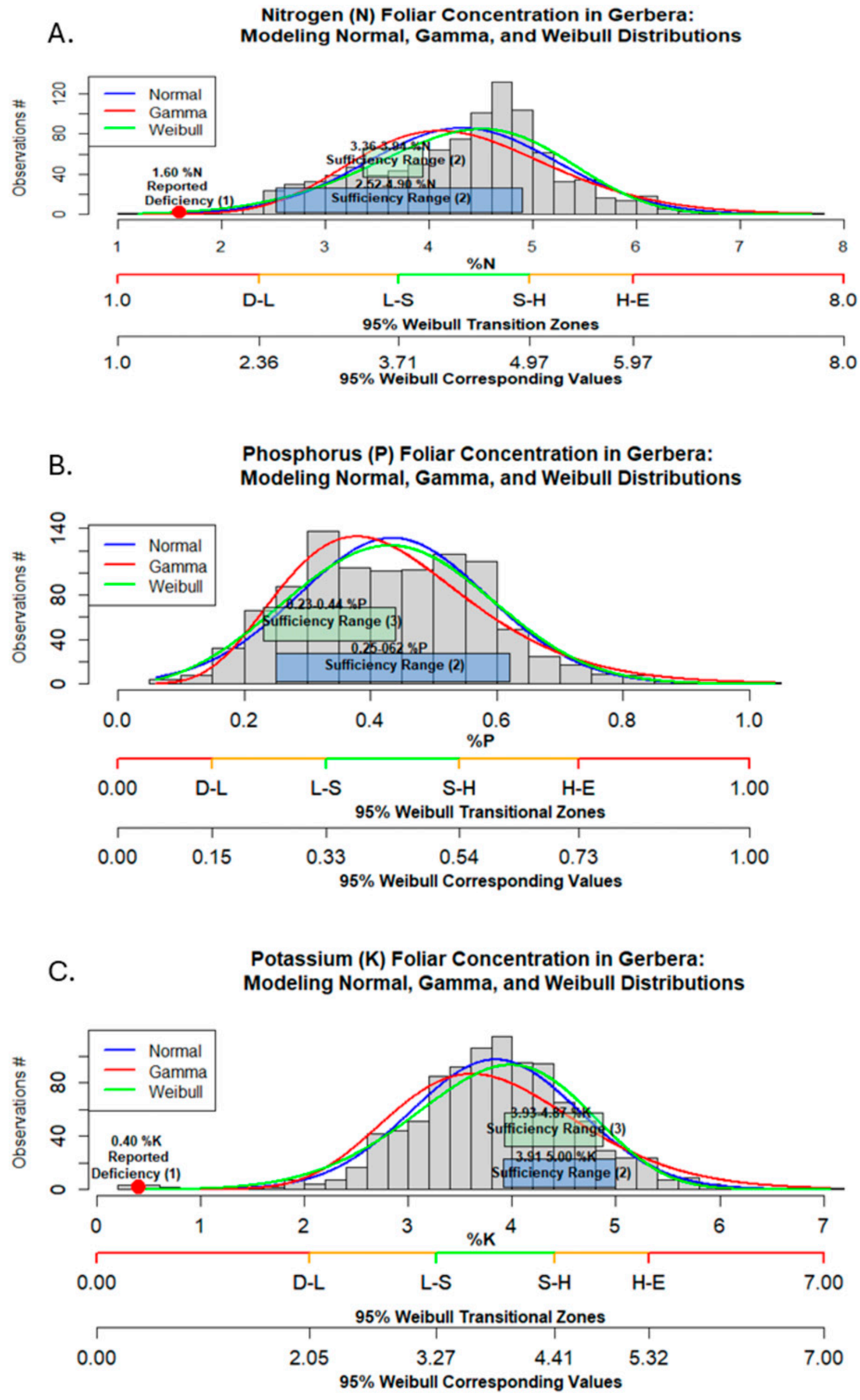

Fig. 1. (**A**) Nitrogen, (**B**) phosphorus, and (**C**) potassium foliar concentrations of gerbera modeled using normal, gamma, and Weibull distributions. Interpretation ranges based include four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Jeong et al. (2009b), (2) Jeong et al. (2009a), and (3) Bryson and Mills (2015).

