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Variation in Grain Mineral Concentrations of 63 Common Bean Genotypes Planted at Malkerns, Eswatini, in Africa

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ABSTRACT

Low soil mineral concentrations are a major limitation to the nutritional quality of grain crops produced in Africa. As a result, 232 million people are suffering from microelement deficiency and 239 million from protein-calorie malnutrition in Africa. This study evaluated the nutritional quality of common bean grain harvested from 63 genotypes planted at Malkerns in Eswatini. The results showed significantly marked differences in the concentrations of 10 dietarily important nutrient elements. Of the macronutrients, Na levels showed the highest variation (12.00–91.00 mg/g) among the 63 bean genotypes, followed by K (14.03–22.03 mg/g) and P (3.30–9.57 mg/g), with Mg (1.57–2.30 mg/g) and Ca (0.80–2.68 mg/g) concentrations exhibiting the least difference among the bean genotypes. Of the micronutrients, Fe levels revealed the highest variation (66.36–151.08 mg/kg), followed by Zn (23.57–70.72 mg/kg) and Mn (11.53–26.84 mg/kg), with B (10.06–17.65 mg/kg) and Cu (6.30–13.67 mg/kg) exhibiting relatively lower differences among the 63 common bean genotypes. However, genotype NUC 461 recorded the highest grain concentrations of P, K, Mg, Fe, Cu, Zn, and B, followed by DAB 155, which also revealed high levels of P, K, Ca, Fe, Zn, and Mn in its seeds. For improved human health and nutrition, the two bean genotypes would be the ideal candidates to recommend to commercial bean growers and resource-poor farmers. However, the mechanisms underlying the greater accumulation of six to seven dietarily important nutrient elements by genotypes NUC 461 and DAB 155 remain to be determined.

1 | Introduction

Even though African soils are nutrient-poor, farmers generally do not apply synthetic fertilizers to their crops. According to Henao and Baanante (2006), only about 8.8 kg NPK fertilizer is applied per hectare by small-scale farmers in Africa on average. The net result is low crop yields, often leading to food insecurity, hunger, and protein-calorie malnutrition in many households in Africa (Henao and Baanante 2006). Around 239 million people are suffering from protein-calorie malnutrition in Africa because of low soil N and crop yields (Fanzo 2012). Additionally, the inherently low concentration of mineral nutrients in African soils that can lead to even reduced plant-available forms implies that crops cultivated in these soils are likely to be low in mineral nutrients. As a result, about 232 million Africans are suffering from microelement deficiency (Andrea and Rose 2015; Dakora and Belane 2019). There is therefore a need to identify crop species and varieties that can accumulate mineral nutrients from these infertile African soils. Symbiotic legumes can take up and accumulate mineral nutrients even under low nutrient conditions using various mechanisms, which include root exudation of Krebs cycle intermediates, bacterial secretion of siderophores, plant release of phytosiderophores, bacterial and plant exudation of acid and alkaline phosphatases, cluster root secretion of organic acids, mycorrhizal-assisted uptake of nutrients and differential synthesis of root ion transporter proteins (Dakora and Phillips 2002; Maseko and Dakora 2013).

Mineral deficiencies are the main public health concern, as they affect about half of the world's population (Blair et al. 2009). "Globally, about three (3) billion people are at risk of iron (Fe) deficiency, and another 1.5 billion are at risk of iodine (I) deficiency" (Belane and Dakora 2011). It has been reported that zinc deficiency currently affects more than one-third of the world's population (Dhaliwal et al. 2022).

Eswatini is a lower middle-income country with an estimated population of 1.2 million and growing at a rate of 1.5% with approximately 42% of the population under the age of 17 annually (Villani 2021). Poverty remains a major challenge with 59% living under the poverty line, 20% (240000) deemed extremely poor, with food insecurity affecting 14% of the population. Most people in Eswatini (70%) live in rural areas, where they rely on smallholder agriculture for food and nutritional security with intermittent food aid (Villani 2021).

The major challenges faced by smallholder farmers in Eswatini include irregular rainfall, frequent droughts, prolonged dry spells, and nonclimatic factors such as poor technical assistance, soil degradation, and lack of access to inputs (Manyatsi, Mhazo, and Masarirambi 2010; Mulungu and Ng'ombe 2019; Mbuli, Fonjong, and Fletcher 2021).

Drought stress can have a long-term negative impact on phosphorus (P) uptake and accumulation in crop species such as the common bean, which is a poor extractor of mineral P (Ghanbari, Mousavi, and Pessarakli 2015). Studies have indicated that the soils of Eswatini are deficient in zinc (Zn), manganese (Mn), and nitrogen (N), with the other minerals varying in levels from area to area (Haque and Lupwayi 2003). For example, adequate concentrations of soil magnesium (Mg) and calcium (Ca) were reported in some regions, whereas potassium (K) and phosphorus (P) were deficient (Haque and Lupwayi 2003), thus limiting the cultivation of maize (the staple crop) without the use of synthetic fertilizers.

In Eswatini, about 31% of children below the age of 5 years are stunted in growth, 6% are underweight, and 1% are wasted (Masuku-Maseko and Owaga 2012). Around 13% of children from Eswatini do not receive the minimum level of dietary energy intake (2100 Kcal) with the highest occurrence of low-calorie intake recorded in the Lubombo region (18%), followed by Shiselweni (15.4%), Hhohho (7.9%), and Manzini (6.1%) (Masuku-Maseko and Owaga 2012).

Common bean is widely grown in Eswatini for its rich protein content (25.6%), lipids (1.12%), fiber (4%), carbohydrates (37.2%), and mineral nutrients such as Mn (1.87 mg/100 g), Mg (158 mg/100 g), K (1580 mg/100 g), Zn (3.71 mg/100 g), P (543 mg/100 g), Fe (4.7 mg/100 g), B (1040 μg/100 g), Cu (1.03 mg/100 g), and Ca (158 mg/100 g) (Edje and Ossom 2009).

These macronutrients and trace elements are needed for human nutrition and health. It is therefore important to identify nutrient-dense grains and legume to complement the maize-based staple diet which is poor in essential nutrients. Common bean is also an N_2-fixing grain legume that can be used to improve soil N fertility. The world production statistics of common bean have increased over the years from 24.94 to 31.41 million metric tons (MMT) between 2013 and 2017, and the latest statistics for 2019 show that 88.38 MMT were produced globally (FAO STAT 2021). In contrast, in 2019 Eswatini imported 7625 t of common bean to complement the 5425 t it produced (Wamucii et al. 2021). Short-season, drought-tolerant, disease-resistant, and high-yielding common bean cultivars with high mineral density must be developed to meet local consumption and thus address protein-calorie malnutrition and trace element deficiency.

Due to nutrient deficiency of African soils that limits the nutrient uptake in plants, as well as the expensive synthetic fertilizers and them having negative impact on the environment, there is a need to develop sustainably green and affordable technologies to increase the nutritional quality of food legumes for use by resource-poor, smallholder farmers in Africa. Although common bean cultivars have been developed, few have been evaluated for the nutritional quality of the edible grain. This study aimed to assess the macronutrients (P, K, Ca, Na, and Mg) and micronutrients (Fe, Cu, Zn, Mn, and B) in the grain of the 63 common bean genotypes in Eswatini to select superior genotypes for improving food and nutritional security in the country.

2 | Materials and Methods

2.1 | Description of Study Site

Field trial was conducted during the 2017/2018 cropping season at the Malkerns Agricultural Research Station, Eswatini, with reference co-ordinate 31°10′10.29″ E; 26°33′18.33″ S, and elevation of 700 m above sea level. The climate of the area is classified as subtropical with an annual average temperature ranging from 7°C to 26.6°C and average annual rainfall ranging between 800 and 1000 mm. The environmental details of Malkerns research station during cropping season (temperature, relative humidity, and rainfall) are described in Table 1.

2.2 | Origin of the Common Bean Genotypes

Common bean genotypes used in this study originated from the Malkerns Research Station Gene Bank at Eswatini. The 63 tested genotypes showed different valuable biological traits ranging from a number of days to 50% flowering and number of days to physiological harvest to levels of nitrogen fixation and grain yield.

2.3 | Experimental Design, Planting, and Pest Management

The 63 self-pollinated common bean genotypes were planted in a randomized complete block design (RCBD) using four replicate plots per genotype. The size of the plots was 6m^2 (i.e., 3 × 2 m) with 1 m separating adjacent blocks. The trial was planted in mid-December, with a 60 cm inter-row and 10 cm intra-row spacing. The experimental field was ploughed mechanically, and the harrowing was done with a ploughing disc. The field trial was

TABLE 1 | Temperature, rainfall, and relative humidity recorded during the 2017/2018 cropping season.

