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Assessing nutrient export and defining sufficiency ranges for sun-grown cocoa clones

Carolina Santos Benjamin*[1], Luiz Antônio dos Santos Dias[1], Wedisson Oliveira Santos[2], Larissa Carmelina Alves Pinto*[2], Marcela Carvalho Valente[2]

[1] Federal University of Viçosa, MG, Brazil

[2] Institute of Agricultural Sciences, Federal University of Uberlândia (UFU), Campus Uberlândia, MG, Brazil

***Corresponding author: larissa.carmelina@ufu.br**

Abstract: Cocoa (*Theobroma cacao* L.) is a worldwide important crop, which the cultivation under full-sun has emerged as a promising strategy to mitigate witches' broom disease (*Moniliophthora perniciosa*) incidence. However, the yield potential and nutritional requirements of cocoa grown under full sun conditions remain poorly understood. This study evaluated six cocoa clones cultivated under full-sun for eight years to establish nutrient sufficiency ranges, quantify nutrient export, and analyze nutrient partitioning in fruits. Leaf samples were collected from four plants per clone, and fruit samples were collected from ten plants per clone. Shells and beans were separated for nutrient quantification and yield assessment. The experimental design followed a hierarchical classification scheme, with 14 randomized plots per clone. Compared to conventional shaded cultivation, the cocoa clones under full-sun conditions exhibited high dried bean yields of 2.9; 2.1; 2.5; 1.2; 1.6 and 1.5 t ha^{-1} for clones CCN 51, PH 16, PS 1319, CCN 10, CP 49, and SJ 02, respectively. Nutrient export patterns among clones were strongly influenced by yield variability, reflecting distinct nutritional demands. Nutrient sufficiency ranges varied for among clones, with smaller amplitudes for the macronutrients N, P, K, Mg, and S, and wider amplitudes for the micronutrients Cu, Mn, Fe, Zn, and B. Nutrient export analysis revealed that K, Ca, S, and all micronutrients were preferentially allocated to the shell. These findings provide important insights for developing clone-specific nutritional management strategy of cocoa cultivation under full-sun cultivations.

Keywords: Environmental adaptation; Leaf diagnosis; Nutrient partitioning; Plant nutrition; *Theobroma cacao* L.

Abbreviations: CAPES_Coordination for the Improvement of Higher Education Personnel; CNPq_National Council for Scientific and Technological Development; DPS-UFV_Soil Department of Federal University of Viçosa; DRIS_Diagnosis and Recommendation Integrated Systems; FAPEMIG_Research Support Foundation of the State of Minas Gerais; OPD_Optimal Percentage Deviation; CV_coefficient of variation.

Introduction

Cocoa (*Theobroma cacao* L.), a dicotyledonous species of the Malvaceae family, is native to the humid tropical forests of South and Central America. During its peak economic cycle in Brazil (1920s–1980s), cocoa was the country's leading agricultural export commodity. However, it is no longer among Brazil's top ten agricultural commodities, largely due to the epidemic spread of the fungal pathogen *Moniliophthora perniciosa*, the causal agent of witches' broom disease, which severely reduced production in southern of Bahia state. Currently, cocoa is also cultivated in other Brazilian states, including those in the Amazon region and northern of Espírito Santo state (SIDRA-IBGE, 2025).

Cocoa production is currently concentrated in the states of Pará (53 %) and Bahia (38 %), while Espírito Santo accounted for 4% of national production in 2024 (SIDRA-IBGE, 2025). As a shade-adapted species, cocoa in Brazil is typically cultivated beneath native forest canopies in the *cabruca* agroforestry system. This production system promotes soil conservation through continuous vegetative cover, which reduces rainfall-induced erosion and surface residue accumulation, thereby enhancing biogeochemical nutrient cycling. However, the shaded and humid microclimate characteristics of *cabruca* systems favors the proliferation of *M. perniciosa* (Jaimez et al., 2022).

Given the yield losses associated with witches' broom disease in cabruca systems, full-sun cultivation has emerged as a promising alternative. Reduced relative humidity under increased light exposure creates less favorable conditions for the development of *M. perniciosa* (Jaimez et al., 2022). Furthermore, recent studies have demonstrated the high yield potential of cocoa under these conditions (Sodré, 2017; Bahia et al., 2021; Benjamin et al., 2025). In this study, "full-sun" or "sun-grown" cocoa refer to plants cultivated under open-field conditions without shade trees, in contrast to traditional shaded or agroforestry systems such as cabruca.

The goal of this work was to establish nutrient sufficiency ranges, quantify nutrient export, and characterize fruit nutrient partitioning in the main clones of cocoa cultivated in Brazil under open-field, full-sun conditions. This investigation provides the first comprehensive framework for the nutritional management of cocoa in Brazil under this new production system.

Results and discussion

Nutrient contents

The macronutrient contents of diagnostic leaves, shells, and beans of the cocoa clones are presented in Table 1. Coefficients of variation were calculated only for the nutrient means of diagnostic leaves to provide the measures of dispersion required for nutritional diagnosis approaches, specifically the Kenworthy Balance Index (Kenworthy, 1961) and the Diagnosis and Recommendation Integrated System (Beaufils, 1973).

Table 1. Contents of macronutrients in compartments diagnostic leaf, shell and bean, in six cocoa clones, grown in full sun in the municipality of Linhares, ES.

