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RESEARCH ARTICLE

Development of preliminary multielement norms for the Diagnosis and Recommendation Integrated System (DRIS) in sweet potato, *Ipomoea batatas* (L.) Lam., in Cañete Province, Peru

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Abstract

Nutritional balance is a key factor influencing sweet potato productivity, particularly under intensive production systems where multiple nutrient interactions may affect crop performance. Reliable foliar diagnostic approaches are therefore needed to assess these interactions and identify nutritional imbalances associated with yield. This study aimed to develop Diagnosis and Recommendation Integrated System (DRIS) norms and characterize multielement nutritional balance in sweet potato using a yield-linked foliar database from Cañete, Lima, Perú. The database comprised 160 foliar samples collected from commercial fields and experimental plots, each associated with a corresponding yield record and analyzed for 13 elements (N, P, K, Ca, Mg, S, Na, Cl, Cu, Zn, Mn, Fe, and B). Following complementary univariate and multivariate screening, 120 observations were retained and stratified by yield, with the high-yield population used as the reference population for norm development. Of the 156 direct and inverse elemental relationships evaluated, 72 were retained as DRIS norms after normality screening and subsequent selection based on the variance-ratio criterion. The mean DRIS profile of the low-yield population showed pronounced differences in the direction and magnitude of the elemental indices, with Zn showing the largest negative mean index (−69.76) and Ca the largest positive mean index (+55.49). Associations between individual DRIS indices and yield varied in both direction and magnitude. The resulting norms provide a multielement reference framework for characterizing nutritional balance under the production conditions represented by the Cañete dataset. However, the DRIS indices should be interpreted as indicators of relative nutritional imbalance rather than as experimentally validated nutrient requirements. Therefore, the diagnostic accuracy and transferability of these norms should be evaluated using independent datasets and nutrient-response experiments before they are applied to support nutrient-management recommendations.

Keywords: Foliar analysis; Mineral nutrition; Nutrient balance; Nutritional assessment; Nutrient interactions.

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1. Introduction

Ipomoea batatas (L.) Lam. is an important storage-root crop in tropical and subtropical agricultural systems, with a prominent role in food production and diversified farming systems (Tanaka et al., 2017). In Perú, sweet potato production is concentrated mainly in coastal areas; official agricultural information indicates that approximately half of the national production is located in the Lima department and identifies Cañete as its principal production zone (MIDAGRI, 2024). This territorial concentration makes Cañete a particularly relevant production environment for developing nutritional reference information under the conditions represented by commercial and experimental cropping systems in the Peruvian coast.

Mineral nutrition is an important determinant of sweet potato productivity because storage-root formation, yield, and nutrient accumulation respond not only to the supply of individual nutrients but also to the nutritional context in which they are supplied (Zhao et al., 2025). Two-year field experiments have shown that potassium management can alter storage-root number, individual root weight, and final yield, while recent nutrient-omission experiments demonstrated substantial yield reductions when N, P, or K supply was inadequate. Experimental evaluation of combined N and

K supply has further shown that physiological performance, yield, and quality depend on the joint nutritional environment rather than exclusively on a single nutrient considered in isolation (Liu et al., 2023; Shu et al., 2024; Zhao et al., 2025).

This dependence on nutritional context also has implications for crop diagnosis. Approaches based on critical concentrations or nutrient-specific indices remain useful for assessing individual elements, but recent research in sweet potato increasingly shows that the nutritional status of one element can depend on the supply of another (Zhao et al., 2026). For example, critical K dilution relationships have been evaluated under contrasting N conditions, demonstrating that the K requirement associated with maximum yield changes with N supply, while a more recent N/K model was specifically developed to characterize the nitrogen–potassium balance of sweet potato (He et al., 2023; Zhao et al., 2026). These developments reinforce the relevance of diagnostic approaches that consider relationships among nutrients rather than interpreting every element independently. DRIS provides such a complementary framework by comparing bivariate elemental relationships in an evaluated sample with reference relationships derived from a high-yield population and integrating the resulting functions into element-specific indices (Ramakrishna et al., 2009; Walworth & Sumner, 1987). Accordingly, DRIS characterizes the relative position of each element within the multielement system included in the diagnosis rather than relying exclusively on isolated foliar concentrations.

For sweet potato, Ramakrishna et al. (2009) developed a preliminary DRIS model from yield and foliar nutrient data collected in the highlands of Papua New Guinea; however, its diagnostic scope was restricted to N, P, K, and S. Importantly, those authors explicitly identified the expansion of the database and the inclusion of additional macro- and micronutrients as directions for subsequent refinement of the model. Broadening the elemental coverage of DRIS therefore represents a relevant methodological step for characterizing nutritional balance in sweet potato under production environments not represented by that preliminary framework. Nevertheless, expansion of the number of elements and statistical establishment of reference norms should not be equated with validation of diagnostic accuracy. Experimental assessment of DRIS in other crops has shown that diagnostic performance may differ according to the nutrient and nutritional state evaluated, demonstrating that norm development and independent agronomic validation constitute distinct stages of the diagnostic process (Ramakrishna et al., 2009; Villaseñor-Ortiz et al., 2022).

Within this context, an unresolved question is whether a broader multielement DRIS reference system can be established from yield-linked foliar data representative of sweet potato production in Cañete and what relative nutritional patterns can be identified from such a system. Accordingly, this study aimed to develop preliminary DRIS norms for sweet potato in Cañete Province, Perú, using foliar concentrations of 13 elements (N, P, K, Ca, Mg, S, Na, Cl, Cu, Zn, Mn, Fe, and B) and their associated yield data. Multielement nutritional patterns were subsequently characterized using sample-level elemental DRIS indices, mean elemental DRIS profiles, and Pearson correlations among the indices and between each index and yield.

