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Research article

Promoting the elemental profile of sorghum grain: Driving factors affecting nutritional properties under nitrogen fertilizer conditions

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ABSTRACT

Monitoring nitrogen utilization is crucial in agricultural practices, emphasizing the interrelationship between soil health, nutrient management, and human health.

The study was conducted to evaluate the impact of N fertilizer on the nutritional characteristics of diverse *S. bicolor* varieties, namely Alföldi 1, ES Föehn (Lidea Seeds) with a red pericarp, ES Albanus, Albita, and Farmsugro 180 (all white varieties), the study was conducted in sorghum-producing areas where the crop is non-native. Specifically, the study investigated two soil types: loam clay and sandy soil. Furthermore, the respective varieties were grown under N (27% N CAN) fertilizer conditions, involving 60 kg/ha^{-1} and 120 kg/ha^{-1} of the treatment rates applied at each experiment site. We measured the specific element concentration in each sample using the Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) technology. Certainly, the results demonstrated that the different *S. bicolor* varieties had unique nutritional characteristics attributed to several factors such as soil type, variety, and treatment, which showed a significance value of ($P < 0.05$).

The findings demonstrated that the treatments had distinct impacts as stimulators and inhibitors for certain elements. Specifically, the application of 120 kg/ha^{-1} negatively affected the levels of particular elements, such as Ca mg/kg^{-1}, in loam clay and sandy soil. The statistical analysis of trace microelement variance did not show a significance value ($P > 0.05$) when considering the year factor, which supported the data analysis's reliability and accuracy.

In summary, to enhance the nutritional value of sorghum grain and supply nutrient-rich food choices for individuals, consider factors such as fertilizer response, nutrient uptake by grain, element mineral accumulation, and advisory variety. Additional research could enhance the nutritional properties of sorghum to provide the required dietary stuff, such as grain processing, which can render sorghum a proper addition to a healthy and balanced human diet.

1. Introduction

The impact of climate change on sorghum agriculture is adverse since it hampers growth and decreases yield due to rising temperatures and heat stress [1]. Climate change affects land and agriculture via multiple mechanisms, such as variations in annual

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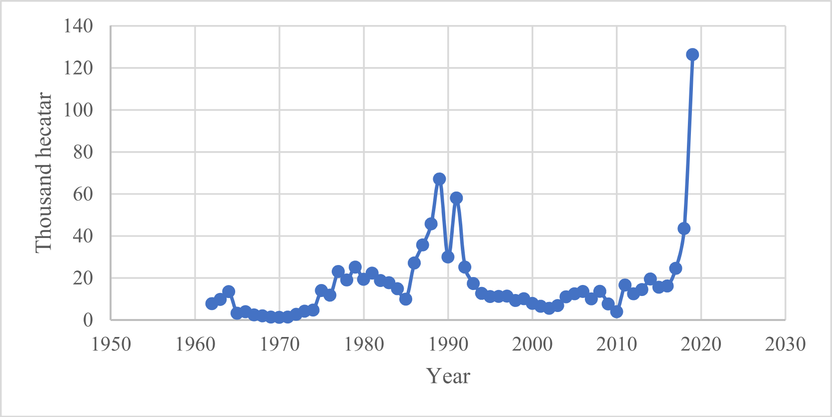

*Source: FAO database

Fig. 1. Hungarian sorghum production from 1961 to 2019.
*Source: FAO database

precipitation, average temperatures, heat waves, changes in weeds, pests, or microbial populations, global alterations in atmospheric CO_2 or ozone levels, and sea level reduction [2]. Many adaptation techniques were used to guarantee food security in the face of climate change; these strategies include diversifying crops, storing water, preparing for disasters, and using higher-quality varieties [3–5]. The European Academies Science Advisory Council (EASAC) has released recommendations for agricultural practices to increase biodiversity, reduce tillage, and target smallholder farms for higher biodiversity and ecosystem service [6]. Questions about which crop to grow, where, when, and with what management will be increasingly challenging for farmers against climate change [6,7]. *S. bicolor* is a drought-tolerant, short-day C_4 crop cultivated for grain, forage, and biomass [8]. Increasingly, sorghum has been recognized as an essential crop for enhancing global food security [9]. More global efforts were needed to ensure sustainable food production and consumption, which can be integrated into creative strategies [10].

Nevertheless, cereal production climbed by 2700 million metric tonnes annually, closely matching demand and supply [11]. In the European Union, sorghum was primarily used for animal feed, although there was increasing interest in biofuels and human consumption [12]. Italy, France, Spain, Romania, Austria, Hungary, and Bulgaria were the top sorghum-producing nations in the EU [12]. The strategies of sorghum cultivation in Hungary were established based on a spatial decision support system that considered soil quality, climate, and topography [13]. Hungary has optimal conditions for cultivating early and intermediate-maturity sorghum hybrids [14].

Fig. 1 shows Hungary's dynamic increase in sorghum production between 1961 and 2019.

That was highlighted by the recommendation to utilize integrated classification strategies in describing the diverse range of cultivated sorghum varieties [15]. Multiple factors, such as sorghum cultivar, soil type, and characteristics of sorghum roots, played a role in nutrient availability and integrated nutrient management [16].

In recent decades, soil fertility has declined due to agricultural intensification and land over-exploitation [17]. Therefore, previous Hungarian literature emphasized the critical role of soil analysis in supporting sustainable agricultural practices [18].

In addition, the annual escalation in prices of fossil fuels and fertilizers has resulted in elevated cultivation costs, prompting a greater utilization of nitrate fertilizers to enhance crop productivity [17].

Nitrogen is a crucial mineral nutrient for sorghum growth and development. It can enhance crop yield if it minimizes the leaching [19]. The response to nitrogen fertilizer varies depending on cultivar differences. Studies investigated nitrogen fertilization's impact on sorghum grain size, nutritional composition, and protein content, aiming to promote efficient practices for effective sorghum cultivation [17].

On the other hand, previous studies emphasized the strong association between crop varieties, soil pH, and the adsorption and accumulation of mineral elements in cereal grains. Incorporating diverse genetics into breeding programs [20]. Proper nutrient management and fertilization are essential for maintaining an optimal nutrient balance and promoting healthy plant growth and productivity [21]. The literature found that mineral levels and yield traits significantly differed between sorghum genotypes [22–24], emphasizing the importance of genetically enhancing sorghum cultivars, such as the strategy of mineral biofortification in nutrient management [24]. According to the Food and Agriculture Organization, the probable differences in the bioavailability of nutritional content in yield grains are attributable to location and crop variety [25]. However, the correlation between the genetic diversity of these varieties and their adaptation to different environmental conditions needs further explanation. Furthermore, research is needed to promote sorghum grains for human consumption in developed nations [26,27].

The recent findings can contribute to optimizing the nutritional intake and sufficiency of minerals; it is necessary to gather data on the mineral content of foods and the sources of dietary foodstuffs for human consumption [28]. The ES Föehn variety was selected as the benchmark for comparing the nutritional value of diverse investigated varieties due to its exceptional attributes, including its remarkable adaptability to climatic change and rich nutritional profile [29]. The ES Föehn seed variety is cultivated throughout Europe, including Ukraine, Russia, Romania, Hungary, Albania, Bulgaria, and Spain [12,29]. Previous research evaluated the bioactive

Table 1
The agricultural practice of the experiment locations in Karcag and Nyíregyháza.

Experimental details	Karcarg Experiment	Nyíregyháza Experiment
Design	Small Split Design	Complete Randomised Block Design (CRBD)
N fertiliser type	Nitrate (27% N CAN)	Nitrate (27% N CAN)
Treatments	60 kg/ha^{-1} and 120 kg/ha^{-1}	60 kg/ha^{-1} and 120 kg/ha^{-1}
Plot measurements	4,25 m x 4,5 m = 19,1 m^2 net area per plot	4,25 m x 4,5 m = 19,1 m^2 net area per plot
Replication	4 replicates	4 replicates

Table 2
Properties and constructions of soil types for the 2020 and 2021 seasons.

Regions	Karcag (Loam clay)		Nyíregyháza (Sandy)	
Year	2020	2021	2020	2021
Collected depth [cm]	15	15	25	25
pH (KCl 1:2.5) [–]	4.7	4.9	7.2	7.5
Plasticity index [KA]	39	44	26	27
Carbon content [m/m%]	0.21	0.21	<0.1	<0.1
Organic matter [m/m%]	2.8	3.3	0.9	1.05
(NO3+NO2)N mg/kg	5.2	9.2	3.61	5.04
AL-(P2O5) mg/kg	87	175	113	136
AL-(K2O) mg/kg	255	462	66	67.5
Na mg/kg	36.5	37.1	34.8	34.2
Zn mg/kg	2.6	2	1.7	1.2
Cu mg/kg	2.2	1.9	2.2	2
Mn mg/kg	48.2	47.8	37.2	37.6

*Source: Research Institute of Karcag and Nyíregyháza. K_A = soil cohesion number, AL-P_2O_5 = phosphorus–pentoxide (ammonium lactate solution), AL-K_2O = potassium–oxide (ammonium lactate solution).

content profiles of the same varieties [30]. The investigation can offer a thorough nutritional analysis of the studied varieties and simplify understanding and evaluating superior varieties for European conditions.

The study aimed to assess and compare the effects of N fertilizer on nutritional compositions such as crude protein, macro, microelements, and trace microelements sourced from five sorghum grain varieties cultivated on two soil types (loam clay and sandy soil) in non-native sites. Furthermore, the investigation focused on the grains as potential raw materials for human consumption.

2. Materials and procedures

2.1. *The study layout*

Field experiments were conducted at two locations: the Research Institute of Nyíregyháza for Agricultural Research and Educational Farm, Westsik Field (47°58′387″ N 21°42′16.2″ E), and the Hungarian University of Agriculture and Life Sciences Research Institute at Karcag (47°17′27.2″ N 20°53′27.8″ E), during the 2020 and 2021 seasons. The experiments in Table 1 encompassed different soil types, including loam clay and sandy soils. The study incorporated five sorghum varieties from both the Karcag and Nyíregyháza sites. Specifically, a small split design was utilized in loam clay soil, while a randomized block design was employed in sandy soil. Calcic ammonium-nitrate (27% N CAN) fertilizer was applied at two rates (60 kg/ha^{-1} and 120 kg/ha^{-1}) to assess its impact on the respective soil types across the two seasons. The experimental setup facilitated simultaneous testing, optimized variety distinction, evaluated interactions between soil types and affected factors, assessed nutrient uptake by the *S. bicolor* variety, and allowed for rigorous statistical analysis.