2017/2018	Temperature (°C)		Rainfall (mm)	Relative humidity (%)	
	Min.	Max.		Min.	Max.
December	16.9	26.8	228.6	66.6	95.8
January	16.9	28.9	100	55.6	95.5
February	18.3	28.3	175	64	96.8
March	16.8	28.5	200	62.4	97.8
April	15.7	26.7	76.6	62.6	97.8
May	16.92	25.3	36.2	51.9	96.7
Mean	16.9	27.4	136.1	60.5	96.7

conducted under natural rainfed conditions without irrigation or any chemical input. There was also no seed treatment used.

Two seeds were planted in 5 cm depth per hole and later thinned to one plant. Total number of seeds used per genotypes in a plot was 120. Four to five weeks after emergence, weeds were controlled manually using hand hoes and pests were controlled chemically using a mixture of chlorpyrifos and beef oil before flowering.

2.4 | Chemical Soil Analyses

To determine the soil chemical properties of the study site, the bulk soil samples were collected across the field at a depth of 30 cm before sowing, pooled and air-dried at room temperature, sieved (2.0 mm), and sent for analysis of pH, P, K, Ca, Mg, and Na at the Agricultural Research Council (ARC)-Institute for Soil, Climate and Water, Arcadia, South Africa. Analyses were done using the citric acid method (Dyer 1894; Dakora and Belane 2019).

2.5 | Plant Sampling and Processing

At physiological maturity, 72 days after planting (DAP), 10 plants were dug up from the two inner rows, and pods were detached, shelled, oven-dried at 65°C, weighed to determine grain yield per hectare, 100-seed weight, and ground to fine powder (0.85 mm) for mineral analysis.

2.6 | Determination of Macro- and Micronutrient Concentrations in Common Bean Grains

The mineral nutrient concentrations in the grain were analyzed at the Soil, Water and Plant Laboratory, Western Cape Department of Agriculture, Elsenburg, South Africa. Each ground seed sample was analyzed in duplicates as described by Belane et al. (2014). Briefly,1 g ground common bean grain sample was washed in a porcelain crucible at 500°C overnight, followed by dissolving the ash in 5 mL HCl for 6 M, placing it in an oven for 30 min at 50°C, and then adding 35 mL deionized water. The mixture was filtered using Whatman No. 1 filter paper, and the concentration of mineral elements seed extracts from four replicate samples using inductively coupled plasma mass spectrometry (IRIS/AP HR DUO Thermo Electron Corporation, Franklin, Massachusetts, USA) (Ataro et al. 2008; Maseko and Dakora 2017). Standard solutions with certificates of analysis were used to check the quality of data collected. In place of analyte isotopes to monitor each element, a known sample was used as standard after every 10 samples.

2.7 | Statistical Analysis

The data on macro- and micronutrient concentration in common bean grains were tested for normality by calculating skewness and kurtosis values using the Statistical Package for Social Science (SPSS) Version 29. The skewness and kurtosis values ranged from 0.153 to 0.786 and −0.024. to +1.30, respectively, and are consistent with values of a normal distribution (Holmes et al. 2017). Thereafter, data was subjected to analysis of variance (ANOVA) using Statistica analytical software program Version 10.1. A one-way ANOVA was used to compare mineral concentration among genotypes and to determine the means differences, Duncan's multiple range test at $p \leq 0.05$ level of significance was performed.

3 | Results

3.1 | Soil Analysis

Analysis of bulk soil sampled from the experimental site prior to planting showed an acidic pH, ranging from pH 4.5 to 4.9; total N ranged from 0.05 to 0.06%; soil available P ranged from 9 to 22 mg/kg, Na 0.03 to 0.04 cmol $^{(+)}$/kg, K 0.29 to 0.34 cmol $^{(+)}$/kg, Ca 1.39 to 1.98 cmol $^{(+)}$/kg and Mg 0.83 to 1.2 cmol $^{(+)}$/kg; and CEC ranged from 4.05 to 5.70 cmol $^{(-)}$/kg, as shown in Table 2. The soil type is classified as deep red loam of the Malkerns Series (Kunene et al. 2019).

3.2 | Concentrations of Macronutrients in the Grain of 63 Common Bean Genotypes

There was a significant difference in the level of macronutrients (P, K, Ca, Na, and Mg) accumulated by the 63 tested common bean genotypes at $p < 0.05$. Grain macronutrient concentration varied

TABLE 2 | Chemical properties of the soil sampled from Malkerns during the 2017/2018 cropping season.

pH	Total N %	Available P mg/kg	Na cmol $^{(+)}$/kg	K cmol $^{(+)}$/kg	Ca cmol $^{(+)}$/kg	Mg cmol $^{(+)}$/kg	CEC cmol $^{(-)}$/kg
4.9	0.062	11	0.044	0.338	1.966	1.209	5.443
4.5	0.062	22	0.033	0.286	1.392	0.831	4.049
4.8	0.052	9	0.036	0.343	1.976	1.193	5.685

Abbreviation: CEC, cation exchange capacity.

from genotype to genotype in common bean (Table 3). For example, P concentration ranged from 3.30 mg/g for genotype CZ 113-15 (SAB 630) to 9.57 mg/g for NUA 743, with the latter being about threefold higher in P concentration than the former.

The common bean genotype with the next highest P level was NUA 461 (8.07 mg/g), followed by DAB 155 (6.37 mg/g) and NUC 451 (6.20 mg/g). In contrast, genotype CZ 113-15 (SAB 630) revealed the least P concentration (3.30 mg/g), followed by NUC 219 (3.57 mg/g) and genotype DAB 559 (3.86 mg/g) (Table 3).

Seed K level also differed among the 63 common bean genotypes and ranged from 14.03 mg/g for genotype MCA 78 to 22.03 mg/g for NUC 461 (Table 3), producing a 1.57-fold greater K in the latter than the former. Genotype KAB 06 F2.8-51 showed the next highest grain K density (19.67 mg/g), followed by DAB 410 (19.47 mg/g) and CZ 104-13 (19.05 mg/g). The genotypes with the lowest K included MCA 78 (14.03 mg/g), DAB 559 (14.42 mg/g), and CIM-RM02-79-1 (14.85 mg/g).

Grain concentrations of Ca varied from 0.80 mg/g for NUC 219 to 2.68 mg. g^{-1} for DAB 381. The next highest grain Ca density was 2.40 mg/g for NUA 735 and 2.33 mg/g for KAB 77 F7.2-52 (Table 3), with genotypes NUC 219 (0.80 mg/g), DFA 73 and DAB 378 (1.00 mg/g), DAB 369 (1.13 mg/g), DAB 387 (1.17 mg/g), and CZ 104-13, CIM-KHAK02-14-1, DAB 470, and CIM-RM07-ALS-71-2 (1.23 mg/g) exhibiting the lowest concentration of Ca in common bean grain (Table 3).

The distribution of Mg also differed among the 63 common bean genotypes with levels ranging from 1.58 mg/g for DAB 429 to 2.30 mg/g for genotype KAB 77 F7.2-52 (Table 3). Genotype CIM-SUG-03-09-04 also revealed a high grain level of Mg (2.27 mg/g), whereas genotypes DAB 429 (1.58 mg/g) and DAB 370 and DAB 386 (1.60 mg/g) recorded the lowest Mg concentrations in bean seeds (Table 3).

The grain concentration of Na varies between 12 and 91 mg/g with genotypes NUA 743 (91 mg/g), NUA 720 (63.3 mg/g), DAB 410 (52.8 mg/g), and CIM-RM07-ALS-71-2 (54.5 mg/g) recording the highest Na grain level, and the lowest was recorded in genotypes CZ 104-13 (12.00 mg/g), CIM-RM02-62-1 (12.3 mg/g), CIM-RM01-92-3 (12.7 mg/g), and CIM-RM02-46-1 (13.7 mg/g) (Table 3).

3.3 | Micronutrient Concentrations in the Grain of 63 Common Bean Genotypes

Micronutrients (viz., Fe, Cu, Zn, Mn, and B) showed significant differences among the 63 common bean genotypes at $p < 0.05$. Grain Fe concentration varied significantly between and among the 63 tested common bean genotypes (Table 4), with NUC 461 recording the highest concentration (151.08 mg/kg), followed by DAB 155 (128.77 mg/kg), MCA 98 (107.51 mg/kg), CIM-RM05-ALS-103 (106.37 mg/kg), and MCA 78 (103.04 mg/kg). In contrast, genotypes CIM-RM01-92-3 (66.36 mg/kg), KAB 77 F7.2-52 (68.50 mg/kg), DAB 386 (70.48 mg/kg), and NUC 219 (70.91 mg/kg) exhibited the lowest grain Fe of the 63 genotypes (Table 4).

