Journal of Agriculture and Environment for International Development - JAEID 2023, 117 (2): 23-40
DOI: https://doi.org/10.36253/jaeid-14528

Diagnosis of nutrient imbalance and interactions in wheat and faba bean in Kharga Oasis, Egypt

ALI M. ALI [1*], SAFWAT E. A. ABDELHAMID [2], ASHRAF N. EL-SADEK [2], EMAD M. M. SALEM [2]

[1] *Department of Soil Fertility and Microbiology, Desert Research Center, Cairo 11753, Egypt*

[2] *Department of Plant Production, Desert Research Center, Cairo 11753, Egypt*

[*] *Correspondence details: alimohamed1982@gmail.com*

Submitted on: 2023, 21 March ; accepted on 2023, 7 July. Section: Research Papers

Abstract: Imbalanced nutrition has a major impact on crop productivity, particularly in hyper-arid environments, and precise interpretation is essential for designing appropriate nutrient management strategies. Compositional nutrient diagnosis (CND) was used to identify nutritional imbalances of multiple nutrients (N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu) in wheat and faba bean cultivated in Kharga Oasis, Egypt. Significant nutrient interactions were also assessed using principal component analysis. Due to large differences in water and soil characteristics, wheat and faba bean yields from the surveyed area varied greatly, ranging from 2118 to 8211 and 1373 to 4962 kg ha^{-1}, respectively. The CND indexes for the low-yield subpopulation of wheat were negative for P, Ca, and Zn, with average values of -0.82, -2.66, and -1.26, but positive for K, Mg, Fe, and Mn with average values of 4.80, 4.92, 1.70, and 0.57, respectively. In faba bean, N, P, Ca, and Zn were negative, with average values of -1.73, -0.67, -8.19, and -1.41, but K, Mg, Fe, Mn, and Cu were positive with average values of 2.62, 0.50, 1.32, 1.10, and 0.40, respectively. Synergistic interactions P-Zn and Mg-Fe, as well as antagonistic interactions P-Mg, P-Fe, Zn-Fe, Zn-Mg, Ca-Cu, N-Mn, Mn-Cu, and P-Ca, were evident from the principal component analysis of the data. This investigation reveals that the decline in crop yields in the study area is due to nutritional imbalance induced by a deficiency of Ca, Zn, and P and a surplus of Mg, K, Fe, and Mn, in addition to nutrient antagonism.

Keywords: Nutritional imbalance; nutrient interactions; compositional nutrient diagnosis; principal component analysis; wheat; faba bean, hyper-arid environment

Introduction

The availability of essential nutrients to plants should be balanced because an imbalanced supply induced by natural and/or human occurrences, particularly in arid lands, generates nutrient interactions that may limit the absorption and utilization of other nutrients. As a consequence, determining nutrient imbalances in crops is critical for establishing decision support and suitable nutrient management strategies to increase crop production and nutrient use efficiency (Magallanes-Quintanar *et al.* 2006; Parent *et al.* 2012; Parent *et al.* 2013; Barłóg 2016; Tadayon *et al.* 2022). To detect nutrient imbalances or deficiencies, several approaches, such as visual deficiency symptoms, soil analysis, and plant tissue tests, can be employed, allowing producers to make nutrient management decisions. Over the years, plant tissue analysis has been used in several ways to diagnose and evaluate plant nutritional status. The Critical Value Approach (CVA; Bates 1971), the

Diagnosis and Recommendation Integrated System (DRIS; Walworth and Sumner 1987), and the Compositional Nutrient Diagnosis (CND; Parent and Dafir 1992; Parent *et al.* 1993; Khiari *et al.* 2001) are among these techniques.

The CVA is a univariate approach that compares observed and reference nutrient concentrations. A deficiency is assumed when the nutrient in question falls below the reference value, and vice versa. The CVA norms are based on the premise that other nutrients are not yield-limiting and do not interact with one another. This approach has been criticized for failing to account for nutrient interactions (Wilkinson *et al.* 2000; Marschner 2011), and it is also difficult to determine whether nutrients are more or less necessary for plants. The DRIS is a bivariate approach that employs dual nutrient ratios to account for some nutrient interactions (Walworth and Sumner 1987). In addition to detecting nutritional imbalances partly, DRIS identifies the sequence in which other nutrients are expected to become limiting and was able to assess plant nutrient demands earlier in the crop growth period than CVA (Mourão 2004). DRIS indexes, on the other hand, are empirical, lacking a correct sketch of the covariance matrix for conducting multivariate statistical analysis, potentially leading to misinterpretation when associated with yield (Barłóg 2016; Parent *et al.* 2012). Based on compositional data analysis, Parent and Dafir (1992) suggested a multi-ratio CND concept. Compositional nutrient diagnosis takes into account multiple and complex interactions between plant nutrients (Fageria 2001) and precisely specifies a covariance matrix that allows multivariate calculation of ratios resulting from mutually exclusive nutrient concentrations (Parent 2011), avoiding potential misinterpretation in correlation with yield.

There could be differences in diagnostic method efficiency, but in some studies, sufficiency ranges of nutrients generated by CND and CVA for sugar maple (Vizcayno-Soto and Côté, 2004), as well as DRIS and CND for carrot (Dezordi *et al.* 2016) and maize (Gott *et al.* 2017), were found to be somewhat similar. Others have indicated that CND norms are more sensitive for identifying optimal leaf nutrient concentrations, such as Serra *et al.* (2010) for cotton and Ali (2018) for mango trees. Until recently, CND norms for identifying nutrient imbalance in several plants have been established, including for potatoes (Parent et al. 1994; Bélanger *et al.* 2005), maize (Magallanes- Quintanar *et al.* 2006), mango trees (Ali 2018), sugar beet (Barłóg 2016), orange trees (Hernández-Caraballo *et al.* 2008; Tadayon *et al.* 2022), *Opuntia ficus-indica* (Blanco-Macías *et al.* 2010), eucalypt (Silva *et al.* 2004), *Aloe vera* L. (García-Hernández *et al.* 2006), banana (Raghupathi *et al.* 2002; Wairegi and van Asten, 2011), and coffee plants (Wairegi and van Asten, 2012). However, due to the increased usage of only two types of fertilizers—urea/ammonium nitrate and ordinary superphosphate—nutritional imbalances are expected in crops cultivated in Kharga Oasis (the study area), as is common in many developing countries. The nutritional composition of crops, particularly wheat (*Triticum aestivum*) and faba bean (*Vicia faba*) has not yet been examined in this area.

In Kharga Oasis, there are productivity gaps between potential and actual crop yields, particularly for wheat and faba bean. A multitude of reasons, including soil and water issues as well as poor agricultural practices, contribute to these gaps. These issues are exacerbated by the Oasis' hyper-arid climate. Filling this gap with appropriate practices may lead to increased productivity and farmers' profitability. Nutrient management strategies should therefore be devised to provide an appropriate and balanced supply of nutrients in order to increase crop yields. However, information on how, where, and why nutrient imbalances and restrictions occur in crops at large scales is required to design such nutrient management strategies. Therefore, the objectives of this research were to: i) identify major water and soil constraints for crop production in Kharga Oasis; ii) identify and quantify the nutritional imbalance of wheat and faba bean using the CND approach; and iii) identify major nutrient interactions using principal component analysis (PCA) of the derived CND indexes.

Materials and Methods

Description of the study area

The Kharga Oasis is an elongated depression in Egypt's Western Desert that stretches for approximately 180 × 15-30 km in a North-South direction, around 200 km West of the Nile. Kharga has around 17300 ha of agricultural land, which is mostly cultivated with date palm and field crops. All activities in Kharga Oasis are reliant on underground water. There are two types of wells: deep wells with good water quality and surface wells (around 50 m depth) with poor water quality. The dominant type of irrigation in the Oasis is surface flood irrigation in excessive quantities. The climate in Kharga Oasis is typically hyper-arid that is characterized by relatively high temperatures with almost no rainfall. The maximum mean temperature occurs in the summer, reaching 31.4 °C in July, while the minimum mean temperature occurs in the winter, reaching 12.55 °C in January. Annually, the maximum temperature is 30.95 °C and the minimum temperature is 15.7 °C.