2. Methodology

2.1 Study area

Foliar sampling and yield evaluations used to construct the diagnostic database were conducted during 2022 and 2023 in experimental plots with different fertilization rates and in commercial sweet potato fields located in six districts of Cañete Province, Lima, Perú: San Luis (13°03′04″S, 76°25′50″W), Cerro Azul (13°01′30″S, 76°28′45″W), San Vicente de Cañete (13°04′40″S, 76°23′15″W), Imperial (13°03′40″S, 76°21′11″W), Quilmaná (12°56′46″S, 76°26′02″W), and Nuevo Imperial (13°04′35″S, 76°19′04″W). According to the Thornthwaite & Mather (1955) classification, the climate of the study area corresponds to the E(d)B′ type, characterized by arid conditions, water deficit, and moderate thermal efficiency.

2.2 Foliar sampling, sample preparation, and laboratory analysis

Foliar samples were collected between 45 and 50 days after planting following a zigzag sampling pattern. A 5-m perimeter around each plot was excluded from sampling to avoid collecting material from areas considered unrepresentative of the evaluated field. Each composite foliar sample comprised 80 subsamples obtained from the main stem of sweet potato plants. Leaves were counted downward from the apical leaf, and the third or fourth fully expanded leaf was selected for analysis. A total of 160 foliar samples were obtained following this procedure.

After collection, the samples were washed twice with tap water and subsequently rinsed twice with distilled water. The plant material was dried in a forced-air oven (LadTech-LIB060M-South Korea) at 65 °C until constant weight and then finely ground prior to chemical analysis (Pereira et al., 2013). Foliar analyses were performed at the laboratories of the Instituto de Educación Superior Valle Grande (San Vicente de Cañete, Cañete, Lima, Perú). Total nitrogen (N) was determined by the Dumas combustion method using a LECO nitrogen analyzer, whereas atomic absorption measurements were performed using a PinAAcle 500 flame atomic absorption spectrometer (PerkinElmer). The elemental analysis included N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), sodium (Na), chlorine (Cl), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), and boron (B).

The resulting foliar analytical data were associated with their corresponding yield records and compiled in Microsoft Excel, forming the database used for data screening and subsequent development of the DRIS norms.

2.3 Data screening and yield-based stratification

Prior to the establishment of the DRIS norms, the database was screened for atypical observations using complementary univariate and multivariate procedures. Univariate screening was performed independently for each analyzed element using the interquartile range (IQR). The IQR and its corresponding lower and upper limits were calculated as:

$$IQR = Q_3 - Q_1$$
$$Lower\ limit = Q_1 - 1.5(IQR)$$
$$Upper\ limit = Q_3 + 1.5(IQR)$$

where Q_1 and Q_3 represent the 25th and 75th percentiles, respectively. Values below the lower limit or above the upper limit were identified as univariate outliers. This procedure was applied to the original elemental concentration values using Microsoft Excel.

Multivariate screening complemented the IQR procedure and was performed using generalized Mahalanobis distance after transformation of the foliar elemental data by the centered log-ratio (clr) method, considering their compositional nature (Escobedo & Salas, 2008). Observations with Mahalanobis distances exceeding the 95th percentile of the chi-square distribution were identified as multivariate outliers.

The IQR and Mahalanobis procedures were used as complementary screening criteria, and observations identified as outliers by either procedure were excluded from the diagnostic database (Conceição et al., 2024; de Souza et al., 2023). The resulting screened dataset was subsequently used to define the yield subpopulations required for development of the DRIS norms. Yield-based stratification was performed following Pereira et al. (2013). The threshold separating the two subpopulations was established as the overall mean yield plus two-thirds of its standard deviation. Observations with yields above this threshold constituted the high-yield or reference population (PAR), whereas the remaining observations constituted the low-yield population (PBR). PAR was used as the reference population for establishing the DRIS norms.

2.4 Development of DRIS norms and calculation of nutritional indices

DRIS norms were developed from elemental relationships calculated separately for the high-yield reference population (PAR) and the low-yield population (PBR). Because elemental concentrations were originally reported using different units, all concentrations were expressed on a common mass basis before elemental ratios were calculated, thereby preventing differences in measurement scale from affecting the resulting relationships. Considering the 13 elements analyzed, 156 direct and inverse ratios were generated, and consequently 78 unique elemental pairs. For each relationship, the mean, standard deviation, variance, and coefficient of variation (CV) were calculated separately for PAR and PBR.

The distribution of each direct and inverse elemental relationship within PAR was evaluated using the Shapiro–Wilk test. Relationships for which the null hypothesis of normality was not rejected ($p > 0.05$) were retained as candidates for subsequent norm selection (Agbangba et al., 2024; Cavalcanti et al., 2021; Shehu et al., 2023). Among the 111 relationships retained after normality screening, 78 corresponded to 39 elemental pairs for which both the direct and inverse orientations satisfied the normality criterion. For each of these pairs, the orientation with the higher variance ratio was retained. The remaining 33 relationships corresponded to elemental pairs for which only one orientation satisfied the normality criterion and were therefore retained directly. This procedure resulted in 72 relationships used to establish the DRIS reference norms.

For each candidate relationship, the variance ratio between PBR and PAR was calculated as: $F = \frac{S^2_{PBR}}{S^2_{PAR}}$ where S^2_{PBR} and S^2_{PAR} represent the variances of the corresponding elemental relationship in the low-yield and reference populations, respectively (Beaufils & Sumner, 1977; Gimenez et al., 2021; Parent & Dafir, 1992; Walworth & Sumner, 1987). For elemental pairs in which both orientations had passed the normality screening, the orientation with the higher F-value was selected. The mean of each selected relationship in PAR constituted its DRIS reference norm. For a selected relationship, the reference norm was denoted as $N_{A/B}$, whereas

$SD_{A/B}$ and $CV_{A/B}$ represented its standard deviation and coefficient of variation, respectively, in PAR. The coefficient of variation was calculated as $CV_{A/B} = 100(SD_{A/B}$ / $N_{A/B}$ and was expressed as a percentage. These parameters were subsequently used to calculate the DRIS functions for individual observations.

