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ORIGINAL PAPER

The effects of transplant age on elemental content determined by wavelength-dispersive X-ray fluorescence spectrometry of broccoli cultivars

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Abstract

The aim of this study was to investigate the effects of cultivar and transplant age on the elemental composition of broccoli (*Brassica oleracea* L. var. *italica*.) and to evaluate the suitability of wavelength-dispersive X-ray fluorescence (WDXRF) as a quantitative method for mineral analysis in broccoli samples. Three broccoli cultivars were used in the field experiment: Jade F₁, Monaco F₁, and Monopoly F₁. The results showed that all the elements were present at considerable levels. Among the factors assessed in the experiment, cultivar had the greatest impact on the elemental composition, followed by year and transplant age. The Monopoly F₁ cultivar generally showed a greater ability to accumulate multiple elements. P, S, and Cl contents were significantly affected by the year factor, underscoring the importance of environmental factors in nutrient absorption. Higher concentrations of P, S, and Cl were also associated with an increasing transplant age. Principal component analysis (PCA) further showed that the nutrient composition of broccoli varied depending on the interaction between genotype, transplant age and experiment year, with some nutrients being more closely associated with specific combinations of genotype and transplant age. Additionally, the findings indicate that WDXRF is a rapid and accurate method for determining the elemental makeup of broccoli samples. Overall, the findings imply that the mineral composition of broccoli is influenced by a combination of developmental, environmental, and genetic factors.

Keywords: broccoli, elemental analyses, transplant age, WDXRF

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INTRODUCTION

Vegetables are an important part of the human diet, providing a substantial amount of minerals, vitamins and dietary fibres (Kaymak et al. 2020, 2025, Stansluos et al. 2026). Mineral nutrients act as electrolytes in tissues and fluids, where they play a key role in maintaining acid-base balance, regulating osmotic pressure and regulating cell membrane permeability. In particular, macro-minerals such as Ca, P, Na, and I are essential for the proper functioning of these physiological processes. And also some elements participate in enzymatic reactions; Cu and Mn function as enzyme activators, while Zn and Mn are integral parts of metalloenzyme structures. Consequently, minerals play a fundamental role in sustaining human health and normal physiological functioning (López-Alonso et al. 2025).

The human body requires essential mineral nutrients in different quantities, generally ranging between 50 µg and 18 mg per day, and more than twenty chemical elements are recognized as important components of a balanced human diet. Insufficient intake of one or more of these elements can result in significant physiological disorders, including conditions such as anemia, osteoporosis, and goiter (Ali 2023). These minerals occur widely in various foods, especially in plant-derived products such as leafy green vegetables, tea leaves, and other plant materials (Castagnino et al. 2023, Nurzyńska-Wierdak 2025).

Recently, increasing attention has been drawn to establishing criteria for the development of novel “functional foods” that may help reduce the risk of specific cancers. Epidemiological findings indicate that a high intake of Brassica vegetables, including broccoli, is strongly linked to a lower risk of several cancers, particularly those of the lung, stomach, colon, and rectum (Zhang et al. 2018, Baladia et al. 2024). Several studies suggest that *Brassica* vegetables, and especially broccoli, contribute to cancer prevention in humans. This protective effect is largely associated with their substantial mineral composition and high levels of biologically active compounds, including flavonoids, vitamins, and glucosinolates (Li et al. 2022, Gudiño et al. 2024). Furthermore, the pharmaceutical importance of broccoli arises not only from its anticancer effects, but also from its antimicrobial, antioxidant, immunomodulatory, antidiabetic, hepatoprotective, cardioprotective properties (Syed et al. 2023).

Broccoli (*Brassica oleracea* var. *italica*), a member of the Cruciferae family within the genus *Brassica*, is widely consumed as a nutritious vegetable. The edible part of broccoli mainly consists of sprouts and florets that collectively form the inflorescence. This vegetable is largely composed of water (89.30%) and contains very low levels of fat (0.37%). Furthermore, Li et al. (2022) discovered that it supplies vitamins, minerals, proteins, dietary fiber, and carbohydrates. Due to its rich mineral content, broccoli is considered an important source of key micronutrients such as Na, K, Ca, Cl, P, and S,

as well as trace elements such as Fe, Zn, Mn and Cu, which play important roles in human nutrition and health (AlJuhaimi et al. 2024, Ramos-Salazar et al. 2025). However, the mineral content of broccoli can vary considerably depending on the environmental and agronomic conditions in which it is grown. Factors such as seasonal variation, low and high temperatures, low relative humidity and transplant age can significantly influence the accumulation of mineral elements in broccoli tissues (Albaladejo-Marico et al. 2025).

Several investigations have reported on the effect of transplant age on yield and growth of broccoli. While some studies indicate a decrease in yield and quality with increasing seedling age in broccoli, other studies report that younger seedlings yield more. For example, yield increased with increasing seedling age in broccoli seedlings at 14, 21, 28, and 35 days old, with the highest yield obtained from 35-day-old seedlings (Moon et al. 2025). Similarly, the highest yield per plant was reported from 35-day-old broccoli seedlings, compared to those in the 21- and 28-day-old age groups. It was declared that the reason for this could be that older seedlings in the evaluated age groups adapt more easily and better to field conditions than younger seedlings (Yasmin et al. 2021). However, sometimes young seedlings can perform better than older seedlings in parameters such as yield and growth characteristics. Indeed, Soniya et al. (2019) reported that the highest yield was obtained from 30-day-old seedlings and the lowest yield from 40-day-old seedlings. Also, in similar research, which used 20-, 30-, and 40-day-old broccoli seedlings, the highest yield and performance were obtained from 30-day-old seedlings (Sonia et al. 2019). Briefly, there are studies that have been conducted about the effect of transplant age on yield and growth parameters; however, it is still unclear whether younger or older transplants have an effect on the elemental composition of broccoli.