Clone	N	P	K	Ca	Mg	S
Diagnostic leaf (g kg^{-1})						
CCN 51	21.04 (12.96) b	1.67 (11.51) a	14.77 (15.99) a	12.09 (20.16) c	5.97 (14.70) c	2.16 (10.63) a
PH 16	22.56 (11.26) a	1.69 (12.39) a	15.92 (17.79) a	12.04 (31.58) c	5.37 (12.90) d	2.04 (11.24) a
PS 1319	18.90 (12.85) c	1.34 (20.13) b	12.52 (15.78) b	14.56 (25.76) b	6.15 (16.40) c	1.93 (22.14) b
CCN 10	20.17 (8.71) b	1.35 (26.98) b	12.52 (18.01) b	15.22 (23.78) b	6.90 (13.96) b	2.21 (14.92) a
CP 49	18.95 (12.60) c	1.21 (28.03) b	10.07 (27.56) c	18.15 (27.58) a	7.80 (15.87) a	1.95 (18.70) b
SJ 02	17.84 (16.57) c	1.19 (21.04) b	12.49 (20.36) b	16.35 (16.41) b	6.81 (10.16) b	1.80 (19.22) b
Mean	19.91	1.41	13.05	14.74	6.50	2.01
CV (%)	12.49	20.0	19.25	24.21	14.00	16.14
Shell (g kg^{-1})						
CCN 51	12.23 a	1.43 a	19.18 a	2.95 b	2.91 a	1.88 a
PH 16	13.04 a	1.39 a	19.53 a	3.83 a	2.71 a	1.89 a
PS 1319	10.68 a	1.09 a	19.99 a	2.37 b	2.23 a	1.63 b
CCN 10	12.58 a	1.20 a	20.16 a	3.47 a	3.04 a	1.97 a
CP 49	11.76 a	1.24 a	18.90 a	3.23 b	2.60 a	1.66 b
SJ 02	11.94 a	1.37 a	19.57 a	4.34 a	3.41 a	1.79 a
Mean	12.04	1.29	19.55	3.36	2.82	1.80
CV (%)	6.71	10.22	2.43	20.41	14.32	7.52
Bean (g kg^{-1})						
CCN 51	21.30 a	4.20 b	09.44 a	0.89 a	3.34 a	1.44 a
PH 16	22.01 a	4.02 b	10.49 a	1.04 a	3.32 a	1.41 a
PS 1319	22.19 a	4.00 b	10.57 a	0.92 a	3.44 a	1.42 a
CCN 10	22.56 a	4.82 a	10.35 a	1.17 a	3.67 a	1.35 a
CP 49	22.43 a	4.19 b	10.06 a	0.91 a	3.38 a	1.41 a
SJ 02	20.33 a	3.97 b	9.61 a	1.19 a	3.20 a	1.50 a
Mean	21.80	4.20	10.09	1.02	3.39	1.42
CV (%)	3.88	7.60	4.67	13.21	4.65	3.43

Means followed by the same letter, in the columns, do not differ from each other by the Scott-Knott test at 5% probability. Numbers in brackets correspond to the coefficient of variation of the mean: CV = (SD/$\bar{x}$) * 100.

Nutrient contents of leaf tissues revealed distinct patterns among clones for each element. PH 16 consistently showed the highest N content, followed by CCN 51 and CCN 10, whereas CP 49, PS 1319, and SJ 02 exhibited the lowest concentrations. Phosphorus concentrations separated the clones into two distinct groups, with CCN 51 and PH 16 containing significantly higher levels than the remaining clones. Potassium distribution followed a similar pattern, except for CP 49, which exhibited markedly lower K concentrations. In contrast, Ca content showed the opposite trend, with CP 49 exhibiting the highest concentrations, whereas PH 16 and CCN 51 showed relatively lower values. For S, clones CCN 10, PH 16, and CCN 51 exhibited substantially higher concentrations than the remaining genotypes.

Analysis of shell tissues revealed significant differences among clones only for Ca and S contents (Table 1). Clones CCN 51, PS 1319, and CP 49 exhibited notably higher Ca concentrations in their shells. In contrast, PS 1319 and CP 49 showed comparatively lower S content than the other genotypes.

Nutrient contents in bean tissue were highly stable among clones (Table 1). A significant difference was observed only for P content ($p < 0.05$), which was highest in clone CCN 10.

Nutrient concentration varied most markedly in leaves, likely because they function as metabolically active organs that directly reflect genetic differences in nutrient uptake and utilization. Consistent with the findings of Bahia et al. (2021) under full-sun conditions, variations among clones was lower for macronutrients (CV: 17.7%; Table 1) than for micronutrients (CV: 38.2%; Table 2) with the exception of B. Variation was lower in the shell, whose primary structural function involves less active physiological regulation. The greatest stability was observed in beans, likely because, as seeds, their nutrient composition is tightly regulated by the plant. This homeostasis ensures a balanced and genetically determined nutrient reserve essential for seedling establishment (Li et al., 2023; Wu et al., 2019).

Analysis of leaf nutrient composition revealed consistent patterns among cocoa clones, accompanied by significant variation that may reflect differences in nutrient allocation under full-sun cultivation, an environment that contrasts with the species' native understory habitat characterized by diffuse radiation (Bahia et al., 2021). Nitrogen was the most concentrated element in most clones, highlighting its central role in chlorophyll synthesis and protein formation, both essential for maintaining photosynthetic activity under high irradiance. The exception was clone CP 49, in which Ca was the most abundant element. The ranking of the second and third most concentrated nutrients further differentiated the clones. Calcium ranked second and K third in PS 1319, CCN 10, and SJ 02, whereas this order was reversed in CCN 51 and PH 16. Clone CP 49 exhibited a distinct pattern, with N as the second most concentrated element, followed by K.