2.5. DRIS functions and elemental indices

For each observation, the selected elemental relationships were converted into DRIS functions according to their deviation from the corresponding PAR-derived reference norm. For an observed relationship $\frac{A}{B}$, the DRIS function was calculated as:

$$f\left(\frac{A}{B}\right) = \{\left(\frac{\frac{A}{B}}{\frac{a}{b}} - 1\right)\frac{1000}{CV}, si\ \frac{A}{B} \geq \frac{a}{b}\ \left(1 - \frac{\frac{a}{b}}{\frac{A}{B}}\right)\frac{1000}{CV}, si\ \frac{A}{B} < \frac{a}{b}$$

When the observed relationship was equal to the reference norm, $\frac{f\,(A}{B)} = 0$. Here, $\frac{A}{B}$ is the elemental ratio observed in an individual sample, $N_{A/B}$ is the mean value of that relationship in the high-yield reference population (PAR), and $CV_{A/B}$ is its coefficient of variation in PAR, expressed as a percentage. The scaling factor 1000 was used to express the magnitude of the deviation according to the conventional DRIS formulation.

The PAR-derived reference norms were applied to each observation in PBR to calculate sample-level DRIS indices for the 13 elements. For element A in observation i, the elemental DRIS index was calculated as:

$$I_A = \frac{\Sigma f\left(\frac{A}{B}\right) - \Sigma f(\frac{B}{A})}{n + m}$$

where $\Sigma f\left(\left(\frac{A}{B}\right)\right)$ is the sum of the functions in which element appears in the numerator, $\Sigma f\left(\left(\frac{B}{A}\right)\right)$ is the sum of the functions in which the element A appears in the denominator, and n and m are the corresponding numbers of relationships. Positive and negative indices indicate relative positions above and below the multielement reference balance, respectively; they do not by themselves represent absolute nutrient excess or deficiency.

The PAR-derived reference norms were then applied to each observation in PBR to calculate sample-level DRIS indices for the 13 elements. To characterize the nutritional pattern of the low-yield population, the resulting indices were averaged across PBR observations for each element, yielding the mean elemental DRIS profile presented in Figure 1.

The overall magnitude of imbalance in this mean PBR profile was summarized using the mean nutritional balance index (IBNm), calculated as:

$$IBN_m = \frac{\sum|element|}{n}$$

where I_i is the mean DRIS index of element across PBR observations and is the total number of elements included in the profile. Accordingly, the IBNm reported for Figure 2 represents the mean absolute magnitude of the 13 mean elemental DRIS indices and should not be interpreted as the arithmetic mean of the sample-level IBNm values.

For graphical presentation of the mean PBR profile, the mean elemental DRIS indices in Figure 2 were displayed on a signed logarithmic scale to reduce visual compression of indices with small absolute values caused by the wide range of index magnitudes. This transformation was used solely for graphical display; the sign, ranking, and original DRIS index values were preserved, and the untransformed values are reported as numerical labels. The overall analytical workflow, from database screening and yield-based stratification to DRIS norm development, calculation of sample-level indices, and characterization of the low-yield population, is summarized in Figure 1.

2.6 Correlation analyses

Using the sample-level elemental DRIS indices calculated for each observation in PBR from the PAR-derived reference norms, Pearson correlation coefficients were calculated among the 13 elemental indices and between each index and its corresponding sweet potato yield. The coefficients were used descriptively to characterize the direction and magnitude of association patterns within the low-yield population; no inferential significance testing was applied. Because the elemental DRIS indices are derived from overlapping bivariate functions, correlations among indices were interpreted as patterns of covariation within the DRIS system rather than as direct evidence of physiological interactions among nutrients.

3. Results and discussion

3.1 Development and statistical characterization of the DRIS norms

Application of the univariate and multivariate screening procedures excluded 40 observations from the initial database of 160 foliar samples. The IQR procedure identified 39 observations with at least one elemental concentration outside the established limits, whereas Mahalanobis distance applied to clr-transformed data detected one additional multivariate outlier. The screened database therefore comprised 120 observations for subsequent yield stratification and DRIS norm development.