Water, soil and plant sampling

Water samples were collected for chemical analysis from 43 different locations in Nasser El-Thawra, El-Mounira, and El-Shirka villages, representing deep and surface wells used for irrigation in Kharga Oasis. Seventy-eight surface soil samples (0–30 cm) were collected to represent the distribution of wheat and faba bean fields in the study area. The samples were bagged for further physical and chemical analysis. In the vicinity of the collected water and soil samples, 128 samples of wheat and 84 samples of faba bean were harvested manually at maturity (during April 2022) from a net area of 6 m^2 for wheat and 10.5 m^2 for faba bean in three replicates located at the center of each field. Following that, wheat grains and faba bean seeds were separated from straw and weighed in the field before being bagged for further analysis. All the agricultural practices in these fields, including cultivation, manure application, seed-bed preparation, sowing time, variety selection, pest and weed control were performed by farmers.

Analytical Procedure

The water samples were analyzed for salinity, pH, and soluble cations and anions as described in Richards (1954). Sodium adsorption ratio (SAR) and soluble sodium percentage (SSP) were calculated based on meq L^{-1} concentrations according to the formulas:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{+2}+Mg^{+2}}{2}}} \qquad \text{(Eq. 1)}$$

$$SSP = \frac{Na^{+}+K^{+}}{Na^{+}+K^{+}+Ca^{+2}+Mg^{+2}} \times 100 \qquad \text{(Eq. 2)}$$

Air-dried soil samples were ground and sieved using a 2 mm sieve. For assessing soil texture, particle size was measured on soil samples using the pipette method (Gee and Bauder, 1986). Soil electrical conductivity (EC) and pH were measured in soil paste as described by Page *et al.* (1982). Based on soil SAR, the exchangeable sodium percentage (ESP) was calculated using the formula:

$$ESP = \frac{[100(-0.0126+0.01475 \times SAR)]}{[1+(-0.0126+0.01475 \times SAR)]} \qquad \text{(Eq. 3)}$$

The Walkely and Black method was used to assess soil organic matter as outlined by Page *et al.* (1982). According to Dahnke and Johnson (1990), available N was extracted using a 2 *M* KCl solution and then measured using a micro-Kjeldahl. Available P, K, Fe, Mn, Zn, and Cu were extracted by 1 *M* NH_4HCO_3 in 0.005 *M* DTPA adjusted to a pH of 7.6 (Soltanpour 1991). The extracted P was colorimetrically determined using ascorbic acid and ammonium molybdate by a spectrophotometer, whereas the extracted K was determined by a flamphotometer. The extracted Fe, Mn, Zn, and Cu were measured using inductively coupled plasma-atomic emission spectroscopy as described by Varma (1991).

Plant samples were ground after being dried at 70 °C in a hot air oven to a constant weight. The samples were wet digested using an H_2SO_4 - H_2O_2 mixture, according to Wolf (1982). The acid digest was analyzed for N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu content as described in Kalra (1997).

The CND approach

The CND norms were calculated as described by Khiari *et al.* (2001). Plant tissue composition, according to Parent and Dafir (1992), provides a dimensional nutrient arrangement, *i.e.*, simplex (S^d), formed of a d+1 nutrient proportion comprising d nutrients (number of nutrients) and a filling value under the following assumptions:

$$S^d = [(N, P, K, .., Rd): N > 0, P > 0, K > 0 .... Rd > 0, N + P + K + \cdots + Rd = 100] \quad \text{(Eq. 4)}$$

where 100 is the dry matter concentration (%), N, P, K, etc. are the nutrient concentrations (%), and Rd is the filling value between 100% and the total of the nutrient concentrations as follows:

$$Rd = 100 - (N + P + K + \cdots) \quad \text{(Eq. 5)}$$

The nutrient proportions become scale invariant after being divided by the geometric mean (G) of the d+1 components, including Rd (Aitchison 1982) as follows:

$$G = (N \times P \times K \times \ldots\ldots\ldots \times Rd)^{\frac{1}{d+1}} \quad \text{(Eq. 6)}$$

Row-centered log ratios are then derived as follows:

$$VN = \ln\frac{N}{G}, VP = \ln\frac{P}{G}, VK = \ln\frac{K}{G}, \ldots\ldots\ldots VRd = \ln\frac{Rd}{G} \quad \text{(Eq. 7)}$$

and the following assumption should be met:

$$VN + VP + VK + \cdots + VRd = 0 \quad \text{(Eq. 8)}$$

where Vx is the nutrient X CND row-centered log ratio.

By assuming that V^*_N, V^*_P, V^*_K,…V^*_{Rd} and SD^*_N, SD^*_P, SD^*_K,… SD^*_{Rd} are the CND norms as means and standard deviations of row-centered log ratios, respectively, the values of separate specimens are then standardized as follows:

$$IN = \frac{(V_N - V*_N)}{SD*_N},\ IP = \frac{(V_P - V*_P)}{SD*_P},\ IK = \frac{(V_K - V*_K)}{SD*_K}, \ldots.\ IRd = \frac{(V_{Rd} - V*_{Rd})}{SD*_{Rd}} \quad \text{(Eq. 9)}$$

where IN, IP, IK,….., IRd are the CND indexes.

The derived CND indexes closer to zero suggest a greater likelihood of obtaining a high yield, whereas negative or positive values indicate an imbalance in both dimensions, deficit or excess, respectively.

Data processing and statistical analysis

Excel software (as part of Microsoft Office 2016) and Statistical Product and Service Solutions (SPSS 18.0 software) were used to process data, create graphs, and perform statistical analysis for this study.

Results and Discussion

Irrigation water quality indicators

Chemical characteristics of irrigation water varied substantially in the study area (Table 1). Water salinity ranged from 257.9 to 4041.7 mg L^{-1}, with an average value of 889.2 mg L^{-1}, indicating minimal to severe restrictions for irrigation (FAO 1985). The pH was in the neutral range, with an average of 6.77, possibly due to the high salt content of the water, which restricts the pH increase. Deep wells (about 700 m depth) have considerably lower salinity than surface wells (about 50 m depth), yet both are used for irrigation, either independently or in combination.

The SAR of irrigation water measures the relative proportions of Na^+ to Ca^{+2} and Mg^{+2} and is a measure of crop Na^+ hazards. The SAR varied from 6.10 to 70.30 with an average value of 23.45 (Table 1), indicating a moderate to high Na^+ hazard (FAO 1985). SSP is another metric used to assess the Na^+ hazard in water and its suitability for irrigation. Levels of SSP in irrigation water varied from 59.46 to 86.83%, with an average of 74.72%. Todd and Mays (2004) suggested that the highest allowable limit of SSP in water without degrading the soil is 60 %. Consequently, the majority of irrigation water exceeded the limit.

The relationship between Na^+ and Cl^- ions is utilized to determine the process that regulates salinity and saline incursion (Dixon and Chiswell 1992). The Na^+/Cl^- ratio in irrigation water ranged from 0.47 to 1.85, with an average of 1.14 (Table 1). Most samples have nearly equal Na^+/Cl^- ratios, indicating that there is a source of Na^+ dissolution in irrigation water, soil interaction, or irrigation water connection with drainage water. This is expected to have a major impact on nutrient biochemical interactions in both soil and plants.

Table 1– Chemical characteristics of irrigation water at various locations in Kharga Oasis.