The observed contrast in Ca and K accumulation patterns among clones may reflect differences in nutrient allocation strategies under full-sun cultivation conditions. Clones PS 1319, CCN 10, and SJ 02 exhibited relatively greater Ca accumulation, whereas CCN 51 and PH 16 accumulated proportionally more K. Because Ca contributes to cell wall structure and membrane stability, greater Ca accumulation may be associated with enhanced tolerance to environmental stresses such as drought and high temperatures. Conversely, K plays a key role in stomatal regulation, osmotic adjustment, and enzyme activation, suggesting that higher K accumulation may support physiological processes associated with carbon assimilation and water-use efficiency. Beyond these elements, a consistent descending order of Mg, S, P, Mn, and Zn was observed across clones, indicating a conserved requirement for these nutrients in fundamental physiological processes such as photosynthesis and energy metabolism. A minor variation was observed only for the least concentrated elements, B and Fe, with B occurring at lower concentrations than Fe exclusively in clone CCN 10.

The relative consistency observed for secondary nutrients, together with variation in primary macronutrients, suggests that uniform fertilization management may not adequately meet the nutritional requirements for all clones. Consequently, clone-specific nutrient management may improve crop performance under full-sun conditions. Clones exhibiting greater K accumulation, such as CCN 51 and PH 16, may require particular attention to K supply and water availability to sustain physiological processes dependent on this nutrient. In contrast, clones exhibiting greater Ca accumulation, such as PS 1319, CCN 10, and SJ 02, may perform better under environments subject to abiotic stress, provided that soil Ca availability is adequate. Clone CP 49 deserves special attention because of its unusually high Ca accumulation, which may represent a useful trait for breeding programs aimed at improving stress tolerance. Overall, differences in nutrient partitioning among clones reflect functional diversity in nutrient utilization and adaptation to cultivation conditions. Understanding these patterns may contribute to the development of management strategies that optimize productivity and enhance the sustainability of full-sun cocoa production systems.

Our data for N, P, and S concentrations in sun-grown cocoa are consistent with the findings of Bahia et al. (2021), who compared nutrient contents in cocoa cultivated under full-sun and shaded conditions. According to those authors, the higher leaf concentrations of N, P, and S observed under full-sun cultivation may represent an adaptive response to increased radiation. To mitigate photoinhibition and maintain photosynthetic efficiency, plants increase the synthesis of protective compounds, including proteins, carotenoids, and glutathione, as well as energy carriers such as ATP. Because N, P, and S are essential structural components of these compounds, their increased demand may explain the higher nutrient concentrations observed under full-sun conditions.

Analysis of micronutrient contents revealed distinct clone-specific patterns among plant tissues (Table 2). In general, Zn was concentrated primarily in shells and beans, whereas Mn accumulated predominantly in leaves. Statistical analysis of leaf tissues revealed significant differences among clones for Cu, Zn, and Mn. Clones CCN 51, PS 1319, and CCN 10 exhibited significantly higher Cu concentrations. For Zn, the highest concentrations were observed in CCN 51 and PH 16. Notably, clone CP 49 exhibited significantly greater Mn concentrations than the other clones, which may indicate differences in micronutrient utilization and physiological regulation (Arévalo-Gardini et al., 2021; Benjamin et al., 2025). Genotypic variation was also reflected in the order of micronutrient concentrations in the shell. The sequence Zn > B > Mn was observed in CCN 51, PS 1319, and CCN 10, whereas the sequence Zn > Mn > B occurred in PH 16, CP 49, and SJ 02. These differences suggest variation in nutrient allocation during shell development (Alonso-Báez et al., 2020). In beans, a significant difference was detected for most micronutrients, except Fe. The concentration sequences were Zn > Fe > B > Mn > Cu for CCN 51; Zn > Fe > Cu > Mn > B for PH 16, PS 1319, CP 49, and SJ 02; and Zn > Fe > Mn > Cu > B for CCN 10.

Table 2. Content of micronutrients of compartments diagnostic leaf, shell and bean of six cocoa clones grown in full sun in the municipality of Linhares, ES.

Clone	Cu	Fe	Zn	Mn	B
Diagnostic leaf (mg kg^{-1})					
CCN 51	16.46 (53.20) a	31.83 (17.21) a	67.90 (24.18) a	75.46 (32.82) b	37.98 (24.82) a
PH 16	11.38 (52.51) b	35.47 (38.88) a	65.94 (21.78) a	120.35 (51.19) b	40.11 (23.96) a
PS 1319	33.58 (43.43) a	29.01 (31.30) a	56.55 (26.46) b	135.66 (44.18) b	41.03 (22.09) a
CCN 10	29.39 (50.27) a	44.55 (70.86) a	54.44 (26.38) b	111.19 (48.27) b	35.60 (19.08) a
CP 49	21.42 (85.11) b	26.95 (25.47) a	56.27 (28.58) b	398.65 (73.35) a	40.70 (21.92) a
SJ 02	4.15 (62.06) c	38.16 (49.33) a	54.44 (25.22) b	105.73 (33.60) b	38.52 (19.60) a
Mean	19.40	34.32	59.26	157.84	38.99
CV (%)	57.76	38.84	25.43	47.23	21.91
Shell (mg kg^{-1})					
CCN 51	6.01 a	16.72 a	45.38 a	11.42 b	19.69 a
PH 16	6.97 a	12.00 a	37.40 b	18.11 a	16.61 a
PS 1319	6.92 a	14.45 a	36.83 b	7.96 b	10.24 b
CCN 10	7.27 a	14.06 a	40.56 b	18.45 a	19.45 a
CP 49	6.92 a	9.18 a	37.74 b	26.90 a	16.82 a
SJ 02	7.88 a	10.51 a	39.57 b	15.35 b	10.24 b
Mean	6.99	12.82	39.58	16.36	15.51
CV (%)	8.67	21.69	8.01	40.02	27.58
Bean (mg kg^{-1})					
CCN 51	13.03 b	29.49 a	55.71 a	14.13 b	15.42 a
PH 16	17.69 a	25.19 a	50.58 b	13.92 b	11.08 b
PS 1319	15.27 b	27.18 a	42.88 c	11.04 b	9.25 b
CCN 10	17.22 a	27.03 a	47.66 b	17.87 a	15.39 a
CP 49	16.80 a	27.25 a	48.32 b	15.93 a	11.17 b
SJ 02	19.95 a	31.13 a	58.68 a	12.89 b	9.20 b
Mean	16.66	27.88	50.64	14.30	11.92
CV (%)	14.03	7.52	11.34	16.61	23.76

