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Original Article

Assessment of Sugarcane Nutritional Imbalances in Burundi's Sosumo Industrial Plantations Using the CND Diagnostic Approach

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The present study evaluated the nutritional status of industrial sugarcane (*Saccharum officinarum* L.) plantations managed by SOSUMO in Burundi using the Compositional Nutrient Diagnosis (CND) method via the CND^{r2} index. Foliar samples from 41 plots were analysed for seven key nutrients: Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Copper (Cu) and Zinc (Zn). A CND^{r2} threshold of 7.4 was established to identify significant nutritional imbalances. Results showed that 56.1% of plots had low yields linked to nutrient deficiencies, mainly Magnesium (27%), Nitrogen (17%), and Potassium (15%). Zinc and Copper deficiencies affected 12–14% of plots. About 22% of plots had low yields despite balanced nutrition, highlighting non-nutritional factors such as soil or management issues. Conversely, 9.8% of plots achieved high yields despite imbalances, suggesting short-term compensation through intensive practices. The CND^{r2} index proved a reliable tool for diagnosing nutrient imbalances and guiding fertilisation strategies aligned with the 4R nutrient stewardship principles. The study underscores the importance of adapting nutrient recommendations to local soil, climate, and crop conditions while addressing non-nutritional constraints to sustain and improve sugarcane productivity in Burundi.

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INTRODUCTION

Sugarcane (*Saccharum officinarum L.*) is one of the most economically and strategically important industrial crops worldwide. It is cultivated on approximately 26.3 million hectares and supplies more than 80% of the global sugar output, with an estimated annual production of 1.9 billion metric tons (Martini et al., 2020). In addition to its primary role in sugar manufacturing, sugarcane is a major source of renewable energy, particularly through bioethanol production and cogeneration from bagasse, making it a key component of energy diversification strategies in tropical and subtropical regions (Balat, 2009; Bezerra et al., 2020). Furthermore, despite ongoing trends toward mechanisation and industrial consolidation, sugarcane cultivation remains a critical pillar of rural economies in many developing countries, sustaining considerable levels of direct and indirect employment (Moraes et al., 2015; Ruths et al., 2023).

Although Africa contributes only about 5% of global sugar output (Mabeta & Smutka, 2023), sugarcane remains socio-economically significant across numerous Sub-Saharan African countries. In these contexts, sugarcane cultivation supports rural livelihoods, generates foreign exchange earnings,

and stimulates agro-industrial development by expanding sugar processing industries (Dubb, 2017) and integrating smallholder farmers into inclusive, vertically coordinated value chains (Manda & Miti, 2024). However, the long-term sustainability and regional competitiveness of the sector are threatened by substandard agronomic practices and inadequate nutrient management strategies (Van Antwerpen et al., 2022).

In East Africa, sugar production is undergoing a notable expansion, particularly in countries such as Uganda, Kenya, and Tanzania, where the sector remains primarily oriented toward local and regional markets (Mwavu et al., 2018; Mwinuka & Mlay, 2015). This expansion is driven by the rising demand for sugar and bioenergy. However, it frequently occurs under conditions of agronomic intensification that lack robust diagnostic frameworks, particularly with regard to plant nutritional management (Tamale et al., 2024). The absence of a systematic evaluation of foliar nutrient deficiencies hinders yield optimisation and endangers the long-term sustainability of production systems (Otieno et al., 2019). Burundi is no exception to this broader regional trend, although its sugarcane production system presents unique structural and agronomic characteristics.

In Burundi, sugarcane is an essential industrial crop cultivated exclusively in the Moso region by the Moso Sugar Company (SOSUMO), which produces nearly all of the country's formal sugar. The sugarcane industry contributes significantly to rural employment, stimulates local economic activity, and plays a strategic role in reducing the country's dependence on imported sugar. However, despite its economic and social importance, domestic production is insufficient to meet national demand, necessitating the importation of large quantities of sugar at a significant economic cost (Bamber et al., 2015).

Moreover, sugarcane cultivation in Burundi faces significant nutritional constraints. Deficiencies in essential nutrients, such as Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), and Zinc (Zn), have been identified in sugarcane plantations (Kameya et al., 2025). These deficiencies are often underdiagnosed and negatively affect vegetative growth, the technological quality of the cane, and the overall industrial performance of the sugar sector (Bhatt & Oliveira, 2022; L. C. da Silva et al., 2021; Kihara et al., 2020). In a context where sustainable intensification is imperative, the absence of an integrated nutritional diagnostic system poses a significant challenge to the development, resilience, and long-term sustainability of the national sugar industry (Ranjan, 2019)

In light of these challenges, the Compositional Nutrient Diagnosis (CND) approach provides a scientifically robust and methodologically innovative framework for accurately assessing foliar nutrient imbalances. It also guides sustainable, site-specific fertilisation strategies adapted to the country's agroecological conditions (Calheiros et al., 2018; Neisi et al., 2025; Parent & Dafir, 1992; Pereira da Silva & Justino Chiaia, 2021). As a nutrient management tool, the CND method has significant potential to enhance agricultural productivity, preserve soil fertility, and strengthen the economic resilience of the sugarcane

sector under variable environmental conditions (Fernandes et al., 2023; Kumar et al., 2023).

Against this backdrop, the present study aims to assess the nutritional status of sugarcane cultivated in the Moso region of Burundi using the Compositional Nutritional Diagnostic (CND) approach. The overall objective is to establish context-specific nutritional standards adapted to the local agroecological environment. More specifically, the study aims to: (i) assess the current nutritional balance of sugarcane crops through the analysis of leaf tissue, (ii) identify nutritional deficiencies or excesses that affect crop growth and productivity by applying the CND method, (iii) develop nutritional standards and diagnostic thresholds based on CND and adapted to the Moso context, and (iv) provide evidence-based recommendations for improving nutrient management practices to increase sugarcane yields, optimize fertilizer use efficiency, and promote sustainable soil fertility management in the region.

MATERIALS AND METHODS

Study Area

This study was conducted in the industrial sugarcane plantations of the Moso Sugar Company (SOSUMO) in the Rutana commune of Burunga province in southeastern Burundi (Figure 1). This area is located in the Moso agroecological zone, which is characterised by significant climatic variability.

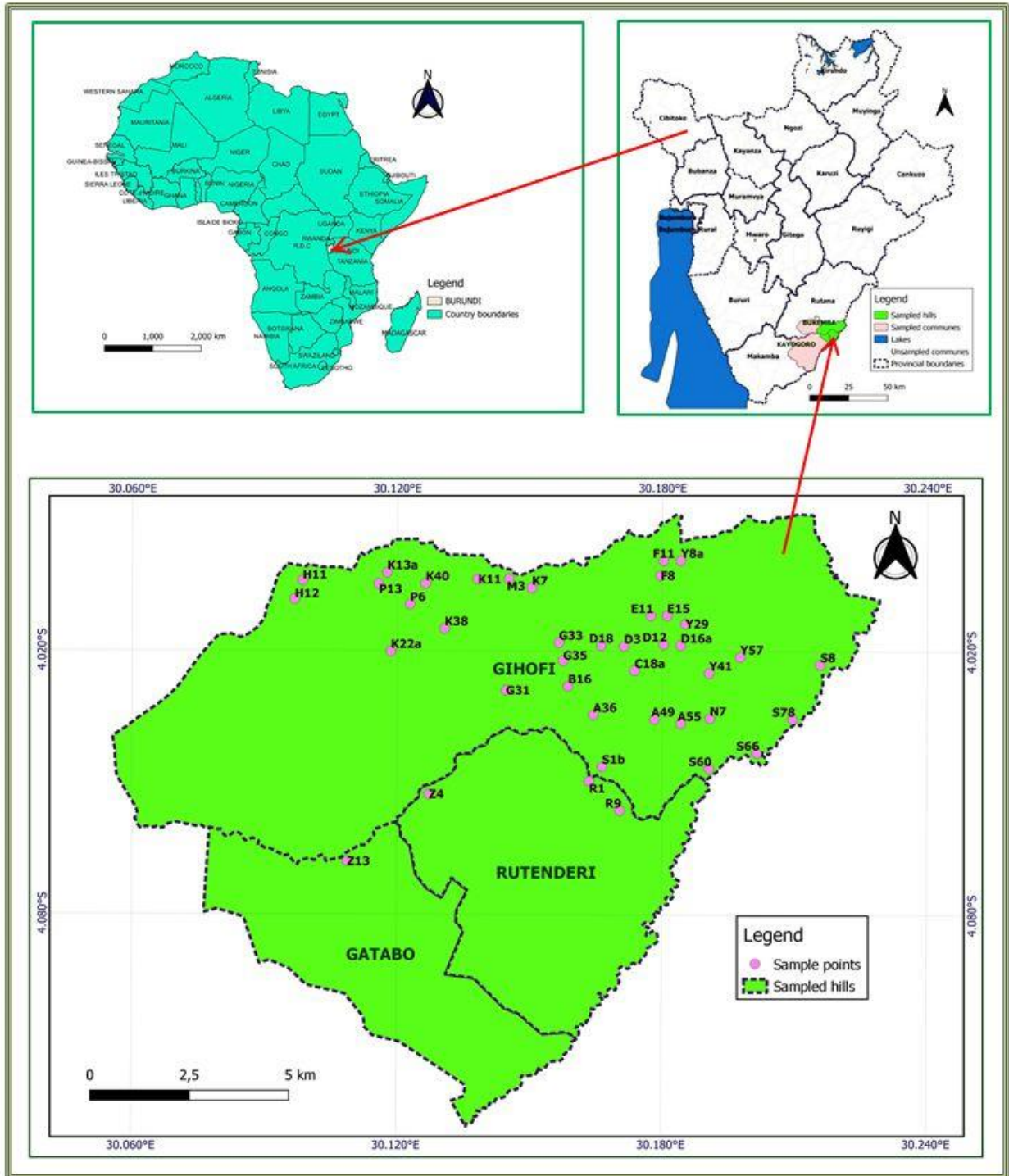
The region has an average annual precipitation of approximately 1,175 mm, with the majority occurring during a seven-month rainy season and a five-month dry season. Ambient temperatures generally fluctuate between 14°C and 28°C (MPDRN, 2006). Diurnal temperature amplitudes range from 16°C to 20°C (Nzigidahera & Nindorera, 2009).