Results and Discussion

Nitrogen. Of the three examined distributions, the Weibull distribution best represented N foliar concentrations due to the lowest BIC value (Table 2). A recommended sufficiency range of 3.71% to 4.97% N raises the sufficiency range reported by Bryson and Mills (2015) and the survey range reported by Jeong et al. (2009a). A deficiency range of <1.0% N that represents the lowest 2.5% of the population is lower than the N deficiency critical value of 1.6% N reported by Jeong et al. (2009b). Although N toxicity is not reported in gerbera, this work establishes an excessive range of N to be >5.97% N (Fig. 1A).

Phosphorus. Phosphorus foliar tissue concentrations were best represented by a Weibull distribution due to the lowest BIC observed value (Table 2). This study suggests a higher value of 0.15% P when P deficiencies begin compared with the observed P deficiency value of 0.07% P reported by Jeong et al. (2009b). This higher threshold is likely because Jeong et al. (2009b) identified P deficiency based on the appearance of visual symptoms,

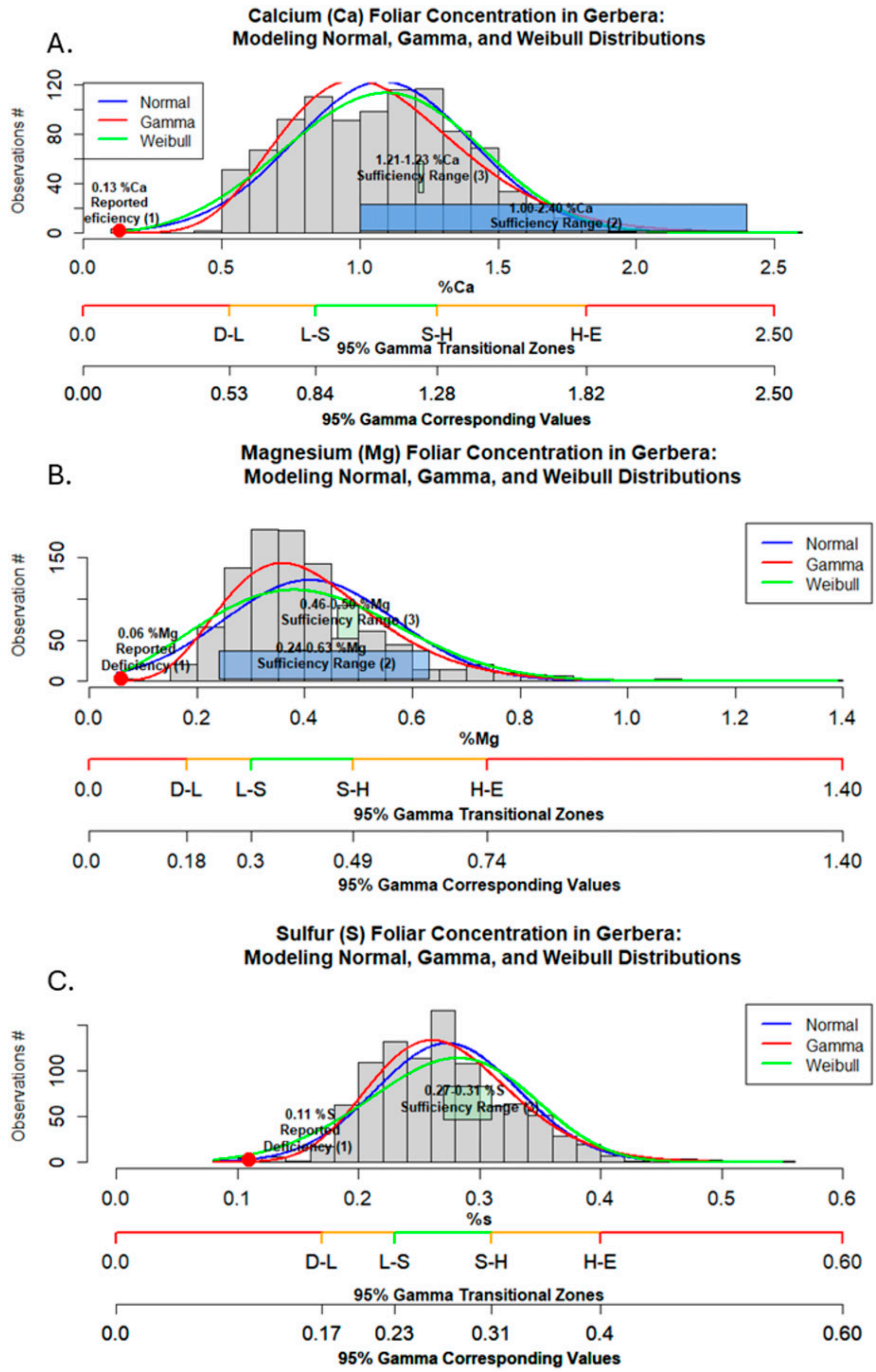

Fig. 2. (**A**) Calcium, (**B**) magnesium, and (**C**) sulfur foliar concentrations of gerbera modeled using normal, gamma, and Weibull distributions. Interpretation ranges based include four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Jeong et al. (2009b), (2) Jeong et al. (2009a), and (3) Bryson and Mills (2015).

whereas a plant may experience deficiency before such symptoms become visible. This study determined 0.33% to 0.54% P to be the sufficiency range, which is higher than the values recommended by Bryson and Mills (2015) and Jeong et al. (2009B) (Fig. 1B). Although P toxicity is rare, excessive P foliar concentrations can induce Fe deficiency through antagonism, even when sufficient Fe is available (Marschner 2011). This study also established the first reported excessive P threshold of 0.73% P (Fig. 1B), providing a reference for potential nutrient imbalances.