	Minimum	Maximum	Mean	SD [c]	CV [d]
Salinity, mg L^{-1}	257.9	4041.7	889.2	858.6	96.57
pH	6.50	7.20	6.77	0.23	3.40
Ca^{+2}, meq L^{-1}	16.00	192.00	46.35	43.88	94.69
Mg^{+2}, meq L^{-1}	7.30	72.90	29.18	19.53	66.91
Na^{+}, meq L^{-1}	33.00	1040.00	196.77	220.17	111.89
K^{+}, meq L^{-1}	24.00	75.00	42.54	11.71	27.54
CO_3^{-2}, meq L^{-1}	0.20	1.00	0.59	0.28	47.46
HCO_3^{-}, meq L^{-1}	93.90	503.90	235.18	105.87	45.01
Cl^{-}, meq L^{-1}	42.50	615.50	180.50	162.23	89.88
SO_4^{-2}, meq L^{-1}	16.50	2050.00	276.23	438.94	158.91
SAR [a]	6.10	70.30	23.45	15.14	64.56
SSP [b]	59.46	86.83	74.72	7.67	10.23
Na/Cl	0.47	1.85	1.14	0.47	41.03

[a] *Sodium adsorption ratio*
[b] *Soluble sodium percentage*
[c] *Standard deviation*
[d] *Coefficient of variation*

Variability of soil properties

The physical and chemical properties of topsoil samples (0–30 cm) collected from the study area are shown in Table 2. Clay content, as an indication of soil texture, varied from 1.36 to 63.21 % with an average value of 31.53%. It covers a wide range of soil textures, from sandy to clayey, with heavy-textured classes prevailing. pH of the soil ranged from 7.7 to 9.7, with an average value of 8.55, putting the majority of soils in the alkaline class. Soil salinity ranged from low (1.04 dS m^{-1}) to extremely high (34.48 dS m^{-1}) with an average value of 7.28 dS m^{-1}, putting many soils in the salt-affected category. Organic matter content of the soil ranged from very low (0.18%) to medium (2.10%), with an average value of 0.64 %. This also implies poor soil structure and a deteriorated soil surface. The ESP varied from 3.2 to 71.8%, with an average of 24.59%. The majority of soils have ESP values greater than 15%, indicating that soil sodicity is a dominant concern. In the saline-sodic field conditions that predominate the study area, the processes at the soil-plant interface are complicated and influenced by soil water dynamics, pH concerning salt solubility in the rhizosphere, nutrient availability, soil aggregate stability, and redox potential (Rengasamy 2010; Osman 2018; Bello *et al.* 2021).

DOI: https://doi.org/10.36253/jaeid-14528

Table 2 – Some physical and chemical properties of the surface soil layer (0–30 cm) at various locations in Kharga Oasis.

	Minimum	Maximum	Mean	SD [d]	CV [e]
Clay, %	1.36	63.21	31.53	18.69	59.26
pH	7.70	9.70	8.55	0.39	4.51
EC [a], dS m^{-1}	1.04	34.48	7.28	8.40	115.38
OM [b], %	0.18	2.10	0.64	0.38	58.92
ESP [c], %	3.20	71.80	24.59	17.00	69.13
Available N, mg kg^{-1}	7.70	215.60	47.06	31.66	67.26
Available P, mg kg^{-1}	0.36	28.23	6.95	6.61	95.14
Available K, mg kg^{-1}	63.20	978.40	435.03	201.08	46.22
Available Fe, mg kg^{-1}	3.12	155.24	31.09	27.58	88.73
Available Mn, mg kg^{-1}	2.50	96.60	26.83	22.18	82.67
Available Zn, mg kg^{-1}	0.90	37.90	3.37	6.14	182.02
Available Cu, mg kg^{-1}	0.02	1.54	0.42	0.30	72.37

[a] *Electrical conductivity*
[b] *Organic matter*
[c] *Exchangeable sodium percentage*
[d] *Standard deviation*
[e] *Coefficient of variation*

The nutrient classifications described by Jones (1999) assisted in the interpretation of soil fertility status. The available N varied from low (7.70 mg kg^{-1}) to medium (215.6 mg kg^{-1}) with an average of 47.06 mg kg^{-1} (Table 2). The available P varied from low (0.36 mg kg^{-1}) to adequate (28.33 mg kg^{-1}) with an average value of 6.96 mg kg^{-1}. The available K varied from marginal (63.20 mg kg^{-1}) to adequate (978.4 mg kg^{-1}) with an average value of 435.03 mg kg^{-1}. The available Fe varied from medium (3.12 mg kg^{-1}) to high (155.24 mg kg^{-1}) with an average value of 31.09 mg kg^{-1}, putting the majority of soils in the high category of Fe. The available Mn was high in general, with values varying from 2.50 to 96.6 mg kg^{-1}. The available Zn varied from low (0.90 mg kg^{-1}) to high (37.90 mg kg^{-1}) with an average value of 3.37 mg kg^{-1}. The available Cu varied from low (0.02 mg kg^{-1}) to high (1.54 mg kg^{-1}) with an average value of 0.42 mg kg^{-1}. The most notable findings of these data reveal that the majority of soils in the study area have an excess of available K, Fe, and Mn, which may hamper the absorption of other nutrients, besides luxury consumption.

Variability in wheat and faba bean yields and nutrient concentrations

Table 3 presents the descriptive statistics for wheat and faba bean yields as well as nutrient concentrations in wheat grains and faba bean seeds. The magnitude of variability was determined using standard criteria as indicated in Wilding *et al.* (1994), with a coefficient of variation (CV) of < 15%, 15-35%, and > 35% indicating low, medium, and high variability, respectively. There were robust variations in wheat grain yield and faba bean seed yield, which varied from 2118.2 to 8210.6 and 1373.3 to 4961.8 kg ha^{-1}, respectively. This indicates that there are factors that lead to a substantial reduction in crop yields in some parts of the study area. Grain yield and Fe concentration in wheat exhibited medium variability, whereas the remaining parameters showed high variability. Seed yield, N, K, Ca, Mg, and Zn concentrations in faba bean exhibited medium variability, whereas the remaining parameters showed high variability.

Table 3 – Summary descriptive statistics of wheat and faba bean yields and nutrient concentrations at various locations in Kharga Oasis.

	Minimum	Maximum	Mean	SD [a]	CV [b]
		Wheat			
Grain yield, kg ha^{-1}	2118.2	8210.6	6457.9	1726.05	26.7
N, %	0.92	3.23	1.42	0.50	35.4
P, %	0.13	2.47	0.65	0.50	77.4
K, %	0.12	0.55	0.28	0.11	40.6
Ca, %	0.06	0.24	0.13	0.05	35.9
Mg, %	0.09	0.22	0.14	0.03	21.9
Fe, mg kg^{-1}	134.60	928.00	306.07	158.47	51.8
Mn, mg kg^{-1}	20.20	127.80	64.70	25.82	39.9
Zn, mg kg^{-1}	9.99	107.60	33.71	16.65	49.4
Cu, mg kg^{-1}	4.39	178.00	21.34	35.05	164.3
		Faba bean			
Seed yield, kg ha^{-1}	1373.3	4961.8	3564.4	1236.9	34.7
N, %	1.18	3.76	2.41	0.58	24.3
P, %	0.36	9.60	2.08	1.46	70.2
K, %	0.59	1.47	0.85	0.17	20.4
Ca, %	0.09	0.32	0.18	0.06	31.1
Mg, %	0.08	0.29	0.15	0.05	31.4
Fe, mg kg^{-1}	24.20	1473.00	279.11	313.16	112.2
Mn, mg kg^{-1}	18.40	170.44	69.71	36.22	52.0
Zn, mg kg^{-1}	25.40	87.40	61.73	12.55	20.3
Cu, mg kg^{-1}	11.00	51.60	23.66	9.54	40.3

[a] *Standard deviation*
[b] *Coefficient of variation*

Variability is important for identifying nutritional status restrictions in an area and defining nutrient-sufficiency ranges (Barłóg 2016; Ali 2023). Yield and nutrient concentrations can be considered plant responses to biotic and abiotic variables, particularly those linked with field-to-field variability. Because there are low- and high-yield subpopulations, the database acquired in this study can be utilized as a diagnostic indicator to determine the variables limiting yields.