2.2. *Soil characteristics*

Soil samples were extracted from a depth of 15 cm at the experimental site in Karcag, characterized by a physical loam clay texture and a relatively high acidity level ranging from 4.5 to 5.4. In the 2021 season, sorghum was cultivated in soil exhibiting an ample supply of phosphorus and potassium compared to the preceding year, as evidenced in Table 1.

Conversely, the Nyíregyháza site featured sandy soil with a neutral pH range of 7.2–7.5 detected at a depth of 25 cm. However, no significant variation was observed in the soil chemical composition for 2020 and 2021 at the Nyíregyháza site. The preliminary soil analysis results are provided in Table 2.

2.3. *Environmental conditions*

Based on the weather conditions at the Karcag site, seeding occurred in mid-May on May 13, 2020. The weeds were removed manually, and the harvest date was October 15, 2020. At the beginning of the growing season, the multiannual average was 17.8 mm,

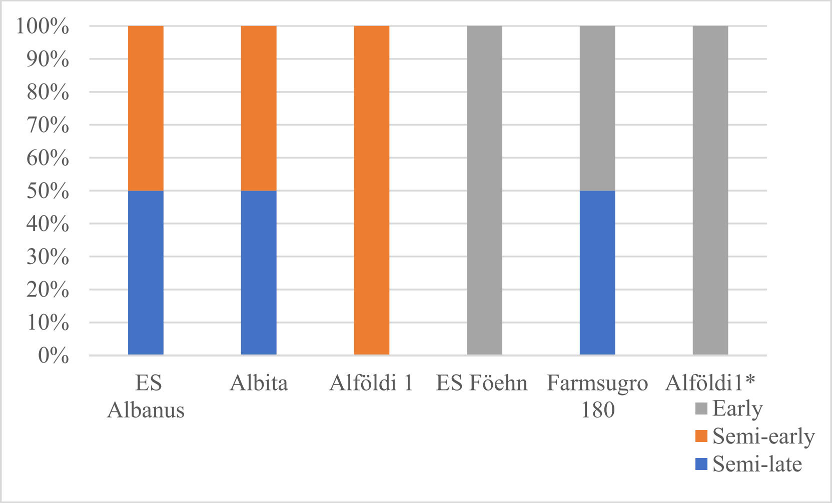

Fig. 2. The maturity stages of the respective varieties cultivated in the loam clay and sandy soil.
* The percentage value shows the maturity stages of five varieties among Karcag and Nyíregyháza for 2020 and 2021. Alföldi 1 refers to the Karcag source, and Alföldi 1* refers to the Nyíregyháza site, blue colour (Semi-late) associated with the Karcag site. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

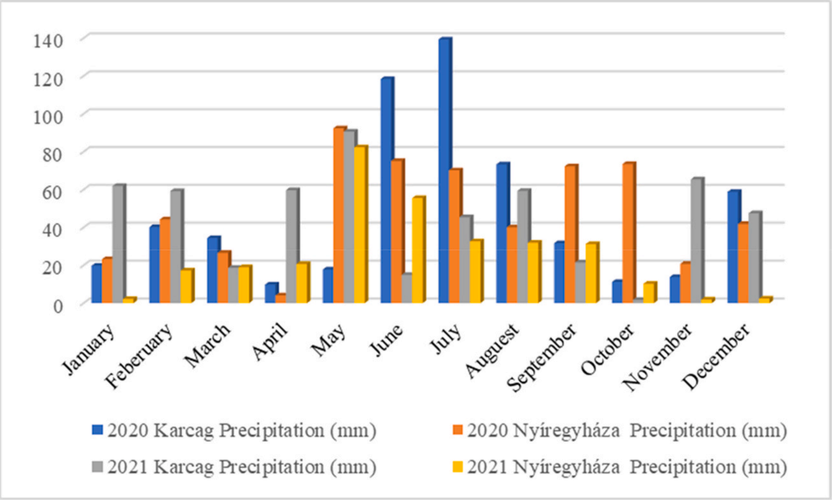

Fig. 3. Average of the precipitation in Karcag and Nyíregyháza for 2020 and 2021seasons
*The values of the weather conditions for the experimental years 2020 and 2021, including monthly "Measurements for precipitation in millimetres". The parameter was sourced from the Research Institute of Nyiregyhaza and Karcag.

lower than the multiannual average of 54.2 mm. while the temperature degree was lower (14.6° C), compared with the multiannual average of 16.6° C, which caused the initial emergence and development of the crop to be delayed. The considerable rainfall in June and July (Fig. 3) has positively impacted the crop's development, especially before the October 15, 2020, harvest period.

Regarding the 2021 cultivation season, the sowing was carried out on May 13, 2021. It was varied when the precipitation average (73.6 mm) was higher than the multiannual average (54.6 mm). At the same time, the temperature (17.5° C) was higher than the annual temperature (16.3° C).

In contrast, the weather conditions in Nyíregyháza were significantly different. In 2020, the sowing date was May 2, 2020, and the average precipitation was 92.2 mm, which was lower than the long-term average precipitation of 525.6 mm for the 2020 season. The moisture content during the vegetative period was recorded at 71%. In May 2021, the precipitation at the beginning of the growing season was 82.8 mm below the multiannual average of 573.3 mm, making it the driest meteorological condition documented. The harvesting period for 2021 was undertaken on October 10, 2021; further specifics on the explanation of the precipitation circumstances are provided in Fig. 3.

The environmental conditions for sorghum production were mixed at the two cultivation sites, with increased precipitation during

Table 3
Analysis of N g/kg^{-1} variance based on the interactions of Variety, Year, and Treatment factors.

Variables	DF	MS	P-value
Variety	4	439.59141	<0.001
Year	1	9.76411	0.26
Treatment	1	61.66462	0.28
Soil type	1	143.6422	<0.001
Variety× Year	4	59.97497	0.006
Variety× Treatment	4	38.07854	0.66
Variety× Soil type	4	20.95576	0.15
Year× Treatment	1	1.955355	0.88

] * Values were analysed from two reading replicates based on the dry matter basis.

the vegetative period and before harvesting providing favourable conditions. However, the variability of water availability limited initial emergence and crop growth, which resulted in various maturity stages (Fig. 2).

2.4. Collection and sorting of samples

We collected grain samples from two distinct locations (Karcag and Nyíregyháza), and we took meticulous measures in packaging and labelling to safeguard against sample damage or infestation. The grain samples were ground using the Retsch SK-3 (Retsch GmbH Haan, Germany) hammer mill fitted with a 1 mm sieve. The samples were carefully ground and homogenized before analysis at the Central Chemistry Laboratories of the University of Debrecen.

2.5. Chemical investigation methods

2.5.1. Determination of crude protein

The crude protein measurement was detected by using the Kjeldahl procedure. 1 g from each sample was weighed and put into a digestion tube. Two S/3.55-inch catalyst tablets were added to speed up the process and ensure the sample was completely homogenous, followed by 14 mL of 97% sulfuric acid (H_2SO_4). The tube was placed into a block heater set at 420–430 °C for 2 h; after the digestion, the samples were allowed to cool, and we applied the converter 6.25 for the total protein content [31].

2.5.2. Determination of mineral elemental contents

We employed the technology of Inductively Coupled Plasma Optical Emission Spectroscopy, ICP-OES iCAP 7400 (Thermo Scientific). The wheat sample used in our investigation was identified as BCR CRM 189 (whole grain) and obtained from the International Plant Exchange Network at the University of Wageningen to ensure precision [32]. The measurements were conducted according to Ref. [33]. We carried out element detections at specific wavelengths for each element: P 177.495 nm, K 404.721 nm, S 183.801 nm, Ca 183.034 nm, Mg 285.204 nm, Na 330.237 nm, Cu 324.754 nm, Fe 238.204 nm, Zn 213.856 nm, Mn 259.373 nm, Mo 204.598 nm, Ni 221.647 nm, and Sr 407.771 nm. We weighed 1 g of each sample. The samples were subjected to aqueous acid digestion, which included predigesting and digestion phases. We heated the samples at 60 °C for 30 min in a model block digestion (MIM OE-718/A) apparatus after adding 10 ml of nitric acid (HNO_3, 69% v/v). After a few minutes of chilling, 3 cm^3 of hydrogen peroxide (H_2O_2, 30% v/v) was added to the samples, and they were redirected to the primary digestion stage. We heated the digestor to 120 °C for 90 min before turning it off and allowing it to settle for 10–20 min. The volume was increased to 50 cm^3 using ultra-pure water (Millipore S.A. S., France). Finally, we purified the homogenized suspension using an MN 640 W filter paper. The concentration of elements was expressed on a grain dry-weight basis (mg kg^{-1}).

2.6. Statistical analysis test

All essential data findings were reported based on a mean-variance of three for element data replication readings and two for the nitrogen mineral data. The statistical test analysis was conducted using SPSS software (version 28.1), document No. 64442933, and SAS 17.2.0 (serial No. B9HSPF008) for the visualization. The Shapiro-Wilks test verified that the data followed a Gaussian curve. The variance of the element content was evaluated by employing a one-way ANOVA and a two-way ANOVA for findings analysis. Post hoc analysis showed the variance between groups. At the same time, we performed a Pearson correlation coefficient analysis to examine the relationships between continuous variables (trace microelements). We also created a Principal Component Analysis (PCA) for the correlations between the varieties and essential macro and microelements in the original pattern of the data set.

3. Results

3.1. Detailed statistical outcomes

The nitrogen (N) fertilizer effect evaluation, as shown in (Table 3), elucidates the interactions between various variables, encompassing variety, year, treatments, and soil type. As elaborated below, several interactions among these variables influenced the

Table 4

Analysis of essential macro and microelements mg/kg^{-1} variance based on the interactions of Variety, Year, and Treatment factors.