The region exhibits significant soil heterogeneity. As Nshinyabakobeje (1987) described, the predominant soil types include hygroxeroferrisols,

relatively young soils derived from dolomitic limestone; hygroxeroferralsols, formed on schistose substrates with basic influence; ferrisols, occurring

in lower slope positions; and hygroxeroferralsols, originating from schisto-quartzitic parent materials

Figure 1: Sampling Area Map



Leaf Sampling Methodology

The collection of leaf samples was carried out across 41 sugarcane plots managed by SOSUMO, with the first fully expanded leaf counted from the top of the stalk (Dos Santos et al., 2019). In each plot, 32 leaves were sampled following an imaginary "V-shaped" pattern, ensuring sampling occurred at least 10 meters inside the plot boundaries to minimise edge effects (McCray et al., 2019).

Samples were collected from 4- to 6-month-old ratoon crops during the rainy season, a critical period for sugarcane nutrient uptake and vegetative growth (L. C. da Silva et al., 2021).

Sample Analysis Methods

Laboratory Analyses

The samples were analysed at the Soil and Agro-food Products Analysis Laboratory (LASPA) at the Burundi Institute of Agronomic Sciences (ISABU). AOAC International official methods of analysis were used to determine the nutrient concentrations in the leaves. All samples were initially pretreated according to the AOAC method 922.02, 21st edition (AOAC, 2019). AOAC 2001.11 was used to determine the Nitrogen content using the Kjeldahl method, which involves digesting organic Nitrogen with sulfuric acid and catalysts to convert it into ammonium sulfate (Thiex, 2009). Phosphorus concentration was measured using a colorimetric method assay based on the formation of a yellow phospho-vanado-molybdate complex with an absorbance reading of 470 nm (Theodore & Ikechukwu, 2024). Cations (K, Ca, Mg, Cu, and Zn) were quantified by atomic absorption spectrophotometry (AAS) using the AOAC method 975.03 (AOAC, 2019).

Diagnosis of Nutrient Composition (CND) of Sugarcane Leaves

To assess the nutritional status of sugarcane, the compositional nutrient diagnosis (CND) approach was employed as a multivariate diagnostic tool to

distinguish between high- and low-yielding sub-populations. The main objectives were to determine the minimum yield threshold associated with optimal performance and to identify the corresponding critical index of nutritional imbalance (Khiari et al., 2001; Parent & Dafir, 1992).

As established by Parent and Dafir (1992), plant tissue composition can be represented as a d -dimensional nutritional arrangement, expressed as a compositional simplex S^d , which includes d nutrients and a residual component R_d . Thus, sugarcane S^8 , or the eighth dimension ($d+1$), includes seven nutrients: N, P, K, Ca, Mg, Cu, and Zn, as well as the residual value R_8 , which accounts for all other nutrients not included in this analysis. A total of 41 samples were used for the CND computation. Data were first sorted in descending order of sugarcane yield, and the following calculations were performed (Equation 1) :

$$\begin{aligned} S^d &= [(N, P, K, Ca, Mg, Cu, Zn, R_d): N > 0, P > 0, K > 0, Ca > 0, Mg > 0, Cu > 0, Zn > 0, R_d > 0, N + P + K + Ca + Mg + Cu + Zn + R_d = 100] \quad [1] \end{aligned}$$

Where N, P, K, Ca, Mg, Cu, and Zn are nutrient ratios contained in the dry matter, 100 represents the dry matter concentration in percent, and R_d is a filling value calculated as the difference between 100% and the sum of the proportions of the d -determined nutrients (Equation 2) :

$$\begin{aligned} R_d &= [100 - (N + P + K + Ca + Mg + Cu + Zn)] \quad [2] \end{aligned}$$

Aitchison (1986) states that the geometric mean allows for a symmetrical treatment of all d components and that by dividing each component by the geometric mean (G) of the $d+1$ components, including R_d , the nutrient proportions become

invariant (Khiari et al., 2001; Rozane et al., 2020) (Equation 3):

$$G = [N * P * K * Ca * Mg * Cu * Zn * R_d]^{\frac{1}{d+1}}$$

Subsequently, nutrient concentrations obtained from sugarcane leaf analyses were converted into centred log-ratios (V_x) for element X (Aitchison & Egozcue, 2005). These log-ratios were calculated as follows (Equations 4 & 5) :

$$\begin{aligned} V_N &= \ln\left(\frac{N}{G}\right), V_P = \ln\left(\frac{P}{G}\right), V_K = \ln\left(\frac{K}{G}\right), V_{Ca} \\ &= \ln\left(\frac{Ca}{G}\right), V_{Mg} = \ln\left(\frac{Mg}{G}\right), V_{Cu} = \ln\left(\frac{Cu}{G}\right), \\ V_{Zn} &= \ln\left(\frac{Zn}{G}\right), V_{R_d} \\ &= \ln\left(\frac{R_d}{G}\right) \end{aligned}$$

$$\text{With : } V_N + V_P + V_K + V_{Ca} + V_{Mg} + V_{Cu} + V_{Zn} + V_{R_d} = 0 \quad [5]$$

The separation of high-yielding subpopulations from low-yielding subpopulations was achieved using a yield threshold value obtained at the most significant inflection point among the eight cubic functions (Khiari et al., 2001).

The means and standard deviations of V_x for the high-yield samples $V_N^*, V_P^*, V_K^*, V_{Ca}^*, V_{Mg}^*, V_{Cu}^*, V_{Zn}^*, V_{R_d}^*$ and $SD_N^*, SD_P^*, SD_K^*, SD_{Ca}^*, SD_{Mg}^*, SD_{Cu}^*, SD_{Zn}^*, SD_{R_d}^*$ were used to determine the compositional nutrient diagnosis (CND) standards. The I_x indices represent deviations from these standards. Thus, the centred log-ratios of the independent sample lines were standardised using Equation 6.

$$\begin{aligned} I_N &= \frac{V_N - V_N^*}{SD_N}, I_P = \frac{V_P - V_P^*}{SD_P}, I_K \\ &= \frac{V_K - V_K^*}{SD_K}, I_{Ca} = \frac{V_{Ca} - V_{Ca}^*}{SD_{Ca}}, I_{Mg} \\ [3] &= \frac{V_{Mg} - V_{Mg}^*}{SD_{Mg}}, \\ I_{Cu} &= \frac{V_{Cu} - V_{Cu}^*}{SD_{Cu}}, I_{Zn} = \frac{V_{Zn} - V_{Zn}^*}{SD_{Zn}}, I_{R_d} \\ &= \frac{V_{R_d} - V_{R_d}^*}{SD_{R_d}} \end{aligned} \quad [6]$$

Where $I_N, I_P, I_K, \dots, I_{R_d}$ are the CND indices

A measure of nutrient imbalance in a sample, called the nutrient imbalance index CNDr2, was calculated as the sum of the squared CND indices of the individual nutrients and the residual component (Equation 7).

$$\begin{aligned} r^2 &= I_N^2 + I_P^2 + I_K^2 + I_{Ca}^2 + I_{Mg}^2 + I_{Cu}^2 + I_{Zn}^2 \\ &+ I_{R_d}^2 \end{aligned} \quad [7]$$

To characterise each sample based on overall nutrient imbalance, CNDr2, the radius was calculated from the CND nutritional index. The minimum CNDr2 required to reach the high-yield target, referred to as the critical imbalance index, was derived by assigning the proportion of the low-yield subpopulation as an exact probability in the cumulative yield distribution function with eight degrees of freedom (Khiari et al., 2001).