The compositional nutrient diagnosis for simplex S^9

The S^9, or 10 dimensional (d+1) simplex, was made up of the nine nutrients investigated (N, P, K, Ca, Mg, Fe, Mn, Zn, Cu) and the filling value R. There are several techniques for selecting the reference subpopulation in the scientific literature. In the current study, the box-and-whiskers diagram was employed to define the upper and lower limits of yield data, hence the selection of the turning point between low- and high-yield subpopulations. The interquartile range of wheat grain yield was from 4377 to 7854 kg ha^{-1} with a median value of 6745 kg ha^{-1}, and for faba bean seed yield from 2404 to 4260 kg ha^{-1} with a median value of 3808 kg ha^{-1} (Figure 1). The upper interquartile values can be considered the cutoff limit between the low- and high-yield subpopulation. The upper interquartile value of wheat grain yield was 7854 kg ha^{-1}, whereas for faba bean seed yield was 4260 kg ha^{-1}. However, in comparison to growing conditions in Egypt, average wheat and faba bean yields across the country are 65682 and 39437 kg ha^{-1}, respectively (FAOSTAT 2022), indicating the possibility of achieving high production levels across the country by closing the yield gap.

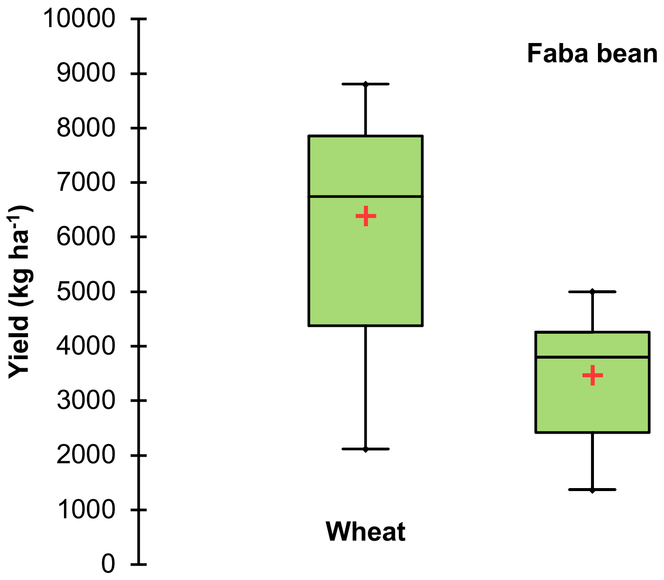

Figure 1 – Box-and-whiskers graph of wheat grain yield and faba bean seed yield at various locations in Kharga Oasis. The box represents the interquartile range (IQR) of yields; the solid line within the box is the yield median; the red cross indicates the yield mean; and the whiskers represent 1.5 times the IQR.

The preliminary CND norms, as mean and standard deviations (V_x^* and SD, respectively) of the CND row-centered log ratios for the high-yield subpopulation, are presented in Table 4, which also includes the optimum ranges for nutrient concentrations associated with the preliminary CND norms. The optimum ranges for N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu in wheat (as mean ± SD) were 1.528 ± 0.701%, 0.828 ± 0.368%, 0.353 ± 0.059%, 0.149 ± 0.034 %, 0.139 ± 0.026%, 302.67 ± 119.54 mg kg^{-1}, 65.57 ± 22.31 mg kg^{-1}, 44.78 ± 17.23 mg kg^{-1}, and 24.34 ± 17.61 mg kg^{-1}, respectively. For faba bean, these ranges were 2.602 ± 0.474 %, 1.901 ± 0.509 %, 0.929 ± 0.140 %, 0.173 ± 0.045 %, 0.140 ± 0.029 %, 159.34 ± 47.09 mg kg^{-1}, 88.51 ± 32.67 mg kg^{-1}, 59.98 ± 12.44 mg kg^{-1}, and 26.95 ± 11.72 mg kg^{-1}, respectively.

For the low-yield subpopulation dataset, the inferred norms were utilized to compute nutrient imbalance indexes, *i.e.,* IN, IP, IK, ICa, IMg, IFe, IMn, IZn, and ICu. Theoretically, CND index interpretation consists of categorizing them into three groups: zero, positive, or negative. These categories indicate balanced nutritional status, excess nutritional status, or deficient nutritional status, respectively. As shown in Figure 2, IP, ICa, and IZn for wheat were negative, with average values of -0.82, -2.66, and -1.26, respectively. But IK, IMg, IFe, and IMn were positive with average values of 4.80, 4.92, 1.70, and 0.57, respectively. IN and ICu are close to zero and can be regarded as balanced. For faba bean, IN, IP, ICa, and IZn were negative with average values of -1.73, -0.67, -8.19, and -1.41, respectively. However, IK, IMg, IFe, IMn, and ICu were positive, with average values of 2.62, 0.50, 1.32, 1.10, and 0.40, respectively.

Calcium seems to be the nutrient in wheat that is most deficient, followed by Zn and P, whereas Mg is the most excessive nutrient, followed by K, Fe, and Mn. On the other hand, Ca also the most deficient nutrient in faba bean, followed by N, Zn, and P, whereas K is the most excessive nutrient, followed by Fe, Mn, and Cu. Nutritional management, environmental conditions, high soil pH, and salinity might all influence variations in nutrient status and, as a result, nutrient imbalances (Grattan and Grieve 1998; Parent *et al.* 2013). The majority of the soils in the study area have alkalinity and salinity issues (Table

2). Under these circumstances, the availability and absorption of nutrients are impacted by the formation of insoluble compounds and antagonistic reactions (Grattan 1994; Sun *et al.* 2018; Liu *et al.* 2019). High salinity stress primarily results in mineral ion imbalances at both the cellular and whole plant levels (Silva *et al.* 2015). Because Ca is the most deficient nutrient in both wheat and faba bean, high soil ESP and water SAR may have a detrimental influence on Ca absorption (Cramer 2002; Cabot 2009). Plant deficiencies in Ca are particularly problematic because of their low mobility and their crucial function in vegetative and reproductive growth (Marschner 2011). Increasing the NaCl content in the nutritional solution, for example, increased Na, Cl, and K while lowering Ca and Mg (Grattan and Grieve 1998; Naeini *et al.* 2005; Fageria *et al.* 2011; Liu *et al.* 2019). Nitrogen deficiency in faba bean was observed, which can be explained by the harmful effect of salt stress on the Rhizobium-legume symbiosis (Abd-Alla 1992). Salinity, according to Zahran and Sprent (1986), has the potential to decrease root hair curling, infection thread formation, and nodule number. Iron and Mn indexes, on the other hand, increase owing to the presence of these nutrients in high concentrations in available forms in the soil, while the Zn index decreases likely because of its low availability in the soil and interaction with Fe.

Table 4 – Compositional nutrient diagnosis norms for d=9 nutrients and the derived optimal ranges (mean ± standard deviation, SD) of nutrients for wheat and faba bean high-yield subpopulations.