There is insufficient information on the effects of transplant age on the nutritional content of broccoli. The use of direct and multi-elemental analysis methods of food samples including X-ray fluorescence spectrometry (XRF) has increased over the last few years. Simplicity of sample preparation, minimum need for manipulation, speed and opportunity of analysing several different elements have promoted XRF as a useful alternative to conventional spectroscopic techniques (Marguí et al. 2022). Therefore, the objective of this study was to determine the effects of transplant age on the elemental composition of broccoli cultivars, and to evaluate the applicability of the WDXRF technique for mineral analysis in broccoli samples.

MATERIALS AND METHODS

Plant material

This study was conducted out both in field conditions and in XRF laboratory at Atatürk University, Erzurum, Türkiye. In this study, three broccoli

(*Brassica oleracea* L. var. *italica*) cultivars (Monaco F₁, Monopoly F₁ and Jade F₁) were used.

Growing plants

The field experiment was conducted on a loamy Lithosol soil with a pH of 6.5. Soil analyses indicated that the organic matter content ranged between 4.25 and 4.60%, while available phosphorus (P₂O₅) and potassium (K₂O) levels varied between 42.5-45.6 kg ha⁻¹ and 210-287 kg ha⁻¹, respectively. Each experimental plot received 200 kg ha⁻¹ nitrogen (N) and 200 kg ha⁻¹ phosphorus (P₂O₅) in the form of ammonium nitrate and triple superphosphate, respectively (Tripathi et al. 2020). Prior to planting, the entire amount of P₂O₅ was applied to the soil surface and incorporated into the soil. The N fertilization was split into two applications (Frieman et al. 2026). Half of the nitrogen fertilizer was applied with transplanting; the remaining nitrogen was top-dressed at the onset of head formation of plants.

Seeds of all cultivars were initially sown in multi-cell trays containing peat as the growing medium and maintained in an unheated greenhouse. The seedlings were then transferred to field plots of 6 m². Seeds were sown on 24-25 April in the experimental years. To obtain seedlings aged 30, 40, and 50 days, transplanting was performed at 10-day intervals starting from 23-24 May. Plants were spaced 30 cm between rows and 45 cm within rows (Singh et al. 2022). Irrigation was provided by means of furrow irrigation throughout the experiment, and regular crop management practices were maintained on each plot.

Determination of nutrient element content

Nine plants were randomly selected for sampling in each plot of fifteen plants. The heads of broccoli obtained from the selected plants were harvested and individually dried in a furnace at 67.5°C until uniform weight was obtained. After drying, the samples were ground into fine powder in a porcelain mortar, and the powder was used for X-ray fluorescent (XRF) analysis. For the elemental analysis, the XRF laboratory prepared pellets from 2 g of powdered samples. The pellets with a thickness of 2.5 mm and a diameter of 35 mm were produced by applying a force of 15 t with the Spex press (Cat. B25). Each pellet was carefully labeled and kept in a desiccator until the analysis was performed. Before measurement, the pellets were incubated at 80°C for 20 min to remove any remaining moisture. Elemental determination was carried out using wavelength-dispersive X-ray fluorescence (WDXRF) spectroscopy (Figure 1). During the analysis, LiF, Ge (111), PET (002), and TAP (100) crystals were used to separate the X-rays emitted from the sample pellets. The elemental composition of the broccoli samples was quantified with a WDXRF spectrometer (Rigaku ZSX-100e, Rhodium target X-ray source), and the results were expressed as weight percentage (wt%). The instrument was operated and monitored using ZSX software

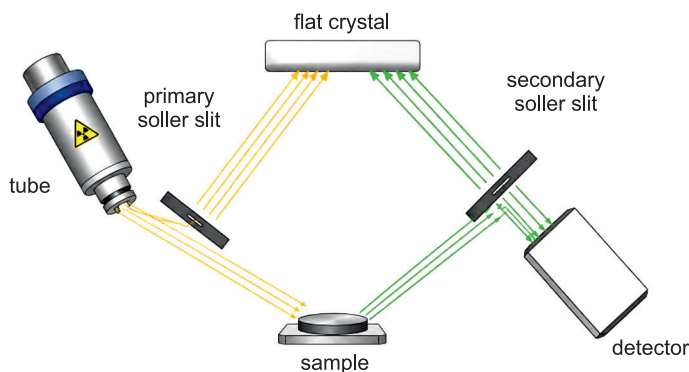


Fig. 1. Schematic representation of the spectrometer detection geometry

(Rigaku, Japan). The WDXRF system was equipped with a 4 kW, 70 kV end-window X-ray tube, enabling the detection of elements ranging from boron (B) to uranium (U). In addition, the instrument included micro-area mapping capability down to 0.5 mm, up to five primary beam filters, four analyzing crystals [LiF, Ge (111), PET (002), and TAP (100)], eight limiting area diaphragms, optional secondary collimators, an automatic sample changer, and multi-window fundamental parameter software for elemental analysis (Marguá et al. 2022).