Seed Cu density was highest in common bean genotypes MCA 98 (13.67 mg/kg), NUC 451 (13.55 mg/kg), NUC 461 (13.39 mg/kg), CIM-RM02-20-3 (12.42 mg/kg), and CIM-RM01-97-8 and DFA 73 (12.01 mg/kg). In contrast, genotypes NUC 219 (6.30 mg/kg), NUA 35 (7.23 mg/kg), and DAB 369 (7.27 mg/kg) recorded the lowest concentration of Cu in common bean seeds (Table 4).

Zinc concentration in grain was significantly different between and amongst the 63 tested common bean genotypes. The Zn grain levels were markedly higher in genotypes NUC 461 (70.72 mg/kg) and NUC 451 (50.30 mg/kg), with the rest ranging from a low 23.57 mg/kg for NUC 219, 26.39 mg/kg for CIM-RM01-92-3, and 28.91 mg/kg for CIM-RM02-73-1 to 48.29 mg/kg for DAB 155, 47.68 mg/kg for NCB 281, and 46.06 mg/kg for DAB 207 (Table 4).

Grain Mn similarly varied significantly between and among the 63 common bean genotypes, with DAB 155 exhibiting the highest concentrations (26.84 mg/kg), followed by DAB 270 (22.24 mg/kg), NUA 35 (22.04 mg/kg), NUA 720 (21.35 mg/kg), DAB 190 (20.64 mg/kg), and CIM-RM00-141 (20.16 mg/kg). In contrast, genotype NAIN DEKYONDO recorded the lowest seed Mn concentration (11.53 mg/kg), followed by DAB 470 (11.75 mg/kg) and NUA 743 and NUC 219 (12.20 mg/kg).

Seed B concentration was rather low, with the highest being 17.65 mg/kg in CIM-RM01-97-8, 17.48 mg/kg in NUC 461, 17.04 mg/kg in NUA 743 and 16.36 mg/kg in NUA 735 compared with the lowest of 10.06 mg/kg in DAB 411, 10.21 mg/kg in DAB 387, 10.30 mg/kg in NUC 219, 10.51 mg/kg in DAB 410, and 10.60 mg/kg in DAB 174 (Table 4).

3.3.1 | Grain Yield and Hundred Grain Weight (HGW)

The grain yield of the 63 common bean genotypes ranged from 420.42 kg/ha for NUC 461 to 3618.75 kg/ha for CIM-RM02-79-1. Of the 63 bean genotypes, 24 recorded grain yield above 2000 kg/ha, and of these 24, five genotypes could produce over 3000 kg/ha grain yield. Genotype CIM-RM02-79-1

TABLE 3 | Macronutrient (P, K, Ca, Mg, and Na), grain yield, and 100-grain weight of 63 common bean genotypes cultivated at Malkerns Research Station, Eswatini, during the 2017/2018 cropping season.

Genotype	Phosphorus mg/g	Potassium mg/g	Calcium mg/g	Magnesium mg/g	Sodium mg/g	Grain yield kg/ha	100-grain weight g
NUC 461	8.07 ± 0.05b	22.03 ± 0.06a	1.77 ± 0.02f-o	2.20 ± 0.08a-d	44.25 ± 0.63d-i	420.42 ± 3.98C	20.05 ± 1.31C-F
DAB 155	6.37 ± 0.10c	18.07 ± 0.14b-l	2.13 ± 0.15b-f	1.93 ± 0.02f-k	30.25 ± 1.25m-t	1132.50 ± 125.03q-t	28.50 ± 2.23w
MCA 98	5.60 ± 0.29d-i	17.57 ± 0.35b-o	1.37 ± 0.06n-v	1.87 ± 0.06f-n	50.25 ± 1.03c-f	2648.75 ± 118.78de	43.69 ± 0.99i-l
CIM-RM05-ALS-103	4.67 ± 0.21k-r	16.57 ± 0.42h-r	1.40 ± 0.00m-v	1.80 ± 0.08i-p	35.25 ± 2.25j-n	788.75 ± 19.65w-A	29.71 ± 0.89u-A
MCA 78	5.33 ± 0.17e-l	14.03 ± 0.06s	1.73 ± 0.02f-o	1.57 ± 0.02p	52.75 ± 1.25cde	2690.00 ± 47.08d	41.26 ± 1.38j-o
KAB 06 F2.8-51	5.70 ± 0.04c-g	19.67 ± 0.37b	1.20 ± 0.04s-v	1.87 ± 0.02f-n	14.67 ± 0.47z-D	2075.00 ± 94.42hij	46.99 ± 1.14f-i
DFA 73	5.48 ± 0.42d-k	18.70 ± 0.69b-i	1.00 ± 0.15vw	1.73 ± 0.06j-p	17.25 ± 3.17x-D	1017.50 ± 55.59r-w	16.03 ± 0.42F
DAB 387	5.97 ± 0.05cde	16.73 ± 0.56e-q	1.17 ± 0.06t-w	1.63 ± 0.02m-p	28.25 ± 1.93m-v	1141.67 ± 7.73q-t	27.72 ± 0.58x-A
CIM-RM00-141	5.23 ± 0.10e-m	18.10 ± 0.58b-l	1.63 ± 0.15h-r	1.97 ± 0.05e-j	25.75 ± 1.25o-x	1774.58 ± 54.54lmn	31.45 ± 0.84r-x
CIM-RM01-97-8	5.75 ± 0.38c-f	18.85 ± 1.32b-h	1.78 ± 0.17e-n	2.08 ± 0.11b-g	17.00 ± 0.41x-D	1200.00 ± 96.47qr	52.24 ± 5.29ef
DAB 470	5.23 ± 0.13e-m	18.50 ± 0.86b-i	1.23 ± 0.05r-v	1.78 ± 0.09j-p	25.25 ± 1.03o-y	1087.50 ± 47.81q-u	37.91 ± 1.73m-q
DAB 411	5.00 ± 0.04f-q	17.60 ± 0.77b-o	1.73 ± 0.05f-o	1.73 ± 0.05j-p	46.25 ± 2.88c-g	2616.67 ± 18.00de	35.69 ± 0.48o-s
CZ 104-13	4.50 ± 0.04m-s	19.05 ± 0.27bcd	1.23 ± 0.10r-v	1.77 ± 0.02j-p	12.00 ± 1.78A	2541.67 ± 52.87def	51.83 ± 2.17efg
DAB 190	4.87 ± 0.14h-r	17.13 ± 0.10d-p	1.70 ± 0.04g-p	1.93 ± 0.05f-k	35.75 ± 1.70i-n	2620.42 ± 79.40de	35.54 ± 0.96o-t
CIM-RM02-73-1	4.70 ± 0.37k-r	16.83 ± 0.86d-q	1.67 ± 0.15h-q	1.77 ± 0.10j-p	22.00 ± 1.47s-C	2005.42 ± 10.39h-k	35.48 ± 0.91o-u
NCB 281	5.75 ± 0.21c-f	17.83 ± 0.45b-m	1.88 ± 0.19d-l	1.85 ± 0.09g-n	33.00 ± 1.47j-q	2436.25 ± 104.64ef	25.20 ± 0.69z-C
DAB 429	5.13 ± 0.19f-p	17.75 ± 0.58b-m	1.30 ± 0.08p-v	1.58 ± 0.03p	29.75 ± 1.18m-u	2090.83 ± 43.58hi	31.36 ± 0.58r-x
DAB 207	5.55 ± 0.09d-j	18.00 ± 0.25b-l	1.35 ± 0.03n-v	1.75 ± 0.06j-p	17.25 ± 0.95x-D	1857.08 ± 31.36j-m	34.95 ± 1.43p-v
DAB 410	5.67 ± 0.14c-h	19.47 ± 0.59bc	1.43 ± 0.06m-u	1.77 ± 0.05j-p	52.75 ± 2.06cde	2005.83 ± 96.04h-k	102.96 ± 5.31a
KAB 10 F2.8-84	5.60 ± 0.07d-i	17.25 ± 0.55c-p	1.35 ± 0.13o-v	1.90 ± 0.04f-l	25.00 ± 1.470o-y	1492.08 ± 48.69op	17.21 ± 0.16EF
CIM-RM00-109	5.07 ± 0.22f-p	16.90 ± 0.58d-q	1.47 ± 0.15l-u	1.83 ± 0.06g-o	18.00 ± 0.82w-D	812.08 ± 48.88v-A	30.39 ± 1.14s-z
CIM-RK06-ALS-S1-2	5.58 ± 0.34d-i	17.23 ± 1.14c-p	1.58 ± 0.05i-t	1.85 ± 0.10g-n	33.50 ± 9.77j-o	2956.67 ± 98.02c	59.28 ± 2.68d
NUA 720	5.00 ± 0.04f-q	18.10 ± 0.72b-l	2.23 ± 0.06bcd	1.90 ± 0.00f-l	63.25 ± 0.63b	2485.42 ± 123.09def	41.07 ± 1.13k-o
DAB 378	5.53 ± 0.09d-j	17.37 ± 0.31c-o	1.00 ± 0.04vw	1.63 ± 0.02m-p	40.25 ± 1.84g-k	815.00 ± 7.58v-A	25.41 ± 0.16y-C
CIM-RM00-27-4	5.15 ± 0.30f-o	18.93 ± 1.10b-g	1.80 ± 0.27e-m	1.95 ± 0.10e-j	31.50 ± 1.55k-r	886.67 ± 64.08u-Z	15.49 ± 0.66F