Source of variation	DF	P	K	S	Ca	Mg	Na	Cu	Fe	Zn
Variety	**4**	216942.7***	12761506**	231781.64***	231781.64***	302363.64***	3885.26***	2.24464^{NS}	209.6047**	40.3546^{NS}
Year	**1**	608228.0**	4400886**	5183332^{NS}	81916.83***	1197.49^{NS}	458.587^{NS}	0.4123298^{NS}	124.19324**	1.920695^{NS}
Treatments	**1**	1774920**	6733110.0**	47042.8^{NS}	2135.7^{NS}	429703.37***	1786.588^{NS}	1.594015^{NS}	341.8363***	107.53333***
Soil type	**1**	1690.6^{NS}	10310975***	3403.07^{NS}	3403.07^{NS}	303919.09***	303919.09***	5.877845***	155.81064**	58.10965***
Variety × *Year*	**4**	1222109.6^{NS}	8684965^{NS}	319561.7^{NS}	9508.97**	27781.33**	323.127^{NS}	1.2145947^{NS}	84.19092^{NS}	33.19503^{NS}
,	**4**	1613011^{NS}	26620008^{NS}	43134.9^{NS}	1703347.**	165543.9^{NS}	1060.301^{NS}	1.739524^{NS}	198.0003^{NS}	41.4461^{NS}
Variety × *Soil type*	**4**	28599.0^{NS}	12761509^{NS}	358486.3^{NS}	37170.2^{NS}	43570.22^{NS}	3148**	0.6792296^{NS}	112.79251^{NS}	84.6806***
Year × *Treatment*	**1**	1217987.9^{Ns}	1148466^{NS}	189984.14^{NS}	513.298^{NS}	178504.41**	7302.7722***	4.88878451***	103.45315^{NS}	37.53395^{NS}

*Asterisks indicate statistically significant variances. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, values based on dry basis.

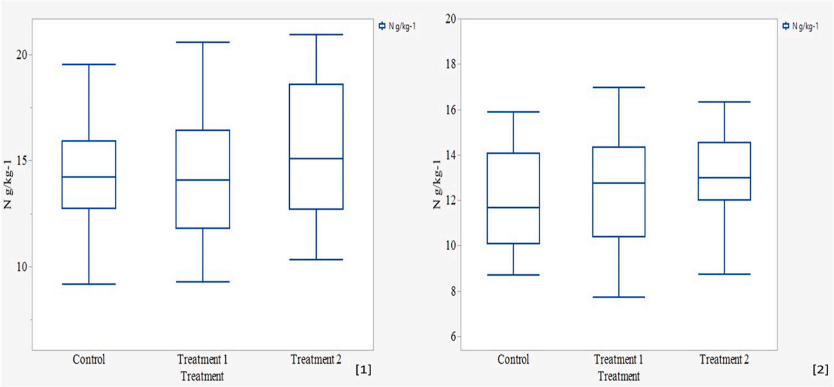

Fig. 4. N g/kg^{-1} based on treatment for the 2020 and 2021seasons
* Analysis of N g/kg^{-1}, the values were calculated based on a dry matter basis, the numbers refer to [1]: Loam clay soil, [2] Sandy soil, control (untreated sample), Treatment 1: treated sample (60 kg/ha^{-1}), Treatment 2: treated sample (120 kg/ha^{-1}), $P > 0.05$.

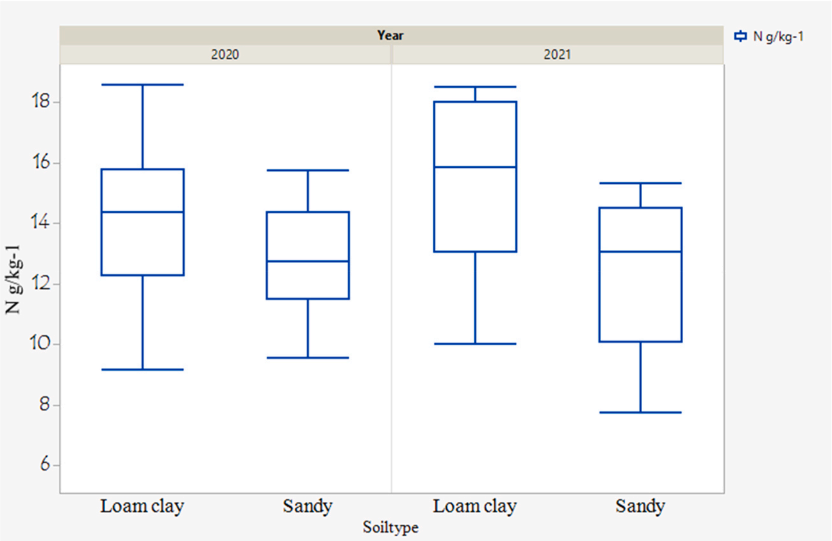

Fig. 5. N g/kg^{-1} based on the soil types for the 2020 and 2021
* Variability analysis of N (g/kg^{-1}) units refers to values on a dry matter basis, $p \leq 0.05$.

N g/kg^{-1} content in *S. bicolor* grains.

Table 4 shows that the Variety, Year, Treatment, and Soil type factors impacted the elemental content of sorghum grains, besides the impact of the Variety × Year, Variety × Treatment, Variety × Soil type, and Year × Treatment factor interactions with the elemental contents.

3.2. *The effect of N fertilizer on macro elements*

3.2.1. *Nitrogen (N)*

3.2.1.1. Nitrogen content variation-based year. According to results of the interaction between the Year and factor are shown in Table 3. The statistical analysis did not show a significant difference ($P > 0.05$). In 2020, the average N g/kg^{-1} concentration in *S. s* grains grown in loam clay soil was 14.0 g/kg^{-1}, while in sandy soil, it was 12.7 g/kg^{-1}. In 2021, the average N g/kg^{-1} concentration in loam clay soil was 15.5 g/kg^{-1}; in sandy soil, it was 12.5 g/kg^{-1}. Although there were fluctuations in the average results, the Year x Treatment factor did not show a significance value of ($P > 0.05$), as seen in Table 3 and Fig. 5.

3.2.2. *Nitrogen content variation-based treatment*

The research assessed the effects of N fertilizer application at two different rates (60 kg/ha^{-1} and 120 kg/ha^{-1}). The findings demonstrated that 60 kg/ha^{-1} significantly enhanced the N g/kg^{-1} content in *S. bicolor* grains. Nevertheless, there is no mentionable

Table 5

Analysis of trace elements mg/kg^{-1} variance based on the interactions of Variety, Year, and Treatment factors.

Source of variation	DF	Mn	Sr	Al	B	Ba	Mo	Cr	Ni
Variety	**4**	5792899***	6.7610939^{NS}	72.828939***	15.984662***	4.9032493*	0.0616051***	0.1753989***	1.8312157**
Year	**1**	5.290229**	8.9837470 ^{NS}	2.153694^{NS}	0.061462^{NS}	0.3536845^{NS}	0.00013840^{NS}	0.008^{NS}	0.030397^{NS}
Treatments	**1**	4.8372142^{NS}	0.6003857^{NS}	2,24933^{NS}	0.2387667^{NS}	6.967555***	0.00136259^{NS}	0.4074291^{NS}	0.4074291^{NS}
Soil type	**1**	11.506477**	5.060751**	9.6722202***	1.594257**	6.3653175***	0.00038883^{NS}	0.0309397^{NS}	0.0309397^{Ns}
Variety × Year	**4**	4.049608**	8.9728984^{NS}	3.204348^{NS}	3.334950**	4.1705015^{NS}	0.00411698^{NS}	0.9618801**	0.9618801*
Variety × Treatment	**4**	6.9483814^{NS}	7.7810253^{NS}	12.482442^{NS}	3.8344399^{NS}	9.503149**	0.02970898^{NS}	1.2561048^{NS}	1.2561048^{NS}
Variety × Soil type	**4**	1.52658^{NS}	5.9394239^{NS}	8.558656**	8.105593***	0.4322786^{NS}	0.01192518^{NS}	0.8129^{NS}	0.8129^{NS}
Year × Treatment	**1**	1.51931125^{NS}	1.5951129 ^{NS}	5.9145265^{NS}	1.5193125 ^{NS}	0.5435032 ^{NS}	0.00289545 ^{NS}	0.05093618 ^{NS}	1.6769156 ***

*Asterisks indicate statistically significant variances. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, values based on dry basis.

Table 6
Descriptive analysis of essential nutritional content profiles for the diverse *S. bicolor* grain after N fertilizer treatment applications in loam clay soil.

Variables	*N g/kg^{-1}*	*P mg/kg^{-1}*	*K mg/kg^{-1}*	*S mg/kg^{-1}*	*Ca mg/kg^{-1}*	*Mg/kg^{-1}*	*Fe mg/kg^{-1}*	*Zn mg/kg^{-1}*	*Cu mg/kg^{-1}*	*Na mg/kg^{-1}*	*Mn mg/kg^{-1}*
Standard	15.8 ± 1.8$^{\#}$	3257.85 ± 415.10	5211.13 ± 901.86	1166.66 ± 71.62	430.56 ± 97.27	1079.81 ± 567.5	49.17 ± 3.63	27.11 ± 2.01	3.98 ±0 .33	32.97 ± 1.56	14.35 ±0 .71
Alföldi 1	16.5 ± 1.7$^{\#}$	3200.20 ± 302.73	4861.37 ± 921.81	1225.75 ± 188.43	397.72 ± 107.77	1361.34 ± 82.60	41.39 ± 5.89	24.77 ± 1.2	3.91 ±0 .55	38.45 ± 1.38	14.13 ±0 .76
ES Albanus	12.3 ± 1.4$^{\#}$	2840.55 ± 232.07	3967.68 ± 732.85	1079.21 ± 30.22	313.85 ± 75.67	1357.94 ± 251.15	43.71 ± 2.03	23.08 ±0 .44	3.40 ±0 .20	53.32 ± 4.92	14.70 ±0 .64
Albita	11.9 ± 1.9$^{\#}$	2868.96 ± 159.31	3911.27 ± 573.81	1056.77 ± 56.68	297.25 ± 83.38	1281.50 ± 68.68	44.53 ± 2.03	23.61 ±0 .72	3.49 ±0 .81	56.76 ± 11.38	13.35 ±0 .76
Farmsugro 180	18.7 ± 2.4$^{\#}$	3065.99 ± 167.03	4695.81 ± 1089.79	1441.89 ± 351.01	470.15 ± 39.61	1265.22 ± 92.48	42.90 ± 1.2	24.83 ± 73.61	3.40 ±0 .24	42.46 ± 6.13	12.65 ± 1.15
P-value	<0.001	0.05	0.04	<0.001	0.03	0.03	0.33	0.02	0.65	0.04	0.17

#N element content was not involved in comparing the difference due to different content values. average of element contents among different sorghum grain varieties was calculated from three replication readings, dry basis ($P < 0.05$).

Table 7
Descriptive analysis of essential nutritional content profiles for the diverse *S. bicolor* grain after N fertilizer treatment applications in sandy soil.