Statical analyses

The experiment was conducted using a randomized complete block design with three replications. The collected data were analyzed by analysis of variance (ANOVA), and the differences between treatment means were determined using the Tukey's multiple range test at a 5% significance level. In order to examine the relationships among nutrient elements and to evaluate the similarities among genotype $\times$ transplant age $\times$ experiment combinations, principal component analysis (PCA) was performed. The resulting principal components were assessed based on their contribution to the total variance explained, and a biplot was generated using the first two principal components. All statistical analyses were carried out using the JMP Pro 14 software package (SAS Institute, NC, USA).

RESULTS AND DISCUSSION

The results showed that nutrient element contents were significantly affected by cultivar, experiment, and transplant age, although the magnitude of these effects varied depending on the element (Table 1). Generally, elements with contents ≥ 0.1 wt% were classified as major elements. Among the examined factors, cultivar had the strongest effect on mineral composi-

Table 1
Major element composition of broccoli cultivars at different transplant age (wt%)

Cultivar	Trans-plant age	Experiment-1															Experiment-2																	
		P	S	K	Cl	Ca	Fe	Ni	Mn	Cr	Zn	Br	Cu	Co	Se	Ge	P	S	K	Cl	Ca	Fe	Ni	Mn	Cr	Zn	Br	Cu	Co	Se	Ge			
Jade F ₁	30	29.53bc	10.82d/g	8.71def	7.67bc	3.54abc	1.62e	1.12a	0.95a	0.79b-e	0.54bcd	0.47b	0.53bc	0.52a-d	0.37a	0.32a	Jade F ₁	30	21.02ef	10.67d/g	8.62d-g	6.42cd	3.09b-e	1.82cde	0.88bcd	0.69b-f	0.71b-e	0.57a-d	0.49b	0.48bcd	0.41de	0.38a	0.31a	
	40	23.75c-f	10.84d/g	7.51gh	7.23bcd	3.86ab	1.81cde	0.89bcd	0.63c-g	0.73b-e	0.66a	0.45b	0.44cd	0.52a-d	0.36a	0.29ab		40	24.17c-f	12.51c-f	7.59gh	7.42bcd	3.66abc	1.81de	1.11a	0.60c-g	0.87b	0.62ab	0.71a	0.56abc	0.49bcd	0.34a	0.26ab	
	50	25.33c-f	10.56d/g	8.03gh	8.26bc	3.51abc	1.98b-e	0.85bcd	0.60d-g	0.73b-e	0.62ab	0.40b	0.61ab	0.51a-d	0.38a	0.23b		50	31.65b	13.40c	2.40i	5.28d	1.15g	1.08e	0.36f	0.47g	0.70cde	0.17g	0.40b	0.15e	0.27e	0.42a	0.05c	
	mean	26.21B	10.74 D	8.09 C	7.72B	3.63A	1.79B	0.95A	0.72A	0.75BC	0.61AB	0.44BC	0.53A	0.52B	0.37A	0.28AB		mean	25.61B	12.19C	6.20D	6.37C	2.64C	1.57C	0.79B	0.59C	0.76BC	0.45D	0.53A	0.40C	0.39C	0.38A	0.21C	
	30	26.48b-e	9.16g	11.51a	7.41bcd	2.45def	1.78e	0.75cde	0.57efg	0.63e	0.41ef	0.48b	0.41cd	0.68a	0.36a	0.25ab		30	28.15bcd	10.49d/g	11.08ab	7.49bcd	2.23f	1.62e	0.63e	0.54fg	0.66cde	0.38f	0.45b	0.37d	0.63ab	0.34a	0.23b	
Monaco F ₁	40	23.14def	10.31fg	8.41d-h	6.52cd	2.16f	1.84cde	0.75cde	0.60c-g	0.72b-e	0.57a-d	0.50b	0.48bcd	0.55a-d	0.35a	0.23b	40	26.94b-e	12.44c-f	9.98bc	6.35cd	2.54def	2.19abc	0.88bcd	0.71b-f	0.73b-e	0.63ab	0.48b	0.54bc	0.55a-d	0.35a	0.28ab		
	50	22.46def	11.06d-g	7.77gh	6.73cd	3.08b-e	2.17a-d	0.82b-e	0.62c-g	0.78b-e	0.65a	0.50b	0.70a	0.55a-d	0.43a	0.27ab	50	28.30bcd	12.45c-f	9.28cde	6.64cd	3.23bcd	1.98b-e	0.81cde	0.76bcd	0.68cde	0.51cde	0.44cd	0.44cde	0.41a	0.25ab			
	mean	24.03B	10.18D	9.23 B	6.89BC	2.56C	1.93B	0.77B	0.60C	0.71BC	0.54C	0.49ABC	0.53A	0.59AB	0.38A	0.25B	mean	24.03B	10.18D	9.23 B	6.89BC	2.56C	1.93B	0.77B	0.60C	0.71BC	0.54C	0.49ABC	0.53A	0.59AB	0.38A	0.25B		
	30	19.40f	12.51cde	7.45h	7.37bcd	2.93c-f	1.73e	0.87bcd	0.62c-g	0.70cde	0.50de	0.51b	0.60ab	0.64ab	0.40a	0.27ab	30	19.40f	12.51cde	7.45h	7.37bcd	2.93c-f	1.73e	0.87bcd	0.62c-g	0.70cde	0.50de	0.51b	0.60ab	0.64ab	0.40a	0.27ab		