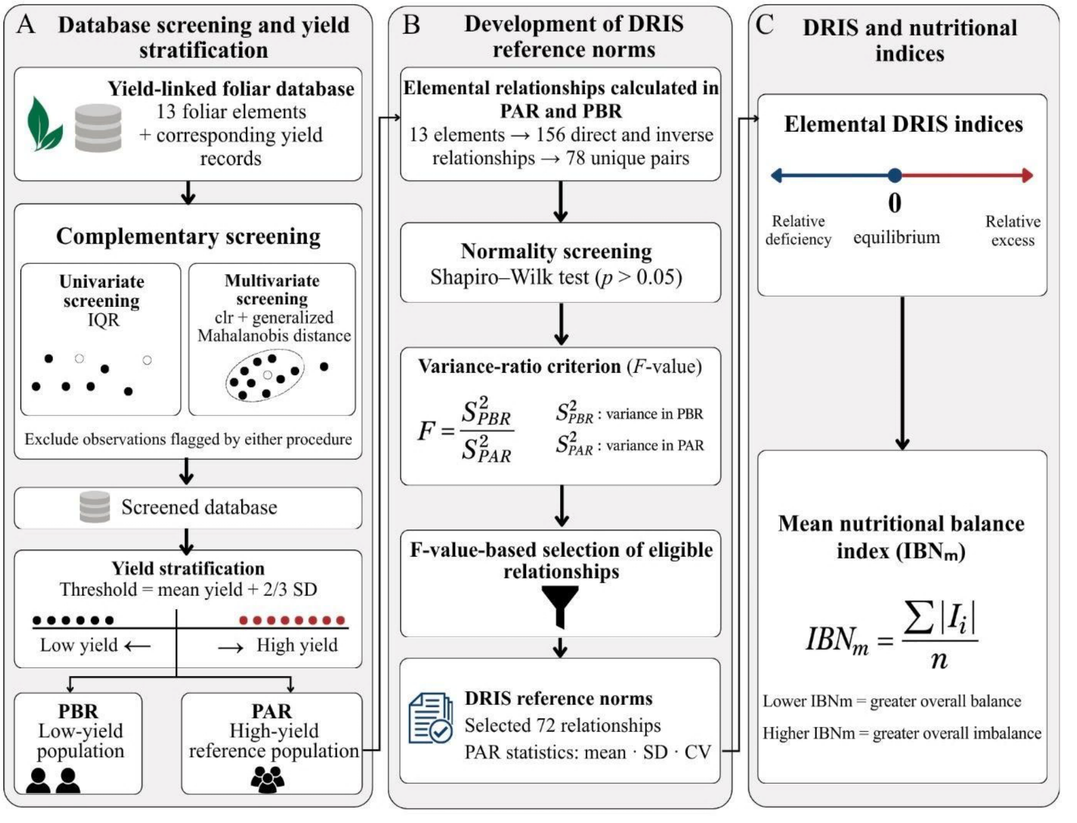

Figure 1. Analytical workflow used to develop multielement DRIS norms and characterize nutritional patterns in sweet potato. The workflow includes foliar sampling and elemental analysis, complementary database screening, yield-based stratification into high-yield reference (PAR) and low-yield (PBR) populations, selection of DRIS reference relationships, calculation of sample-level DRIS indices, and complementary correlation.

The yield threshold separating the high-yield reference population (PAR) from the low-yield population (PBR) was 24.02 t ha^{-1}. Yield ranged from 24.02 to 30.90 t ha^{-1} in PAR and from 12.80 to 23.70 t ha^{-1} in PBR. Under the stratification criterion defined in Section 2.3, PAR constituted the high-yield fraction used to establish the reference elemental relationships. This population should therefore be interpreted as a productive reference subset of the screened database rather than as a physiologically optimal nutritional condition.

The 13 elements analyzed generated 156 direct and inverse ratios and, consequently, 78 unique elemental pairs. The Shapiro–Wilk criterion was satisfied by 111 relationships (71.15%; $p > 0.05$), whereas 45 relationships (28.85%) were excluded from the subsequent selection stage. Variance ratios between PBR and PAR were then calculated for the retained relationships, and those with the highest F-values were selected according to the procedure described in Section 2.4, resulting in 72 DRIS reference relationships (Table 1). Normality and variance ratio served different purposes in this process: the former screened candidate relationships according to their distribution, whereas the latter quantified the contrast in variance between the low- and high-yield populations. Variance-ratio approaches based on contrasting productivity populations have likewise been used for DRIS norm selection in other crops (Reis Junior & Monnerat, 2003; Teixeira et al., 2019). The statistical properties used to select these relationships should not, however, be interpreted as evidence of diagnostic accuracy. A high F-value identifies a greater variance contrast between PBR and PAR, but does not demonstrate that the corresponding norm correctly identifies an agronomically limiting nutrient. This distinction has been demonstrated experimentally in banana, where DRIS diagnoses evaluated against crop responses to N and K fertilization differed in accuracy according to both the nutrient and nutritional status considered (Villaseñor-Ortiz et al., 2022). Statistical norm construction and agronomic validation therefore represent distinct stages of the diagnostic process.

The 72 selected relationships encompassed macronutrients, micronutrients, Na, and Cl, thereby broadening the elemental scope of DRIS for sweet potato. The preliminary sweet potato model developed by Ramakrishna et al. (2009) was restricted to N, P, K, and S, whereas the present reference system integrates these nutrients with Ca, Mg, Na, Cl, Cu, Zn, Mn, Fe, and B. The resulting norm set therefore expands the sweet potato DRIS framework from four nutrients to a 13-element nutritional matrix under the production conditions represented by the Cañete database. This expanded elemental coverage permits relative relationships involving nutrients absent from the preliminary model to be incorporated into the diagnostic system, but does not by itself imply greater diagnostic accuracy.

Relative dispersion differed substantially among the selected reference relationships. Within PAR, CV values ranged from 5.1% for Zn/N to 32.6% for Fe/S. Zn/N (5.1%), Zn/Cu (7.4%), and Cu/N (7.4%) showed the lowest relative dispersion, whereas Fe/S (32.6%), B/Cl (31.5%), and Mn/Fe (30.4%) showed the highest. Comparison of the two yield populations revealed an even broader pattern: CV was higher in PBR than in PAR for 71 of the 72 selected relationships (98.6%), with B/N being the only exception (22.2% in PAR and 21.4% in PBR). Thus, relative dispersion of the selected elemental relationships was generally greater in the low-yield population.

The predominance of higher CV values in PBR is consistent with the statistical rationale of variance-ratio selection, which favors relationships exhibiting greater variance contrast between low- and high-yield populations (Reis Junior & Monnerat, 2003; Teixeira et al., 2019). Nevertheless, this pattern describes the statistical structure of the two populations and does not demonstrate that greater variability in elemental relationships caused lower yield. Similarly, the low CV values observed for Zn/N, Zn/Cu, and Cu/N indicate comparatively concentrated reference distributions within PAR, but do not establish tighter physiological regulation, greater biological importance, or superior diagnostic performance.

Accordingly, the statistics reported in Table 1 characterize the construction and dispersion of the reference relationships rather than their agronomic validity. Whether these norms correctly identify nutrient limitations must be determined against independent crop responses. The resulting norms should therefore be regarded as reference relationships specific to the population structure and production conditions represented by the Cañete database. Their diagnostic performance and transferability to other cultivars, soils, climatic environments, or management systems require independent evaluation before they are used to support nutrient-management recommendations.