Potassium. Potassium foliar concentrations were best represented by a Weibull distribution due to a similar BIC value compared with a normal distribution (Table 2). Additionally, Weibull provided a better fit of the population's left and right tails (Fig. 1C). This study reports a lower K sufficiency range of 3.27% to 4.41% K (Fig. 1C) compared with those reported by Bryson and Mills (2015) and Jeong et al. (2009a). This lower sufficiency range is likely due to less luxury consumption of K where the plant will accumulate K when it is not necessary for plant growth. However, the data identifies a higher K deficiency value, set at 2.05% K, than the K deficiency value of 0.40% K reported by Jeong et al. (2009b). This discrepancy is likely because Jeong et al. (2009B) collected samples as visual nutrient deficiencies appeared; however, plants may experience stunted growth before such symptoms become visible. This study also established the first reported excessive K threshold of 5.32% K (Fig. 1C), providing a reference for potential nutrient imbalances. When K foliar concentrations become excessive, antagonistic interactions with Ca, Mg, and B have been reported (Marschner 2011). High K levels can compete with Ca and Mg for uptake, potentially leading to deficiencies that affect cell wall stability, enzyme activation, and photosynthetic efficiency (Marschner 2011).

Calcium. Of the three examined distributions, the gamma distribution best represented Ca foliar concentrations due to the lowest BIC value (Table 2). A recommended sufficiency range of 0.84% to 1.28% Ca widens the sufficiency range reported by Bryson and Mills (2015) of 1.21% to 1.23% Ca and the survey range of 1.00% to 2.40% Ca reported by Jeong et al. (2009a). A deficiency range of <0.53% Ca represents the lowest 2.5% of the population and encompasses the Ca deficiency value of 0.13% Ca reported by Jeong et al. (2009b). Although Ca toxicity is not reported in gerbera, this work establishes an excessive range of Ca to be >1.82% Ca (Fig. 2A). When Ca foliar concentrations become excessive, antagonistic relationships between Ca and Mg, Fe, K, B, and P have been reported (Marschner 2011). High Ca concentrations can interfere with Mg and K uptake due to competition at root absorption sites, and excessive Ca fertility can raise substrate pH, resulting in limiting Fe availability (Marschner 2011).