Means followed by the same letter, in the columns, do not differ from each other by the Scott-Knott test at 5% probability. Numbers in brackets correspond to the coefficient of variation of the mean.

The predominance of Zn in beans across all clones underscores its importance in seed development and enzyme activation, with potential implications for bean quality and nutritional value. Variation in the concentrations of the remaining micronutrients, particularly the elevated B concentration in CCN 51 and the relatively higher Cu concentrations observed in other clones, may contribute to differences in bean composition and quality. These results further demonstrate substantial clonal diversity in nutrient partitioning and reinforce the potential benefits of site-specific and clone-specific nutrient management strategies aimed at maximizing yield, improving bean quality, and increasing the sustainability of cocoa production systems.

Differences among clones in nutrient contents across plant compartments were expected because of variation in yield among genotypes. However, no direct relationship was observed between nutrient concentrations and yield. Variation in leaf nutrient concentrations among cocoa clones has been previously reported and may reflect differences in nutrient requirements, nutrient-use efficiency, or nutrient acquisition capacity. Nevertheless, these hypotheses cannot be evaluated conclusively because dry matter allocation and nutrient distribution among plant organs (leaves, stems, roots, and reproductive structures) were not investigated in the present study.

Comparisons between nutrient concentrations in commercial plantations and reference values allow diagnosis of the nutritional status of the crop. Such reference values, known as norms, should be obtained from populations of plants of the same species, preferably of the same cultivar, grown under optimal conditions and expressing high productivity (Martinez et al., 2014). Given the cultivation conditions and the high yields obtained in the present study, the nutrient means and their coefficients of variation represent valuable and unprecedented reference parameters for nutritional diagnosis of cocoa

cultivated under full-sun conditions. These data may support the application of dynamic diagnostic methods such as the Optimal Percentage Deviation (OPD) (Montañés et al., 1993) and the Kenworthy Balance Index (Kenworthy, 1961).

Regarding the establishment of Diagnosis and Recommendation Integrated System (DRIS) norms (Beaufils, 1973), the number of samples per clone was relatively low. Combining data from all clones would increase the sample size to 84 observations, making DRIS development statistically feasible. However, considering the nutritional differences observed among clones, establishing DRIS norms based on the pooled dataset is not recommended.

Adequate sufficiency range

The occurrence of normal distribution of the nutrient contents in the diagnostic leaf, within each clone, allowed adequate sufficiency ranges considering "$\mu \pm \sigma$" (Table 3). For this purpose, it was assumed that all the clones presented high yield of dried bean in that year, CCN 51: 2 889.8 kg ha^{-1}; PH 16: 2 083.5 kg ha^{-1}; PS 1319: 2 470.5 kg ha^{-1}; CCN 10: 1 220.4 kg ha^{-1}; CP 49: 1 655.1 kg ha^{-1} and SJ 02: 1 526.2 kg ha^{-1}. Fruit number per clone strongly correlated with these yield variations among clones under the given conditions (Benjamin et al., 2025). Direct light incidence on the stems under full sun conditions also stimulates flowering in cocoa, a cauliferous species, thereby driving higher yields (Wibaux et al., 2025). This increased reproductive activity makes the trees more productive but also increases their demand for mineral nutrients (Bahia et al., 2021).

Table 3. Adequate sufficiency ranges established for cocoa clones grown in full sun in the municipality of Linhares, ES.

Clone	N	P	K	Ca	Mg	S
Macronutrients (g kg^{-1})						
CCN 51	18.3–23.8	1.5–1.9	12.4–17.1	9.7–14.5	5.1–6.9	1.9–2.4
PH 16	20.0–25.1	1.5–1.9	13.1–18.8	8.2–15.8	4.7–6.1	1.8–2.3
PS 1319	16.5–21.3	1.1–1.6	10.5–14.5	10.8–18.3	5.1–7.2	1.5–2.4
CCN 10	18.4–21.9	1.0–1.7	10.3–14.8	11.6–18.8	5.9–7.9	1.9–2.5
CP 49	16.6–21.3	0.9–1.5	7.3–12.9	13.1–23.1	6.6–9.0	1.6–2.3
SJ 02	14.9–20.8	0.9–1.4	10.0–15.0	13.7–19.0	6.1–7.5	1.4–2.1
Average	17.4–22.4	1.1–1.7	10.6–15.5	11.2–18.2	5.6–7.4	1.7–2.3
Micronutrients (mg kg^{-1})						
Clone	**Cu**	**Fe**	**Zn**	**Mn**	**B**	
CCN 51	7.7–25.2	26.3–37.3	51.5–84.3	50.1–100.2	28.5–47.4	
PH 16	5.4–17.4	21.7–49.3	51.6–80.3	58.7–182.0	30.5–49.7	
PS 1319	19.0–48.2	19.9–38.1	41.6–71.5	75.7–195.6	32.0–50.1	
CCN 10	14.6–44.2	13.0 – 76,1	40.1–68.8	57.5–164.9	28.8–42.4	
CP 49	3.2–39.7	20.1–33.8	40.2–72.3	106.2–691.1	31.8–49.6	
SJ 02	1.6–6.7	19.3–57.0	46.7–68.2	70.2–141.3	31.0–46.1	
Average	8.6–30.2	20.0–48.6	45.3–74.2	69.7–245.9	30.4–47.6	