	40	26.09b-e	13.28cd	8.16c-h	8.28bc	3.09b-e	1.86cde	0.82b-e	0.84ab	0.68cde	0.63ab	0.46b	0.45cd	0.53a-d	0.35a	0.28ab	40	26.09b-e	13.28cd	8.16c-h	8.28bc	3.09b-e	1.86cde	0.82b-e	0.84ab	0.68cde	0.63ab	0.46b	0.45cd	0.53a-d	0.35a	0.28ab		
Monopoly F ₁	50	28.30bcd	12.45c-f	9.28cde	6.64cd	3.23bcd	1.98b-e	0.81cde	0.76bcd	0.68cde	0.51cde	0.53b	0.44cd	0.44cde	0.41a	0.25ab	50	28.30bcd	12.45c-f	9.28cde	6.64cd	3.23bcd	1.98b-e	0.81cde	0.76bcd	0.68cde	0.51cde	0.53b	0.44cd	0.44cde	0.41a	0.25ab		
	mean	24.60B	12.75BC	8.30 C	7.43B	3.08B	1.86B	0.83B	0.74A	0.69C	0.54C	0.50AB	0.50AB	0.54AB	0.39A	0.27AB	mean	24.60B	12.75BC	8.30 C	7.43B	3.08B	1.86B	0.83B	0.74A	0.69C	0.54C	0.50AB	0.50AB	0.54AB	0.39A	0.27AB		
	Cultivar	Trans-plant age	P	S	K	Cl	Ca	Fe	Ni	Mn	Cr	Zn	Br	Cu	Co	Se	Ge	Cultivar	Trans-plant age	P	S	K	Cl	Ca	Fe	Ni	Mn	Cr	Zn	Br	Cu	Co	Se	Ge
	Jade F ₁	30	21.02ef	10.67d/g	8.62d-g	6.42cd	3.09b-e	1.82cde	0.88bcd	0.69b-f	0.71b-e	0.57a-d	0.49b	0.48bcd	0.41de	0.38a	0.31a	Jade F ₁	30	21.02ef	10.67d/g	8.62d-g	6.42cd	3.09b-e	1.82cde	0.88bcd	0.69b-f	0.71b-e	0.57a-d	0.49b	0.48bcd	0.41de	0.38a	0.31a
		40	24.17c-f	12.51c-f	7.59gh	7.42bcd	3.66abc	1.81de	1.11a	0.60c-g	0.87b	0.62ab	0.71a	0.56abc	0.49bcd	0.34a	0.26ab		40	24.17c-f	12.51c-f	7.59gh	7.42bcd	3.66abc	1.81de	1.11a	0.60c-g	0.87b	0.62ab	0.71a	0.56abc	0.49bcd	0.34a	0.26ab
50		31.65b	13.40c	2.40i	5.28d	1.15g	1.08e	0.36f	0.47g	0.70cde	0.17g	0.40b	0.15e	0.27e	0.42a	0.05c	50		31.65b	13.40c	2.40i	5.28d	1.15g	1.08e	0.36f	0.47g	0.70cde	0.17g	0.40b	0.15e	0.27e	0.42a	0.05c	
mean		25.61B	12.19C	6.20D	6.37C	2.64C	1.57C	0.79B	0.59C	0.76BC	0.45D	0.53A	0.40C	0.39C	0.38A	0.21C	mean		25.61B	12.19C	6.20D	6.37C	2.64C	1.57C	0.79B	0.59C	0.76BC	0.45D	0.53A	0.40C	0.39C	0.38A	0.21C	
30		28.15bcd	10.49d/g	11.08ab	7.49bcd	2.23f	1.62e	0.63e	0.54fg	0.66cde	0.38f	0.45b	0.37d	0.63ab	0.34a	0.23b	30		28.15bcd	10.49d/g	11.08ab	7.49bcd	2.23f	1.62e	0.63e	0.54fg	0.66cde	0.38f	0.45b	0.37d	0.63ab	0.34a	0.23b	
Monaco F ₁	40	26.94b-e	12.44c-f	9.98bc	6.35cd	2.54def	2.19abc	0.88bcd	0.71b-f	0.73b-e	0.63ab	0.48b	0.54bc	0.55a-d	0.35a	0.28ab	40	26.94b-e	12.44c-f	9.98bc	6.35cd	2.54def	2.19abc	0.88bcd	0.71b-f	0.73b-e	0.63ab	0.48b	0.54bc	0.55a-d	0.35a	0.28ab		
	50	43.16a	17.19b	11.45a	9.19b	4.36a	1.94b-e	0.95abc	0.59d-g	1.20a	0.66a	0.47b	0.43cd	0.61abc	0.31a	0.24ab	50	43.16a	17.19b	11.45a	9.19b	4.36a	1.94b-e	0.95abc	0.59d-g	1.20a	0.66a	0.47b	0.43cd	0.61abc	0.31a	0.24ab		
	mean	32.75A	13.38B	10.84A	7.68B	3.04B	1.92B	0.82B	0.61BC	0.87A	0.56BC	0.47BC	0.45BC	0.60A	0.38A	0.27AB	mean	32.75A	13.38B	10.84A	7.68B	3.04B	1.92B	0.82B	0.61BC	0.87A	0.56BC	0.47BC	0.45BC	0.60A	0.38A	0.27AB		
	30	27.89bcd	10.18/g	8.51d-h	8.51bc	2.47def	2.31ab	0.72de	0.78abc	0.83bcd	0.60a-d	0.43b	0.53bc	0.60abc	0.36a	0.25ab	30	27.89bcd	10.18/g	8.51d-h	8.51bc	2.47def	2.31ab	0.72de	0.78abc	0.83bcd	0.60a-d	0.43b	0.53bc	0.60abc	0.36a	0.25ab		
	40	26.49b-e	10.74c/g	9.40cd	7.47bcd	3.28bcd	1.90cde	0.85bcd	0.55fg	0.67cde	0.61abc	0.43b	0.47bcd	0.50a-d	0.36a	0.32a	40	26.49b-e	10.74c/g	9.40cd	7.47bcd	3.28bcd	1.90cde	0.85bcd	0.55fg	0.67cde	0.61abc	0.43b	0.47bcd	0.50a-d	0.36a	0.32a		
Monopoly F ₁	50	48.91a	24.46a	10.30bc	12.62a	3.74abc	2.47a	1.03ab	0.73b-e	0.84bc	0.62ab	0.42b	0.51bcd	0.62ab	0.35a	0.31a	50	48.91a	24.46a	10.30bc	12.62a	3.74abc	2.47a	1.03ab	0.73b-e	0.84bc	0.62ab	0.42b	0.51bcd	0.62ab	0.35a	0.31a		
	mean	34.43A	15.13A	9.40 B	9.54A	3.16B	2.23A	0.87AB	0.69AB	0.78B	0.62A	0.43C	0.51AB	0.59AB	0.36A	0.29A	mean	34.43A	15.13A	9.40 B	9.54A	3.16B	2.23A	0.87AB	0.69AB	0.78B	0.62A	0.43C	0.51AB	0.59AB	0.36A	0.29A		