Row-centered log ratio	Mean	SD	Nutrient	Mean	SD
			Wheat		
V_N^*	2.412	0.350	N, %	1.528	0.701
V_P^*	1.791	0.409	P, %	0.828	0.368
V_K^*	1.011	0.163	K, %	0.353	0.059
V_{Ca}^*	0.188	0.188	Ca, %	0.149	0.034
V_{Mg}^*	0.074	0.156	Mg, %	0.139	0.026
V_{Fe}^*	-1.510	0.340	Fe, mg kg^{-1}	302.667	119.536
V_{Mn}^*	-3.032	0.328	Mn, mg kg^{-1}	65.579	22.310
V_{Zn}^*	-3.397	0.264	Zn, mg kg^{-1}	44.777	17.228
V_{Cu}^*	-4.131	0.540	Cu, mg kg^{-1}	24.345	17.612
V_R^*	6.608	0.101	R, %	96.959	0.726
			Faba bean		
V_N^*	2.774	0.191	N, %	2.602	0.474
V_P^*	2.415	0.441	P, %	1.901	0.509
V_K^*	1.718	0.151	K, %	0.929	0.140
V_{Ca}^*	0.224	0.224	Ca, %	0.173	0.045
V_{Mg}^*	-0.173	0.200	Mg, %	0.140	0.029
V_{Fe}^*	-2.543	0.596	Fe, mg kg^{-1}	159.374	47.087
V_{Mn}^*	-3.193	0.372	Mn, mg kg^{-1}	88.512	32.665
V_{Zn}^*	-3.343	0.304	Zn, mg kg^{-1}	59.985	12.438
V_{Cu}^*	-4.209	0.428	Cu, mg kg^{-1}	26.954	11.724
V_R^*	6.311	0.099	R, %	94.221	0.814

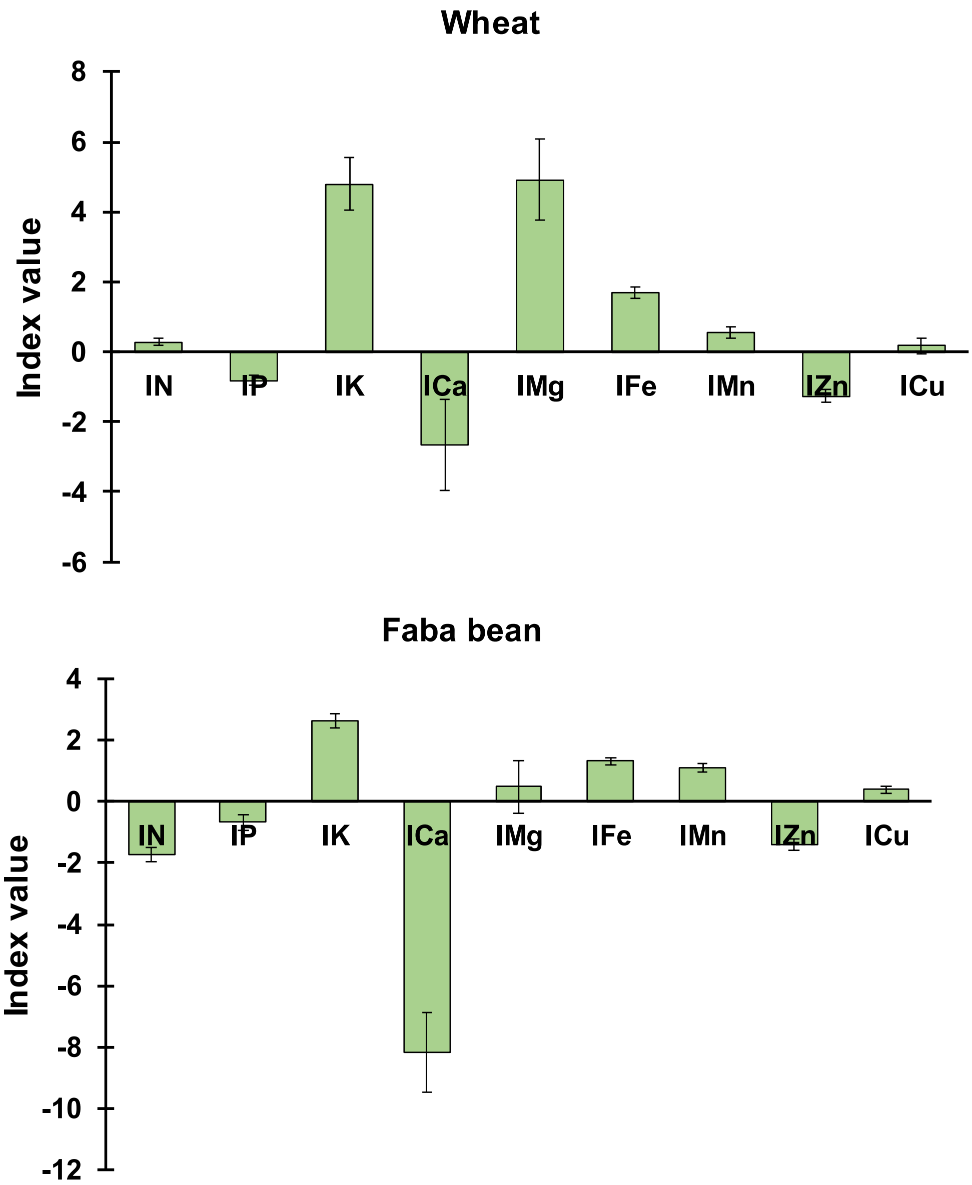

Figure 2 – Nutrient imbalance indexes (± standard error bars) of wheat and faba bean low-yield subpopulations in Kharga Oasis using a compositional nutrient diagnosis approach.

Identification of nutrient interactions

Biochemical activities of nutrients in plants do not operate independently. Therefore, identifying the most relevant interactions is critical for enhancing nutrient use efficiency and, as a consequence, increasing yields. For the low-yield subpopulation dataset, CND indexes were subjected to PCA to reduce the number of interdependent variables into smaller numbers of independent principal components (PC). Inspection of the factor-loading matrix obtained from a varimax rotational technique to get the greatest relationships between indexes and contributions to the PCs helped in the interpretation of the main components. Figure 3 depicts the scree plots of eigenvalue versus component number for wheat and faba bean. The scree plots of eigenvalues reveal that the first three components have eigenvalues greater than one. Therefore, three PCs were retained, and these could explain 73.17% of the pattern variance in wheat and 68.93% in faba bean (Table 5).

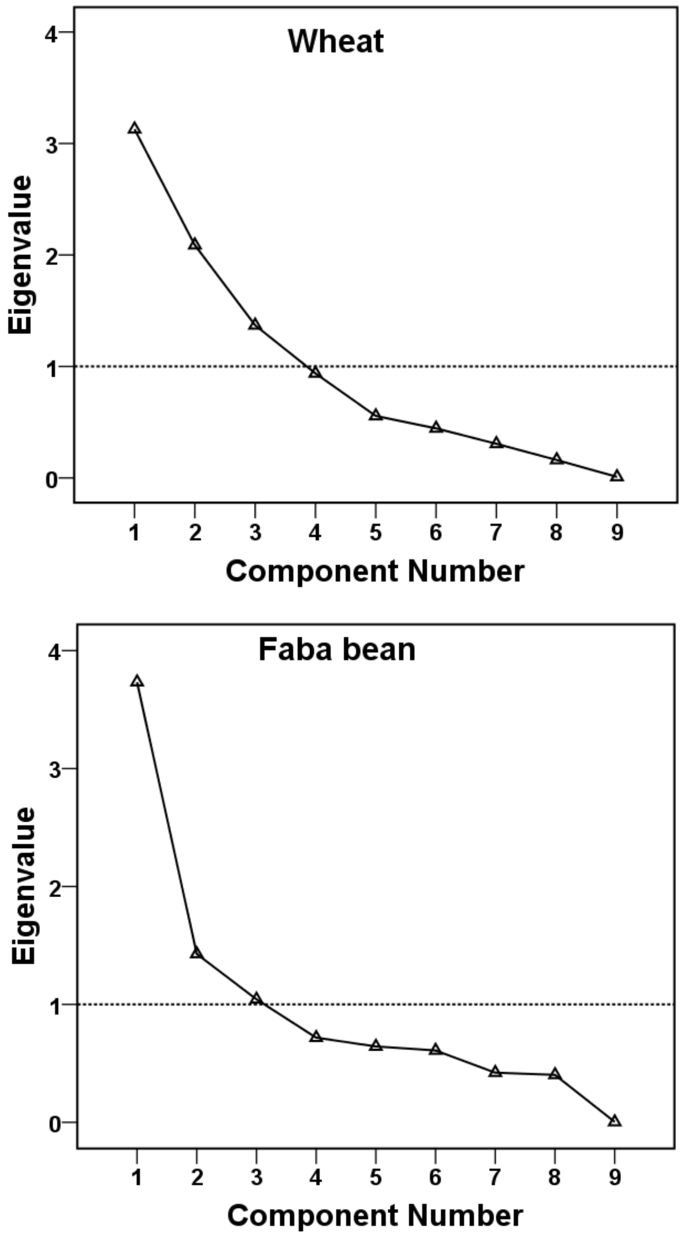

Figure 3 – Scree plots of eigenvalues versus component number of the derived compositional nutrient diagnosis indexes of wheat and faba bean low-yield subpopulations in Kharga Oasis.