Variables	**N g/kg^{-1}**	**P mg/kg^{-1}**	**K mg/kg^{-1}**	**S mg/kg^{-1}**	**Ca mg/kg^{-1}**	**Mg/kg^{-1}**	**Fe mg/kg^{-1}**	**Zn mg/kg^{-1}**	**Cu mg/kg^{-1}**	**Na mg/kg^{-1}**	**Mn mg/kg^{-1}**
Standard	13.8 ± 1.7$^{\#}$	3104.81 ± 109.31	5199.60 ± 362.84	1061.83 ± 69.75	454.05 ± 28.08	1339.15 ± 104.25	46.26 ± 3.29	22.97 ± 1.13	3.38 ±0 .15	26.97 ± 4.34	14.79 ±0 .95
Alföldi 1	13.8 ± 1.7$^{\#}$	3157.75 ± 302.06	4552.84 ± 92.83	1334.00 ± 116.59	386.48 ± 49.73	1290.57 ± 100.63	41.70 ± 1.83	24.26 ± 1.31	3.38 ±0 .06	21.75 ± 4.96	13.88 ±0 .61
ES Albanus	11.2 ± 1.4$^{\#}$	2930.98 ± 300.54	5102.5 ± 200.93	1168.28 ± 99.22	416.26 ± 73.19	1284.01 ± 84.93	41.46 ± 2.42	23.04 ± 1.76	3.13 ±0 .17	27.98 ± 1.94	14.81 ±0 .82
Albita	10.4 ± 1.9$^{\#}$	2925.06 ± 240.56	4790.62 ± 1011	1173.18 ± 130.77	326.76 ± 65.57	1263.96 ± 97.87	42.61 ± 2.39	23.94 ± 1.38	3.29 ±0 .12	30.42 ± 2.13	13.51 ±.,21
Farmsugro 180	15.7 ± 2.4$^{\#}$	3090.79 ± 202.77	4990 ± 405	1442.58 ± 158.57	438.30 ± 51.48	1153.23 ± 60.72	42.95 ± 1.76	23.49 ±0 .94	3.03 ±0 .15	27.1 ± 4.51	13.35 ±0 .27
P-value	<0.001	0.04	0.39	<0.001	0.71	0.49	0.67	0.43	0.7	0.55	0.002

#N element content was not involved in comparing the difference due to different content values. average of element contents among different sorghum grain varieties, was calculated from three replication readings, on dry basis ($P < 0.05$).

variation in the N g/kg^{-1} content between N fertilizer rates (60 kg/ha^{-1} and 120 kg/ha^{-1}) in the sandy soil, as shown in Fig. 4 (1,2), as evidenced by $P > 0.05$.

3.2.3. *Nitrogen content variation-based soil types*

The study examined the impact of N fertilizer application on loam clay and sandy soil types; the findings revealed a significance value of $P < 0.05$, attributed to the soil type factor on N g/kg^{-1} content (Fig. 5) of loam clay and sandy soil; the applied agronomic practice is demonstrated in Table 2. However, loam clay soil had a higher concentration of N g/kg^{-1} than sandy soil, at an average of 14.8 g/kg^{-1} in loam clay soil and an average of 12.6 g/kg^{-1} in sandy soil, indicating the effect of soil type on nitrogen mineral uptake by the sorghum variety. Fig. 5 (1,2) represent the visualization of the nitrogen average concentration based on the soil types.

3.2.4. *Nitrogen content variation-based variety*

The N fertilizer's impact had a significant variance ($P < 0.05$) based on the variety factor, as evidenced by notable variations in N g/kg^{-1} concentration, response, uptake, and accumulation, as elucidated in Tables 6 and 7. A hierarchical cluster analysis determined the optimal number of correlated groups between the total protein content and the respective *S. bicolor* varieties (see Fig. 6); the examined factor revealed 7 cluster groups. The clusters were arranged in ascending order of N g/kg^{-1} contents across the diverse *S. bicolor* varieties.

3.3. *The effect of N fertilizer on essential macro and microelements*

The research discovered that several factors, including the type of sorghum grain, the soil, the treatment, and the year of the study, caused differences in the macro and microelement contents. The revealed differences implied by diverse factors led to varied nutritional profiles of sorghum varieties', which can be seen in Fig. 8 (1,2) and 10 (1,2). Accordingly, the interaction factors were thoroughly analysed and shown in Tables 4 and 5, accompanied by detailed explanations below.

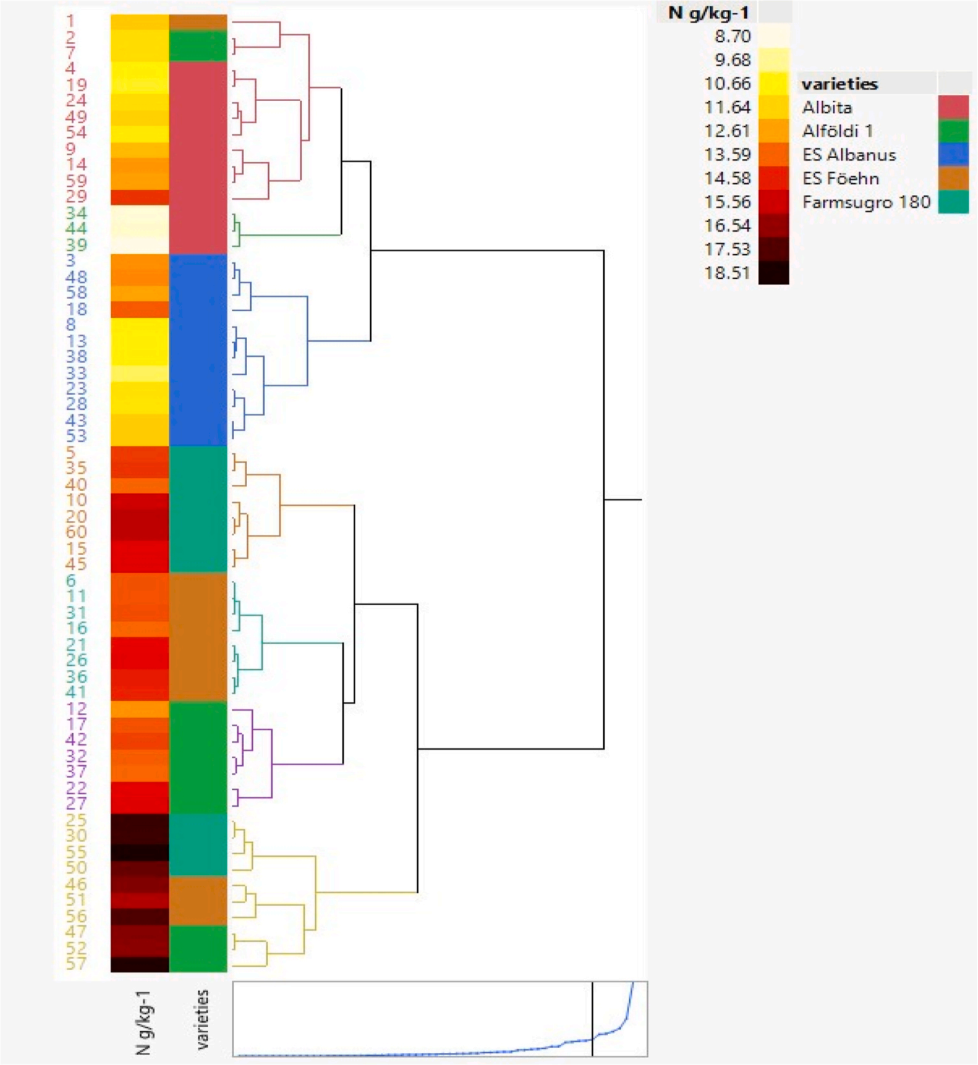

Fig. 6. Correlation map of the relationships between N g/kg^{-1} and the variety groups based on dry matter basis, $P < 0.05$.

3.3.1. *Phosphorus (P)*

The phosphorus (P) element concentration was increased sequentially among the red and white sorghum varieties. However, no noticeable variation or positive interaction was observed of Variety × Year, Variety × Treatment, and Variety × Soil with ($P > 0.05$). The Variety, Treatments and Year variables displayed a significance value of $P < 0.05$, as illustrated in Table 4. Farmsugro180 variety demonstrated approximately 135% variability in sandy soil, as shown in Fig. 8 (1,2). Also, loam clay soil exhibited the highest P mg/kg^{-1} concentration among soil types, averaging 3056.8 mg/kg^{-1}.

The rate of the N fertilizer 120 kg/ha^{-1} positively impacted P mg/kg^{-1} concentration among the loam clay and sandy soil types, as demonstrated in Fig. 7 (1,2) and 8(1,2). A variation of 6.5% was observed in comparing the control to the fertilizer in the case of the loam clay soil Fig. 7 (1,2).

The Alföldi 1 variety showed the highest concentration of P mg/kg^{-1} within (3157.8 mg/kg^{-1}) in the sandy soil, with a significance value of $P > 0.05$ (Table 7.). In addition to a 6.9% variation ratio compared to the control (untreated) sample to the treatment 2 (120 kg/ha^{-1}).

3.3.2. *Potassium (K)*

Table 7 shows that the sandy soil had the highest potassium K mg/kg^{-1} content after N fertilizer application, as treatment 2 rate of (120 kg/ha^{-1}) significantly impacted K mg/kg^{-1} concentration among all respective varieties in the loam clay soil. The Alföldi 1 variety showed the highest level of variability, reaching 159% in both loam clay and sandy soil types, as shown in Fig. 8 (1,2). Potassium levels showed statistical significance ($P < 0.05$) for all analysed variables, including Variety, soil type, year, and Treatment, as shown in Table 4.