(Continues)

TABLE 3 | (Continued)

Genotype	Phosphorus mg/g	Potassium mg/g	Calcium mg/g	Magnesium mg/g	Sodium mg/g	Grain yield kg/ha	100-grain weight g
NAIN DEKYONDO	4.10 ± 0.27rst	17.00 ± 0.54d-q	1.40 ± 0.13m-v	1.85 ± 0.06g-n	44.25 ± 1.93d-i	3383.61 ± 99.22b	16.44 ± 0.49F
CAL 96	5.13 ± 0.18f-p	17.73 ± 0.45b-m	1.50 ± 0.12k-u	1.88 ± 0.06f-m	15.25 ± 1.55z-D	3085.83 ± 76.86c	47.29 ± 1.71f-i
CIM-RM02-62-1	5.20 ± 0.07e-n	16.70 ± 0.25f-q	1.60 ± 0.00i-s	1.97 ± 0.06e-j	12.25 ± 0.85A	623.75 ± 27.63BC	36.63 ± 0.67n-r
KG 98-36	5.37 ± 0.33e-l	18.13 ± 0.44b-l	1.53 ± 0.18j-u	2.17 ± 0.08a-e	16.00 ± 3.24y-D	1912.50 ± 83.37i-m	29.83 ± 0.45t-A
CIM-RM02-20-3	5.53 ± 0.16d-j	16.80 ± 0.47d-g	1.30 ± 0.04p-v	1.83 ± 0.06h-o	35.33 ± 1.25j-n	2996.25 ± 54.54c	43.43 ± 1.42i-m
CIM-RM02-76-1	5.33 ± 0.24e-l	17.00 ± 0.78d-q	1.27 ± 0.08q-v	1.83 ± 0.02h-o	27.25 ± 1.55n-w	2892.92 ± 106.94c	85.67 ± 1.90b
CODMLB 03	5.97 ± 0.17cde	18.45 ± 0.39b-i	2.17 ± 0.24b-e	2.07 ± 0.12b-h	13.33 ± 0.62ABC	2338.75 ± 109.08fg	44.88 ± 1.07h-k
DAB 370	5.33 ± 0.06e-l	16.47 ± 0.12i-r	1.30 ± 0.04p-v	1.60 ± 0.08op	30.25 ± 1.25m-t	752.50 ± 7.74x-B	16.59 ± 0.35EF
CZ 113-15 (SAB 630)	3.30 ± 0.68u	15.37 ± 0.37o-s	2.03 ± 0.08b-h	1.80 ± 0.00i-p	27.25 ± 0.25n-w	1791.67 ± 55.51k-n	34.11 ± 0.44p-w
DAB 369	4.20 ± 0.23q-t	17.17 ± 0.73d-p	1.13 ± 0.05uvw	1.67 ± 0.06l-p	40.0 ± 1.87g-l	2365.83 ± 53.08fg	38.63 ± 0.77l-p
CIM-SUG-03-09-04	5.10 ± 0.07f-p	18.37 ± 0.82b-j	1.97 ± 0.18c-i	2.27 ± 0.06ab	34.00 ± 7.26j-o	1986.67 ± 57.65h-l	31.12 ± 1.34r-x
CIM-RM-03-03-45	5.20 ± 0.22e-n	16.13 ± 0.79j-s	1.28 ± 0.14q-v	1.63 ± 0.09nop	20.50 ± 0.89u-D	1130.56 ± 44.13q-t	29.55 ± 0.72v-A
CIM-RM07-ALS-71-2	4.85 ± 0.30h-r	16.75 ± 1.07d-g	1.23 ± 0.07r-v	1.93 ± 0.03f-k	54.50 ± 2.22c	846.67 ± 35.79v-A	46.58 ± 3.61g-j
NUA 743	9.57 ± 0.25a	19.00 ± 0.04b-f	1.43 ± 0.02m-u	1.77 ± 0.02j-p	91.00 ± 0.82a	1044.58 ± 43.90r-v	20.42 ± 0.51C-F
NUC 451	6.20 ± 0.11cd	15.07 ± 0.08p-s	1.53 ± 0.02j-u	1.87 ± 0.02f-n	37.00 ± 1.22h-m	2054.17 ± 43.23hij	17.04 ± 0.58EF
NUA 735	4.40 ± 0.15n-s	16.83 ± 0.26d-q	2.40 ± 0.15ab	1.80 ± 0.04i-p	31.00 ± 1.47l-s	2192.92 ± 77.80gh	36.68 ± 1.87n-r
DAB 270	5.73 ± 0.24c-f	18.30 ± 0.49b-k	1.77 ± 0.02f-o	1.80 ± 0.07i-p	16.75 ± 1.25x-D	721.25 ± 15.17y-B	18.48 ± 0.49EF
DAB 174	4.23 ± 0.10q-t	16.03 ± 0.68k-s	1.47 ± 0.05l-u	1.83 ± 0.12g-o	23.75 ± 1.25q-A	1306.25 ± 11.15pq	37.81 ± 0.80m-q
CIM-KHAK02-20-1	4.70 ± 0.61k-r	17.80 ± 1.74b-m	1.63 ± 0.25h-s	1.95 ± 0.06e-j	22.25 ± 4.13r-B	707.92 ± 44.44zAB	15.02 ± 0.82F
SMC 17	5.28 ± 0.09e-m	18.70 ± 0.21b-i	1.35 ± 0.06o-v	1.88 ± 0.08f-m	14.75 ± 2.69z-D	983.33 ± 64.90r-x	19.30 ± 0.37DEF
NUA 35	4.87 ± 0.08h-r	16.57 ± 0.45h-r	1.93 ± 0.14d-j	2.03 ± 0.06c-i	25.75 ± 0.85o-x	1735.00 ± 52.45mn	49.54 ± 3.39fgh
AND 277	5.28 ± 0.26e-m	15.40 ± 0.71n-s	1.58 ± 0.10i-t	1.823 ± 0.08h-o	16.75 ± 5.34x-D	1186.25 ± 22.18qrs	34.31 ± 0.27p-w
DAB 381	4.33 ± 0.26p-s	16.40 ± 0.40i-r	2.68 ± 0.13a	2.25 ± 0.03abc	33.25 ± 1.97j-p	2037.22 ± 63.25hij	55.71 ± 1.08de
CIM-RM00-21	4.80 ± 0.07i-r	16.50 ± 0.39i-r	1.63 ± 0.16h-r	1.97 ± 0.05e-j	28.00 ± 0.82m-v	562.92 ± 33.96BC	28.70 ± 0.84w-A
CIM-RM02-76-4	5.00 ± 0.11f-q	17.67 ± 0.60b-n	1.53 ± 0.08j-u	1.83 ± 0.05h-o	19.33 ± 0.85v-D	1106.25 ± 35.65q-u	32.47 ± 1.38q-x
CIM-RM00-7-1	4.90 ± 0.19g-r	15.43 ± 0.64n-s	1.60 ± 0.11i-s	1.67 ± 0.02l-p	14.33 ± 0.94A-D	3322.50 ± 106.52b	39.51 ± 0.55k-p

(Continues)

TABLE 3 | (Continued)