The ranges were established considering μ ± σ, *n= 14*. Considering the same condition of cultivation and clone, superior or inferior values to the superior or inferior limit of the range indicate an excess or insufficiency of the nutrient, respectively. Data presented a normal distribution (Shapiro-Wilk, Kolmogorov-Smirnov or Cramer-von Mises.). Yield of dried bean- CCN 51: 2 889.8 kg/ha; PH 16: 2 083.5 kg/ha; PS 1319: 2 470.5 kg/ha; CCN 10: 1 220.4 kg/ha; CP 49: 1 655.1 kg/ha and SJ 02: 1 526.2 kg/ha.

Typically, the nutrient sufficiency range method is widely used to diagnose the nutritional status of agricultural and forest crops. This method allows for the classification of nutrient content levels, ranging from deficient to excessive (Kenworthy, 1961; Beaufils, 1973; Montañés et al., 1993; Ali, 2018). Thus, the establishment of ranges represents an approach in conditions of cultivation in full sun in Brazil, since the available ranges in the literature are scarce for cocoa cultivation under these conditions (Bahia et al., 2021). Additionally, differences among the ranges established in this work with others can be attributed to the changes in the cultivation conditions (from shading to full sun); however, they do not allow for an evaluation at a clone level, since the traditional ranges are generic.

The broader sufficiency ranges observed for micronutrients (Fe, Cu, Mn) compared with macronutrients reflect greater variability in leaf tissue concentrations (Bahia et al., 2021). This variability is likely associated with spatial and temporal heterogeneity in soil conditions under field environments. In the present study area, the soil is a poorly structured Fluvic Cambisol with inherent drainage limitations, which promotes fluctuations in soil redox potential. These redox dynamics strongly influence the solubility and phytoavailability of Fe, Mn, and Cu by altering their oxidation states, leading to increased variability in plant uptake. Consequently, greater fluctuations in leaf concentrations of these micronutrients are expected, resulting in wider sufficiency ranges. Additionally, physiological mechanisms such as root sequestration, rhizosphere microbial interactions, secretion of complexing compounds, metal chelation, and vacuolar

compartmentalization in cacao may further modulate micronutrient toxicity and contribute to plant adaptation to variable redox environments (Skuza et al., 2022).

While international and national literatures (Araujo et al., 2020; Marrocos et al., 2020; Loureiro et al., 2024; Snoeck et al., 2016) provide general guidelines for adequate leaf nutrient levels in cocoa, these ranges are not specific to particular regions, genotypes, or cultivation conditions. Recent studies emphasize the need for genotype-specific nutrient diagnostics, as clonal variations significantly influence nutritional requirements (Oliveira et al., 2019; Ruseani et al., 2022). Our findings confirm substantial variability in nutrient ranges among clones, underscoring the necessity of establishing clone-specific parameters.

Although clones were cultivated under uniform environmental and agronomic conditions, the observed differences in nutrient profiles cannot be conclusively linked to variations in nutrient demand or use efficiency. This limitation arises because nutrient partitioning, particularly across roots, stems, and leaves, was not assessed.

Nutrient export

The macronutrient export associated with the production of 1.0 t of dried beans is presented in Table 4. Overall, clone CP 49 showed the highest nutrient export at the whole-fruit level for most macronutrients. However, this pattern was mainly driven by its greater nutrient accumulation in the shell, where significantly higher amounts of N, P, K, Ca, Mg, and S were observed compared with most other clones. In contrast, nutrient export through the beans was generally similar among clones. No significant differences were observed for N, K, Mg, or S export in the beans, whereas clone CCN 10 showed the highest P export and clones SJ 02, CCN 10, and PH 16 exhibited greater Ca export. These results indicate that the higher nutrient export observed in CP 49 was primarily associated with nutrient partitioning to the shell rather than with nutrient removal through the beans.

Table 4. Exportation of macronutrients for shell, bean and fruit in six cocoa clones grown in full sun in the municipality of Linhares, ES.