Magnesium. Magnesium foliar tissue concentrations were best represented by a Gamma distribution due to the lowest BIC observed value (Table 2). The critical sufficiency level of 0.30% is lower than 0.46% reported by Bryson and Mills (2015) but higher than the 0.24% reported by Jeong et al. (2009b) (Fig. 2B). This study provides a higher value of 0.18% Mg when deficiencies occur, and this range is inclusive of the critical Mg deficiency value of 0.06% Mg reported by Jeong et al. (2009b). This value is likely higher because Jeong et al. (2009b) reported that when visual symptoms occurred, the plant could be deficient before showing visual symptoms. Magnesium deficiency disrupts the loading of sucrose into the phloem, resulting in carbon accumulation in source leaves (Guo et al. 2016); however, excess leaf tissue Mg can inhibit photosynthesis and plant growth (Rao et al. 1987). Magnesium foliar concentrations must be closely monitored to promote optimal plant growth and also avoid antagonisms with K and Ca uptake. This work establishes the first report of 0.90% Mg as the threshold for excessive Mg foliar concentrations in gerbera.

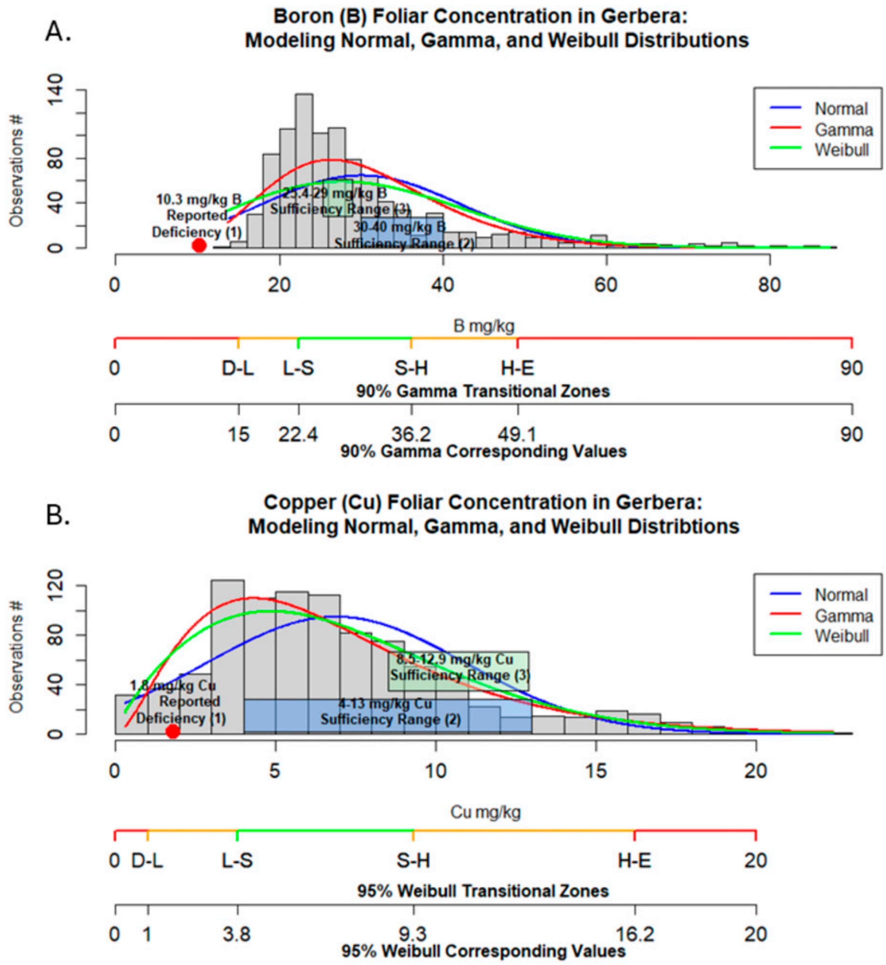

Fig. 3. (**A**) Boron and (**B**) copper foliar concentrations of gerbera modeled using normal, gamma, and Weibull distributions. Interpretation ranges include four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 5%, 25%, 75%, and 95% of sample observations, respectively. Comparison ranges: (1) Jeong et al. (2009b), (2) Jeong et al. (2009a), and (3) Bryson and Mills (2015).