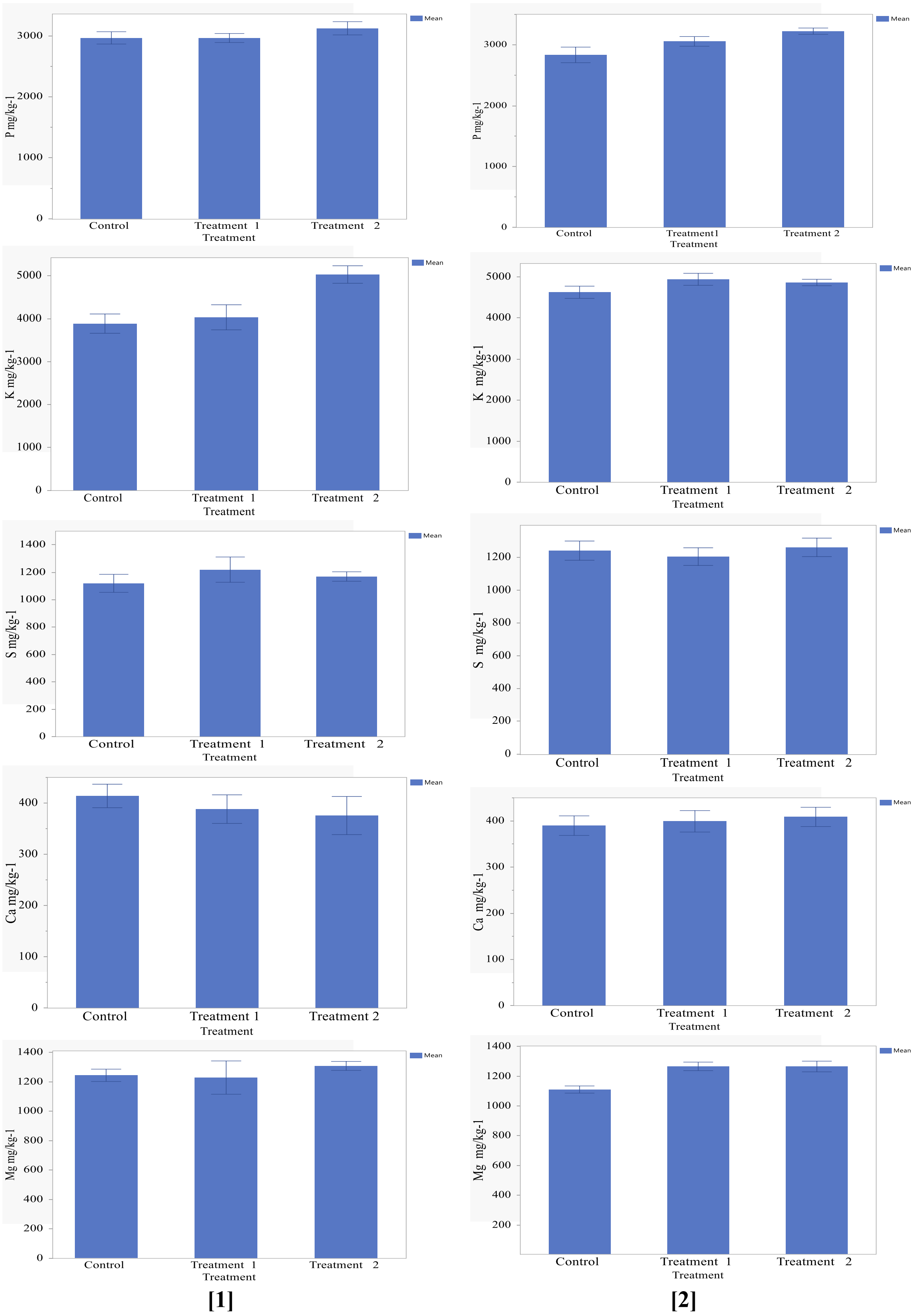

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Fig. 7. Average of macro-elements mg/kg^{-1} based on the control and treatments in the loam clay and sandy soil for 2020 and 2021
* Values were calculated on a dry matter basis, values-based approach, $P < 0.05$
[1] macro-elements Mean ± SD sourced from loam clay soil [2]. macro-elements Mean ± SD sourced from sandy soil. Control (untreated sample), Treatment 1 (60 kg/ha^{-1}), Treatment 2 (120 kg/ha^{-1}).

The Alföldi 1 variety exhibited the highest average of K mg/kg^{-1} content after the ES Föehn (standard variety) within average (3157.7) mg/kg^{-1} in the sandy soil, with no significant differences ($P > 0.05$).

3.3.3. Sulphur (S)

Based on the analysis of soil types, it was observed that the treatment with N fertilizer did not significantly impact the concentration of sulphur element S mg/kg^{-1} content. However, Fig. 8 (1,2) displays variations in the S mg/kg^{-1} contents among diverse sorghum varieties. Notably, Farmsugro 180 (white variety) recorded the highest S mg/kg^{-1} average of 1442.6 mg/kg^{-1} in sandy soil. The S mg/kg^{-1} value exhibited a significant difference ($P < 0.05$) based on variety Tables 4 and 6, while no significant variation was recorded by the treatment, year, or soil type ($P > 0.05$). The examined grain varieties displayed a variability range of S mg/kg^{-1} with values ranging from 45% to 65%, as shown in Fig. 7 (1,2). Moreover, regarding sulphur results, the ES Albanus variety showed the lowest ratios of N/S in loam clay and sandy soil within 10:1 and 8:1. As shown in Table 6, the ES Föehn variety in loam clay soil and Farmsugro in sandy soil recorded the highest ratios of 14:1 and 13:1, respectively.

The impact of N fertilizer 60 kg/ha^{-1} and 120 kg/ha^{-1} on S mg/kg^{-1}content was fluctuated in the loam clay and sandy soil, as demonstrated in Fig. 7 (1,2); a noticeable reduction was shown by treatment 2 (120 kg/ha^{-1}) in comparison to the control, treatment 1, and treatment 2 of 1119.0 mg/kg^{-1}, 1199.5 mg/kg^{-1}, and 1107.2 mg/kg^{-1}, respectively.

3.3.4. Calcium (Ca)

Calcium (Ca) mg/kg^{-1} content exhibited a statistically significance value of $P < 0.05$ based on the variables of variety and year. The Farmsugro180 variety demonstrated the highest average Ca mg/kg^{-1} concentration in loam clay soil, 470.2 mg/kg^{-1}. The treatment variance showed a significance value of ($P > 0.05$). Furthermore, the calcium element positively responded to the interaction between Variety × Treatment and Variety × Year ($P < 0.05$) Table 4.

On the other hand, calcium (Ca) mg/kg^{-1} showed a noticeable reduction of Ca mg/kg^{-1} in loam clay soil after the N fertilizer application attributed to treatment 1 (60 kg/ha^{-1}) and treatment 2 (120 kg/ha^{-1}) as demonstrated in Fig. 8 (1,2). The finding showed that the loam clay soil was affected by the applied N (27% N CAN) fertilizer, which changed the soil conditions and negatively impacted the calcium concentration in the soil and was represented by a reduction of the calcium accumulation on the *S. bicolor* grains; moreover, the revealed result was indicated by observed average Ca mg/kg^{-1} in 2020 and 2021 at: 414.1 mg/kg^{-1} and 360.4 mg/kg^{-1}, respectively Fig. 7 (1,2). Also, Ca mg/kg^{-1} content showed a significance value of $P < 0.05$, as demonstrated by the variation attributed to the respective varieties.

3.3.5. Magnesium (Mg)

Magnesium element showed a significance value of $P < 0.05$, which varied based on the Variety, Soil type, and Treatment, while no significant difference was observed based on the Year factor ($P > 0.05$). Table 7 (1,2) and 8 (1,2) show the different ranges of Mg/kg^{-1} based on the varieties in the two examined soil types, when the highest Mg/kg^{-1} content was attributed to the (Alföldi1) red variety, within an average of 1361.3 mg/kg^{-1}.

N fertilizer positively impacted the Mg/kg^{-1} accumulation on the diverse *S. bicolor* varieties in loam clay and sandy soil. However, treatment 2 (120 mg/kg^{-1}) negatively impacted Mg/kg^{-1} concentration in the sandy soil, as was observed by the control, treatment 1, and treatment 2, 1143.3 mg/kg^{-1}, 1282.6 mg/kg^{-1}, and 1217.0 mg/kg^{-1}, respectively ($P < 0.05$). The revealed result was more observable in sandy than loam clay soil, as shown in Fig. 8 (1,2).

3.3.6. Sodium (Na)

One interesting finding belonged to the sodium element when it exhibited a significance value of $P < 0.05$, and the revealed variation was attributed to the Variety and Soil type factors. However, no significant variation was observed across the Years and Treatment factors. Additionally, Table 5 showed that the loam clay soil had the highest Na mg/kg^{-1} concentration, with an average of 44.8 mg/kg^{-1} (Table 6). And the recorded values of Na mg/kg^{-1} in 2020 and 2021 were 51.28 mg/kg^{-1} in 2020, and 47.50 mg/kg^{-1} in 2021, respectively. However, the observed reduction was recorded by the average of the control, treatment 1, and treatment 2 (60.4 mg/kg^{-1}, 47.0 mg/kg^{-1}, and 42.5 mg/kg^{-1}) and (57.5 mg/kg^{-1}, 29.7 mg/kg^{-1}, and 30.0 mg/kg^{-1}), respectively.

Sodium (Na) mg/kg^{-1} was negatively affected by the applied N (27% N CAN) fertilizer in the loam clay soil and sandy soil as is demonstrated in Fig. 9 [1,2].

3.3.7. Copper (Cu)

The concentration of copper exhibited a significant variance based on the soil type factor ($P < 0.05$), as demonstrated in Table 4. However, copper concentration did not show significance variance ($P > 0.05$) in the variety, year, and treatment cases. Cu mg/kg^{-1} concentration demonstrated variability at 32%, as illustrated in Fig. 10 (1,2).