Genotype	Phosphorus mg/g	Potassium mg/g	Calcium mg/g	Magnesium mg/g	Sodium mg/g	Grain yield kg/ha	100-grain weight g
G 5207	4.50 ± 0.32m-s	17.03 ± 0.09d-q	1.63 ± 0.09h-s	1.83 ± 0.05h-o	20.00 ± 5.05v-D	1602.92 ± 79.81no	16.95 ± 0.31EF
DAB 447	4.60 ± 0.07l-s	18.37 ± 0.58b-j	1.73 ± 0.09g-o	1.70 ± 0.04k-p	41.75 ± 2.32f-j	941.67 ± 17.35t-y	26.93 ± 0.65x-B
CIM-RM02-79-1	4.75 ± 0.13j-r	14.85 ± 0.31qrs	1.40 ± 0.08m-v	1.68 ± 0.05l-p	15.25 ± 1.49z-D	3618.75 ± 173.61a	65.09 ± 4.39c
KG 98-42	4.37 ± 0.18o-s	15.83 ± 1.11l-s	1.70 ± 0.23g-p	1.60 ± 0.04op	31.00 ± 7.64l-s	1847.08 ± 105.43j-m	24.25 ± 1.28A-D
CIM-KHAK02-14-1	4.70 ± 0.15k-r	19.03 ± 0.58b-e	1.23 ± 0.24r-v	2.10 ± 0.08a-f	23.67 ± 4.87q-A	1965.00 ± 44.88h-l	22.18 ± 0.58B-E
DAB 363	4.87 ± 0.10h-r	16.40 ± 0.22i-r	1.27 ± 0.02q-v	1.70 ± 0.04k-p	45.00 ± 2.27d-h	2120.83 ± 30.19hi	32.42 ± 0.24q-x
CIM-RM02-46-1	5.10 ± 0.07f-p	16.73 ± 0.16e-q	1.47 ± 0.12l-u	1.80 ± 0.07i-p	13.67 ± 2.24ABC	846.25 ± 92.63v-A	38.04 ± 2.35m-q
DAB 559	3.86 ± 0.46stu	14.42 ± 0.86rs	2.08 ± 0.13b-g	2.03 ± 0.09d-i	23.92 ± 4.53p-z	1508.02 ± 53.25op	36.58 ± 3.01n-r
NUC 219	3.57 ± 0.10tu	15.70 ± 0.12m-s	0.80 ± 0.04w	1.73 ± 0.02j-p	24.00 ± 1.47p-z	3093.75 ± 52.65c	28.68 ± 0.35w-A
DAB 386	5.53 ± 0.28d-j	16.65 ± 1.15g-q	1.30 ± 0.11p-v	1.60 ± 0.14op	33.75 ± 2.32j-o	1015.42 ± 10.12r-w	30.14 ± 0.85s-z
KAB 77 F7.2-52	4.83 ± 0.14i-r	18.87 ± 0.83b-h	2.33 ± 0.09abc	2.30 ± 0.18a	21.25 ± 1.03t-D	1513.33 ± 135.82op	39.33 ± 2.30k-p
CIM-RM01-92-3	4.33 ± 0.20p-s	15.33 ± 0.62o-s	1.90 ± 0.08d-k	1.87 ± 0.06f-n	12.67 ± 0.85AB	953.75 ± 33.50s-x	41.94 ± 2.14i-n
F-statistics	15.53**	4.82**	9.05**	6.19**	27.80**	138.52**	83.66*
*RDIs 1–3 y	460 mg/d	2000 mg/d	233 mg/d	80 mg/d	800 mg/d		
*RDIs 4–8 y	500 mg/d	2300 mg/d	333 mg/d	130 mg/d	1000 mg/d		

Note: Values represent mean ± SE. Different letters in a column are significantly different at $p \leq 0.05$, $n = 252$.
**$p < 0.01$, and *$p \leq 0.05$.
Source: Rasbold et al. (2016).

TABLE 4 | Micronutrient (Fe, Cu, Zn, Mn, and B), grain yield, and 100-grain weight of 63 common bean genotypes planted at Malkerns Research Station, Eswatini, during the 2017/2018 cropping season.

Genotype	Iron mg/kg	Copper mg/kg	Zinc mg/kg	Manganese mg/kg	Boron mg/kg	Grain yield kg/ha	100-grain weight g
NUC 461	151.08 ± 0.76a	13.39 ± 0.15ab	70.72 ± 0.52a	17.77 ± 0.28c-p	17.48 ± 0.22a	420.42 ± 3.98C	20.05 ± 1.31C-F
DAB 155	128.77 ± 1.25b	11.81 ± 0.41b-g	48.29 ± 0.88bc	26.84 ± 0.73a	14.77 ± 0.33c-g	1132.50 ± 125.03q-t	28.50 ± 2.23w
MCA 98	107.51 ± 3.96c	13.67 ± 1.42a	42.83 ± 0.32d-g	16.01 ± 0.53f-t	13.56 ± 0.38e-l	2648.75 ± 118.78de	43.69 ± 0.99i-l
CIM-RM05-ALS-103	106.37 ± 3.06c	10.45 ± 0.62e-n	30.24 ± 1.70t-w	14.59 ± 0.36l-v	12.83 ± 0.82g-o	788.75 ± 19.65w-A	29.71 ± 0.89u-A
MCA 78	103.04 ± 1.70cd	8.23 ± 0.20q-t	41.24 ± 0.71d-i	20.05 ± 0.45b-f	12.87 ± 0.05g-o	2690.00 ± 47.08d	41.26 ± 1.38j-o
KAB 06 F2.8-51	102.29 ± 2.01cde	9.56 ± 0.16h-r	41.31 ± 0.31d-i	13.19 ± 0.08r-v	15.42 ± 0.17b-e	2075.00 ± 94.42hij	46.99 ± 1.14f-i
DFA 73	101.86 ± 24.03c-f	12.01 ± 1.22a-f	37.06 ± 3.07h-q	13.18 ± 1.29r-v	13.96 ± 0.77d-j	1017.50 ± 55.59r-w	16.03 ± 0.42F
DAB 387	98.65 ± 0.58c-g	11.14 ± 0.35c-h	43.48 ± 1.69c-f	18.72 ± 1.29b-k	10.21 ± 0.57rs	1141.67 ± 7.73q-t	27.72 ± 0.58x-A
CIM-RM00-141	97.31 ± 1.00c-h	10.84 ± 0.55c-j	39.95 ± 0.86e-k	20.16 ± 2.79b-e	14.15 ± 0.70d-i	1774.58 ± 54.54lmn	31.45 ± 0.84r-x
CIM-RM01-97-8	93.70 ± 1.46c-i	12.01 ± 0.52a-f	39.33 ± 1.44e-m	15.41 ± 1.40i-v	17.65 ± 1.82a	1200.00 ± 96.47qr	52.24 ± 5.29ef
DAB 470	92.14 ± 1.85d-i	8.61 ± 0.22n-s	38.63 ± 1.22f-n	11.75 ± 0.39uv	12.44 ± 0.18h-r	1087.50 ± 47.81q-u	37.91 ± 1.73m-q
DAB 411	92.03 ± 3.57d-i	8.64 ± 0.19m-s	31.60 ± 0.31q-w	18.37 ± 0.34b-m	10.06 ± 0.50s	2616.67 ± 18.00de	35.69 ± 0.48o-s
CZ 104-13	91.67 ± 0.72d-j	8.48 ± 0.20o-t	33.94 ± 0.17m-v	14.13 ± 0.39o-v	13.92 ± 0.12d-j	2541.67 ± 52.87def	51.83 ± 2.17efg
DAB 190	90.99 ± 1.22d-k	8.11 ± 0.08q-t	33.39 ± 1.53n-v	20.64 ± 0.52bcd	10.74 ± 0.36o-s	2620.42 ± 79.40de	35.54 ± 0.96o-t
CIM-RM02-73-1	90.75 ± 1.09d-l	9.95 ± 0.43g-q	28.91 ± 0.97vw	14.54 ± 0.48l-v	13.18 ± 1.16e-n	2005.42 ± 10.39h-k	35.48 ± 0.91o-u
NCB 281	90.47 ± 1.40d-m	9.77 ± 0.80h-r	47.68 ± 1.46bc	19.31 ± 1.26b-i	14.69 ± 0.77c-h	2436.25 ± 104.64ef	25.20 ± 0.69z-C
DAB 429	90.20 ± 2.43d-m	8.90 ± 0.24j-s	31.87 ± 1.72p-v	14.88 ± 0.67j-v	11.85 ± 0.26i-s	2090.83 ± 43.58hi	31.36 ± 0.58r-x
DAB 207	90.07 ± 3.84d-m	10.81 ± 0.32c-j	46.06 ± 1.67bcd	15.45 ± 1.44i-v	13.26 ± 0.65e-n	1857.08 ± 31.36j-m	34.95 ± 1.43p-v
DAB 410	89.62 ± 3.07d-m	9.94 ± 0.31g-q	40.81 ± 0.61e-j	17.05 ± 0.44d-r	10.51 ± 0.54p-s	2005.83 ± 96.04h-k	102.96 ± 5.31a
KAB 10 F2.8-84	88.41 ± 3.45d-n	12.22 ± 0.55a-e	37.40 ± 1.68h-p	17.32 ± 2.40d-q	14.43 ± 0.52c-h	1492.08 ± 48.69op	17.21 ± 0.16EF
CIM-RM00-109	88.13 ± 3.67e-o	10.40 ± 0.31e-o	31.32 ± 0.33r-w	16.88 ± 0.87d-s	13.85 ± 0.46d-j	812.08 ± 48.88v-A	30.39 ± 1.14s-z
CIM-RK06-ALS-S1-2	87.89 ± 4.72e-p	12.50 ± 1.01abc	35.81 ± 2.03j-t	15.70 ± 1.42g-u	13.31 ± 0.53e-m	2956.67 ± 98.02c	59.28 ± 2.68d
NUA 720	87.82 ± 4.84e-p	10.61 ± 0.20d-k	33.03 ± 0.68o-v	21.35 ± 0.96bc	14.38 ± 0.20c-h	2485.42 ± 123.09def	41.07 ± 1.13k-o
DAB 378	87.08 ± 2.85f-p	9.98 ± 0.08g-q	39.80 ± 1.55e-l	14.19 ± 0.65o-v	11.02 ± 0.72n-s	815.00 ± 7.58v-A	25.41 ± 0.16y-C
CIM-RM00-27-4	87.00 ± 2.32g-p	9.52 ± 0.80h-r	35.22 ± 1.41k-u	19.73 ± 1.79b-g	14.79 ± 0.86c-g	886.67 ± 64.08u-Z	15.49 ± 0.66F