3.2 DRIS indices and nutritional imbalance

The mean DRIS profile of the low-yield population (PBR), calculated from sample-level indices using the PAR-derived reference norms, showed pronounced differences in the direction and magnitude of the elemental indices (Figure 2). Zn exhibited the largest negative mean index (−69.76), whereas Ca showed the largest positive mean index (+55.49). S (+20.10) and P (+11.17) also showed positive mean indices, while Cu (−12.63) and Fe (−8.69) were negative. The remaining elements were comparatively closer to zero: Cl (+4.06), Mn (+1.72), Na (+1.09), K (+0.91), N (+0.81), Mg (+0.10), and B (+0.03). Within the DRIS framework, these values represent the relative position of each element with respect to the multielement balance defined by the PAR-derived norms. Zn therefore occupied the most negative relative position in PBR, whereas Ca occupied the most positive position. The two extremes should be interpreted jointly as components of the same multielement balance rather than as independent demonstrations of absolute Zn deficiency and Ca excess. Likewise, indices closer to zero indicate greater proximity to the relative reference balance, but do not establish physiological sufficiency or optimal tissue concentrations. The magnitude of the Zn index clearly distinguished it from the other negative indices. However, IZn = −69.76 represents the strongest negative relative imbalance signal in the mean PBR profile and does not demonstrate that Zn was the principal cause of low yield or that Zn fertilization would increase storage-root production. Similarly, the positive Ca and S indices indicate relative abundance within the DRIS system but do not constitute evidence of toxicity or excessive fertilizer application. Experimental validation of DRIS has shown that diagnostic accuracy can vary according to both the nutrient and nutritional state when predictions are tested against independent nutrient-response experiments (Villaseñor-Ortiz et al., 2022). The present indices should therefore be regarded as diagnostic signals requiring agronomic validation rather than as direct fertilizer recommendations.

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Table 1
Selected elemental relationships and reference statistics used as DRIS norms for sweet potato in Cañete, Perú

R	High yield				Low yield				R	High yield				Low yield			
	X	S	CV %	S^2_A	X	S	CV %	S^2_B		X	S	CV %	S^2_A	X	S	CV %	S^2_B
N/K	1.78	0.24	13.6	0.06	2.13	0.82	38.5	0.67	Cu/P	0.01	0.00	16.0	0.00	0.69	0.15	22.4	0.02
N/Na	5.23	0.83	15.8	0.69	6.22	2.44	39.2	5.95	Cu/K	0.00	0.00	17.4	0.00	0.09	0.04	41.0	0.00
N/Cl	2.25	0.44	19.5	0.19	3.59	2.22	61.7	4.91	Cu/Ca	0.00	0.00	16.4	0.00	0.16	0.04	22.6	0.00
P/N	0.07	0.01	15.7	0.00	0.07	0.01	19.6	0.00	Cu/Mg	0.00	0.00	19.5	0.00	0.38	0.09	24.7	0.01
P/K	0.13	0.02	18.0	0.00	0.14	0.04	29.8	0.00	Cu/Na	0.00	0.00	19.5	0.00	0.27	0.09	33.2	0.01
P/Ca	0.21	0.04	21.4	0.00	0.37	0.10	26.8	0.01	Cu/Cl	0.00	0.00	21.7	0.00	0.15	0.08	50.0	0.01
P/Mg	0.49	0.10	20.7	0.01	0.16	0.04	25.4	0.00	Cu/Fe	0.06	0.01	20.2	0.00	0.14	0.05	38.9	0.00
P/S	1.22	0.21	17.3	0.04	1.41	0.34	24.4	0.12	Zn/N	0.00	0.00	5.1	0.00	5.67	0.68	12.0	0.46
P/Na	0.39	0.10	24.9	0.01	0.41	0.16	39.2	0.03	Zn/K	0.00	0.00	13.1	0.00	0.12	0.05	41.4	0.00
P/Cl	0.17	0.04	26.4	0.00	0.23	0.13	55.1	0.02	Zn/Mg	0.00	0.00	20.1	0.00	0.48	0.12	24.0	0.01
P/Zn	122.38	20.55	16.8	422.16	1.19	0.26	21.9	0.07	Zn/Na	0.00	0.00	16.5	0.00	0.35	0.13	36.1	0.02
P/Fe	9.04	2.64	29.2	6.98	0.21	0.09	44.1	0.01	Zn/Cl	0.00	0.00	17.6	0.00	0.20	0.11	56.4	0.01
K/S	9.52	2.33	24.4	5.41	11.06	3.60	32.5	12.92	Zn/Cu	1.27	0.09	7.4	0.01	1.30	0.19	14.9	0.04
K/Na	2.98	0.53	17.9	0.28	3.33	1.80	54.1	3.24	Zn/Fe	0.07	0.01	18.3	0.00	0.18	0.08	45.2	0.01
K/Cl	1.28	0.27	21.1	0.07	1.82	1.22	67.1	1.50	Zn/B	0.30	0.07	25.0	0.01	0.31	0.08	27.4	0.01
Ca/N	0.37	0.05	14.4	0.00	5.60	1.55	27.7	2.41	Mn/N	0.00	0.00	18.2	0.00	0.30	0.08	28.2	0.01
Ca/K	0.66	0.12	17.8	0.01	2.92	1.16	39.6	1.34	Mn/P	0.06	0.01	17.4	0.00	4.63	1.52	32.8	2.31
Ca/Na	1.91	0.25	12.9	0.06	1.80	0.89	49.3	0.79	Mn/K	0.01	0.00	22.2	0.00	0.62	0.22	35.6	0.05
Ca/Cl	0.82	0.14	17.1	0.02	1.04	0.82	79.1	0.67	Mn/Mg	0.03	0.00	15.7	0.00	2.45	0.51	21.0	0.26
Ca/Zn	607.43	88.16	14.5	7771.61	5.24	1.48	28.2	2.18	Mn/Cl	0.01	0.00	27.5	0.00	0.96	0.43	44.4	0.18
Mg/N	0.16	0.03	18.3	0.00	2.35	0.53	22.7	0.29	Mn/Cu	8.61	1.43	16.6	2.04	6.80	1.74	25.6	3.02
Mg/K	0.28	0.06	22.3	0.00	1.21	0.40	33.3	0.16	Mn/Zn	6.81	1.36	19.9	1.84	5.32	1.47	27.6	2.15
Mg/Ca	0.42	0.05	10.8	0.00	0.43	0.06	15.2	0.00	Mn/Fe	0.50	0.15	30.4	0.02	0.87	0.29	33.4	0.08
Mg/Na	0.81	0.14	16.9	0.02	0.74	0.24	33.2	0.06	Fe/N	0.01	0.00	20.7	0.00	0.39	0.18	45.5	0.03
Mg/Cl	0.35	0.07	21.5	0.01	0.42	0.25	60.3	0.06	Fe/K	0.02	0.00	26.9	0.00	0.79	0.43	54.7	0.19
S/N	0.06	0.01	17.8	0.00	0.05	0.01	21.7	0.00	Fe/Ca	0.02	0.01	23.2	0.00	1.31	0.51	38.8	0.26
S/Ca	0.17	0.03	18.1	0.00	0.17	0.04	25.5	0.00	Fe/S	0.15	0.05	32.6	0.00	7.90	2.99	37.9	8.95
S/Mg	0.40	0.07	17.8	0.01	0.41	0.12	28.4	0.01	B/N	0.00	0.00	22.2	0.00	0.19	0.04	21.4	0.00
S/Na	0.33	0.08	23.7	0.01	0.30	0.12	41.5	0.02	B/P	0.03	0.00	16.7	0.00	2.99	0.91	30.5	0.83
S/Cl	0.14	0.04	26.2	0.00	0.17	0.10	57.8	0.01	B/K	0.00	0.00	26.3	0.00	0.41	0.19	45.6	0.03
S/Cu	129.07	20.62	16.0	425.02	1.11	0.24	21.9	0.06	B/Ca	0.01	0.00	19.3	0.00	0.69	0.22	32.3	0.05
S/Zn	102.20	19.72	19.3	388.80	0.87	0.21	24.5	0.05	B/Mg	0.01	0.00	18.3	0.00	1.63	0.52	31.7	0.27
Na/Cl	0.43	0.06	14.1	0.00	0.59	0.31	53.3	0.10	B/S	0.03	0.00	12.8	0.00	4.09	1.07	26.3	1.16
Na/Fe	23.24	4.62	19.9	21.38	0.55	0.31	55.4	0.09	B/Na	0.01	0.00	26.8	0.00	1.20	0.62	51.6	0.39
Cl/Fe	54.16	9.65	17.8	93.15	0.98	0.32	32.2	0.10	B/Cl	0.00	0.00	31.5	0.00	0.71	0.50	70.1	0.25
Cu/N	0.00	0.00	7.4	0.00	0.04	0.01	14.3	0.00	B/Mn	0.52	0.07	14.3	0.01	0.71	0.38	52.6	0.14