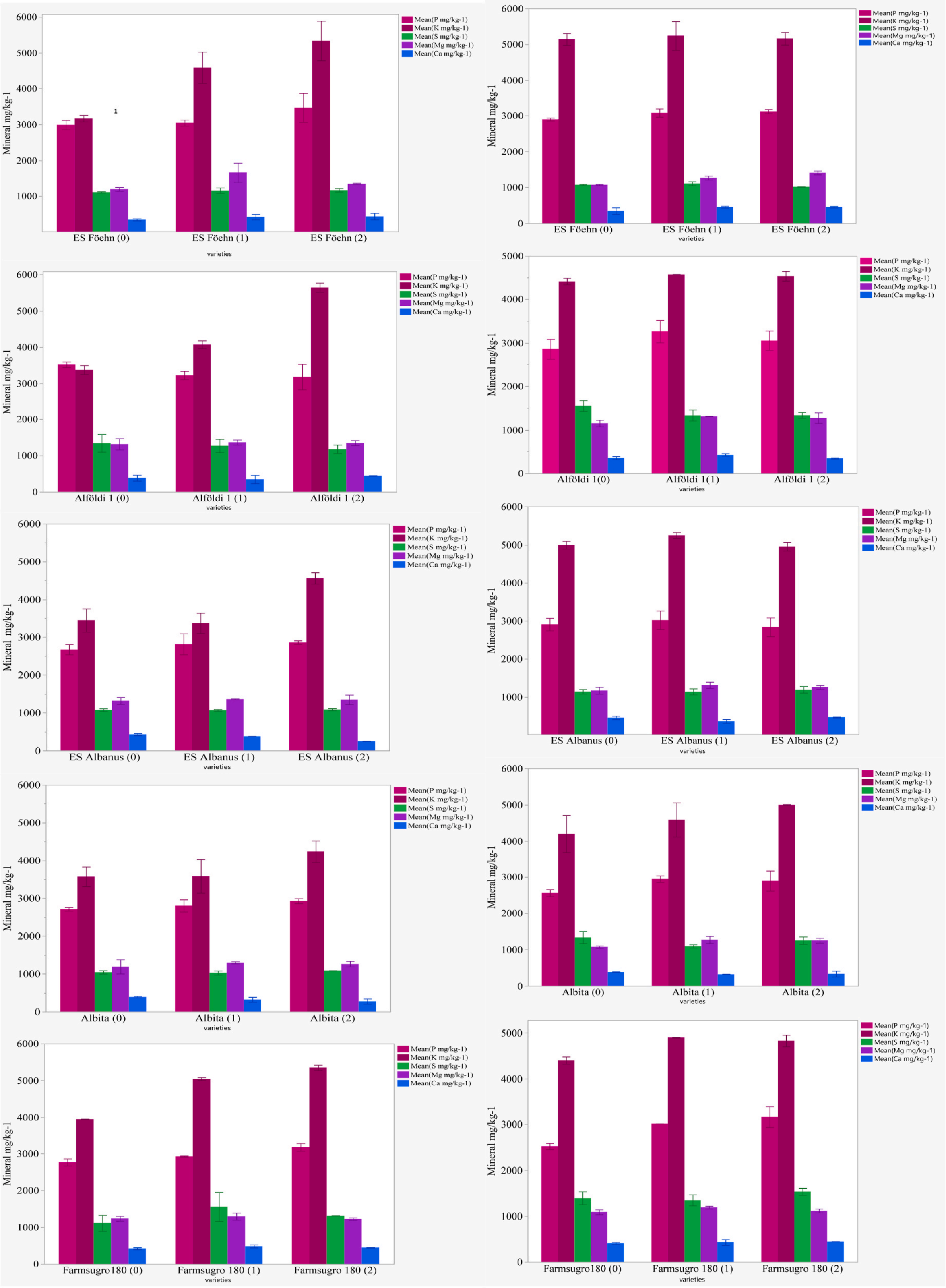

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Fig. 8. Average of macro-elements mg/kg^{-1} concentrations based on the diverse *S. bicolor* varieties in the loam clay and sandy soil for the 2020 and 2021

* Analysis of the macro-element concentrations in dry matter basis: A values-based approach, $P < 0.05$ [1], macro-elements Mean ± SD sourced from loam clay soil based on the variety [2]. macro-elements Mean ± SD sourced from sandy soil based on the variety. Numbers refer to the variety in case of (0) control (untreated sample), (1) Treatment (60 kg/ha^{-1}), (2) Treatment (120 kg/ha^{-1}).

3.3.8. *Iron (Fe)*

According to Table 4, the iron (Fe) mg/kg^{-1} concentration varied significantly depending on the variety, soil type, treatment, and year, with a significance value of $P < 0.05$. Loam clay soil stood out as having the highest concentration of iron observed by ES Föehn (standard variety) within an average of Fe (49.2 mg/kg^{-1}), as is displayed in Table 6 and Fig. 10. No significant differences were detected in iron element interactions attributed to Variety × Year, Variety × Treatment, and Variety × Soil type ($P > 0.05$). Treatment 2 (120 kg/ha^{-1}) negatively impacted the (Fe) mg/kg^{-1} concentration in the loam clay soil, as is demonstrated in Fig. 10 (1,2).

3.3.9. *Zinc (Zn)*

The significance value of ($P < 0.05$) observed by the variance analysis indicated that soil type and treatment factors significantly influenced the zinc (Zn) concentration (Table 4). However, the Farmsugro180 variety ranked second after ES Föehn (standard variety), with the highest average of 24.8 mg/kg^{-1} in loam clay soil ($P < 0.05$) Table 6. Furthermore, an observed variance was attributed to the variety × Soil type interaction, which showed a significance value of ($P < 0.05$) in Table 4, as the statistical variance is explained in Tables 6 and 7

The sequenced average of zinc (Zn) mg/kg^{-1} among the different *S. bicolor* varieties exhibited observable variability based on the soil types, as shown in Fig. 10 (1,2).

3.3.10. *Manganese (Mn)*

The statistical analysis (Table 4) indicates that the variety, soil types, and year variables significantly impacted the Mn mg/kg^{-1} concentration, $P < 0.05$.

As shown in Fig. 9 (1,2), the N fertilizer treatments did not significantly affect the Mn mg/kg^{-1} concentration ($P < 0.05$). On the other hand, the Farmsugro180 variety showed the highest average of 12.7 mg/kg^{-1} in loam clay soil.

3.4. *The effect of N fertilizer on secondary microelements*

3.4.1. *Strontium (Sr)*

According to the soil type, Table 5 demonstrates a significance value of ($P < 0.05$) in the strontium (Sr) mg/kg^{-1} concentration. Nevertheless, there was no substantial variation in strontium levels across the variety factor ($P > 0.05$). Fig. 11 (1-4) illustrates the relationship between strontium Sr mg/kg^{-1} concentration and other trace elements based on N fertilizer influence. The results demonstrated a strong correlation between the strontium (Sr) element and the trace elements on the cultivated white varieties in the sandy soil. Fig. 11 (1-4) shows a strong correlation between Sr mg/kg^{-1} and Al mg/kg^{-1}, with a correlation coefficient of $r = 0.98$, $P = 0.05$.

3.4.2. *Aluminium (Al)*

According to Table 5, the Al mg/kg^{-1} levels varied considerably based on the soil type and the variety, indicated by a significance value ($P < 0.05$). The average Al mg/kg^{-1} concentration in loam clay and sandy soil was recorded at 3.6 mg/kg^{-1} and 3.1 mg/kg^{-1}, respectively. According to Fig. 11(1-4), weak correlations were observed between (Mn), (Ni), and (Cr) elements among red varieties. Specifically, Ni showed a correlation coefficient of $r = 0.69$, $P = 0.05$; Mo had a correlation coefficient of $r = 0.63$, $P = 0.05$, and Cr, $r = 0.59$, $P = 0.05$.

3.4.3. *Boron (B)*

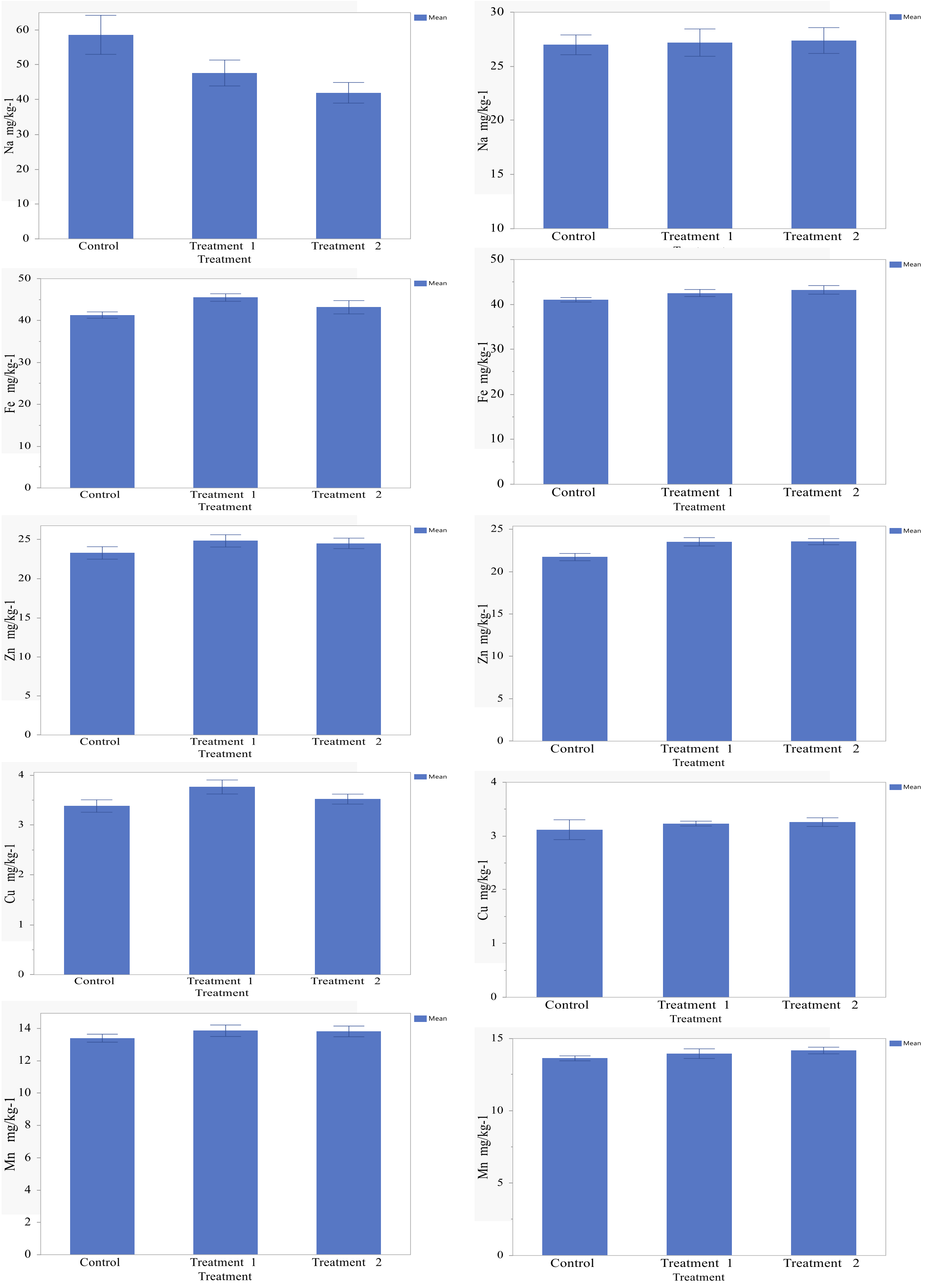
Soil type, variety, and the interaction of the Variety × Year showed a significance value of $P < 0.05$ for the B mg/kg^{-1} concentration. The average B mg/kg^{-1} concentration ranged from 2.8 mg/kg^{-1} in loam clay soil to 2.9 mg/kg^{-1} in sandy soil; the concentration of B mg/kg^{-1} showed a significance value of ($P < 0.05$), based on the interactions of Variety × Year and Variety × Soil types, as shown in Table 4, besides to the relationships between the B element and different trace elements in the loam clay and sandy soil as is displayed in Fig. 11 (1-4).