(Continues)

TABLE 4 | (Continued)

Genotype	Iron mg/kg	Copper mg/kg	Zinc mg/kg	Manganese mg/kg	Boron mg/kg	Grain yield kg/ha	100-grain weight g
NAIN DEKYONDO	85.56 ± 2.84g-q	6.69 ± 0.69tu	32.72 ± 1.55o-v	11.53 ± 0.70v	16.01 ± 1.47a-d	3383.61 ± 99.22b	16.44 ± 0.49F
CAL 96	85.74 ± 2.86g-q	10.66 ± 0.76c-k	38.04 ± 1.91g-o	14.07 ± 1.62o-v	14.34 ± 0.53c-h	3085.83 ± 76.86c	47.29 ± 1.71f-i
CIM-RM02-62-1	85.60 ± 1.41g-q	8.31 ± 0.15q-t	31.52 ± 1.06r-w	15.47 ± 0.74i-v	13.03 ± 0.05f-n	623.75 ± 27.63BC	36.63 ± 0.67n-r
KG 98-36	84.99 ± 3.92g-q	11.11 ± 0.73c-h	35.67 ± 1.73j-t	18.05 ± 1.69c-o	13.73 ± 0.92e-j	1912.50 ± 83.37i-m	29.83 ± 0.45t-A
CIM-RM02-20-3	84.83 ± 0.99g-q	12.42 ± 0.08a-d	34.45 ± 0.68l-v	15.82 ± 0.47g-u	14.16 ± 0.13d-i	2996.25 ± 54.54c	43.43 ± 1.42i-m
CIM-RM02-76-1	84.12 ± 1.89g-q	10.77 ± 0.32c-j	31.57 ± 1.18q-w	14.40 ± 0.76m-v	14.11 ± 0.01d-i	2892.92 ± 106.94c	85.67 ± 1.90b
CODMLB 03	83.91 ± 4.09g-q	8.82 ± 0.20k-s	44.14 ± 2.76cde	15.39 ± 1.32i-v	13.61 ± 0.90e-k	2338.75 ± 109.08fg	44.88 ± 1.07h-k
DAB 370	83.06 ± 1.56h-r	8.55 ± 0.20n-t	33.71 ± 1.38n-v	18.30 ± 0.66b-n	11.34 ± 0.44k-s	752.50 ± 7.74x-B	16.59 ± 0.35EF
CZ 113-15 (SAB 630)	83.05 ± 1.79h-r	7.94 ± 0.21r-u	30.28 ± 0.53t-w	16.19 ± 0.84e-t	12.80 ± 0.40g-o	1791.67 ± 55.51k-n	34.11 ± 0.44p-w
DAB 369	82.95 ± 1.48h-r	7.27 ± 0.42stu	31.14 ± 1.25r-w	12.92 ± 0.26s-v	11.30 ± 0.34l-s	2365.83 ± 53.08fg	38.63 ± 0.77l-p
CIM-SUG-03-09-04	82.60 ± 4.22h-r	11.04 ± 0.81c-i	35.76 ± 0.83j-t	19.31 ± 0.20b-i	15.31 ± 1.12b-f	1986.67 ± 57.65h-l	31.12 ± 1.34r-x
CIM-RM-03-03-45	82.47 ± 3.04h-r	9.06 ± 0.63j-s	37.32 ± 1.36h-p	13.43 ± 1.03q-v	11.36 ± 0.69k-s	1130.56 ± 44.13q-t	29.55 ± 0.72v-A
CIM-RM07-ALS-71-2	82.24 ± 4.13h-r	10.37 ± 0.81e-o	31.36 ± 0.97r-w	14.15 ± 1.36o-v	13.15 ± 0.43e-n	846.67 ± 35.79v-A	46.58 ± 3.61g-j
NUA 743	82.11 ± 0.64h-r	8.52 ± 0.59o-t	42.22 ± 0.54d-h	12.20 ± 0.47tuv	17.04 ± 0.44ab	1044.58 ± 43.90r-v	20.42 ± 0.51C-F
NUC 451	82.00 ± 1.22h-r	13.55 ± 0.20ab	50.30 ± 1.03b	14.10 ± 0.07o-v	11.15 ± 0.03m-s	2054.17 ± 43.23hij	17.04 ± 0.58EF
NUA 735	80.58 ± 2.30i-s	9.06 ± 0.45j-s	32.85 ± 1.05o-v	19.61 ± 1.13b-h	16.36 ± 0.83abc	2192.92 ± 77.80gh	36.68 ± 1.87n-r
DAB 270	80.54 ± 1.00i-s	10.55 ± 0.64d-m	40.40 ± 0.79e-k	22.24 ± 0.76b	12.59 ± 0.20g-p	721.25 ± 15.17y-B	18.48 ± 0.49EF
DAB 174	80.21 ± 2.52i-s	8.35 ± 0.53p-t	30.01 ± 2.10uvw	15.65 ± 0.55h-u	10.6 ± 0.98o-s	1306.25 ± 11.15pq	37.81 ± 0.80m-q
CIM-KHAK02-20-1	79.88 ± 4.45i-s	9.92 ± 1.14g-q	37.28 ± 3.83h-p	18.97 ± 1.92b-i	14.61 ± 1.18c-h	707.92 ± 44.44zAB	15.02 ± 0.82F
SMC 17	79.86 ± 4.03i-s	10.63 ± 0.48c-k	33.70 ± 2.73n-v	17.90 ± 1.20c-o	13.46 ± 0.41e-m	983.33 ± 64.90r-x	19.30 ± 0.37DEF
NUA 35	79.73 ± 0.82i-s	7.23 ± 0.10stu	34.45 ± 0.99l-v	22.04 ± 1.80b	12.47 ± 0.22g-q	1735.00 ± 52.45mn	49.54 ± 3.39fgh
AND 277	79.58 ± 4.52i-s	11.03 ± 0.70c-i	36.34 ± 2.45i-r	16.21 ± 0.48e-t	13.37 ± 0.48e-m	1186.25 ± 22.18qrs	34.31 ± 0.27p-w
DAB 381	79.11 ± 2.91i-s	8.35 ± 0.89q-t	35.67 ± 1.21j-t	18.88 ± 1.65b-j	11.99 ± 0.33i-s	2037.22 ± 63.25hij	55.71 ± 1.08de
CIM-RM00-21	78.72 ± 1.42i-s	10.55 ± 0.28d-m	32.37 ± 0.57p-v	16.78 ± 0.39d-s	13.55 ± 0.82e-l	562.92 ± 33.96BC	28.70 ± 0.84w-A
CIM-RM02-76-4	76.38 ± 2.54j-s	9.13 ± 0.61i-s	31.08 ± 1.02r-w	13.75 ± 1.09p-v	14.06 ± 0.55d-i	1106.25 ± 35.65q-u	32.47 ± 1.38q-x

(Continues)

TABLE 4 | (Continued)