The CND nutrient sufficiency ranges define concentrations of nutrients that are deficient and/or excessive in low-yielding subpopulations. These ranges were obtained by converting individual critical nutrient indices into concentration ranges with lower and upper limits. The resulting ranges were then compared to the values reported by (Guimarães et al., 2015). The advantage of using sufficiency ranges over critical values lies in the fact that they provide a range of values when a nutrient is not limiting.

Nutrient deficiencies in each plot were determined by comparing the CND index of each sample with the nutrient sufficiency ranges. Specifically, a nutrient with a CND index (IX) below the lower limit of the sufficiency range was considered deficient. In each plot, nutrients were ranked based on increasing CND index values, assuming that the nutrient with the lowest CND index was the most limiting for sugarcane production. Finally, these limiting nutrients were ranked according to the average ranking across all sugarcane plots to identify the most limiting nutrient overall.

RESULTS

Yield Thresholds and Nutrient Concentrations in High- and Low-Yielding Subpopulations

The fitting of cubic functions to the centred log-ratio values enabled the identification of characteristic inflection points ($-b/3a$) for each nutrient,

corresponding to critical yield thresholds (in Mg ha⁻¹) (Table 1). These inflection points reflect significant shifts in the relationship between foliar nutrient concentration and yield, serving as key indicators for defining nutrient thresholds specific to the studied population.

Among the macronutrients, Nitrogen (N) showed a threshold at 145.3 Mg ha⁻¹, Phosphorus (P) at 23.3 Mg ha⁻¹, while Calcium (Ca) and Magnesium (Mg) had inflection points at 121.3 and 97.5.7 Mg ha⁻¹, respectively. In contrast, Potassium (K) exhibited a negative inflection point of -3.3 Mg ha⁻¹. For the micronutrients, Copper (Cu) showed a negative inflection point at -0.45 Mg ha⁻¹ while Zinc (Zn) exhibited a threshold at 58.3 Mg ha⁻¹. Overall, all models demonstrated very high coefficients of determination ($R^2 > 0.95$), supporting the robustness of the cubic fits.

Table 1: Determination of Inflection Points ($-b/3a$) for Each Centred Log-Ratio in the Studied Population

(V _x)	F _i ^c (V _x)= aY ³ + bY ² + cY+ d	-b/3a (Mg ha ⁻¹)	R ²
Macronutrient			
V _N	-1E-04x ³ + 0.0436x ² - 6.4213x + 317.89	145,333	0,9844
V _P	3E-05x ³ - 0.0021x ² - 1.6398x + 180.59	23,333	0,9867
V _K	5E-05x ³ + 0.0005x ² - 2.5148x + 211.78	-3,333	0,9901
V _{Ca}	-0.0002x ³ + 0.0728x ² - 8.9413x + 380.03	121,333	0,9605
V _{Mg}	-0.0006x ³ + 0.1755x ² - 17.638x + 588.18	97,5	0,9514
Micronutrient			
V _{Cu}	0.0622x ³ + 0.0849x ² - 17.591x + 107.34	-0.4549	0,998
V _{Zn}	8E-05x ³ - 0.014x ² - 0.4991x + 145.64	58,333	0,9867
Residual			
V _{Fv}	-1E-05x ³ + 0.0103x ² - 2.484x + 192.78	343,333	0,9907

With F_i^c(V_x): functions of the cumulative variance ratio; V_x: centred log-ratio for each nutrient element; R² coefficient of determination; $-b/3a$: inflection point for each nutrient X.

Analysing sugarcane subpopulations based on a yield threshold of 97.5 Mg ha⁻¹ (the inflection points

of the fitted Magnesium function) revealed two groups: a high-yield subpopulation (HP) with a mean yield of 116.03 Mg ha⁻¹ and a low-yield subpopulation (LP) with a mean yield of 67.83 Mg ha⁻¹. The difference between the two groups was highly significant ($p = 0.0001$) (see Table 2).

Foliar nutrient concentrations also varied between the two groups. For macronutrients, the concentrations observed in HP compared to LP were 1.02% versus 1.01% for Nitrogen (N), 0.15% versus 0.16% for Phosphorus (P), 0.91% versus 0.90% for Potassium (K), 0.27% versus 0.26% for Calcium (Ca), and 0.22% versus 0.17% for Magnesium (Mg).

Regarding micronutrients, Copper (Cu) concentrations were 27.01 mg kg⁻¹ in HP and 26.28 mg kg⁻¹ in LP, while Zinc (Zn) levels were 11.51 mg kg⁻¹ in HP versus 14.20 mg kg⁻¹ in LP. All concentration differences were statistically significant ($p \leq 0.05$).

Table 2: Average Sugarcane Yield and Leaf Nutrient Concentrations in High- and Low-Yielding Subpopulations

Sugarcane yield (Mg ha ⁻¹)	HP	LP	p-value
	116,03	67,83	0,0001
Macronutrient (%)			
N	1,02	1,01	0,0001
P	0,16	0,17	0,0001
K	0,91	0,90	0,0413
Ca	0,27	0,26	0,0001
Mg	0,22	0,17	0,0001
Micronutrient (mg kg ⁻¹)			
Cu	27,01	26,28	0,0001
Zn	11,51	14,20	0,0001

Where $p \leq 0.05$ indicates a significant difference between nutrient concentrations in the sugarcane leaves between the high-yield and low-yield subpopulations, HP: High-yield subpopulation, LP: Low-yield subpopulation

Determining CND Standards

The CND standards (V^*_x), which were derived from high-yield sugarcane plots, are presented in Table 3. It highlights the mean values and standard deviations of the nutritional indices for

macronutrients, micronutrients, and the residual component (F_v).

Indeed, Nitrogen, Potassium, calcium, and the residual exhibited positive mean values of 1.63, 1.51, 0.32, and 6.21, respectively. In contrast, Phosphorus (-0.23), Magnesium (0.06), Zinc (-5.17), and Copper (-4.33) had negative or nearly zero mean values. However, the standard deviations ranged between 0.10 and 0.31.

Table 3: Compositional Nutrient Diagnosis (CND) Standards (V^*_x) Derived from the High-Yield Subpopulation

CND Standard	Macronutrient					Micronutrient		Residual
	V^*_N	V^*_P	V^*_K	V^*_{Ca}	V^*_{Mg}	V^*_{Zn}	V^*_{Cu}	V^*_{Fv}
Mean	1.63	-0.23	1.51	0.32	0.06	-5.17	-4.33	6.21
SD	0.16	0.17	0.23	0.18	0.31	0.27	0.26	0.10

With V^*_x : CND standard for nutrient X (means of nutrient ratios obtained from the high-yield subpopulation), SD: Standard deviation of the

nutrient ratios obtained from the high-yield subpopulation.

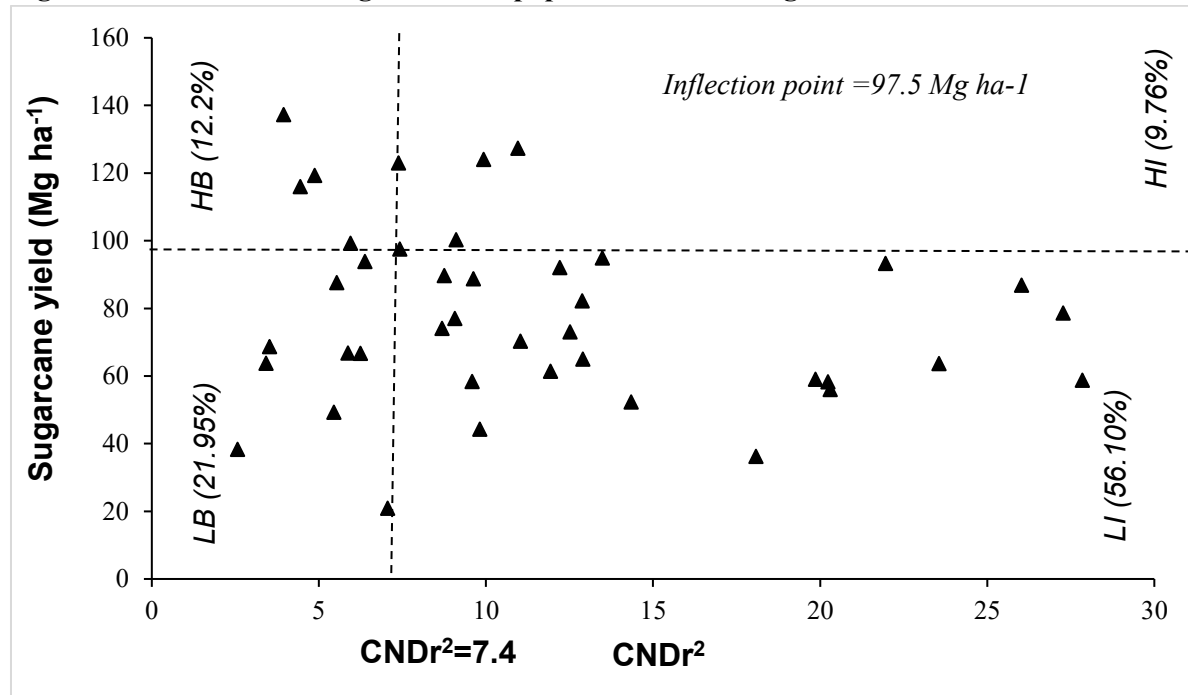
Determination of the Critical Nutritional Imbalance Index (CND^{r2})