In wheat, IP, IMg, IFe, and IZn contributed the most to the structure of the PC1, explaining 34.55% of the variance (Table 5). The PC1 recognized two positive interactions: IP-IZn and IMg-IFe, and four negative interactions: IP-IMg, IP-IFe, IZn-IFe, and IZn-IMg. In the PC2, the structure defined by ICa and ICu explained 23.29% of the variance and interacted negatively. In the PC3, IN and IMn defined the structure and explained 15.33 % of the variance. These two indexes interact negatively.

In faba bean, IFe and IZn are the parameters that determined the structure of the PC1, and they accounted for 33.82% of the variance and interacted negatively (Table 5). In the PC2, the structure defined by IMn and ICu, explained 19.21% of the variance and interacted negatively. In the PC3, IP and ICa defined the structure, explained 15.90% of the variance, and negatively interacted.

Table 5 – Loadings between the first three principal components and the compositional nutrient diagnosis indexes for wheat and faba bean retrieved from a varimax rotated matrix with Kaiser normalization.

Index	Wheat			Faba bean		
	PC1	PC2	PC3	PC1	PC2	PC3
IN	0.448	0.303	**-0.725**	0.620	0.340	-0.011
IP	**-0.751** [a]	-0.031	-0.155	0.606	-0.027	**-0.705**
IK	-0.576	0.641	-0.271	0.582	0.493	0.227
ICa	-0.004	**0.830**	0.270	0.186	-0.049	**0.878**
IMg	**0.820**	0.349	0.155	-0.513	-0.197	0.392
IFe	**0.721**	-0.245	-0.210	**-0.842**	-0.309	-0.256
IMn	0.343	0.192	**0.771**	-0.411	**-0.711**	0.150
IZn	**-0.837**	0.106	0.051	**0.815**	0.017	-0.007
ICu	-0.047	**-0.821**	0.138	0.026	**0.892**	-0.021
Explained variance	3.109	2.096	1.380	3.044	1.729	1.431
Cumulative variance, %	34.55	57.84	73.17	33.82	53.03	68.93

[a] *Index values in boldface are the dominant in the loadings by setting the degree of significance at 0.70.*

In wheat, a synergistic interaction between P and Zn was identified. Nevertheless, several studies have observed that there is a negative interaction between Zn and P in plants (Das *et al.* 2005; Alloway 2008; Kremper *et al.* 2015), in contrast to the current study's finding. However, generally increased plant growth necessitates P and Zn, resulting in growth stimulation and higher absorption of both elements, particularly because both are lacking in the study case (Figure 2). A study by Korkmaz *et al.* (2021) appears to support our findings, as they reported that the effect of P and Zn interaction was considerable on chia plant dry matter, P and Zn concentration, and their uptake. However, high levels of P significantly reduced the Zn concentration. This should confirm the study's result that both nutrients at low levels may have a synergistic impact; however, raising the level of P above what is essential may decrease Zn absorption.

The antagonistic P-Mg interaction in wheat may be related to the dilution-accumulation process (Walworth and Sumner 1987; Marschner 2011). Also, the P-Ca antagonism observed in faba bean in this study has been reported by Parent *et al.* (1994) among other authors. Fageria and Baligar (1999), for example, investigated the interactions of Ca and P in dry bean and found an antagonistic relationship. However, the antagonistic relationship observed between P and Fe in wheat can be explained by the internal immobilization of Fe, most likely due to the production of Fe-phosphate (Ayed 1970).

The antagonistic Zn-Fe relationship in both wheat and faba bean is well documented in the literature (Solomons and Ruz 1997; Mousavi *et al.* 2012; Prasad *et al.* 2016). Mandal *et al.* (2000), for example, observed that high Fe concentrations in soil solutions had an antagonistic influence on Zn absorption. There are three possible mechanisms for this antagonism: (i) there could be competition between Fe and Zn during uptake (Kabata-Pendias 2001); (ii) interference in the chelation process during Fe uptake and translocation (Kabata-Pendias 2001); and (iii) there could be competitive inhibition between Fe and Zn during unloading in the xylem (Alloway 2008). Also, the Zn-Mg antagonistic relationship detected in wheat is documented by Moreira *et al.* (2003) and Canizella *et al.* (2018). For example, excessive dolomite lime soil treatment (>12% MgO) reduced Zn content due to competing inhibitory effects (Moreira *et al.* 2003).

There is an antagonistic effect between Cu and Ca, as observed in wheat. Calcium is known to have a favourable effect on plant growth and to reduce the toxicity of heavy metals (Hagemeyer 2004; Marschner 2011). Several studies have claimed that Ca has the potential to reduce Cu absorption, transport, and accumulation in plants (Kawasaki and Moritsugu 1987; Österås and Greger 2006). On the other hand, the antagonistic relationship between Cu and Mn detected in faba bean has been observed early in the literature (Gupta 1972; Nautiyal and Chatterjee 2002), and some reports suggest that Cu and Mn compete for a common site for uptake but that Cu appears to have a greater affinity than Mn (Harrison *et al.* 1983). The observed antagonism between Mn and N in wheat can be explained by cation competition for absorption between NH_4 and Mn (Fageria 2001), as well as Mn toxicity, which eventually inhibits plant development and, therefore, its capacity to absorb N.

There is a synergistic interaction between Mg and Fe in wheat. To the best of our knowledge, there is no physiological explanation for this relationship. We speculate that soil conditions containing high amounts of both nutrients had a major impact on the observed synergetic effect. As shown in Figure 2, both nutrients displayed severe imbalances in an excessive direction, which may have resulted in a misleading mutual synergistic interaction.

Conclusions

There are considerable variations in the water and soil characteristics of the study area, with salinity being a major issue, which is reflected in variations in wheat and faba bean yields. Multi-nutrient diagnosis through CND indicated that the most imbalanced nutrient with a negative value in wheat is Ca, followed by Zn and P, whereas Mg is the nutrient that is imbalanced with a positive value, followed by K, Fe, and Mn. On the other hand, Ca also the most imbalanced nutrient in faba bean with a negative value, followed by N, Zn, and P, whereas K is the most imbalanced nutrient with a positive value, followed by Fe, Mn, and Cu. The positive interactions P-Zn and Mg-Fe, as well as the negative interactions P-Mg, P-Fe, Zn-Fe, Zn-Mg, Ca-Cu, N-Mn, Mn-Cu, and P-Ca, were evidenced. It is thus possible to infer that the decline in wheat and faba bean yields in Kharga Oasis was caused by a nutritional imbalance induced by a deficiency of Ca, Zn, and P and a surplus of Mg, K, Fe, and Mn, in addition to some predominated nutrient interactions. To enhance wheat and faba bean nutritional status, soil application of calcium sulphate, also known as agricultural gypsum, could reduce soil salinity and Na while improving Ca nutrient status and suppressing Mg, Fe, and Mn availability owing to improved soil aeration and antagonism. Supplementing the soil with an appropriate amount of well-decomposed organic manure would also contribute in this respect. Furthermore, due to soil constraints, foliar Zn should be applied during periods of high nutrient demand, with the premise that soil supply and root uptake may be insufficient.

Declarations

Conflict of interest: The authors declare that they have no conflict of interest.

References

Abd-Alla, M.H. 1992. Nodulation and nitrogen fixation in faba bean (*Vicia faba* L.) plants under salt stress. *Symbiosis*, 12: 311–319.

Aitchison, J. (1982). The statistical analysis of compositional data. *Journal of the Royal Statistical Society: Series B (Methodological)*, *44*(2): 139-160.