Genotype	Iron mg/kg	Copper mg/kg	Zinc mg/kg	Manganese mg/kg	Boron mg/kg	Grain yield kg/ha	100-grain weight g
CIM-RM00-7-1	76.31 ± 1.96j-s	9.03 ± 0.36j-s	33.75 ± 2.14n-v	14.23 ± 1.09n-v	13.39 ± 0.74e-m	3322.50 ± 106.52b	39.51 ± 0.55k-p
G 5207	75.98 ± 4.86k-s	8.52 ± 0.72o-t	37.22 ± 3.35h-p	14.51 ± 1.05l-v	12.91 ± 0.21g-o	1602.92 ± 79.81no	16.95 ± 0.31EF
DAB 447	75.35 ± 2.00l-s	8.30 ± 0.19q-t	30.73 ± 1.04s-w	16.51 ± 1.45e-s	12.63 ± 0.07g-p	941.67 ± 17.35t-y	26.93 ± 0.65x-B
CIM-RM02-79-1	75.07 ± 3.75m-s	10.28 ± 0.36f-p	32.18 ± 1.25p-v	14.71 ± 0.68k-v	13.90 ± 0.23d-j	3618.75 ± 173.61a	65.09 ± 4.39c
KG 98-42	73.52 ± 6.08n-s	8.68 ± 0.24l-s	29.28 ± 1.02vw	19.04 ± 2.62b-i	12.42 ± 0.19h-r	1847.08 ± 105.43j-m	24.25 ± 1.28A-D
CIM-KHAK02-14-1	73.44 ± 3.42n-s	9.15 ± 0.61i-s	36.15 ± 1.54i-s	15.24 ± 0.32i-v	14.71 ± 0.85c-h	1965.00 ± 44.88h-l	22.18 ± 0.58B-E
DAB 363	73.17 ± 1.55n-s	10.59 ± 0.55d-l	31.47 ± 0.97r-w	14.80 ± 0.77k-v	11.24 ± 0.40m-s	2120.83 ± 30.19hi	32.42 ± 0.24q-x
CIM-RM02-46-1	72.79 ± 6.46o-s	10.84 ± 0.10c-j	36.44 ± 1.52i-r	18.57 ± 2.54b-l	13.77 ± 0.49d-j	846.25 ± 92.63v-A	38.04 ± 2.35m-q
DAB 559	72.63 ± 7.19p-s	8.41 ± 0.59p-t	30.75 ± 3.34s-w	14.65 ± 1.29l-v	11.68 ± 0.89j-s	1508.02 ± 53.25op	36.58 ± 3.01n-r
NUC 219	70.91 ± 0.90qrs	6.30 ± 0.06u	23.57 ± 0.61x	12.20 ± 0.39tuv	10.30 ± 0.31qrs	3093.75 ± 52.65c	28.68 ± 0.35w-A
DAB 386	70.48 ± 3.48qrs	8.22 ± 0.53q-t	33.74 ± 1.89n-v	18.89 ± 0.71b-j	11.94 ± 1.08i-s	1015.42 ± 10.12r-w	30.14 ± 0.85s-z
KAB 77 F7.2-52	68.50 ± 3.50rs	10.75 ± 0.47c-k	33.15 ± 1.72n-v	19.28 ± 0.99b-i	13.61 ± 0.63e-k	1513.33 ± 135.82op	39.33 ± 2.30k-p
CIM-RM01-92-3	66.36 ± 1.49s	8.44 ± 0.12p-t	26.39 ± 0.88wx	15.61 ± 0.59h-u	12.41 ± 0.29h-r	953.75 ± 33.50s-x	41.94 ± 2.14i-n
F-statistics	9.86**	8.90**	19.36**	6.51**	7.00**	138.52**	83.66*
*RDIs 1–3 y	2.3 mg/d	340 µg/d	2.3 mg/d	1.2 mg/d	<20 mg/d		
*RDIs 4–8 y	3.3 mg/d	440 µg/d	3.3 mg/d	1.5 mg/d	<20 mg/d		

Note: Values represent mean ± SE. Different letters in a column are significantly different at $p \leq 0.05$, $n = 252$.
$^{**}p < 0.01$, and $^{*}p \leq 0.05$.
Source: Rasbold et al. (2016).

produced grain yield above 3000 kg/ha, followed by genotypes NAIN DEKYONDO, CIM-RM00-7-1, NUC 219 and CAL 96, which produced grain yield of 3383.61, 3322.50, 3093.75 and 3085.83 kg/ha, respectively. Sixteen genotypes recorded grain yield below 1000 kg/ha, with values ranging from 420.42 kg/ha to 983.33 kg/ha.

The 100-seed weight ranged from 15.02 to 102.96 g with genotypes DAB 410, CIM-RM02-76-1, CIM-RM02-79-1, CIM-RK06-ALS-S1-2 and DAB 381 recording the highest hundred grain weight (HGW) of 102.96, 85.67, 65.09, 59.28, and 55.71 g, respectively. Genotypes CIM-KHAK02-20-1 (15.02 g) recorded the lowest HGW, followed by genotypes CIM-RM00-27-4 (15.49 g), NAIN DEKYOMNDO (16.44 g), DAB 370 (16.59 g), and G 5207 (16.95 g) (Tables 3 and 4).

4 | Discussion

Nutritional security and dietary quality are important for human nutrition and health. There is therefore a need to identify crop species that can accumulate mineral nutrients for achieving nutritional security. This study evaluated the seeds of 63 common bean genotypes planted at Malkerns, Eswatini, for dietary quality and nutritional security. The results exhibited significant differences ($p < 0.05$) in grain concentrations of both macronutrients and micronutrients (Tables 3 and 4), a possible indication of dilution of soil mineral elements, which can affect their uptake and translocation to the grain (Seetharama et al. 1987; Shegro et al. 2012; Badigannavar et al. 2016; Phuke et al. 2017). Of the 63 common bean genotypes tested, only seven showed relatively high levels of three or more mineral nutrients in edible seeds.

Of the 63 test bean genotypes, NUC 461 performed the best, as it recorded higher levels of P, K, Mg, Fe, Cu, Zn, and B in its grain (Tables 3 and 4), followed by genotype DAB 155, which also showed relatively higher seed concentrations of P, K, Ca, Fe, Zn, and Mn (Figure 1A,B), and NUA 743 with increased levels of P, K, Na, and B in its seeds (Tables 3 and 4). The next group of bean genotypes exhibiting increased mineral concentrations in the seed included (i) KAB 77 F7.2-52 with relatively high grain concentrations of Ca, Mg, and Mn; (ii) DAB 381 with greater seed levels of Ca, Mg, and Mn; (iii) MCA 78 with increased grain concentrations of Na, Fe, and Mn; and (iv) CIM-RM01-97-8 with relatively higher levels of Fe, Cu, and B in its seeds (Tables 3 and 4). Some bean genotypes however consistently exhibited very low concentrations of the major essential mineral nutrients. These included genotype NUC 219, which recorded low levels of Cu, Fe, Zn, B, and Mn in its grain, and DAB 559, which showed relatively low concentrations of P, Fe, and K in the edible seed (Tables 3 and 4). These differences in the accumulation of dietarily important mineral nutrients in common bean seeds could be genetic. However, the variation can also be attributed to factors such as differences in root architecture and/or the ability of each species to solubilize unavailable or insoluble nutrient elements in the rhizosphere (Beebe et al. 2006). Furthermore, the fact that only three bean genotypes (viz., NUC 461, DAB 155, and NUA 743) out of the 63 could, respectively, accumulate seven, six, and four mineral nutrients in the edible grain, suggests that studies of natural biofortification by legumes should involve a larger pool of varieties or cultivars. However, it is important to note that the micronutrient concentrations of common bean grains were generally higher for this study relative to values reported in the literature (Table 5), which suggests that even though the bean genotypes used in this study may appear to be poor mineral accumulators, they are in fact superior in natural biofortification when compared to other genotypes reported in the literature.

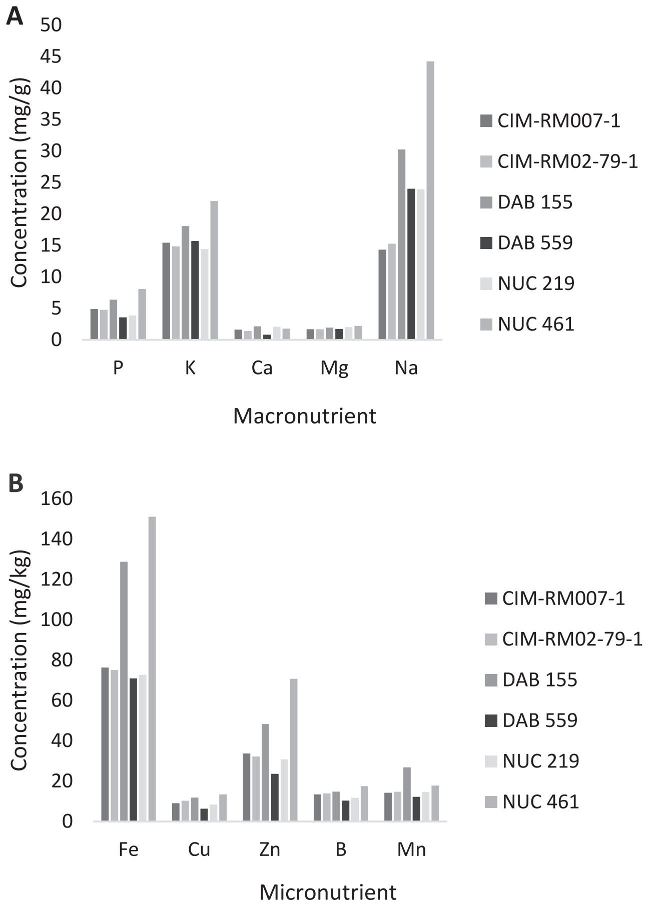

FIGURE 1 | Comparison of (A) macronutrients concentration and micronutrients concentration (B) between high and low accumulator genotypes.