PAR, high-yield reference population; PBR, low-yield population; x̄, mean elemental ratio; SD, standard deviation; CV, coefficient of variation; S^2, variance. Relationships were selected according to the variance-ratio criterion ($F = S^2PBR/S^2PAR$) described in Section 2.4.

Experimental validation of DRIS has shown that diagnostic accuracy can vary according to both the nutrient and nutritional state when predictions are tested against independent nutrient-response experiments (Villaseñor-Ortiz et al., 2022). The present indices should therefore be regarded as diagnostic signals requiring agronomic validation rather than as direct fertilizer recommendations.

The marked Zn response in the present profile cannot be directly compared with the preliminary sweet potato DRIS model of Ramakrishna et al. (2009), because that model was restricted to N, P, K, and S. The current system incorporates Ca, Mg, Na, Cl, Cu, Zn, Mn, Fe, and B in addition to those four nutrients, allowing relative imbalances involving a substantially broader set of elements to be characterized. The occurrence of a large negative Zn index in PBR should therefore be interpreted as information newly accessible through the expanded 13-element framework rather than as confirmation of a Zn limitation previously reported by the sweet potato DRIS model.

The IBNm of 14.35 summarizes the mean absolute magnitude of the 13 elemental indices comprising the PBR profile. It therefore describes the overall displacement of this mean multielement profile from the relative balance position represented by zero, without identifying which elements account for that displacement. Zn and Ca contributed the largest absolute deviations, followed by S. These were also the only three elements whose absolute mean index magnitudes exceeded the numerical value of IBNm. This comparison is descriptive and does not establish validated deficiency or excess thresholds.

Accordingly, the horizontal references at +IBNm and −IBNm in Figure 2 are included solely as symmetric graphical aids for comparing elemental index magnitudes with the mean absolute imbalance of the PBR profile. They should not be interpreted as critical limits, sufficiency boundaries, or experimentally validated diagnostic thresholds.

3.3 Associations among DRIS indices and yield in the low-yield population

Within PBR, Pearson correlation coefficients between sample-level DRIS indices and yield varied in direction and magnitude (Figure 3). The P index showed the largest negative association with yield (r = −0.55), followed by B (r = −0.44) and Cl (r = −0.32), whereas Fe showed the largest positive association (r = +0.41), followed by Cu (r = +0.29). The remaining index–yield coefficients were lower in absolute magnitude: N (−0.05), K (−0.11), Ca (+0.07), Mg (+0.01), S (−0.20), Na (−0.16), Zn (+0.07), and Mn (−0.17). Thus, P, B, Fe, and Cl showed the largest absolute associations with yield within the low-yield population, while most other coefficients did not exceed |r| = 0.29. These coefficients describe association patterns within PBR and should not be interpreted as general relationships across the complete screened population. Because PBR was defined using yield, the analysis was restricted to observations ranging from 12.80 to 23.70 t ha^{-1}, and the resulting coefficients therefore characterize covariation within this low-yield domain. Moreover, no inferential significance testing was applied; consequently, the coefficients are interpreted according to their direction and magnitude rather than as statistically significant relationships.