Based on the nutritional balance indices, sugarcane yield allowed for the distinction between high-yield subpopulations and low-yield ones. The determination of the critical CND^{r2} threshold indicated that 80% of the low-yield subpopulation corresponded to a value of 7.4 (Figure 2). This was therefore the essential CND^{r2} nutritional imbalance index to classify a sample within the high-yield subpopulation.

Thus, four groups were distinguished according to yield and nutritional status:

- HB (12.2%), which are plots with high yield and balanced nutrition, corresponding to the ideal situation to optimise production;
- LB (21.95%), which are plots with low yield despite good nutritional balance, suggesting non-nutritional limiting factors;
- HI (9.76%), which are plots with high yield and unbalanced nutrition, are in a fragile situation that could lead to decreased performance if the imbalance persists;
- LI (56.1%), which are plots with low yield and imbalanced nutrition, represent the majority and indicate a significant constraint.

Figure 2: Distribution of Sugarcane Subpopulations According to Their Nutritional Balance Index



With HB: High and balanced yield, LB: low and balanced yield, LI: low and unbalanced yield, HI: High and unbalanced yield, CND^{r2}: Critical CND balance index.

Determination of Optimal CND Values for Different Nutrients

The critical CND indices I_x^2 were related to sugarcane yield for population partitioning

according to the Cate-Nelson procedure (Mangiafico, 2013). According to the control procedure (Khiari et al., 2001), the squared individual nutrient indices should summarise the critical CND^{r2}, which was 7.4 in this case. The critical CND index ranges were then assigned as sufficient nutrient ranges obtained from the square root of the critical CND I_x^2 indices (Table 4).

However, a comparison of the optimal CND values obtained for sugarcane revealed notable discrepancies compared to the reference ranges found in the literature. For Nitrogen (N), the optimal values observed (0.98 to 1.20%) were considerably lower than the concentrations commonly reported (2.0 to 2.6%). Regarding Phosphorus (P) and Potassium (K), the optimal values (0.17 to 0.20% for P and 0.94 to 1.15% for K, respectively) were slightly below the reference ranges (0.22 to 0.30% for P and 1.0 to 1.6% for K). However, these values remained close to the critical thresholds associated with moderate yield losses, indicating overall consistency. Conversely, the optimal calcium values (0.28 to 0.35%) fell within the reported range

(0.20 to 0.45%), reflecting good agreement between local observations and published standards. Magnesium showed slightly higher optimal values than those reported in the literature (0.27 to 0.33% versus 0.15 to 0.32%), which could indicate a higher nutritional demand under local conditions or strong magnesium availability in the soil.

For micronutrients, the trend was more contrasted. Zinc displayed optimal values (14 to 17 mg kg⁻¹) at the lower limit of the literature range (17 to 32 mg kg⁻¹). Copper, on the other hand, showed optimal values (29 to 35 mg kg⁻¹) that were substantially higher than the reference ranges (4 to 8 mg kg⁻¹).

Table 4. Comparison of Obtained Optimal CND Values for Sugarcane with Literature Values

Nutrient	CND		REFERENCE ^{1&2}			
	Lower	Upper	Lower	Upper	Est. 5-10% loss (Critical value)	Est. 25% loss
Macronutrient (%)						
N	0.98	1.20	2.0	2.6	1.8	1.6
P	0.17	0.20	0.22	0.3	0.19	0.17
K	0.94	1.15	1	1.6	0.9	0.8
Ca	0.28	0.35	0.2	0.45	0.20	0.18
Mg	0.27	0.33	0.15	0.32	0.13	0.11
Micronutrient (mg kg⁻¹)						
Zn	14	17	17	32	15	13
Cu	29	35	4	8	3	2

Where % and mg kg⁻¹ are units for nutrient concentration ranges;

¹(Guimarães et al., 2015). Nutrients optimum range (NOR) based on the IDRIS method to assess the nutritional status of first ratoon sugarcane;

²(McCray & Mylavarapu, 2010). Sugarcane nutrients management using leaf analysis.

Proportion of Sugarcane Plots Showing Nutrient Deficiencies

The assessment of leaf nutrient concentrations, compared to critical standards derived from CND analysis, enabled the determination of the proportion of plots affected by nutrient deficiencies. This analysis was essential for guiding targeted and efficient fertilisation strategies. Across all sampled plots, a classification was carried out by comparing observed concentrations to the critical CND value for each nutrient, which is defined as the

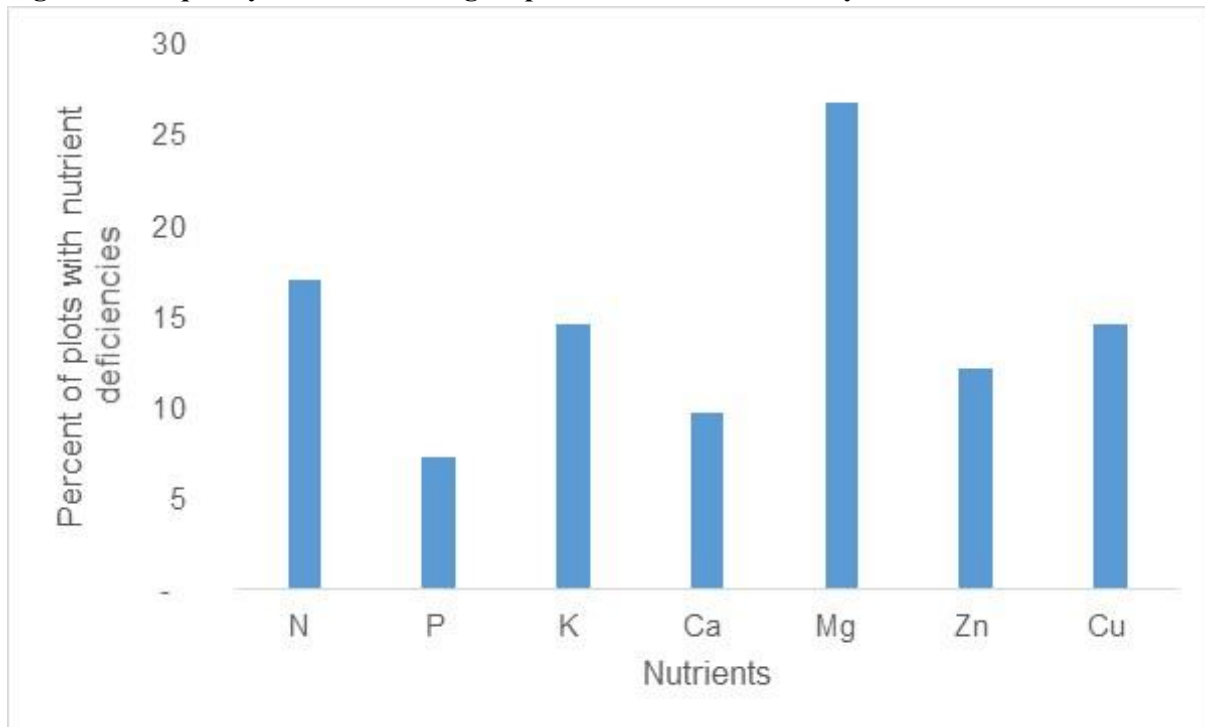
concentration below which yield drops by more than 10% relative to the optimal potential.

Based on the optimal values identified in Table 4, significant differences in nutrient deficiencies were observed across the diagnosed sugarcane plots (Figure 3).