Ali, A.M. (2018). Nutrient sufficiency ranges in mango using boundary-line approach and compositional nutrient diagnosis norms in El-Salhiya, Egypt. *Communications in Soil Science and Plant Analysis*, *49*(2): 188-201.

Ali, A.M. (2023). Establishment of nutrient sufficiency ranges in olive using boundary-line approach. *Journal of Plant Nutrition*, 46(3): 453-461.

Alloway, B.J. (2008). Zinc in soils and crop nutrition. published by IZA and IFA. *Brussels, Belgium and Paris, France*, *139*.

Ayed, I.A. (1970). A study of the mobilization of iron in tomato roots by chelate treatments. *Plant and Soil*, *32*(1): 18-26.

Barłóg, P. (2016). Diagnosis of sugar beet (*Beta vulgaris* L.) nutrient imbalance by DRIS and CND-clr methods at two stages during early growth. *Journal of Plant Nutrition*, *39*(1): 1-16.

Bates, T.E. (1971). Factors affecting critical nutrient concentrations in plants and their evaluation: A review. *Soil Science*, *112*(2): 116-130.

Bélanger, M.C., Viau, A.A., Samson, G. & Chamberland, M. (2005). Determination of a multivariate indicator of nitrogen imbalance (MINI) in potato using reflectance and fluorescence spectroscopy. *Agronomy Journal*, *97*(6): 1515-1523.

Bello, S.K., Alayafi, A.H., AL-Solaimani, S.G., & Abo-Elyousr. K.A. (2021). Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. *Agronomy*, *11*(9), 1735.

Blanco-Macías, F., Magallanes-Quintanar, R. Valdez-Cepeda, R.D., Vázquez-Alvarado, Olivares-Sáenz, Gutiérrez-Ornelas, R. E. E. J.A. Vidales-Contreras, & Murillo-Amador., B. (2010). Nutritional reference values for Opuntia ficus-indica determined by means of the boundary-line approach. *Journal of Plant Nutrition and Soil Science*, *173*(6): 927-934.

Cabot, C., Sibole, J.V. Barceló, J., & Poschenrieder, C. (2009). Sodium-calcium interactions with growth, water, and photosynthetic parameters in salt-treated beans. *Journal of Plant Nutrition and Soil Science*, *172*(5): 637-643.

Canizella, B.T., Sousa, J.A. Moreira, A. & Moraes, L.A. (2018). Magnesium and zinc interaction in four soybean cultivars with different nutritional requirements. *Journal of Plant Nutrition*, *41*(17): 2189-2199.

Cramer, G.R. (2002). Sodium-calcium interactions under salinity stress. In *Salinity: Environment-plants-molecules* (pp. 205-227). Springer, Dordrecht.

Dahnke, W.C., & Johnson, G.V. (1990). Testing soils for available nitrogen. *Soil Testing and Plant Analysis*, *3*: 127-139.

Das, K., Dang, R. Shivananda, T.N., & Sur, P. (2005). Interaction between phosphorus and zinc on the biomass yield and yield attributes of the medicinal plant stevia (*Stevia rebaudiana*). *The Scientific World Journal*, *5*: 390-395.

Dezordi, L.R., Aquino, L.A.D. Aquino, R.F.B.D.A. Clemente, J.M., & Assunção, N.S. (2016). Diagnostic methods to assess the nutritional status of the carrot crop. *Revista Brasileira de Ciência do Solo*, *40*.

Dixon, W., & Chiswell, B. (1992). The use of hydrochemical sections to identify recharge areas and saline intrusions in alluvial aquifers, southeast Queensland, Australia. *Journal of Hydrology*, *135*(1-4): 259-274.

Fageria, N.K., & Baligar, V.C. (1999). Growth and nutrient concentrations of common bean, lowland rice, corn, soybean, and wheat at different soil pH on an Inceptisol. *Journal of Plant Nutrition*, *22*(9): 1495-1507.

Fageria, N.K., Gheyi, H.R, & Moreira, A. (2011). Nutrient bioavailability in salt affected soils. *Journal of Plant Nutrition*, *34*(7): 945-962.

Fageria, V.D. (2001). Nutrient interactions in crop plants. *Journal of Plant Nutrition*, *24*(8): 1269-1290.

FAO. (1985). *Water quality for agriculture* (Vol. 29, p. 174). Rome: Food and Agriculture Organization of the United Nations.

FAOSTAT. (2022). Available online at: https://www.fao.org/faostat/en/#home (accessed 15 December 2022).

García-Hernández, J.L., Valdez-Cepeda, R.D., Murillo-Amador, B., Beltrán-Morales, F.A., Ruiz-Espinoza, F.H., Orona-Castillo, I., Flores-Hernández, A., & Troyo-Diéguez, E. (2006). Preliminary compositional nutrient diagnosis norms in *Aloe vera* L. grown on calcareous soil in an arid environment. *Environmental and Experimental Botany*, *58*(1-3): 244-252.

Gee, G.W., & Bauder, J.W. (1986). Particle Size Analysis. P.404-408. In A. Klute (ed.) Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monoger. No. 9 ASA and SSSA, Madison, WI.

Gott, R.M., Aquino, L.A., Clemente, J.M., Santos, L.P.D.D., Carvalho, A.M.X., & Xavier, F.O. (2017). Foliar diagnosis indexes for corn by the methods diagnosis and recommendation integrated system (DRIS) and nutritional composition (CND). *Communications in Soil Science and Plant Analysis*, *48*(1): 11-19.

Grattan, S.R., & Grieve, C.M. (1998). Salinity-mineral nutrient relations in horticultural crops. *Scientia Horticulturae*, *78*(1-4): 127-157.

Grattan, S.R. (1994). Mineral element acquisition and response of plants grown in saline environment. *Handbook of Plant and Crop Stress*: 203-227.

Gupta, U.C. (1972). Effects of manganese and lime on yield and on the concentrations of manganese, molybdenum, boron, copper and iron in the boot stage tissue of barley. *Soil Science*, *114*(2): 131-136.

Hagemeyer, J. (2004). Ecophysiology of plant growth under heavy metal stress. In *Heavy metal stress in plants* (pp. 201-222). Springer, Berlin, Heidelberg.

Harrison, S.J., Lepp, N.W., & Phipps, D.A. (1983). Copper uptake by excised roots: III. Effect of manganese on copper uptake. *Zeitschrift für Pflanzenphysiologie*, *109*(4): 285-289.

Hernández-Caraballo, E.A., Rodríguez-Rodríguez, O., & Rodríguez-Pérez, V. (2008). Evaluation of the Boltzmann equation as an alternative model in the selection of the high-yield subsample within the framework of the compositional nutrient diagnosis system. *Environmental and Experimental Botany*, *64*(3): 225-231.

Jones Jr, J.B. ed. (1999). *Soil analysis handbook of reference methods*. CRC press.

Kabata-Pendias, A., & Pendias, H. (2001). Trace elements in soils and plants CRC Press Inc. *Boca Raton, FL, USA*.

Kalra, Y. ed. (1997). *Handbook of reference methods for plant analysis*. Boca Raton, FL: CRC press.

Kawasaki, T., & Moritsugu, M. (1987). Effect of calcium on the absorption and translocation of heavy metals in excised barley roots: multi-compartment transport box experiment. In *Plant and soil interfaces and interactions* (pp. 21-34). Springer, Dordrecht.

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.

Korkmaz, K., Akgün, M., Özcan, M.M., Özkutlu, F., & Kara, Ş.M. (2021). Interaction effects of phosphorus (P) and zinc (Zn) on dry matter, concentration and uptake of P and Zn in chia. *Journal of Plant Nutrition*, *44*(5): 755-764.

Kremper, R., Zsigrai, G., Kovács, A.B., & Loch, J. (2015). Long-term effect of high phosphorus doses on zinc status of maize on a non-calcareous loamy soil. *Plant, Soil and Environment*, *61*(1): 1-5.