Clone	N	P	K	Ca	Mg	S
Shell (kg t^{-1})						
CCN 51	13.92 b	1.67 c	21.93 b	3.28 b	3.44 b	2.19 b
PH 16	15.40 b	1.62 c	23.28 b	4.42 b	3.25 b	2.25 b
PS 1319	11.32 b	1.18 c	21.60 b	2.57 b	2.47 b	1.78 b
CCN 10	16.15 b	1.48 c	26.25 b	4.50 b	3.77 b	2.52 b
CP 49	33.00 a	3.47 a	53.27 a	8.85 a	7.02 a	4.57 a
SJ 02	19.94 b	2.40 b	34.25 b	7.45 a	5.45 a	3.06 b
Mean	18.29	1.49	30.01	5.18	4.23	2.73
CV (%)	42.33	14.80	40.81	47.39	39.8	36.5
Bean (kg t^{-1})						
CCN 51	21.31 a	4.20 b	9.44 a	0.89 b	3.35 a	1.44 a
PH 16	22.01 a	4.02 b	10.49 a	1.05 a	3.32 a	1.41 a
PS 1319	22.19 a	4.00 b	10.57 a	0.92 b	3.44 a	1.42 a
CCN 10	22.56 a	4.82 a	10.35 a	1.17 a	3.67 a	1.35 a
CP 49	22.43 a	4.19 b	10.06 a	0.91 b	3.38 a	1.41 a
SJ 02	20.33 a	3.97 b	9.61 a	1.19 a	3.20 a	1.50 a
Mean	21.80	4.20	10.09	1.02	3.39	1.42
CV (%)	3.90	7.60	4.67	13.23	4.63	3.43
Fruit (shell + bean) (kg t^{-1})						
CCN 51	35.23 b	5.87 b	31.37 b	4.18 b	6.79 b	3.63 b
PH 16	37.41 b	5.65 b	33.78 b	5.47 b	6.58 b	3.66 b
PS 1319	33.51 b	5.18 b	32.17 b	3.49 b	5.91 b	3.20 b
CCN 10	38.71 b	6.31 b	36.61 b	5.67 b	7.44 b	3.87 b
CP 49	55.43 a	7.67 a	63.33 a	9.77 a	10.40 a	5.99 a
SJ 02	40.27 b	6.36 b	43.87 b	8.65 a	8.65 a	4.57 b
Mean	40.1	6.17	40.20	6.20	7.63	4.15
CV (%)	19.70	13.83	30.37	40.12	21.55	24.20

Means followed by the same letter, in the columns, do not differ from each other by the Scott-Knott test at 5% probability; Fruit = shell + bean. Yield of dried bean- CCN 51: 2 889.8 kg/ha; PH 16: 2 083.5 kg/ha; PS 1319: 2 470.5 kg/ha; CCN 10: 1 220.4 kg/ha; CP 49: 1 655.1 kg/ha and SJ 02: 1 526.2 kg/ha

For Ca and Mg, in the shell and fruit, clones CP 49 and SJ 02 presented greater exportations. As for S, again material CP 49 exported a greater amount for the shell and fruit. For the exported amount of Mg, in the bean, there was no significant difference among clones. The order of macronutrient export in the shell was similar among all clones: K>N>Ca>Mg>S>P.

For the bean, also the sequence of exportation was N>K>Mg>P>S>Ca for most of the clones, except for CCN 10 (N>K>P>Mg>Ca>S). Under shading conditions, Araujo et al. (2017) reported a different nutrient export pattern for the PH 16 clone. While N and K remained the first and second most exported nutrients, respectively, the relative order of the remaining nutrients differed, with Ca export exceeding that of P and Mg. This change indicates that the growing conditions affected nutrient partitioning and export dynamics.

Regarding the order of exportation of macronutrients to the fruits, the first and second most exported elements altered between N and K, N being more exported by clones CCN 51, PH 16, PS 1319 and CCN 10, and K by CP 49 and SJ 02. As for Ca, P and Mg, they altered among clones for the third, fourth or fifth order of exportation. S was the element exported in the least amount by all the clones.

The export of micronutrients per t of dried beans is presented in Table 5. There was variation in micronutrient export among clones across different compartments. Zn was the most exported micronutrient in all three compartments. Exports through the shell, compared with the bean, were higher for all micronutrients (Table 5). Micronutrient export followed the descending order Zn > Mn > B > Fe > Cu in the shell and fruit, whereas in the bean, the order was Zn > Fe > Cu > Mn > B.

Table 5. Exportation of micronutrients for shell, bean and fruit (shell + bean) in six cocoa clones grown in full sun, in the municipality of Linhares, ES.

Clone	Cu	Fe	Zn	Mn	B
Shell (g t^{-1})					
CCN 51	67.88 b	201.06 a	519.35 b	130.42 b	224.45 b
PH 16	83.12 b	148.76 a	441.09 b	217.91 b	192.05 b
PS 1319	74.61 b	161.70 a	402.03 b	90.72 b	107.88 b
CCN 10	88.78 b	176.35 a	517.90 b	230.81 b	258.03 b
CP 49	198.89 a	291.66 a	1062.40 a	796.84 a	478.29 a
SJ 02	136.10 a	154.03 a	659.22 b	282.51 b	246.44 b
Mean	108.23	188.93	600.33	291.53	251.19
CV (%)	46.68	28.44	40.46	88.23	49.21
Bean (g t^{-1})					
CCN 51	13.03 b	29.49 b	55.71 a	14.13 b	15.42 a
PH 16	17.79 a	25.20 b	50.58 b	13.92 b	11.08 b
PS 1319	15.27 b	49.68 a	42.88 c	11.04 b	9.25 b
CCN 10	17.22 a	27.03 b	47.66 b	17.87 a	15.40 a
CP 49	16.80 a	27.25 b	48.32 b	15.93 a	11.18 b
SJ 02	19.95 a	31.13 b	58.68 a	12.89 b	9.2 b
Mean	16.67	31.63	50.64	14.30	11.92
CV (%)	14.07	28.71	11.34	16.61	27.77
Fruit (shell + bean) (g t^{-1})					
CCN 51	80.92 b	230.55 a	575.07 b	144.56 b	239.88 b
PH 16	100.81 b	173.96 a	491.68 b	231.83 b	203.14 b
PS 1319	89.88 b	211.40 a	444.92 b	101.77 b	117.14 b
CCN 10	106.01 b	203.38 a	565.56 b	248.68 b	273.42 b
CP 49	215.69 a	318.92 a	1110.73 a	812.78 a	489.47 a
SJ 02	156.05 a	185.17 a	717.91 b	295.40 b	255.64 b
Mean	124.89	220.56	650.98	305.83	263.12
CV (%)	41.31	23.63	37.42	84.45	47.12