3.4.4. *Barium (Ba)*

The barium (Ba) mg/kg^{-1} content in the two examined soils varied significantly based on the influence of variety, soil type, treatment, and interaction of Variety × Treatment ($P < 0.05$), as shown in Table 5. Ba mg/kg^{-1} showed a strong correlation between a diverse trace microelement among white varieties in loam clay soil, as is presented in Fig. 11 (1-4).

3.4.5. *Molybdenum (Mo)*

The variety factor showed a significant impact on the molybdenum (Mo) mg/kg^{-1} content (Table 5), with a significance value of $P < 0.05$.



[1] **[2]**

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Fig. 9. Average of macro and microelements mg/kg^{-1} based on the control and treatments in the loam clay and sandy soil for 2020 and 2021 * Values were calculated on a dry matter basis, values-based approach, $P < 0.05$. [1] macro and microelements Mean ± SD sourced from loam clay soil. [2] macro and microelements Mean ± SD sourced from sandy soil. Control (untreated sample), Treatment 1 (60 kg/ha^{-1}), Treatment 2 (120 kg/ha^{-1}).

A strong correlation was found between Mo mg/kg^{-1} and the studied trace microelements of white varieties in the loam clay soil.

3.4.6. *Chromium (Cr)*

Based on Table 5, Variety × Year interaction significantly affected the accumulation of Cr mg/kg^{-1} content in *S. bicolor* grains, as evidenced by the significance value of ($P < 0.05$). Notably, Cr strongly correlated with the Mn element in sandy soil among white varieties, with a correlation coefficient of $r = 0.83$, $P = 0.05$, as shown in Fig. 11 (1-4).

3.4.7. *Nickel (Ni)*

The findings demonstrated that the Variety factor highly influenced the Ni mg/kg^{-1} concentration, besides the interactions between the variety × Treatment and Year × Treatment evidenced by a significance value of $P < 0.05$; the result is presented in Table 5.

An observable correlation between the nickel element content and other trace elements was noticed in Fig. 11 (1-4).

3.5. *Correlation analysis of the essential mineral contents*

We performed a Principal Component Analysis (PCA) test on the original data according to Fig. 12 (1,2), and the results showed a total component variance of 46.4%. They were grouped as follows: the first component showed a strong correlation between P, K, S, Ca, Mg, Fe, Zn, and Mn at 28.1%, as well as a strong correlation between the ES Föehn variety, Alföldi 1 variety, and ES Albanus variety. On the other hand, the Na element showed a strong correlation with the Cu element in the second component at 18.3%.

Despite the strong correlation between the varieties, the Albita variety negatively correlated with the other examined varieties in the second component. Therefore, the preliminary data pattern exhibited a conspicuous and discernible structure in the correlations among the elemental compositions.

4. Discussion

The study was distinguished by employing two experimental designs: small split and randomized block designs. These designs were utilized to comprehensively leverage the variability features of each, alongside assessing and comparing the levels of distribution and concentration of the necessary elements, which are crucial to human health through dietary intake. The elements were involved: N, P, K, S, Ca, Mg, Cu, Na, Fe, Zn, Mn, Al, Sr, B, Ba, Ni, Mo, and Cr. The research was conducted under Mediterranean environmental conditions to examine the impact of N fertilizer on cultivated *S. bicolor* grain in loam clay and sandy soil. Moreover, Tables 6 and 7 explain the implied variance in the essential elements from the soil type factor.

According to the revealed results, the study outcomes suggested that the used N (27% N CAN) fertilizer positively impacted the nutritional content of the examined *S. bicolor* grains; it estimated that the formation of calcium ion compounds sourced from N (27% N CAN) fertilizer might decrease the accessibility of phosphate ions (PO_4^{3-}) after the hydrolysis reaction; which was led to enhancing the nutrient absorption by *S. bicolor* grains, as discussed in a previous report by Ref. [34]. The authors examined several aspects influencing fertilizer usage efficiencies, such as soil type, crop type, and fertilizer application techniques. They also mentioned the need for soil testing to optimize nutrient management planning.

On the other hand, the results suggested that the reduction of sodium (Na) and calcium (Ca) levels were linked to elevated quantities of hydrogen ions (H^+) in the soil, through the cation exchange process was thought to have facilitated the removal of Na^+ and Ca^{2+} ions from the soil particles. As a result, the sodium (Na) and calcium (Ca) concentrations were reduced in *S. bicolor* grains in the loam clay and sandy soil, as seen in Fig. 8 (1,2) and 10 (1,2).

Moreover, the reported results were estimated and returned to be associated with environmental factors, namely the elevated average precipitation over the 2021 season in the Karcag site. The increased precipitation average may have altered the state of the examined soil conditions. Although there was a documented drop in calcium (Ca) levels in both loam clay and sandy soil, the loam clay soil in Karcag exhibited a considerable decline in both calcium (Ca) and sodium (Na) levels, as reported earlier; the estimated result could be supported by the variability of the environment conditions, as was elucidated in the Materials and Methods section, where the cultivation site (loam clay soil) conditions are thoroughly detailed. in comparison, the estimated mechanism was expounded in the literature by Ref. [35].

The results also showed that the different stages of maturity (Fig. 2) were linked to environmental conditions. For example, it was found that the variability in average precipitation during the initial growth stages has resulted in different stages of maturity in loam clay and sandy soil. Accordingly, the *S. bicolor* nutritional profile variation was aligned to the association of the maturity stage and pericarp colour, considering the variations of the soil type and variety factors, as shown in Table 6.

However, the performed statistical analysis of the examined trace microelement did not show a significance value ($P < 0.05$) when considering the year variable, thus confirming the reliability of the data analysis. The findings suggested a substantial correlation between the trace microelement contents and the soil type characteristics. The results were consistent with the earlier study [36], that showed the impact of the interaction between the applied N fertilizer treatment trace elements; besides, our findings related to the

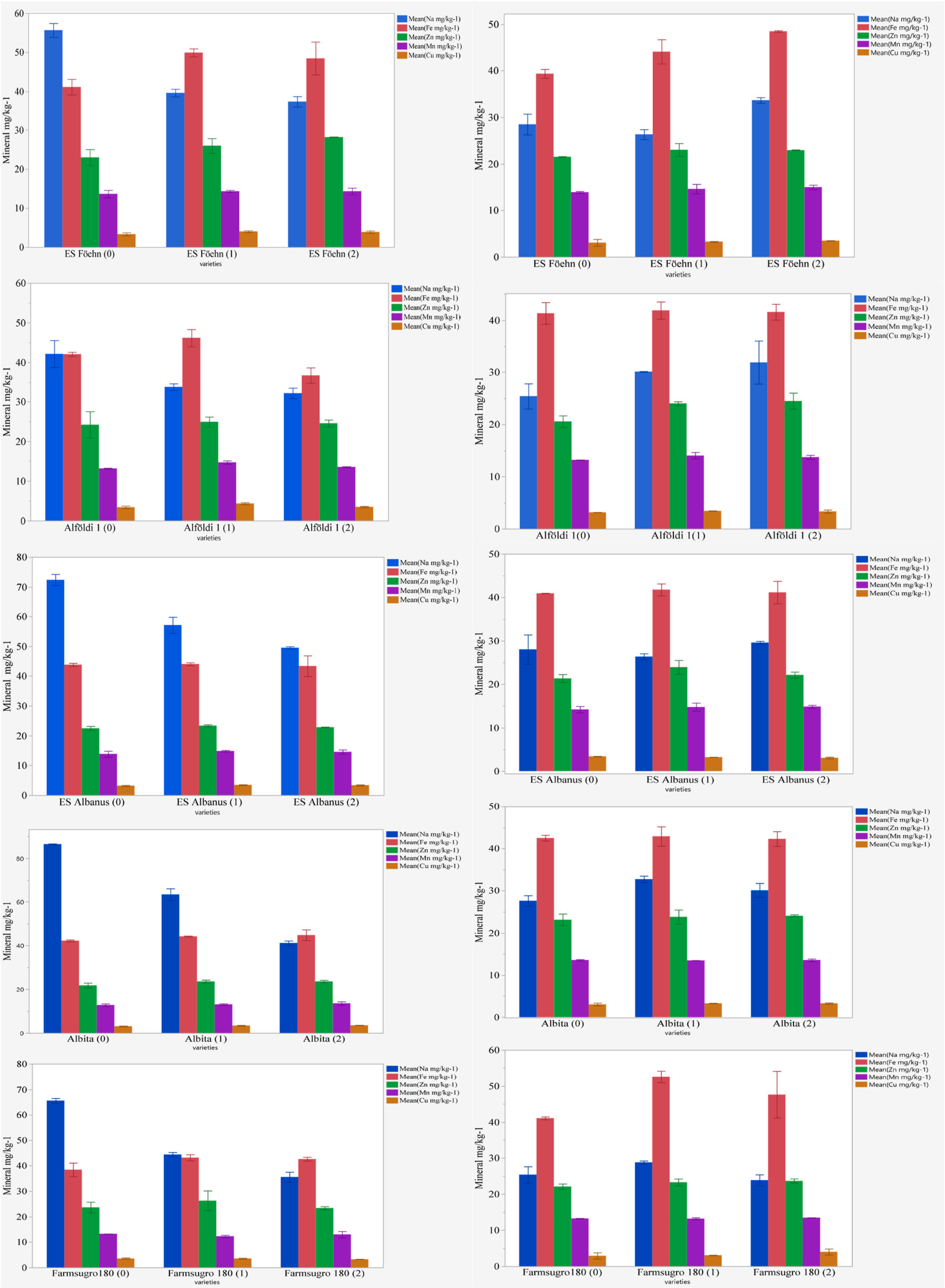

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Fig. 10. Average of essential macro and micro elements mg/kg^{-1} concentration based on the diverse *S. bicolor* varieties in the loam clay and sandy soil for 2020 and 2021
* Analysis of the macro and microelement concentrations in dry matter basis, values-based approach, $P < 0.05$ [1], macro-elements Mean ± SD sourced from loam clay soil based on the variety [2]. macro-elements Mean ± SD sourced from sandy soil based on the variety.
Numbers refer to the variety in case of (0) control (untreated sample), (1) Treatment (60 kg/ha^{-1}), (2) Treatment (120 kg/ha^{-1}).

unique characteristics of each variety, which caused variation in the trace microelement contents among those tested varieties.

According to the investigation, the Year and Treatment factors were among the autonomous factors in the research inquiry. The analysis found that the (Year × Treatment) interaction did not significantly impact the N g/kg^{-1} content (Table 3), and the findings lined up the interaction of Year × Treatment with the other element contents as shown in Table 4 [37,38]. The examined elements did not show a significance value of $P > 0.05$ except for Ni mg/kg^{-1}, which showed a significance value of $P < 0.05$; additional scrutiny is required to analyse this outcome.