Indeed, the results showed that magnesium (Mg) was the most deficient element, affecting 27% of the

plots. Nitrogen (N) showed a deficiency rate of 17%, followed by Potassium (K) and Copper (Cu), each accounting for 15% of cases. Zinc (Zn) and calcium (Ca) presented deficiency rates of 12% and 10%, respectively. Phosphorus (P) appeared to be the least deficient element, with only 7% of the plots affected.

Figure 3: Frequency of Plots Showing a Specific Nutrient Deficiency



DISCUSSION

The comparison between the cubic functions of the CND model (Table 1) and the observed deficiency frequencies (Figure 3) revealed strong consistency, confirming the effectiveness of this method for diagnosing plant nutrition (Passos et al., 2024). Nitrogen (N), Phosphorus (P), Calcium (Ca) and Zinc (Zn) exhibited well-defined optimal ranges and balanced concentrations, indicating favourable plant nutrition that supports growth and productivity (Lisboa et al., 2024). Moreover, the CND r^2 index proved to be a robust and integrative indicator for evaluating the overall nutritional

balance of sugarcane crops. The critical threshold identified in this study (Figure 2) is consistent with values reported using the CND approach, which are widely employed to detect and rank nutritional limitations and distinguish between nutritionally balanced plots and those exhibiting significant imbalances, thereby enabling more targeted and rational fertilisation strategies (de Paula et al., 2020; Pereira da Silva & Justino Chiaia, 2021). Such diagnostic systems are particularly valuable for large-scale crops, such as sugarcane, where maintaining multifactorial nutrient balance is essential to ensure optimal plant growth, high

productivity and improved harvest quality (Calheiros et al., 2018).

Analysis of plot categories (Figure 2) revealed that a large proportion of plots showed low yields associated with nutritional imbalances (LI), confirming the negative impact of nutrient deficiencies on sugarcane productivity (Ishfaq et al., 2022; Khan et al., 2024). Magnesium (Mg) and Zinc (Zn) deficiencies were particularly limiting, as both nutrients are vital for chlorophyll synthesis, photosynthesis, and stress tolerance (Vera-Maldonado et al., 2024). Magnesium deficiency further disrupts carbon and energy metabolism, reducing growth and resistance (Wang et al., 2022).

However, some balanced plots still had low yield, indicating that soil structure, climate, planting density, and microbial diversity also influence productivity (Navarrete et al., 2018; Singh et al., 2019). Conversely, certain imbalanced plots (HI) achieved high yields through intensive management practices such as irrigation, improved cultivars, or organo-mineral inputs (Bhatt et al., 2021; Martins et al., 2024). Nevertheless, such practices only offer short-term compensation, as persistent nutrient imbalance eventually undermines yield stability (Dengia et al., 2022; Pradhan et al., 2023)

Magnesium (Mg) emerged as the most limiting nutrient, suggesting restricted soil availability despite good overall model performance. This observation agrees with recent findings that highlight the essential role of Mg in photosynthesis, enzyme activation and antioxidant regulation (Hauer-Jákli & Tränkner, 2019; Z. Wang et al., 2020). The variability observed in Potassium (K) and Copper (Cu) responses may result from nutrient accumulation or dilution effects, which complicate field-level nutrient management (Mir et al., 2021). These results confirm the diagnostic reliability of the CND approach while emphasising the need for specific monitoring of Mg and Cu to maintain nutritional balance.

While the importance of micronutrients such as Zinc (Zn) and Magnesium (Mg) in sugarcane productivity has been confirmed, the Central role of macronutrients, particularly Nitrogen (N) and Phosphorus (P), remains fundamental. Nitrogen regulates enzymatic activity, drives photosynthesis efficiency and promotes leaf expansion, with its effects depending on the genotype and directly influencing biomass accumulation and overall crop vigour (Yang et al., 2019). Phosphorus, on the other hand, is indispensable for root system development, energy transfer, and nutrient uptake efficiency, especially under resource-limiting conditions, where it interacts closely with the genetic potential of cultivars (Zambrosi et al., 2014).

These findings collectively underscore the necessity of an integrated nutritional management strategy that harmonises both macro- and micronutrient supply to optimise agronomic performance and sustain long-term productivity. Observed deficiencies in Mg, N, and K confirm previous reports that both macronutrient (N, P, K, Ca, Mg) and micronutrient (Zn, Cu) balance are critical for optimal performance (Castro et al., 2023; Montanarella et al., 2015; Rodrigues da Silva & Ferreira de Lima Cruz, 2021). Deficiencies in Zn and Cu further affect enzymatic synthesis, vegetative growth, and sucrose accumulation, while improving Nitrogen use efficiency when corrected (Mellis et al., 2022; M. de A. Silva et al., 2022). Consequently, precise diagnosis combined with integrated fertility management and regular monitoring is essential for sustaining sugarcane productivity and soil fertility (Yadav et al., 2019).

The small number of plots combining high yield and balanced nutrition (HB) highlights the difficulty of achieving optimal fertilisation under heterogeneous conditions (Castro et al., 2023). Therefore, regular leaf diagnosis and fertilisation based on the 4R principles (right source, right rate, right time, right method) is crucial to optimise nutrient use efficiency (Kamboj et al., 2022). In addition, integrated fertilisation combining phosphate and

organo-mineral amendments can further improve plant nutritional status, productivity and sustainability (Vasconcelos et al., 2020; Zhao et al., 2024). Practices must be adapted to local soils and climate as nutrient needs vary across systems (Calheiros et al., 2018). The norms defined for SOSUMO should thus be locally validated before application elsewhere.

Globally, similar strategies exist in Brazil (Calheiros et al., 2018; de Paula et al., 2020), India (Kumar et al., 2023; Singh et al., 2019), Thailand (Chansiri et al., 2021), and South Africa (Moodley et al., 2019), confirming that site-specific nutrient management is key to sustainable sugarcane productivity. The comparison of the optimal CND values obtained from the high-yield subpopulation with literature-reported nutrient ranges highlights important site-specific deviations. The observed concentrations of N, P and K were generally lower than the commonly reported ranges, although they remained close to the critical thresholds associated with moderate yield losses (Andrade et al., 2024; Jalal et al., 2024). Calcium and Magnesium fell within or slightly above the literature ranges, reflecting sufficient or slightly elevated availability under local conditions. Zn was at the lower limit of the reported range, suggesting a potential risk of deficiency if not monitored, whereas Cu substantially exceeded literature norms, indicating potential excess (Majeed et al., 2022; Martinez-Rios et al., 2024). These comparisons confirm that CND standards derived from the high-yield plots provide a robust framework for identifying both deficiencies and excess, offering a locally adapted tool to guide precise fertilisation interventions and optimise nutrient management in the SOSUMO sugarcane System.

Finally, foliar nutrient imbalance identified through CND analysis was found to be consistent with the soil fertility profile reported by Kameya et al. (2025), who found relatively low levels of available Nitrogen and Phosphorus in the surface soils of SOSUMO sugarcane fields, along with substantial

variation in available Potassium. These are limited to moderate soil nutrient pools likely contribute to the sub-optimal foliar concentrations of N, P, and K, highlighting that the observed nutritional constraints are primarily driven by soil nutrient availability (Kameya et al., 2025). Additionally, discrepancies between soil and foliar Zn and Cu levels suggest limitations in nutrient uptake or internal translocation rather than simple deficiency (Guwela et al., 2024; Zevallos et al., 2024). Taken together, these findings support the reliability of the CND diagnostics and underscore the importance of integrating both soil and foliar assessments to guide precise and site-specific fertilisation strategies.

CONCLUSION

The study demonstrated that the $CNDr^2$ index is a robust and effective diagnostic tool for identifying nutritional imbalances in SOSUMO's industrial sugarcane plantations. Specifically, deficiencies in Magnesium, Nitrogen and Potassium, as well as occasional zinc shortages, were found to directly affect both the productivity and quality of the harvests. These results highlight the importance of integrated fertility management, based on regular and accurate nutritional diagnostics combined with rational fertilisation guided by the 4R principles.

Moreover, the local adaptation of nutritional standards is essential. Accounting for specific soil and climate conditions, crop varieties and agronomic practices helps optimise nutrient use efficiency and ensures the sustainability of production systems. In addition, simultaneously considering non-nutritional factors, such as edaphic conditions and cultivation practices, is crucial for improving overall crop performance and achieving stable long-term yields.

Overall, this integrated approach provides a practical framework to enhance the competitiveness and sustainability of the sugarcane sector in the region. By combining precise diagnostics, tailored fertilisation, and consideration of local environmental conditions, stakeholders can secure

both productivity and long-term resilience of the plantations.