tion. In particular, the cv. Monopoly F₁ generally exhibited higher values for several elements, including S, P, Cl, and Fe, in both experiments. This finding indicates that genotypic differences play an important role in nutrient uptake and accumulation. For example, in the second experiment, the P content in the cv. Monopoly F₁ reached 48.91 wt%, and this value was statistically higher than those of the other cultivars, although it was statistically in the same group as the cv. Monaco F₁. Similarly, in the second experiment, the contents of S (24.46 wt%), Cl (12.62 wt%), and Fe (2.47 wt%) also reached their highest levels in the cv. Monopoly F₁. This indicates that the cv. Monopoly F₁ has a greater capacity for mineral uptake and accumulation. In contrast, the cv. Monaco F₁ exhibited higher values particularly in terms of Ca, Cr, and K content. Notably, in the first experiment, the highest K content (11.51 wt% and 11.45 wt%) at 30- and 50-day old transplant was recorded in this cultivar. These results indicate that nutrient element accumulation is largely controlled by genotype and that cultivars differ in their mineral uptake efficiency.

The experimental factor had a significant effect on nutrient element contents. In particular, P, S, and Cl contents reached higher levels in the second experiment compared to the first one. For example, while the maximum P content was 29.53 wt% in the first experiment, it increased to 48.91 in the second experiment. A similar pattern was observed for the content of S, which increased from 13.28 wt% in the first experiment to 24.46 wt% in the second experiment. Similarly, the Cl content showed a significant increase in the second experiment and peaked at 12.62 wt%. These results indicate that environmental conditions, including annual climatic variation, soil characteristics and general growing conditions can have a significant influence on the uptake and accumulation of nutrients. However, only slight seasonal variations were observed for some elements, in particular Ca, indicating that the accumulation of these elements can be relatively stable in changing environmental conditions. The effect of transplant age on the content of nutrients varied according to the element. In general, an increasing trend was observed in P, S, and Cl contents with increasing transplant age. In the second experiment, the mean values of P (48.91 wt%), S (24.46 wt%), Cl (12.62 wt%), and Fe (2.47 wt%) at 50-day-old transplants were statistically higher than those at other transplant ages. This indicates that plants at more advanced developmental stages have a greater nutrient uptake capacity due to their more developed root systems. In contrast, the effect of transplant age was more limited for certain elements, particularly Se, and statistically significant differences were not always observed. This suggests that the accumulation of some elements is more strongly controlled by genetic factors. Additionally, Priyanka et al. (2023) reported that the amounts of N, P, and K in broccoli ranged from 3.08-3.15%, 0.52-0.68%, and 2.17-2.26%, respectively.