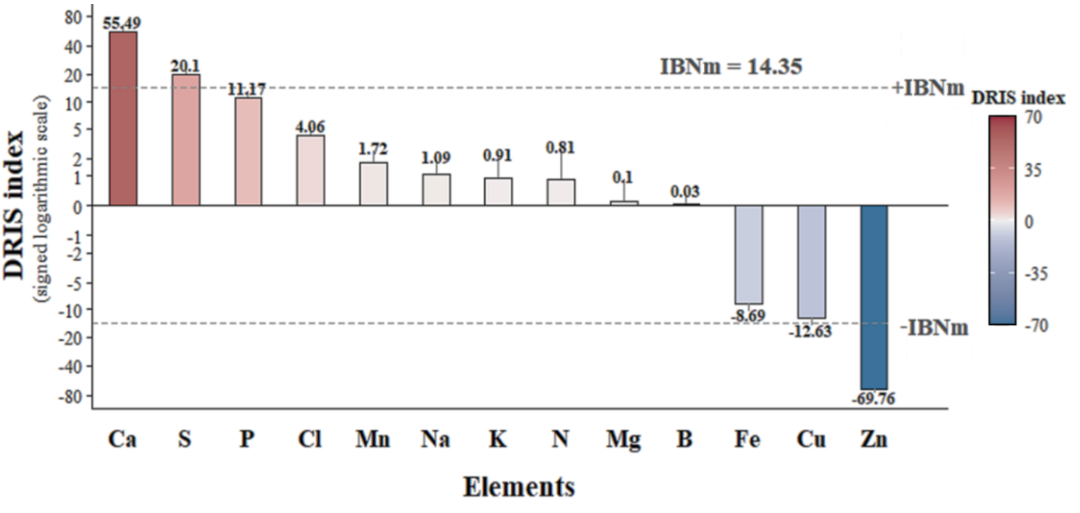

Figure 2. Mean elemental DRIS profile of the low-yield sweet potato population (PBR). Bars represent mean elemental DRIS indices calculated across PBR observations using reference norms derived from the high-yield population (PAR). Positive and negative values indicate relative positions above and below the multielement reference balance, respectively, and should not be interpreted as independently validated excess or deficiency thresholds. Bar heights are displayed on a signed logarithmic scale for graphical visualization, while numerical labels indicate the original untransformed mean DRIS index values.

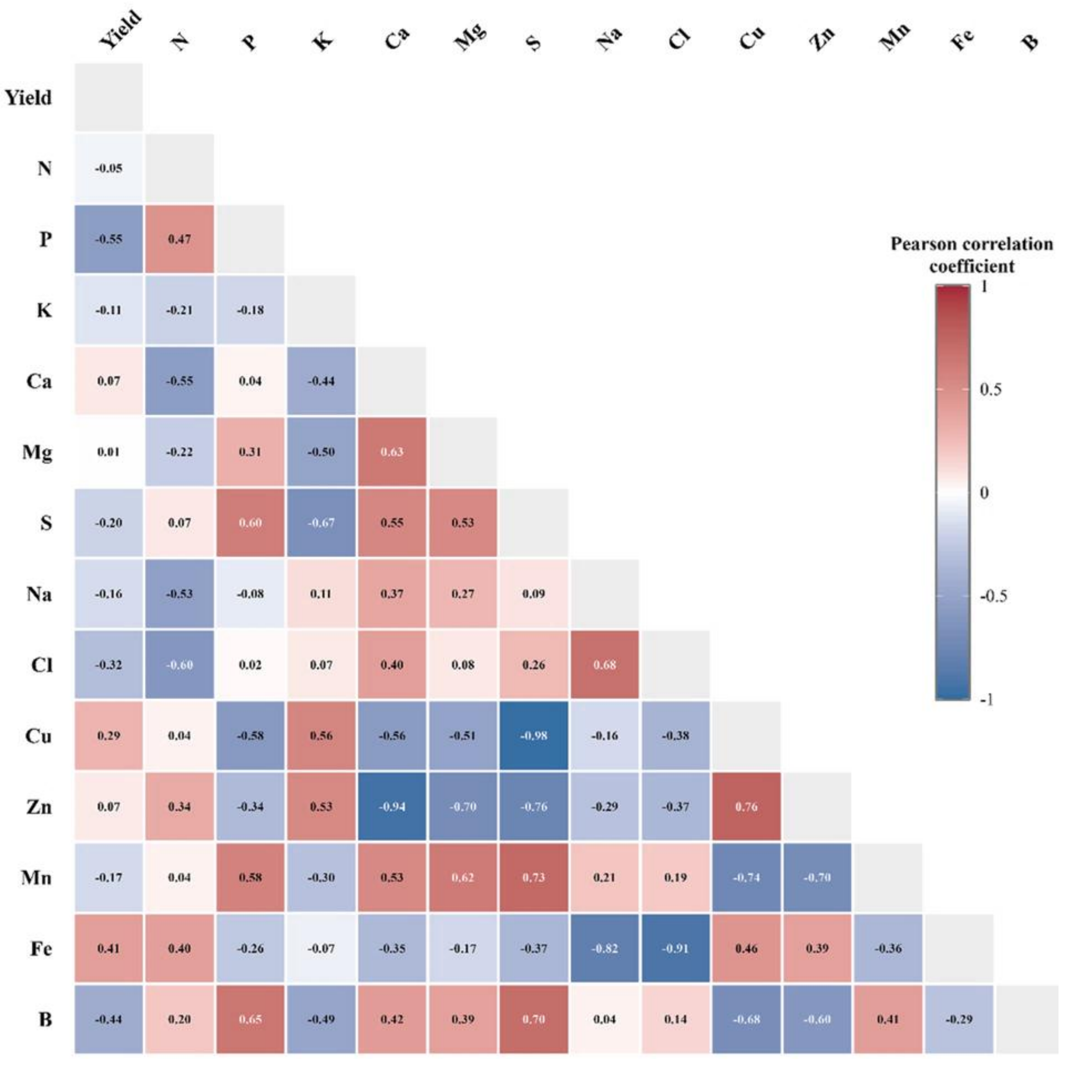

Figure 3. Pearson correlation matrix of sample-level elemental DRIS indices and yield within the low-yield sweet potato population (PBR; n = 100). Red and blue cells denote positive and negative correlations, respectively, and color intensity represents the magnitude of Pearson's r. Coefficients are presented descriptively; no inferential significance testing was applied.