Sulfur. Of the three examined models, S foliar tissue concentrations were best represented by Gamma distribution due to the lowest BIC values (Table 2). This study suggests a higher deficiency level of 0.17% S compared with a value of 0.11% S previously reported by Jeong et al. (2009b) (Fig. 2C). Additionally, a slightly lower sufficiency range of 0.23% to 0.31% S is suggested compared with the 0.27% reported by Jeong et al. (2009a). This study is also the first to suggest a threshold value for excessive S foliar concentration of 0.40% S.

Micronutrients. When examining micronutrient foliar concentrations of gerbera, a gamma distribution best represented Fe, B, Mn, and Zn, whereas a Weibull distribution best represented Cu (Table 2). The only reported micronutrient toxicity value reported for gerbera is 349.5 $mg{\cdot}kg^{-1}$ B by Jeong et al. (2009b). This study suggests a lower excessive threshold value of 49.1 $mg{\cdot}kg^{-1}$ B. The value reported by Jeong et al. (2009b) was observed when plants exhibited visual toxicity symptoms. However, this lower critical excessive value will provide commercial producers with a lower threshold value to prevent problems before visual symptoms occur. Krug et al. (2013) reported visual B deficiency symptoms on gerbera plugs with an observed foliar concentration of 13.33 $mg{\cdot}kg^{-1}$ B value when plants were grown in 100% relative humidity. The B deficiency range of <15.0 $mg{\cdot}kg^{-1}$ B in this study is consistent with the value reported by Krug et al. (2013). Additionally, this study suggests a lower critical sufficiency value of 22 $mg{\cdot}kg^{-1}$ B compared with 25.4 and 30.0 $mg{\cdot}kg^{-1}$ B reported by Bryson and Mills (2015) and Jeong et al. (2009b), respectively (Fig. 3A), and a lower critical sufficiency value of 3.8 $mg{\cdot}kg^{-1}$ Cu compared with 8.5 and 4.0 $mg{\cdot}kg^{-1}$ Cu reported by Bryson and Mills (2015) and Jeong et al. (2009b), respectively (Fig. 3B). The critical sufficiency level for Zn of 35.6 $mg{\cdot}kg^{-1}$ was similar to that reported by Jeong et al. (2009b) of 33.0 $mg{\cdot}kg^{-1}$ and lower than that reported by Bryson and Mills (2015). This work also establishes critical deficiency values for Mn of 15 $mg{\cdot}kg^{-1}$ and 36.2 $mg{\cdot}kg^{-1}$ (Fig. 3A and B), respectively, which were not previously reported.

The need to create more refined tissue value standards that can be used for diagnostics is important for horticultural crops. However, due to the limited data available, new methods must be developed. This study provides an improvement in understanding gerbera foliar tissue analysis compared with the critical value approach. This novel method has also been implemented on other crops, such as lettuce (Veazie et al. 2024b) and pentas and achieved similar results in narrowing previously reported sufficiency ranges and determining threshold excessive values that were not previously reported in the literature.

Conclusion

A more refined system for evaluating leaf tissue nutrient concentrations was needed to aid in diagnosing nutritional problems in gerbera. This study's approach combines grower samples with both fertilizer concentration and nutrient deficiency experiments to create interpretation ranges, enabling a robust metadata modeling method of analysis for the SRA. This method provides more defined ranges beyond the sufficiency zone and also identifies samples that were deficient, low, sufficient, high, or excessive. This modeling method will aid in the evaluation and diagnosis of nutritional disorders of gerbera and can be applied to other horticultural species.