REFERENCES

- Aitchison, J., & Egozcue, J. J. (2005). Compositional data analysis: Where are we and where should we be heading? *Mathematical Geology*, 37(7), 829–850. <https://doi.org/10.1007/s11004-005-7383-7>
- Andrade, J. J. d., Oliveira, E. C. d., Lima, A. M. d. S., Amorim, G. P. S., Oliveira, E. S., Freira, F. J., Adelino, W. S. d. M., & Oliveira Filho, E. C. A. d. (2024). Foliar Fertilization Improves the Nitrogen Nutrition of Sugarcane. *Agriculture*, 14(1984), 1–12. <https://doi.org/https://doi.org/10.3390/agriculture14111984>
- AOAC. (2019). *Official Methods of Analysis of AOAC INTERNATIONAL, 21st Edition*. <https://doi.org/10.1093/9780197610145.001.0001>
- Balat, M. (2009). Energy Sources, Part A: Recovery, Utilization, and Environmental Effects Bioethanol as a Vehicular Fuel: A Critical Review Bioethanol as a Vehicular Fuel : A Critical Review. *Energy Sources, Part A*, 31(14), 1242–1255. <https://doi.org/10.1080/15567030801952334>
- Bamber, P., Abdoulsamad, A., & Gereffi, G. (2015). Burundi in the Agribusiness Global Value Chain. *Skills for Private Sector Development*, 1–91. <https://doi.org/10.13140/RG.2.1.3194.6329>
- Bezerra, P. X. O., De Farias Silva, C. E., Soletti, J. I., & De Carvalho, S. H. V. (2020). Cellulosic Ethanol from Sugarcane Straw : a Discussion Based on Industrial Experience in the Northeast of Brazil. *BioEnergy Research*, 14(3), 761–773. <https://doi.org/https://doi.org/10.1007/s12155-020-10169-w>
- Bhatt, R., & Oliveira, M. W. (2022). Sugarcane nutrition for food and environmental security. *Brazilian Journal of Development*, 7(6), 64431–64467. <https://doi.org/10.34117/bjdv7n6-701>
- Bhatt, R., Singh, P., Ali, O. M., Abdel Latef, A. A. H., Laing, A. M., & Hossain, A. (2021). Polyhalite positively influences the growth, yield and quality of sugarcane (*Saccharum officinarum* L.) in potassium and calcium-deficient soils in the semi-arid tropics. *Sustainability (Switzerland)*, 13(19). <https://doi.org/10.3390/su131910689>
- Calheiros, L. C. S., Freire, F. J., Filho, G. M., Oliveira, E. C. A., Moura, A. B., Costa, J. V. T., Cruz, F. J. R., Santos, Á. S., & Rezende, J. S. (2018). Assessment of Nutrient Balance in Sugarcane Using DRIS and CND Methods. *Journal of Agricultural Science*, 10(9), 164. <https://doi.org/10.5539/jas.v10n9p164>
- Castro, S. G. Q. de, Coelho, A. P., Castro, S. A. Q. de, Souza Chiachia, T. R. de, Castro, R. A. de, & Lemos, L. B. (2023). Fertilizer source and application method influence sugarcane production and nutritional status. *Frontiers in Plant Science*, 14(March), 1–16. <https://doi.org/10.3389/fpls.2023.1099589>
- da Silva, L. C., Freire, F. J., Filho, G. M., de Oliveira, E. C., Freire, M. B. G. do. S., Moura, A. B., da Costa, J. V. T., & Rezende, J. S. (2021). Nutrient balance in sugarcane in Brazil: diagnosis, use and application in modern agriculture. *Journal of Plant Nutrition*, 44(14), 2167–2189. <https://doi.org/10.1080/01904167.2021.1889591>
- de Paula, B. V., Arruda, W. S., Parent, L. E., de Araujo, E. F., & Brunetto, G. (2020). Nutrient diagnosis of eucalyptus at the factor-specific level using machine learning and compositional methods. *Plants*, 9(8), 1–15. <https://doi.org/10.3390/plants9081049>
- Dengia, A., Dechassa, N., Wogi, L., & Amsalu, B. (2022). Changes in Soil Fertility Status under

- Long-term Intensive Sugarcane Production System at Wonji-Shoa Sugar Estate in Central Ethiopia. *Ethiopian Journal of Crop Science*, 10(2), 30–56. [https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Changes+in+Soil+Fertility+Status+under+Long-term+Intensive+Sugarcane+Production+System+at+Wonji-Shoa+Sugar+Estate+in+Central+Ethiopia.+Ethiopian+Journal+of+Crop+Science%2C+10%282%29%2C+30-56.&btnG=](https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Changes+in+Soil+Fertility+Status+under+Long-term+Intensive+Sugarcane+Production+System+at+Wonji-Shoa+Sugar+Estate+in+Central+Ethiopia.+Ethiopian+Journal+of+Crop+Science%2C+10%282%29%2C+30-56.&btnG=%2C+Université+de+Liège-Gembloux+Agro-bio+Tech&btnG=)
- Dos Santos, R. L., Freire, F. J., de Oliveira, E. C. A., Freire, M. B. G. D. S., West, J. B., Barbosa, J. de A., de Moura, M. J. A., & Bezerra, P. da C. (2019). Nitrate reductase activity and nitrogen and biomass accumulation in sugarcane under molybdenum and nitrogen fertilization. *Revista Brasileira de Ciencia Do Solo*, 43, 1–19. <https://doi.org/10.1590/18069657rbcS20180171>
- Dubb, A. (2017). Interrogating the Logic of Accumulation in the Sugar Sector in Southern Africa. *Journal of Southern African Studies*, 43(3), 471–499. <https://doi.org/10.1080/03057070.2016.1219153>
- Fernandes, G. C., Rosa, P. A. L., Jalal, A., Oliveira, C. E. da S., Galindo, F. S., Viana, R. da S., De Carvalho, P. H. G., da Silva, E. C., Nogueira, T. A. R., Al-Askar, A. A., Hashem, A. H., AbdElgawad, H., & Filho, M. C. M. T. (2023). Technological Quality of Sugarcane Inoculated with Plant-Growth-Promoting Bacteria and Residual Effect of Phosphorus Rates. *Plants*, 12(14), 1–16. <https://doi.org/https://doi.org/10.3390/plants12142699>
- Gahungu, A. (2012). *Dynamique et perspectives de la filière cotonnière du Burundi (Doctoral dissertation)* [Liège, Université de Liège-Gembloux Agro-bio Tech]. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Dynamique+et+perspectives+de+la+filière+cotonnière+du+Burundi.+Liège
- Guimarães, F. C. N., Serra, A. P., Marchetti, M. E., Ensinas, S. C., Altomar, P. H., Conrad, V. do A., Potrich, D. C., Rosa, C. B. C. J., Martinez, M. A., & Matos, F. A. (2015). Nutrients optimum range (NOR) based on DRIS method to assess the nutritional status of the first ratoon sugarcane. *Australian Journal of Crop Science*, 9(7), 638–645. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Nutrients+optimum+range+%28NOR%29+based+on+DRIS+method+to+assess+the+nutritional+status+of+the+first+ratoon+sugarcane.+Australian+Journal+of+Crop+Science%2C+9%287%29%2C+638-645.&btnG=
- Guwela, V. F., Broadley, M. R., Hawkesford, M. J., Maliro, M. F. A., Bokosi, J., Banda, M., Grewal, S., Wilson, L., & King, J. (2024). *Unravelling the impact of soil types on zinc, iron, and selenium concentrations in grains and straw of wheat / *Amblyopyrum muticum* and wheat / *Triticum urartu* doubled haploid lines. March*, 1–14. <https://doi.org/10.3389/fagro.2024.1305034>
- Hauer-Jákli, M., & Tränkner, M. (2019). Critical leaf magnesium thresholds and the impact of magnesium on plant growth and photo-oxidative defense: A systematic review and meta-analysis from 70 years of research. *Frontiers in Plant Science*, 10(June), 1–15. <https://doi.org/10.3389/fpls.2019.00766>
- Ishfaq, M., Wang, Y., Yan, M., Wang, Z., Wu, L., Li, C., & Li, X. (2022). Physiological Essence of Magnesium in Plants and Its Widespread Deficiency in the Farming System of China. *Frontiers in Plant Science*, 13(April), 1–17. <https://doi.org/10.3389/fpls.2022.802274>
- Jalal, A., Furlani, E. J., & Filho, M. C. M. T. (2024). Interaction of Zinc Mineral Nutrition and Plant Growth-Promoting Bacteria in Tropical