According to the WDXRF analyses, it can be said that broccoli is a good source of elements such as Ca, Mg, Na, K, Ca, Cl, P, S, Fe, Zn, Mn and Cu,

which are essential for healthy human nutrition. These results are confirmative the results of AlJuhaimi et al. (2024). Indeed, AlJuhaimi et al. (2024) reported that broccoli contained 3114.94 mg 100⁻¹ g P, 29,730.49 mg 100⁻¹ g K, 3555.67 mg 100⁻¹ g Ca, 1197.02 mg 100⁻¹ g Mg, 3935.51 mg 100⁻¹ g S, 46.60 mg 100⁻¹ g Fe, 2.73 mg 100⁻¹ g Cu, 9.61 mg 100⁻¹ g Mn, 11.88 mg 100⁻¹ g Zn and 2.76 mg 100⁻¹ g B. Similarly, Mn content varied between 0.15-1.79 mg 100⁻¹ g under conventional production and 0.04-1.40 mg 100⁻¹ g under organic production, while Zn content ranged from 0.20-1.58 mg 100⁻¹ g and 0.17-1.28 mg 100⁻¹ g, respectively. Among the macro-elements, K was found at relatively high levels, ranging from 317.65 to 484.45 mg 100 g⁻¹ in conventionally grown broccoli and from 321.58 to 521.78 mg 100 g⁻¹ in organically grown broccoli. Ca content varied widely, ranging from 7.14 to 153.50 mg 100 g⁻¹ in conventional samples and from 9.38 to 131.55 mg 100 g⁻¹ in organic samples. In addition, the levels of Mg and Na also varied significantly. Concentrations of Mg ranged from 21.09 to 47.15 mg 100 g⁻¹ in conventionally grown broccoli and from 29.51 to 61.23 mg 100 g⁻¹ in samples from organically grown broccoli. Similarly, Na levels in conventional broccoli ranged from 3.66 to 21.21 mg 100 g⁻¹ and in organic broccoli from 1.89 to 27.09 mg 100 g⁻¹. The results of this study indicate that the mineral content of broccoli may be significantly affected by the culture system as well as by environmental and production factors. Similarly, Grabowska et al. (2018) reported that the age of transplantation has a significant impact on the mineral content of broccoli. Their studies revealed significant differences in a number of elements, notably P, Ca, Mg, Na and Fe.

Broccoli plants from older transplants generally tended to accumulate higher mineral content. For example, the P content of broccoli heads obtained from transplants at 10 weeks of age was 5724 mg kg⁻¹, while those from transplants at 6 weeks of age were approximately 5575 mg kg⁻¹. A similar pattern was observed for calcium, with an average concentration of 4122 mg kg⁻¹ in plants from transplants of 10 weeks of age, compared with 3772 mg kg⁻¹ in plants from transplants of 4 weeks of age. The Mg content followed a similar trend, reaching approximately 1648 mg kg⁻¹ in plants from 10-week-old seedlings, and approximately 1498 mg kg⁻¹ in plants from transplants from 6 weeks of age. The Fe concentrations were also higher in plants from older transplants. The highest value (67.16 mg kg⁻¹) was observed in plants produced from transplants aged 10 weeks, while plants produced from transplants aged 6 weeks had 60.65 mg kg⁻¹. These results suggest that transplant age has a significant effect on mineral accumulation in broccoli heads. Therefore, a longer period of growth of the seedlings may contribute to increased nutrient concentrations, especially of P, Ca and Fe. In line with this finding, Grabowska et al. (2018) reported that the time of sowing and the age of transplantation have a significant impact on the nutritional composition of broccoli. Their study showed that delaying the sowing by about one month resulted in increased concentrations of several chemical substances in the broccoli flowers. In particular, late sowing led to higher levels of dry matter

(3%), P (14%), P (13%), Zn (12%), Fe (8 %) and Mn (9%) in the soil. In addition, the authors reported that plants from younger transplants (seedlings aged 4 weeks) had higher concentrations of K (5%), P (6%), Mg (4%), Na (11%) and Zn (3%) in their flowers compared to transplants from plants from 10 weeks of age. These results show that both transplant age and time spent sowing can play a significant role in determining the chemical composition and nutritional value of broccoli.

The results of the PCA show that the nutrient composition of broccoli varies depending on the interaction between genotype, transplant age and experiment year, and that some nutrients are more closely related to specific combinations of genotype and transplant age (Figure 2). The PCA biplot