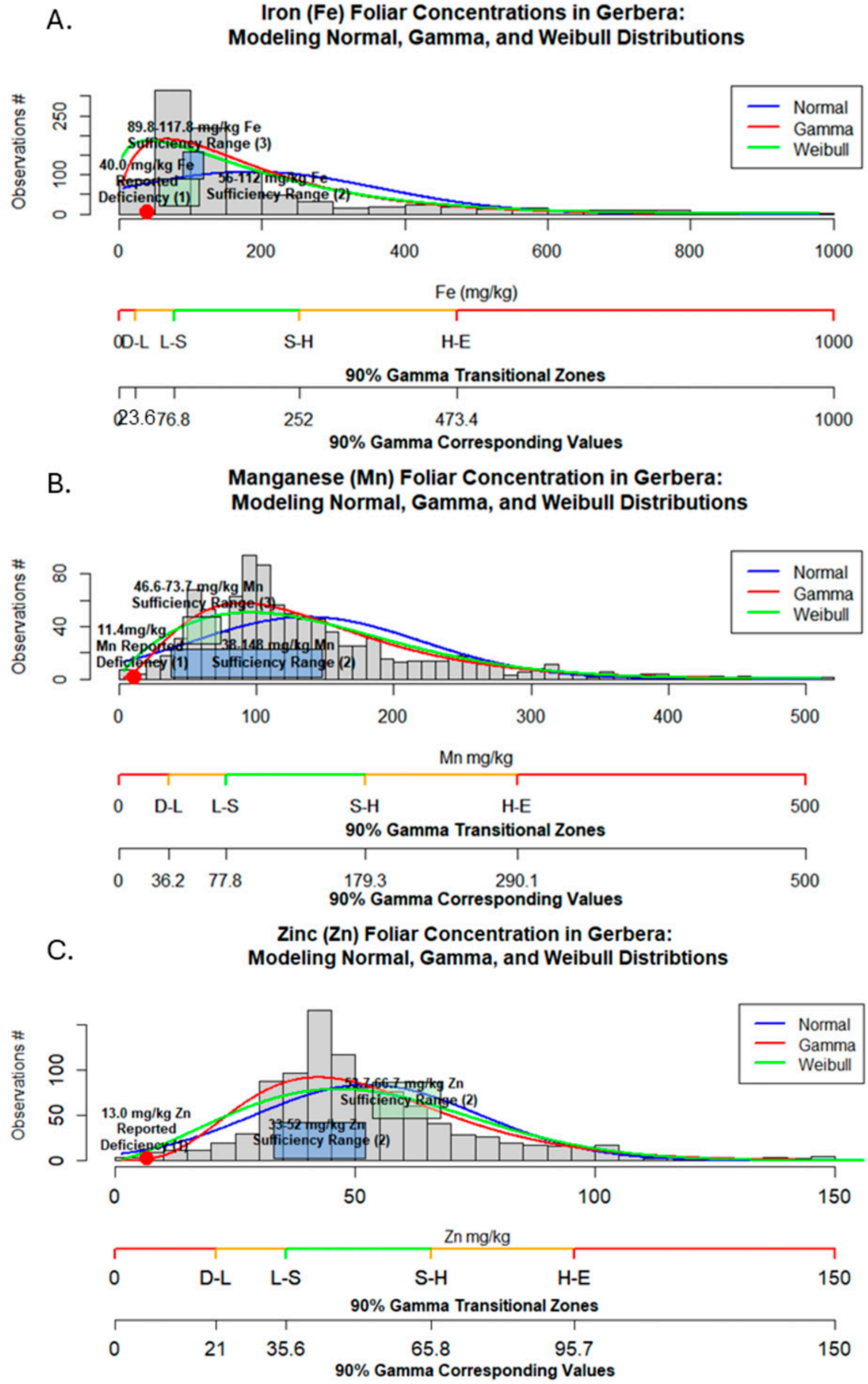

Fig. 4. (**A**) Iron, (**B**) manganese, and (**C**) zinc foliar concentrations of gerbera modeled using normal, gamma, and Weibull distributions. Interpretation ranges include four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 5%, 25%, 75%, and 95% of sample observations, respectively. Comparison ranges: (1) Jeong et al. (2009b), (2) Jeong et al. (2009a), and (3) Bryson and Mills (2015).

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