Means followed by the same letter, in the columns, do not differ from each other by the Scott-Knott test at 5% probability; Fruit = shell + bean. Yield of dried bean- CCN 51: 2 889.8 kg/ha; PH 16: 2 083.5 kg/ha; PS 1319: 2 470.5 kg/ha; CCN 10: 1 220.4 kg/ha; CP 49: 1 655.1 kg/ha and SJ 02: 1 526.2 kg/ha.

To produce 1.0 t of beans, considering all clones, N and P were predominantly exported by the beans, whereas K, Ca, and S were mainly exported by the shell. Magnesium was the only macronutrient for which export differed among clones across compartments; CP 49 and SJ 02 showed greater export through the shell, while no significant differences were observed for the bean.

Regarding total micronutrient export, clones CP 49 and SJ 02 stood out compared with the others, except for Fe. For example, CP 49 exported approximately nine times more total micronutrients than PS 1319. All clones showed Zn as the most exported micronutrient in both the shell and the bean.

When considering total fruit export, clone CP 49 differed from the others for N, P, K, and S. Potassium showed the greatest difference, with CP 49 exporting about twice the amount observed in CCN 51. Calcium was the nutrient with the greatest variation among clones in total export.

In studies evaluating yield and nutrient export of similar cocoa clones (CCN 10, CCN 51, PH 16, and PS 1319) in southern Bahia, Silva (2015) reported different macro- and micronutrient export values in fruits. Nutrients such as K, Mg, Cu, Fe, Mn, and Zn were exported in greater amounts in that study compared with the present work.

The order of nutrient uptake and export depends on complex interactions among soil, plant, and climatic conditions, as also reported by Araujo et al. (2017) for the 'PH16' clone across ten municipalities in southern Bahia.

Variations in soil fertility among different experimental conditions significantly influence nutrient partitioning between plant compartments, including the harvested product, making direct comparisons with other studies difficult or unreliable. Therefore, a key finding of this study is the establishment of clone-specific nutritional sufficiency ranges for cocoa grown under full-sun conditions. Additionally, our results demonstrate that returning cocoa shell to the cultivation area can restore a substantial proportion of the nutrients exported during harvest, namely 46% of N, 32% of P, 75% of K, 84% of Ca, 56% of Mg, 66% of S, 87% of Cu, 86% of Fe, 92% of Zn, and 95% of both Mn and B. Furthermore, enriching shell with calcium oxyhydroxides as a phytosanitary treatment not only increases their calcium content but also provides a soil acidity correction effect.

Materials and methods

Cultivation conditions and clones

In the state of Espírito Santo, Brazil, the area under commercial cocoa cultivation under full-sun conditions has expanded in recent years. Because this production system is relatively new in Brazil, growers have established plantations using different genetic materials (clones) to identify those best adapted to these conditions.

The present study was conducted at Três Lagoas Farm, located in the municipality of Linhares, northern Espírito Santo, Brazil (19°17′28.3″ S, 40°10′13.3″ W), where the adaptation of the main commercial cocoa clones cultivated in Brazil has been evaluated. Homogeneous fields planted with the following clones were selected: PS 1319, CCN 10, CCN 51, PH 16, SJ 02, and CP 49. At the time of the study, the trees were eight years old. The plantation was established on flat terrain with a spacing of 3.5 × 2.5 m and managed under a drip fertigation system. All experimental fields received the same fertilization, phytosanitary, and irrigation management practices.

According to the Köppen climate classification, the regional climate is Aw, characterized by a humid summer and a dry winter. During the experimental period, daily climatic data were recorded. Monthly mean air temperature followed a seasonal pattern characteristic of the Southern Hemisphere, with the highest values (32.0 °C) recorded from January to March (summer), followed by a decrease during autumn. The lowest monthly mean temperatures (21.75 °C) occurred in July and August (winter), followed by a gradual increase during spring. Mean relative humidity was 78% (range: 55–96%), cumulative precipitation totaled 1,291 mm, and mean solar radiation was 16.4 MJ m^{-2} day^{-1} (range: 8.2–22.5 MJ m^{-2} day^{-1}) (Fig. 1). Sunny days (>70% of possible sunshine duration) accounted for 142 days over the 365-day evaluation period. The predominant soil type in the experimental area was a Fluvic Cambisol.

From February 2018 to February 2019, climatic monitoring was conducted using a meteorological station (model E 5.000/IRRIPLUS) installed near the experimental area. Monthly mean air temperature ranged from 21.51 °C in July to 29.60 °C in September (Fig. 1A). Rainfall distribution (Fig. 1B) showed the highest precipitation during spring (37%) and summer (31%), whereas lower values were recorded in autumn (23%) and winter (9%), resulting in a wetter main growing season and a drier intercrop period. Solar radiation (Fig. 1A) was lowest in June (15.57 MJ m^{-2} day^{-1}) and highest in January and February (22.32 and 22.42 MJ m^{-2} day^{-1}, respectively).