- Agricultural Systems: A Review. *Plants*, 13(5), 571. <https://doi.org/https://doi.org/10.3390/plants13050571>
- Kamboj, A., K. Khokhar, K., Raj, D., Kumar, P., Kumar, S., Kamboj, P., & Rani, M. (2022). Optimizing the Methods and Schedule of Fertilization Escalated Nutrient Uptake, Nutrient Use Efficiency and Dry Matter Yield of Sugarcane (*Saccharum officinarum* L.). *International Journal of Environment and Climate Change*, 12(12), 1639–1652. <https://doi.org/10.9734/ijecc/2022/v12i121606>
- Kameya, F., Nibasumba, A., Kaboneka, S., Bizimana, S., Nizigiyimana, C., Ntwari, J. C., Wakana, A., & Delvaux, B. (2025). Abiotic and biotic factors affecting sugarcane yield in Gihofi Industrial plantations, Burundi. *African Journal of Agricultural Research*, 21(9), 722–738. <https://doi.org/10.5897/ajar2025.16988>
- Khan, A., Bibi, S., Javed, T., Mahmood, A., Mehmood, S., Javaid, M. M., Ali, B., Yasin, M., Abidin, Z. U., Al-Sadoon, M. K., Babar, B. H., Iqbal, R., & Malik, T. (2024). Effect of salinity stress and surfactant treatment with zinc and boron on morpho-physiological and biochemical indices of fenugreek (*Trigonella foenum-graecum*). *BMC Plant Biology*, 24(1), 1–13. <https://doi.org/10.1186/s12870-024-04800-7>
- Khiari, L., Parent, L. E., & Tremblay, N. (2001). Selecting the high-yield subpopulation for diagnosing nutrient imbalance in crops. *Agronomy Journal*, 93(4), 802–808. <https://doi.org/10.2134/agronj2001.934802x>
- Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., & Piikki, K. (2020). Micronutrient deficiencies in African soils and the human nutritional nexus : opportunities with staple crops. *Environmental Geochemistry and Health*, 42(9), 3015–3033. <https://doi.org/10.1007/s10653-019-00499-w>
- Kumar, N., Rana, L., Singh, A. K., Pramanick, B., Gaber, A., Alsuhaibani, A. M., Skalicky, M., & Hossain, A. (2023). Precise macronutrient application can improve cane yield and nutrient uptake in widely spaced plant-ratoon cycles in the Indo-Gangetic plains of India. *Frontiers in Sustainable Food Systems*, 7(July), 1–10. <https://doi.org/10.3389/fsufs.2023.1223881>
- Lisboa, B. B., Abichequer, A. D., de São José, J. F. B., Moura-Bueno, J. M., Brunetto, G., & Vargas, L. K. (2024). Compositional Nutrient Diagnosis Methodology and Its Effectiveness to Identify Nutrient Levels in Yerba Mate (*Ilex paraguariensis*). *Agriculture (Switzerland)*, 14(6). <https://doi.org/10.3390/agriculture14060896>
- Mabeta, J., & Smutka, L. (2023). Trade and competitiveness of African sugar exports. *Frontiers in Sustainable Food Systems*, 7, 1–14. <https://doi.org/10.3389/fsufs.2023.1304383>
- Majeed, A., Rashid, I., Niaz, A., Ditta, A., Sameen, A., Al-Huqail, A. A., & Siddiqui, M. H. (2022). Balanced Use of Zn, Cu, Fe, and B Improves the Yield and Sucrose Contents of Sugarcane Juice Cultivated in Sandy Clay Loam Soil. *Agronomy*, 12(3), 696. <https://doi.org/10.3390/agronomy12030696>
- Manda, S., & Miti, C. (2024). Does value chain inclusiveness increase smallholder resilience during pandemics ? Lessons from the Zambia’s sugar-belt. *Journal of International Development*, 36(2), 773–794. <https://doi.org/10.1002/jid.3837>
- Mangiafico, S. S. (2013). Cate-Nelson analysis for bivariate data using R-project. *Journal of Extension*, 51(5). <https://doi.org/10.34068/joe.51.05.33>
- Martinez-Rios, O., Bravo-vinaja, Á., San-mart, C., Hidalgo-moreno, C. I., Antonio, M., David, J., & Santillan-balderas, D. R. (2024). Zinc Deficiency in Calcareous Soils : A Bibliometric

- Analysis from 1989 to 2024. *Agriculture*, 14(12), 2285. <https://doi.org/https://doi.org/10.3390/agriculture14122285>
- Martini, A. F., Valani, G. P., Boschi, R. S., Bovi, R. C., Fernanda, L., & Cooper, M. (2020). Soil & Tillage Research Is soil quality a concern in sugarcane cultivation? A bibliometric review. *Soil & Tillage Research*, 204(March), 104751. <https://doi.org/10.1016/j.still.2020.104751>
- Martins, M. L. T., Sforca, D. A., dos Santos, L. P., Pimenta, R. J. G., Mancini, M. C., Aono, A. H., da Silva, C. B. C., Vautrin, S., Bellec, A., Vicentini, R., Berges, H., da Silva, C. C., & de Souza, A. P. (2024). Identifying Candidate Genes for Sugar Accumulation in Sugarcane Cultivars: From a Syntenic Genomic Region to a Gene Coexpression Network. *BioRxiv*, 1–57. <https://doi.org/https://doi.org/10.1101/2024.05.08.593213>
- McCray, J. M., & Mylavarapu, R. (2010). Sugarcane Nutrient Management Using Leaf Analysis. *Edis*, 2010(4). <https://doi.org/10.32473/edis-ag345-2010>
- McCray, J. M., Newman, P. R., Rice, R. W., & Ezenwa, I. V. (2019). Sugarcane Leaf Tissue Sample Preparation for Diagnostic Analysis. *Edis*, 2005(15). <https://doi.org/10.32473/edis-sc076-2005>
- Mellis, E. V., Kölln, O. T., Moreira, L. A., Otto, R., Ferraz-Almeida, R., Ramos, L. F., Andrade, R. de P., & Franco, H. C. J. (2022). Molybdenum increases nitrogen use efficiency of sugarcane under limited N supply. *Journal of Plant Nutrition*, 45(9), 1360–1369. <https://doi.org/10.1080/01904167.2021.2020834>
- Mir, A. R., Pichtel, J., & Hayat, S. (2021). Copper: uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. *BioMetals*, 34(4), 737–759. <https://doi.org/10.1007/s10534-021-00306-z>
- Montanarella, L., Pennock, D., Mckenzie, N., Alavipanah, S. K., Alegre, J., Alshankiti, A., Arrouays, D., Aulakh, M. S., Badraoui, M., Costa, I. D. S. B., & Black, H. (2015). *The status of the world's soil resources (Technical summary)*. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=The+status+of+the+world's+soil+resources+%28Technical+summary%29.&btnG=
- Moraes, M. A. F. D., Oliveira, F. C. R., & Diaz-Chavez, R. A. (2015). Socio-economic impacts of Brazilian sugarcane industry. *Environmental Development*, 16, 1–29. <https://doi.org/10.1016/j.envdev.2015.06.010>
- MPDRN. (2006). *Monographie de la commune Bukemba*. 1–70.
- Mwavu, E. N., Kalema, V. K., Bateganya, F., Byakagaba, P., Waiswa, D., Enuru, T., & Mbogga, M. S. (2018). Expansion of Commercial Sugarcane Cultivation among Smallholder Farmers in Uganda: Implications for Household Food Security. *Land*, 7(2), 1–15. <https://doi.org/10.3390/land7020073>
- Mwinuka, L., & Mlay, F. (2015). Determinants and Performance of Sugar Export in. *Journal of Finance and Economics*, 3(1), 6–14. <https://doi.org/10.12691/jfe-3-1-2>
- Navarrete, A. A., Pitombo, L. M., Brandani, C. B., Bento, C. B., Escanhoela, A. S. B., Ramos, J. C., Ramos, L. P., Quevedo, H. D., Nishisaka, C. S., & Carmo, J. B. do. (2018). Multi-Analytical Interactions in Support of Sugarcane Agroecosystems Sustainability in Tropical Soils. *Sugarcane - Technology and Research*, 3–28. <https://doi.org/10.5772/intechopen.71180>
- Neisi, A., Chorom, M., Ghafari, H., & Alkasir, J. (2025). Evaluation of Nutritional Status of Sugarcane Fields in North of Khuzestan Province Using the Compositional Nutrient Diagnosis Method. *Journal of Water and Soil*,