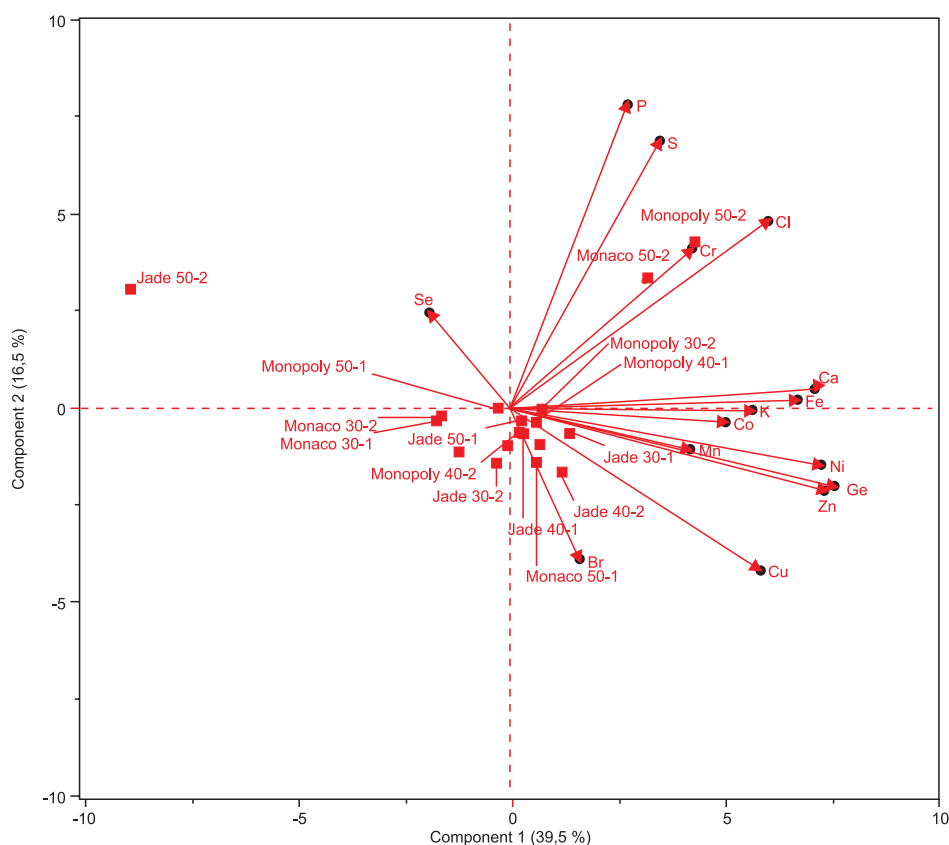


Fig. 2. Relationships among the cultivars, transplant age, experiment and the mineral content

showed that 39.5% of the total variation was explained by the first principal component (PC1) and 16.5% by the second principal component (PC2). Approximately 56% of the total variability was represented by these two factors combined. Elements with comparatively long vectors and similar orientations along the PC1 axis included Ca, Fe, K, Co, Ni, Ge, Zn, and Cu.

This distribution shows a positive correlation between these components and indicates that they contribute significantly to the overall variation. Se, on the other hand, showed a different distribution pattern than the other elements because they were located on the negative side of the PC1 axis. The distribution of the samples on the biplot showed that the 50-day-old transplants exhibited a more distinct separation. The 50-day-old transplants of the cv. Monopoly F_1 and cv. Monaco F_1 , particularly in the second experiment, were more closely associated with P, S, Cl, and Cr, whereas the cv. Jade F_1 at the same transplant age exhibited a different elemental profile. In contrast, the positioning of a considerable proportion of the samples from the 30- and 40-day-old transplants closer to the center indicates that the differentiation among elemental profiles was generally more limited in these treatments. Similarly, a stronger correlation with Ca, Fe, and K is suggested by the placement of 30-day-old transplants of cv. Monopoly F_1 in the second experiment and 40-day-old transplants of cv. Monopoly F_1 in the first experiment on the positive side of the PC1 axis. On the other hand, a number of combinations, such as 30-day-old transplants of cv. Monaco F_1 in the first and second experiment, and 50-day-old transplants of cv. Jade F_1 in the first experiment, were located close to the biplot's center, suggesting a more evenly distributed and comparable distribution of element concentrations. The distinct separation of the 50-day-old transplants of cv. Jade F_1 in the second experiment on the negative side of the PC1 axis, which sets it apart from the other samples, is another remarkable aspect of the biplot. This separation indicates that this treatment has a different elemental profile from the other combinations.

CONCLUSIONS

The cultivar had the greatest impact on nutrient element contents, according to the study's findings, followed by the experiment factor (1 and 2) and transplant age. Cv. Monopoly F_1 showed a higher capacity for mineral accumulation than the other tested cultivars. The experiment factor, which represents environmental conditions, had a major impact on the contents of P, S, and Cl. Furthermore, the accumulation of some nutrients, especially P, S, and Cl, was generally encouraged by an increase in transplant age. Overall, the findings imply that a combination of developmental, environmental, and genetic factors influence the mineral composition of broccoli. Furthermore, the elemental composition of broccoli samples could be quickly and accurately determined using the WDXRF technique.

Author contributions

H.Ç.K and F.Y.K. – writing – original draft preparation, data curation, validation, visualization, writing – review and editing, investigation, supervision, resource, H.Ç.K., F.Y.K. and A.G. – methodology, H.Ç.K., F.Y.K., S.T. and A.G. – software, formal analysis. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Authors state no conflict of interest.