Liu, C., Zhao, X., Yan, J., Yuan, Z., & Gu, M. (2019). Effects of salt stress on growth, photosynthesis, and mineral nutrients of 18 pomegranate (*Punica granatum*) cultivars. *Agronomy*, *10*(1), 27.

Magallanes-Quintanar, R., Valdez-Cepeda, R.D., Olivares-Sáenz, E., Pérez-Veyna, O., García-Hernández, J.L., & Lopez-Martinez, J.D. 2006. Compositional nutrient diagnosis in maize grown in a calcareous soil. *Journal of Plant Nutrition*, *29*(11): 2019-2033.

Mandal, B., Hazra, G.C., & Mandal, L.N. (2000). Soil management influences on zinc desorption for rice and maize nutrition. *Soil Science Society of America Journal*, *64*(5): 1699-1705.

Marschner, H. ed. (2011). *Marschner's mineral nutrition of higher plants*. Academic press.

Moreira, A., Malavolta, E., Heinrichs, R., & Tanaka, R.T. (2003). Magnesium influence on manganese and zinc uptake by excised roots of soybean. *Pesquisa Agropecuária Brasileira*, *38*: 95-101.

Mourão Filho, F.D.A.A. (2004). DRIS: Concepts and applications on nutritional diagnosis in fruit crops. *Scientia Agricola*, *61*: 550-560.

Mousavi, S.R., Galavi, M., & Rezaei, M. (2012). The interaction of zinc with other elements in plants: a review. *International Journal of Agriculture and Crop Sciences*, *4*(24): 1881-1884.

Naeini, M.R., Khoshgoftarmanesh, A.H., Lessani, H., & Fallahi, E. (2005). Effects of sodium chloride-induced salinity on mineral nutrients and soluble sugars in three commercial cultivars of pomegranate. *Journal of Plant Nutrition*, *27*(8): 1319-1326.

Nautiyal, N., & Chatterjee, C. (2002). Copper–manganese interaction in cauliflower. *Journal of Plant Nutrition*, *25*(8): 1701-1707.

Osman, K.T. (2018). Saline and sodic soils. In *Management of soil problems* (pp. 255-298). Springer, Cham.

Österås, A.H., & Greger, M. (2006). Interactions between calcium and copper or cadmium in Norway spruce. *Biologia Plantarum*, *50*(4): 647-652.

Page, A.L., Miller, R.H., & Keeney, D.R. (1982). Methods of soil analysis, part 2: Chemical and microbiological properties. Madison WI: American Society of Agronomy. In *Soil Science Society of America*: 595-624.

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.

Parent, L.É. (2011). Diagnosis of the nutrient compositional space of fruit crops. *Revista Brasileira de Fruticultura*, *33*: 321-334.

Parent, L.E., Cambouris, A.N. & Muhawenimana, A. (1994). Multivariate diagnosis of nutrient imbalance in potato crops. *Soil Science Society of America Journal*, *58*(5): 1432-1438.

Parent, L.E., Karam, A. & Visser, S.A. (1993). Compositional nutrient diagnosis of the greenhouse tomato. *HortScience*, *28*(10): 1041-1042.

Parent, S.É., Parent, L.E., Egozcue, J.J., Rozane, D.E., Hernandes, A., Lapointe, L., Hébert-Gentile, V., Naess, K., Marchand, S., Lafond, J., & Mattos Jr, D. (2013). The plant ionome revisited by the nutrient balance concept. *Frontiers in Plant Science*, *4*, 39.

Parent, S.E., Parent, L.E., Rozanne, D.E., Hernandes, A., & Natale, W. (2012). Nutrient balance as paradigm of soil and plant chemometrics. *Soil fertility. New York: InTech Publications*: 83-114.

Prasad, R., Shivay, Y.S., & Kumar, D. (2016). Interactions of zinc with other nutrients in soils and plants-A Review. *Indian Journal of Fertilisers*, *12*(5): 16-26.

Raghupathi, H.B., Reddy, B.M.C., & Srinivas, K. (2002). Multivariate diagnosis of nutrient imbalance in banana. *Communications in Soil Science and Plant Analysis*, *33*(13-14): 2131-2143.

Rengasamy, P. (2010). Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology*, *37*(7): 613-620.

Richards, L.A. (1954). *Diagnosis and improvement of saline and alkali soils* (No. 60). US Salinity Laboratory Staff, Washington.

Serra, A.P., Marchetti, M.E., Vitorino, A.C.T., Novelino, J.O., & Camacho, M.A. (2010). Determination of normal nutrient ranges for cotton by the ChM, CND and DRIS methods. *Revista Brasileira de Ciência do Solo*, *34*: 105-113.

Silva, E.N., Silveira, J.A.G., Rodrigues, C.R.F., & Viégas, R.A. (2015). Physiological adjustment to salt stress in Jatropha curcas is associated with accumulation of salt ions, transport and selectivity of K^+, osmotic adjustment and K^+/Na^+ homeostasis. *Plant Biology*, *17*(5): 1023-1029.

Silva, G.G.C.D., Neves, J.C.L., Alvarez V, V.H., & Leite, F.P. (2004). Nutritional diagnosis for eucalypt by DRIS, M-DRIS, and CND. *Scientia Agricola*, *61*: 507-515.

Solomons, N.W., & Ruz, M. (1997). Zinc and iron interaction: concepts and perspectives in the developing world. *Nutrition Research*, *17*(1): 177-185.

Soltanpour, P.N. (1991). Determination of nutrient availability and elemental toxicity by AB-DTPA soil test and ICPS. In *Advances in Soil Science* (pp. 165-190). Springer, New York, NY.

Sun, Y., Niu, G., Masabni, J.G., & Ganjegunte, G. (2018). Relative salt tolerance of 22 pomegranate (*Punica granatum*) cultivars. *HortScience*, *53*(10): 1513-1519.

Tadayon, M.S., Saghafi, K., & Sadeghi, S. (2022). Determining the compositional nutrient diagnosis (CND) norms and main nutrient interactions in "Valencia" orange orchards on calcareous soils. *Journal of Plant Nutrition*: 1-16.

Todd, D.K., & L. Mays, W. (2004). *Groundwater hydrology*. John Wiley & Sons.

Varma, A. (1991). *Handbook of inductively coupled plasma atomic emission spectroscopy*. Boca Raton, FL: CRC, Inc.

Vizcayno-Soto, G., & Côté, B. (2004). Boundary-line approach to determine standards of nutrition for mature trees from spatial variation of growth and foliar nutrient concentrations in natural environments. *Communications in Soil Science and Plant Analysis*, *35*(19-20): 2965-2985.

Wairegi, L., & van Asten, P. (2011). Norms for multivariate diagnosis of nutrient imbalance in the East African highland bananas (Musa spp. AAA). *Journal of Plant Nutrition*, *34*(10): 1453-1472.

Wairegi, L.W.I., & van Asten. P. (2012). Norms for multivariate diagnosis of nutrient imbalance in arabica and robusta coffee in the east african highlands. *Experimental Agriculture*, *48*(3): 448-460.

Walworth, J.L., & Sumner, M.E. (1987). The diagnosis and recommendation integrated system (DRIS). In *Advances in soil science* (pp. 149-188). Springer, New York, NY.

Wilding, L.P., Bouma, J., & Goss, D.W. (1994). Impact of spatial variability on interpretive modeling. *Quantitative Modeling of Soil Forming Processes*, *39*: 61-75.

Wilkinson, S.R., Grunes, D.L., & Sumner, M.E. (2000). Nutrient interactions in soil and plant nutrition. *Handbook of Soil Science*: 89-112.

Wolf, B. (1982). A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. *Communications in Soil Science and Plant Analysis*, *13*(12): 1035-1059.

Zahran, H.H., & Sprent, J.I. (1986). Effects of sodium chloride and polyethylene glycol on root-hair infection and nodulation of *Vicia faba* L. plants by Rhizobium leguminosarum. *Planta*, *167*(3): 303-309.