- 38(6), 733– 747. <https://doi.org/https://doi.org/10.22067/jsw.2025.91029.1452>
- Nzigidahera, B., & Nindorera, D. (2009). *Plan de gestion et d'aménagement de la Réserve Naturelle de la Malagarazi*. 1–71. <https://bi.chm-cbd.net/sites/bi/files/2020-04/plan-gestio-malagarazi.pdf>
- Otieno, H. M., Onduru, G. O., & Okumu, O. O. (2019). World Journal of Advanced Research and Reviews through the use of existing technologies : Sugarcane agronomy. *World Journal of Advanced Research and Reviews*, 03(02), 55–65. <https://doi.org/10.30574/wjarr>
- Parent, L. E., & Dafir, M. (1992). A Theoretical Concept of Compositional Nutrient Diagnosis. *Journal of the American Society for Horticultural Science*, 117(2), 239–242. <https://doi.org/10.21273/jashs.117.2.239>
- Passos, D. dos R. C., Cecílio Filho, A. B., Soratto, R. P., Rozane, D. E., Yamane, D. R., Fernandes, A. M., Souza, E. de F. C. de, Fernandes, F. M., Job, A. L. G., & Nascimento, C. S. (2024). Nutritional Diagnosis of Potato Crops Using the Multivariate Method. *Agronomy*, 14(7), 1–14. <https://doi.org/10.3390/agronomy14071500>
- Pereira da Silva, G., & Justino Chiaia, H. L. (2021). Limitation Due to Nutritional Deficiency and Excess in Sugarcane Using the Integral Diagnosis and Recommendation System (DRIS) and Nutritional Composition Diagnosis (CND). *Communications in Soil Science and Plant Analysis*, 52(12), 1458–1467. <https://doi.org/10.1080/00103624.2021.1885690>
- Pradhan, A., Wakchaure, G. C., Shid, D., Minhas, P. S., Biswas, A. K., & Reddy, K. S. (2023). Impact of residue retention and nutrient management on carbon sequestration, soil biological properties, and yield in multi-ratoon sugarcane. *Frontiers in Sustainable Food Systems*, 7. <https://doi.org/10.3389/fsufs.2023.1288569>
- Ranjan, A. (2019). *Effect of integrated nutrient management modules on soil fertility and productivity of sugarcane in Calcareous soil* [(Doctoral dissertation, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, BIHAR-848 125, INDIA)]. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=EFFECT+OF+INTEGRATED+NUTRIENT+MANAGEMENT+MODULES+ON+SOIL+FERTILITY+AND+PRODUCTIVITY+OF+SUGARCANE+IN+CALCAREOUS+SOIL&btnG=
- Rodrigues da Silva, L. D., & Ferreira de Lima Cruz, J. M. (2021). Micronutrient nutrition in sugarcane: a brief review. *Scientia Agraria Paranaensis*, 214–218. <https://doi.org/10.18188/sap.v20i3.28188>
- Rozane, D. E., de Paula, B. V., George Wellington Bastos de Melo, Dos Santos, E. M. H., Trentin, E., Marchezan, C., da Silva, L. O. S., Tassinari, A., Dotto, L., de Oliveira, F. N., Natale, W., Baldi, E., Toselli, M., & Brunetto, G. (2020). Compositional nutrient diagnosis (CND) applied to grapevines grown in subtropical climate region. *Horticulturae*, 6(3), 1–13. <https://doi.org/10.3390/horticulturae6030056>
- Ruths, J. C., Shikida, P. F. A., & Fracarolli, I. F. L. (2023). Rural work in the sugarcane sector and its influences on health: scoping review. *Revista Brasileira de Medicina Do Trabalho*, 21(1), 1–12. <https://doi.org/10.47626/1679-4435-2023-779>
- Silva, M. de A., Germino, G. H., de Holanda, L. A., Oliveira, L. C., Santos, H. L., & Sartori, M. M. P. (2022). Sugarcane Productivity as a Function of Zinc Dose and Application Method. *Agriculture (Switzerland)*, 12(11), 1–12. <https://doi.org/10.3390/agriculture12111843>

- Singh, K., Mishra, S. K., & Singh, V. (2019). Sugarcane and Wheat Productivity Under Different Cropping Systems. *Sugar Tech*, 21(3), 415–420. <https://doi.org/10.1007/s12355-018-00697-3>
- Tamale, J., Nasta, P., Doetterl, S., Hutson, J., Straaten, O. Van, Turyagyenda, L. F., & Fiener, P. (2024). Impact of urea fertilization rates on nitrogen losses, productivity and profitability in East African sugarcane plantations. *Soil Use and Management*, 40(2), 1–23. <https://doi.org/10.1111/sum.13030>
- Theodore, O. O., & Ikechukwu, I. A. (2024). Proximate Constituent and Mineral Content of the Seeds of Africa Yam Bean (*Sphenostylis Stenocarpa*) Purchased in Ebonyi State, Eastern Nigeria. *African Journal of Agriculture and Food Science*, 7(4), 189–200. <https://doi.org/10.52589/ajafs-skf0dmwj>
- Thiex, N. (2009). Evaluation of analytical methods for the determination of moisture, crude protein, crude fat, and crude fiber in distillers dried grains with solubles. *Journal of AOAC International*, 92(1), 61–73. <https://doi.org/10.1093/jaoac/92.1.61>
- Van Antwerpen, R., Derek, A. W., Gillespie, W., & Van Heerden, P. D. R. (2022). Promoting Adoption of Soil Health Related Regenerative Agriculture Practices Amongst Small-Scale Sugarcane Grower Communities in South Africa. *Sugar Tech*, 26(3), 635–638. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Promoting+Adoption+of+Soil+Health+Related+Regenerative+Agriculture+Practices+Amongst+Small-Scale+Sugarcane+Grower+Communities+in+South+Africa+Abstract%3A&btnG=
- Vasconcelos, R. L., Cremasco, C. P., de Almeida, H. J., Neto, A. ., Mauad, M., & Gabriel Filho, L. R. A. (2020). Multivariate behavior of irrigated sugarcane with phosphate fertilizer and filter cake management : nutritional state, biometry, and agroindustrial performance. *Journal of Soil Science and Plant Nutrition*, 20(4), 1625–1636. <https://doi.org/https://doi.org/10.1007/s42729-020-00234-w>
- Vera-Maldonado, P., Aquea, F., Reyes-Díaz, M., Cárcamo-Fincheira, P., Soto-Cerda, B., Nunes-Nesi, A., & Inostroza-Blancheteau, C. (2024). Role of boron and its interaction with other elements in plants. *Frontiers in Plant Science*, 15(February), 1–14. <https://doi.org/10.3389/fpls.2024.1332459>
- Wang, Y., Li, Y., Hua, X., Zhang, Z., Fan, T., Yao, W., Zhang, M., & Zhang, J. (2022). Transcriptome Dynamics Underlying Magnesium Deficiency Stress in Three Founding Saccharum Species. *International Journal of Molecular Sciences*, 23(17), 9681. <https://doi.org/10.3390/ijms23179681>
- Wang, Z., Hassan, M. U., Nadeem, F., Wu, L., Zhang, F., & Li, X. (2020). Magnesium Fertilization Improves Crop Yield in Most Production Systems: A Meta-Analysis. *Frontiers in Plant Science*, 10(January), 1–10. <https://doi.org/10.3389/fpls.2019.01727>
- Yadav, S. P., Singh, S. C., Yadav, S., Yadav, S. K., Tiwari, A. K., & Sharma, B. L. (2019). Integrated Nutrient Management Approaches for Enhancing Production Potential and Sustainability of Sugarcane (*Saccharum* spp. hybrid) Plant–Ratoon System in North Region of India. *Sugar Tech*, 21(1), 170–175. <https://doi.org/10.1007/s12355-018-0641-z>
- Yang, Y., Gao, S., Jiang, Y., Lin, Z., Luo, J., Li, M., Guo, J., Su, Y., Xu, L., & Que, Y. (2019). The physiological and agronomic responses to nitrogen dosage in different sugarcane varieties. *Frontiers in Plant Science*, 10(April), 1–18. <https://doi.org/10.3389/fpls.2019.00406>
- Zambrosi, F. C. B., Ribeiro, R. V., Marchiori, P. E. R., Cantarella, H., & Landell, M. G. A. (2014).

Sugarcane performance under phosphorus deficiency: physiological responses and genotypic variation. *Plant and Soil*, 386(1–2), 273–283. <https://doi.org/10.1007/s11104-014-2252-0>

Zevallos, S., Salas, E., Gutierrez, P., Burgos, G., Boeck, B. De, Mendes, T., Campos, H., & Lindqvist-kreuze, H. (2024). Foliar Zn Application Increases Zn Content in Biofortified Potato. *Agriculture*, 14(12), 2186. <https://doi.org/https://doi.org/10.3390/agriculture14122186>

Zhao, J., Sun, X., Xue, Y., Sher, A., Ran, J., Liu, P., Zhao, B., Ren, B., Yu, N., Ren, H., & Zhang, J. (2024). Optimizing nitrogen management for grain yield and nitrogen use efficiency in summer maize via coordinating the N supply–demand balance. *Journal of Integrative Agriculture*, 1–16. <https://doi.org/10.1016/j.jia.2024.12.028>