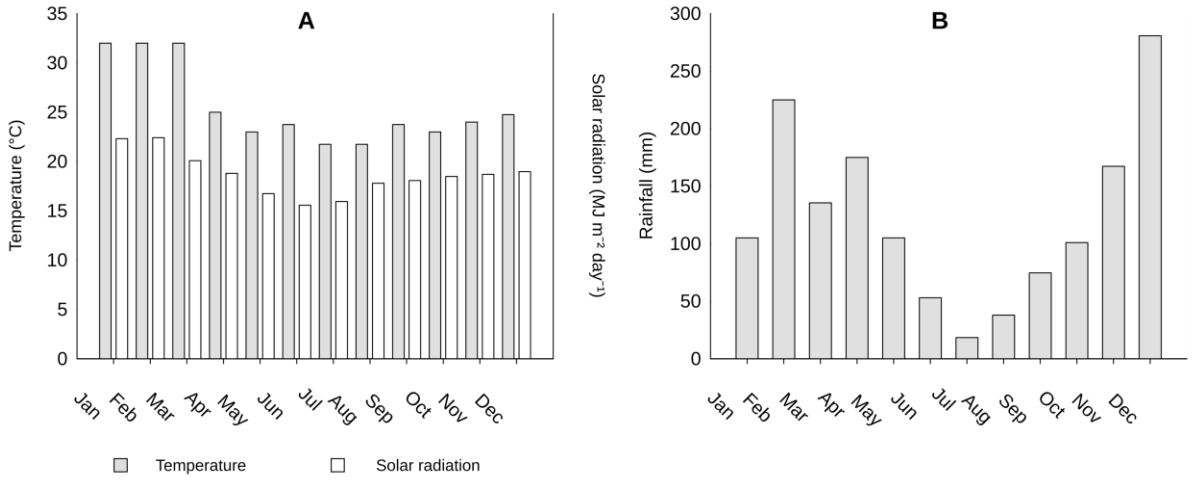


Fig. 1. Mean air temperature and solar radiation (A), and rainfall (B) in the municipality of Linhares, Espírito Santo, Brazil, during 2018. Data from Benjamin et al. (2025).

Sampling, processing and analysis of leaves and fruits

For leaf sampling, four plants of each clone were randomly selected, and four diagnostic leaves were collected from each plant. Two leaves were collected from branches oriented along the planting row, and two from branches oriented perpendicular to the row. The sampled leaves were newly mature, located at approximately half the canopy height, and positioned as the third leaf from the branch apex.

The leaf samples were washed with running water and subsequently rinsed with cotton moistened with distilled water. Samples were then placed in paper bags and dried in a forced-air oven at 65 ± 5 °C until constant weight was achieved.

Ten ripe fruits were collected from each clone. The fruits were separated into shells (including the placenta) and beans. After drying, all plant materials (leaves, beans, and shells) were ground in a Wiley mill for nutrient analysis. Nutrient concentrations of P, K, Ca, Mg, S, Zn, Cu, Mn, Fe, and B were determined after acid digestion using inductively coupled plasma optical emission spectrometry (ICP-OES; PerkinElmer Optima 8300, USA). Nitrogen concentration was determined following sulfuric acid digestion and subsequent Kjeldahl distillation.

The analyzed variables included nutrient concentrations in leaves, beans, and shells, as well as nutrient export through beans and shells. Total nutrient export by the fruit corresponded to the sum of nutrient export in the beans and shells.

Nutrient concentration data obtained from diagnostic leaves of each clone were subjected to tests of normality (Shapiro–Wilk, Kolmogorov–Smirnov, or Cramér–von Mises). Bean yield was evaluated during both the main and secondary harvest seasons from February 2018 to February 2019, corresponding to one complete production cycle. For each clone, healthy fruits produced in each plot were harvested, counted, and weighed, and the seeds were subsequently weighed after processing. Fourteen plots were evaluated per clone, each consisting of a single plant. After confirmation of data normality and evaluation of clonal yield, nutrient sufficiency ranges were established using the mean ± standard deviation ($\mu \pm \sigma$).

Statistical analysis

The experiment was analyzed using a hierarchical classification design. Fourteen plots were randomly established for each of the six clones, with each plot consisting of a single plant. Data were subjected to analysis of variance (ANOVA), and means were compared using the Scott–Knott test at the 5% probability level ($p \leq 0.05$).

Conclusions

Full-sun cocoa cultivation demonstrated considerable production potential, resulting in high bean yields across the evaluated clones. The cocoa clones PS 1319, CCN 10, CCN 51, PH 16, SJ 02, and CP 49 demonstrated distinct nutrient sufficiency ranges, indicating differences in their nutritional requirements. Variation among clones in nutrient export and nutrient partitioning within the fruit highlights the importance of adopting clone-specific nutrient management strategies to improve the accuracy of fertilization recommendations. Furthermore, the use of cocoa shells as an organic fertilizer may replenish between 32% and 95% of the nutrients exported by the fruits, representing a sustainable approach to nutrient recycling and resource use efficiency in cocoa production systems.

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Author contributions

Carolina Santos Benjamin (Conceptualization, Methodology, Data analysis and Writing original Draft); Luiz Antônio dos Santos Dias (Conceptualization, Methodology, Data analysis, and Funding Acquisition); Wedisson Oliveira Santos (Writing, Review & Editing); Larissa Carmelina Alves Pinto (Writing, Review & Editing) and Marcela Carvalho Valente (Writing, Review & Editing).

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