The insertion of the ES Föehn variety was advantageous as a benchmark when comparing nutritious content since it showed the highest element concentrations among the listed elements in Table 6; the finding was aligned with previous studies [30,39], the results provided insight into the capacity to adapt and the nutritional characteristics of the superior variety to necessitate and improve grain production of *S. bicolor* under various cultivation environments. The outcomes of the study can provide an updated inquiry on the factors that can affect the elemental compositions of *S. bicolor* grain bred in a non-native site of production and offer a comprehensive insight into factors related to sorghum grain production, which can contribute to meeting the standard parameters for sorghum grain quality statements, as established by Refs. [40,41].

Beneficially, the Sr mg/kg^{-1} levels in the examined varieties were low, ranging from 1.6 mg/kg^{-1} to 2.2 mg/kg^{-1}, which was lower than the strontium-element exposure levels found in dietary stuff, according to Ref. [42]. The findings showed a significance value of $P < 0.05$, which was attributed to the soil type (Table 4), which can confirm the precision of the findings. Furthermore, based on Table 6, the displayed results of N g/kg^{-1} levels and the ratios of N/S in the examined *S. bicolor* grain varieties can offer opportunities to develop innovative protein products based on the plant sources, as stated in the study objectives [43,44]. Fig. 12 (1,2) shows how the relationships between the varieties and the amounts of essential elements can help us predict future research to engage the varieties in further grain food processing, which can allow making sorghum grain healthier through different processing methods, according to Ref. [37], the nutritional level analysis of the various varieties revealed that the dietary contents could offer high-quality raw material from *S. bicolor* grain that satisfies the nutritional needs of human diets.

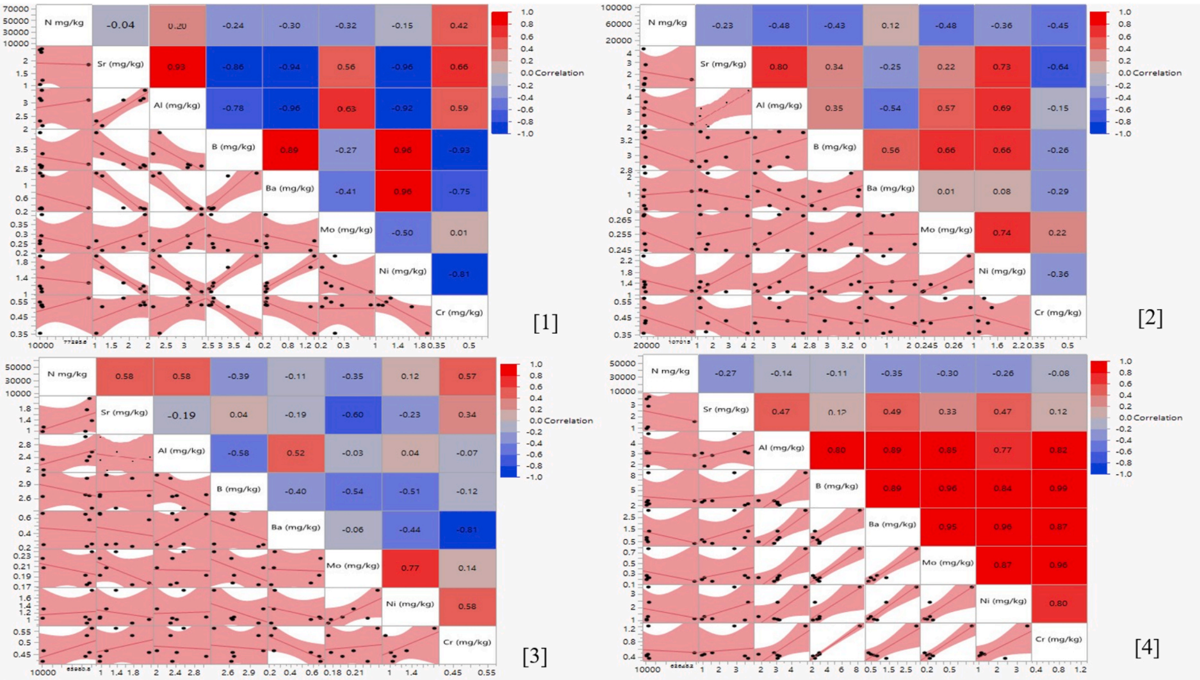

Fig. 11. Analysis of the correlations between nitrogen and trace microelements based on varieties.
*Analysis of N (mg/kg^{-1}) and trace microelement values based on mean values on a dry matter basis, correlation values displayed values based on $P < 0.05$, [1] N mg/kg^{-1} and trace microelements mg/kg^{-1}in red varieties (Sandy soil), [2] N mg/kg^{-1} and trace microelements mg/kg^{-1}in red varieties (Loam clay soil), [3] N mg/kg^{-1} and trace microelements mg/kg^{-1}in white varieties (Sandy soil), [4] N mg/kg^{-1} and trace microelements mg/kg^{-1}in white varieties (Loam clay soil). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

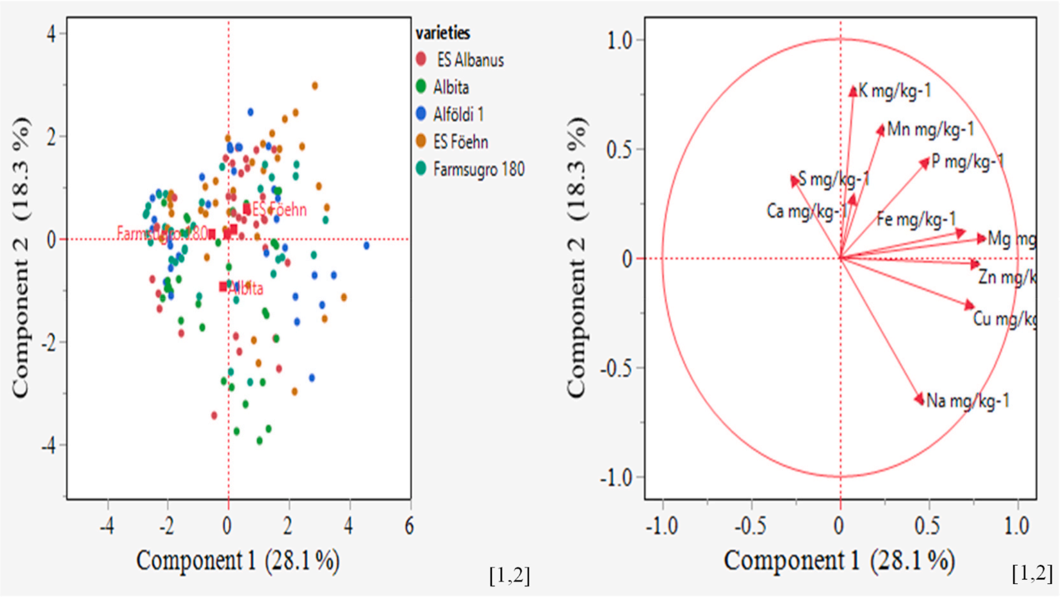

Fig. 12. Principal component analysis for relationships between the investigated essential mineral mg/kg^{-1} contents and respective *S. bicolor* varieties in the original pattern of the data,
*Values were demonstrated based on dry matter basis; numbers [1,2] refer to all investigated variables
(relationships of the elemental contents among white and red varieties), $P < 0.05$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Additional investigation is necessary to examine other factors affecting nutrient availability and their accumulation in sorghum grains. The research is limited, particularly by the constrained time of testing. The study's time frame, limited to just two cultivation seasons, restricts the depth of the research. Furthermore, the need for information on the influence of soil microbes on the uptake and conversion of nutrients is significant, given their crucial involvement in activities related to vital elements such as potassium, nitrogen, and phosphorus in various soil types and varieties. Specifically, our finding was estimated and referred to as the impact outcome resulting from the hydrolysis process, which affected the nutrient uptake by *S. bicolor* grains, highlighting the need for additional scientific investigation. The authors argue that there is a gap in research, which justifies the need for more exploration.

5. Conclusion

The research was conducted in response to several issues that necessitated it, including sorghum production as an immediate solution to several agricultural challenges, such as climate change and food security concerns. In particular, the study investigated the impact of N fertilizer on the element profile of *S. bicolor* grain grown in regions where it is non-native for sorghum production, mainly in Nyíregyháza and Karcag, Hungary.

The results highlighted the importance of soil type factors in nutrient management for sorghum grain production. Differences in results were attributed to N fertilizers, soil type, and diverse sorghum varieties. The findings revealed that N fertilizer positively affected sorghum grain's nutritional composition. In particular, the 120 kg/ha^{-1} treatment rate greatly increased the nutrients in loam clay soil, and it was estimated that the used rate stimulated the accessibility of specific nutrients for uptake by the sorghum variety. However, as we estimated, the same treatment rate (120 kg/ha^{-1}) negatively affected some microelements, such as sodium and calcium elements. The observed decrease in sodium (Na) and calcium (Ca) elements negatively impacted their accumulation in *S. bicolor* grains originating from the loam clay soil site, presumably due to chemical reaction factors (hydrolysis), which led to a varied nutrient composition profile of sorghum grains was assessed by comparing them with ES Föehn, a European sorghum variety used as a benchmark. The results highlighted the importance of soil type factors in nutrient management for sorghum grain production.

It was also noted that the red pericarp varieties, which matured early or semi-early, were associated with rich nutritional profiles of sorghum varieties; as we estimated, the maturity stages were highly related and strongly correlated with the N fertilizer response and the nutrient uptake by the respective varieties.

Hence, farmers and agricultural experts must thoroughly comprehend soil properties and the precise needs of crops. One may optimize benefits while limiting adverse environmental impacts using effective nutrient management strategies, such as performing soil testing, utilizing suitable N fertilizer, and inserting adapted varieties. Summarized that the experiment outcomes can be attempted to assess the elemental composition of *S. bicolor* grains to ascertain their viability as a viable source for human nutrition.

Availability of data

The authors affirm that the data supporting this research's conclusions may be found inside the paper. Data set is available in (https://data.mendeley.com/drafts/j46m5922zd).

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Ethics declarations

Not applicable.

Disclosure of conflicting interests

The authors affirm that they do not own any identifiable conflicting financial interests or personal ties that might have potentially influenced the findings presented in this study.

CRediT authorship contribution statement

Maha Khalfalla: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **László Zsombik:** Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Róbert Nagy:** Methodology, Writing – review & editing. **Zoltán Győri:** Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e28759.

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