A recent study (Jan et al. 2021) similarly found significant differences between 60 bean genotypes grown in the Himalayas. Grain concentrations of Mg (1.22–2.74 mg/g), P (1.98–4.05 mg/g), K (8.34–14.79 mg/g), and Ca (0.30–5.35 mg/g) were, respectively, 2.24-, 2.04-, 1.77-, and 17.8-fold greater in the high mineral-accumulating genotypes than low accumulators (Jan et al. 2021). In this study, KAB 77 F7.2-52, NUA 743, DAB 381, and NUC 461 were, respectively, 1.45-, 2.9-, 1.57-, and 3.37-fold higher in concentrations than DAB 429, CZ-113-15, DFA 73, and DAB 559, which were the lowest in mineral concentration.

Although the Mg levels reported by Jan et al. (2021) are similar to those found in this study, the concentration of P and K are higher in our study, whereas Ca is lower. The 14.7 mg/g Ca and 3.68 mg/g P reported by Beebe, Gonzalez, and Rengifo (2000) for a cultivated common bean variety in Colombia suggest that the Colombian genotypes exhibit lower

TABLE 5 | A comparison of the concentration of micronutrients found in this study versus values in the literature.

Seed micronutrient	Concentration (mg/kg)	References
Zinc	10.0–33.1	Guzmán-Maldonado, Acosta-Gallegos, and Paredes-López (2000)
	17.8–37.9	Celmeli et al. (2018)
	21.0–54.0	Beebe, Gonzalez, and Rengifo (2000)
	22.3–37.7	Brigide, Canniatt-Brazaca, and Silva (2014)
	22.0–40.0	Makamuhirwa et al. 2012)
	24.8–33.3	Ray et al. (2014)
	30.9–64.6	Golam Masum Akond et al. (2011)
	38.0	Koehler et al. (1987)
	45.6	Poshtmasari et al. (2008)
	23.0–70.7	**This study**
Iron	8.9–112.9	Golam Masum Akond et al. (2011)
	34–89	Beebe, Gonzalez, and Rengifo (2000)
	45.0–87.0	Makamuhirwa et al. (2012)
Iron	57.7–80.7	Ray et al. (2014)
	86.9	Gelin et al. (2007)
	68.5–151.1	**This study**
Boron	9.0	Beebe, Gonzalez, and Rengifo (2000)
	10.1–17.7	**This study**
Copper	1.1–11.6	Ray et al. (2014)
	12.0	Beebe, Gonzalez, and Rengifo (2000)
	6.3–12.7	**This study**
Manganese	10.0	Beebe, Gonzalez, and Rengifo (2000)
	11.5–26.8	**This study**

Ca and P accumulation in comparison to the genotypes tested at Eswatini. Relative to this study, lower concentrations of P (4.79 mg/g), K (8.47 mg/g), Ca (0.98 mg/g), Mg (1.47 mg/g), and Na (0.16 mg/g) were reported in the grain of common bean (Grela et al. 2017). Chávez-Servia et al. (2016) also recorded lower seed levels of P (2.66–3.6 mg/g), K (8.46–9.46 mg/g), Na (0.63–0.74 mg/g), Mg (1.14–1.26 mg/g), and Ca (0.91–1 mg/g) when compared to this study. However, the grain concentrations of Mg (1.84–2.49 mg/g) and K (18.85–22.8 mg/g) reported by Ray et al. (2014) for common bean are comparable to the values obtained in this study.

The study by Jan et al. (2021) found that grain concentrations of Fe, Zn, and Cu were, respectively, 80.5–180.6, 14.64–104.08, and 0.9–13.4 mg/kg, levels that are much higher when compared to those obtained in this study. In contrast, seed concentrations of Mn (10 mg/kg), Cu (12 mg/kg), B (9 mg/kg), Fe (15 mg/kg), and Zn (35 mg/kg) reported by Beebe, Gonzalez, and Rengifo (2000) for common bean were much lower than those obtained in this study. Estimates of Fe (61.12–80.8 mg/kg), Cu (5.2–11.07 mg/kg), Zn (22.3–37.7 mg/kg), and Mn (11.26–17.9 mg/kg) concentrations in five common bean genotypes by Brigide, Canniatt-Brazaca, and Silva (2014) were also lower than those obtained in this study, suggesting that many of our test genotypes were superior in mineral accumulation. In fact, the so-called biofortified bean cultivars identified by Brigide, Canniatt-Brazaca, and Silva (2014) exhibited lower concentrations of Cu, Fe, and Mn when compared to the values obtained in this study.

Several studies showed that, the concentrations of micronutrients (e.g., Fe, Zn, Mn, and Cu) in common bean seeds were generally lower than those obtained in this study at Eswatini (see Table 5; Brigide, Canniatt-Brazaca, and Silva 2014; Ray et al. 2014; Chávez-Servia et al. 2016; Grela et al. 2017). These variations could be attributed to the type of genotypes used in each study, the environmental conditions, and/or the soil chemical properties. The observed differences in grain macronutrient and micronutrient accumulation seem to suggest that, depending on the common bean genotype, a greater or smaller amount of grain material must be consumed to meet the recommended daily intake (RDI) of mineral per age group. Genotypes such as CIM-RM02-79-1 and CIM-RM00-7-1 that recorded high grain yield had low P, K, Mg, Na, Fe, and Zn in the seed. This inverse relationship implies that there was a decrease in these minerals with increasing grain yield. The decrease in mineral concentration of common bean seed could be caused by decreased translocation of nutrients from vegetative organs to grain and/or dilution by dry matter accumulation. Although grain mineral levels are reported to rise with increasing seed weight (Fan et al. 2008; Gu et al. 2015), in this study, we observed the opposite. This may be attributed to breeders selecting solely for grain yield, and not for grain quality, which has contributed to a reduction in grain nutrient concentrations.

The daily recommended intake of the micronutrients Fe, Cu, Zn, Mn, and B is 2.3 mg/d, 340 µg/d, 2.3 mg/d, 1.2 mg/d, and < 20 mg/d, respectively, for 1- to 3-year-old children and 3.3 mg/d, 440 µg/d, 3.3 mg/d, 1.5 mg/d, and < 20 mg/d, respectively, for 4- to 8-year-old children. The macronutrients P, K, Ca, Mg, and Na for 1- to 3-year-old children are 400, 2000, 233, 80, and 800 mg/d, respectively, and 500, 2300, 333, 130, and 1000 mg/d, respectively, for 4- to 8-year-old children (Rasbold et al. 2016). The estimated amount of grain to consume to meet the daily intake of Fe, Cu, Zn, Mn, B, P, K, Ca, Mg, and Na was found to vary with common bean genotypes. Less grain material was required for genotypes with high grain concentrations of Fe, Cu, Zn, Mn, B, P, K, Ca, Mg, and Na to meet the daily recommended intake.

There was substantial variability among the 63 common bean genotypes in all the parameters studied, an outcome important for any biofortification program aimed at enhancing mineral accumulation in legumes. The best performing genotypes such as NUC 461, which recorded significantly higher levels of P, K, Mg, Fe, Cu, Zn, and B in its grain, and DAB 155, with greater concentrations of P, K, Ca, Fe, Zn, and Mn, can be recommended for use in breeding programs. The micronutrient concentrations of common bean seeds were generally higher in this study relative to the values reported in the literature (Table 5), indicating the superior natural biofortification traits of the genotypes used in this study.

Taken together, only a few of the 63 bean genotypes could accumulate dietarily important mineral nutrients in edible grain for human nutrition/health. This indicates that more legume varieties should be used in future studies of natural biofortification. In this study, however, genotypes NUC 461 (P, K, Mg, Fe, Cu, Zn, and B) and DAB 155 (P, K, Ca, Fe, Zn, and Mn), which recorded much higher grain concentrations of mineral nutrients should be recommended for use in breeding programs to produce new varieties with naturally biofortified grain for alleviating nutrient deficiency in Africa.

Author Contributions

R.P. collected samples, analyzed data and prepared the manuscript. F.D.D. was the doctoral supervisor of R.P., secured funding for the research and assisted in manuscript writing, editing and organization.

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Conflicts of Interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

All datasets generated for this study are included in the manuscript.

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