The negative P–yield association requires particular caution. A more positive P DRIS index was associated with lower yield within PBR (r = −0.55), but the variable represented in Figure 3 is a relative DRIS index rather than foliar P concentration, soil P availability, or P fertilizer supply. Accordingly, this coefficient does not indicate that increasing P availability would reduce sweet potato yield. Experimental evidence illustrates this distinction: in a recent nutrient-omission experiment, P omission substantially reduced storage-root yield relative to complete NPK fertilization, demonstrating that crop response to P supply and the association between a relative P index and yield represent fundamentally different types of evidence (Zhao et al., 2025).

Several correlations among DRIS indices were stronger in magnitude than the largest association observed between an individual DRIS index and yield. The strongest negative correlations were S–Cu (r = −0.98), Ca–Zn (r = −0.94), Cl–Fe (r = −0.91), Na–Fe (r = −0.82), S–Zn (r = −0.76), Cu–Mn (r = −0.74), Mg–Zn (r = −0.70), and Zn–Mn (r = −0.70). The strongest positive correlations were Cu–Zn (r = +0.76), S–Mn (r = +0.73), S–B (r = +0.70), and Na–Cl (r = +0.68). Positive correlations of comparable magnitude were also observed for P–B (r = +0.65), Ca–Mg (r = +0.63), Mg–Mn (r = +0.62), and P–S (r = +0.60).

The direction and magnitude of the correlations were not consistent across nutritionally related elements. For instance, Ca and Mg were positively correlated (r = +0.63), whereas K was negatively correlated with both Ca (r = −0.44) and Mg (r = −0.50), as well as with S (r = −0.67). Similarly, the relationships among Zn, Mn, and Fe did not follow a uniform pattern: Zn–Mn (r = −0.70) and Mn–Fe (r =

−0.36) were negative, whereas Zn–Fe showed a weaker positive correlation (r = +0.39). These contrasting patterns indicate substantial interdependence among DRIS indices and should therefore be interpreted cautiously. Because the indices are mathematically constructed from shared nutrient ratios, these correlations do not necessarily represent direct physiological interactions or distinct nutritional groupings.

Interpretation of these index–index correlations must account for the mathematical structure of DRIS. Each elemental index integrates several bivariate functions, and individual elements participate in multiple shared relationships. Consequently, the resulting indices are mathematically interdependent, and pairwise correlations among them contain a structural component arising from the DRIS calculation itself. Interdependence among nutrient indices has previously been recognized as an inherent issue in DRIS calculations (Bataglia et al., 2004). The positive Na–Cl coefficient (r = +0.68) similarly indicates coordinated variation between the two DRIS indices within PBR but does not establish a salinity effect. Attribution of this association to salinity would require direct characterization of the saline environment or crop exposure, such as soil or irrigation-water electrical conductivity or related salinity variables, which were not included in the present analytical framework. The Na–Cl relationship is therefore interpreted only as a covariation pattern within the DRIS matrix.

Therefore, even coefficients of very high magnitude, such as S–Cu (−0.98) or Ca–Zn (−0.94), cannot independently demonstrate physiological antagonism, synergism, competition for uptake, or shared transport mechanisms. They should instead be interpreted as patterns of covariation among derived nutritional indices.

Finally, the associations between DRIS indices and yield should be regarded as exploratory internal relationships rather than as validation of the diagnostic accuracy of the norms. Yield was used to define PAR and PBR, and information from both populations contributed to the statistical selection of the reference relationships through the PBR/PAR variance-ratio criterion. Consequently, Figure 3 does not provide an independent test of whether a DRIS diagnosis correctly predicts crop response to nutrient supply. Experimental DRIS validation requires an external agronomic response; for example, Villaseñor-Ortiz et al. (2022) evaluated diagnoses against independent N and K fertilization responses and showed that diagnostic accuracy varied with both nutrient and nutritional status. The correlations reported here should therefore be used to characterize the internal structure of the PBR nutritional profile and to generate hypotheses for subsequent validation, rather than as evidence for causal nutrient–yield relationships or fertilizer recommendations.

4. Conclusions

A set of 72 selected DRIS reference relationships integrating 13 elements (N, P, K, Ca, Mg, S, Na, Cl, Cu, Zn, Mn, Fe, and B) was established for sweet potato under the production conditions represented by the Cañete dataset. The resulting DRIS indices indicated a multielement nutritional imbalance, with Zn showing the strongest negative relative deviation and Ca the largest positive relative deviation. The mean nutritional balance index (IBNm = 14.35) summarized the mean absolute magnitude of the elemental DRIS indices. Exploratory correlations between individual DRIS indices and yield varied in both direction and magnitude and should not be interpreted as independent validation of the proposed norms. Overall, the resulting 13-element norm set provides a broader framework for DRIS-based nutritional assessment under the conditions represented by the Cañete dataset. However, these indices should be interpreted as indicators of relative nutritional imbalance rather than as evidence of absolute nutrient deficiency, excess, or experimentally validated nutrient requirements. Independent datasets and nutrient-response experiments are therefore needed to assess the diagnostic accuracy, robustness, and transferability of these norms before they are used to support nutrient-management recommendations.

Author contributions

R. A. Cortez-Lázaro, **J. W. Mendoza-Cortez**: Conceptualization, Investigation, Methodology, Formal analysis; Data curation; Writing - original draft; Funding acquisition. **S. J. García-Bendezú, A. V. Casas-Díaz, A. A. Cortez-Lázaro, R. Coaquira-Incacari**: Formal analysis, Validation, Investigation; Data Curation, Writing - review and editing.

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