REFERENCES

- Albaladejo-Marico, L., Gomez-Molina, M., Garcia-Ibañez, P., Carvajal, M., Yepes-Molina, L. (2025) 'Valorization of broccoli by-products: seasonal variations in bioactive compounds and their biostimulant effects on pak choi germination', *PLoS One*, 20(5), e0323848, available: <https://doi.org/10.1371/journal.pone.0323848>
- AlJuhaimi, F., Mohamed Ahmed, I.A., Özcan, M.M., Uslu, N., Albakry, Z. (2024) 'Quantitative determination of biogenic element contents and phytochemicals of broccoli (*Brassica oleracea* var. *italica*) cooked using different techniques', *Plants*, 13(10), 1283, available: <https://doi.org/10.3390/plants13101283>
- Ali, A.A.H. (2023) 'Overview of the vital roles of macro minerals in the human body', *Journal of Trace Elements and Minerals*, 4, 100076, available: <http://dx.doi.org/10.1016/j.jtemin.2023.100076>
- Baladia, E., Moñino, M., Pleguezuelos, E., Russolillo, G., Garnacho-Castaño, M.V. (2024) 'Broccoli consumption and risk of cancer: an updated systematic review and meta-analysis of observational studies', *Nutrients*, 16(11), 1583, available: <https://doi.org/10.3390/nu16111583>
- Castagnino, A.M., Diaz, K.E., Rosini, M.B. (2023) 'Consumption of vegetables as a health factor', *Horticulture International Journal*, 7(5), 146-147, available: <http://dx.doi.org/10.15406/hij.2023.07.00288>
- Frieman, A., Vorsatz, C., Schön, H.G., Daum, D. (2026) 'Influence of vegetative growth and head traits on the hollow stem formation in broccoli affected by cultivation factors', *Agronomy*, 16(1), 42, available: <https://doi.org/10.3390/agronomy16010042>
- Grabowska, A., Sękara, A., Kalisz, A., Kunicki, E., Wojciechowska, R., Kopta, T. (2018) 'Optimisation of transplant age in combination with dark-chilling to enhance the biological quality of broccoli cultivated in summer', *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 46(2), 494-500, available: <https://doi.org/10.15835/nbha46211073>
- Gudiño, I., Casquete, R., Martín, A., Wu, Y., Benito, M.J. (2024) 'Comprehensive analysis of bioactive compounds, functional properties, and applications of broccoli by-products', *Foods*, 13(23), 3918, available: <https://doi.org/10.3390/foods13233918>
- Kaymak, H.C., Aksoy, A., Kotan, R. (2020) 'Inoculation with N₂-fixing plant growth promoting rhizobacteria to reduce nitrogen fertilizer requirement of lettuce', *Acta Scientiarum Polonorum Hortorum Cultus*, 19(5), 23-35, available: <https://doi.org/10.24326/asphc.2020.5.3>
- Kaymak, H.C., Akan, S., Yarali Karakan, F., Tıraşçı, S. (2025) 'The pathway between phytochemical properties and fatty acid content of pumpkin (*Cucurbita pepo* L.) seeds', *Journal of Agricultural Science and Technology*, 27(3), 663-675.
- Li, H., Xia, Y., Liu, H.Y., Guo, H., He, X.Q., Liu, Y., Wu, D.T., Mai, Y.H., Li, H.B., Zou, L., Gan, R.Y. (2022) 'Nutritional values, beneficial effects, and food applications of broccoli (*Brassica oleracea* var. *italica* Plenck)', *Trends in Food Science and Technology*, 119, 288-308, available: <https://doi.org/10.1016/j.tifs.2021.12.015>

- López-Alonso, M., Rivas, I., Miranda, M. (2025) 'Trace mineral imbalances in global health: challenges, biomarkers, and the role of serum analysis', *Nutrients*, 17(13), 2241, available: <http://dx.doi.org/10.3390/nu17132241>
- Marguí, E., Queralt, I., De Almeida, E. (2022) 'X-ray fluorescence spectrometry for environmental analysis: Basic principles, instrumentation, applications and recent trends', *Chemosphere*, 303(1), 135006, available: <https://doi.org/10.1016/j.chemosphere.2022.135006>
- Moon, M.R.I., Hossain, M.M., Haque, T., Hafiz, M.M.H., Yasmin, A. (2025) 'Growth and yield of broccoli (*Brassica oleracea* L. var. *italica*) influenced by seedling age and plant density', *Plant Physiology and Soil Chemistry*, 5(1), 27-34, available: <http://doi.org/10.26480/ppsc.01.2025.27.34>
- Nurzyńska-Wierdak, R. (2025) 'Green leafy vegetables (GLVs) as nutritional and preventive agents supporting metabolism', *Metabolites*, 15(8), 502, available: <http://dx.doi.org/10.3390/metabo15080502>
- Priyanka, Bhatt, L., Singh, D., Singh, P.K., Gautam, P., Singh, U.K. (2023) 'Influence of NPK on growth, yield and nutrient content in broccoli (*Brassica oleracea* L. var. *italica*) under drip and conventional irrigation system', *The Pharma Innovation Journal*, 12(8), 2051-2056.
- Ramos-Salazar, R.A., Mendoza-Villarreal, R., Robledo-Torres, V., López-López, H., Sandoval-Rangel, A. (2025) 'Influence of biofertilizers on the development and mineral composition of broccoli (*Brassica oleracea* var. *italica*)', *Terra Latinoamericana*, 43, e2227, available: <https://doi.org/10.28940/terra.v43i.2227>
- Singh, S., Kumar, S., Singh, S.P., Yadav, S., Yadav, S., Singh, A., Awasthi, M.K. (2022) 'Effect of plant spacing and cultivar on quality attributes in sprouting broccoli', *South African Journal of Botany*, 148, 737-741, available: <https://doi.org/10.1016/j.sajb.2022.04.049>
- Soniya, I.A., Mostarin, T., Khatun, K., Haq, M.E., Akhter, S., Sharmin, I., Monira, S., Parvin, A. (2019) 'Effect of starter solution and age of seedling on growth and yield of broccoli (*Brassica Oleracea* var. *italica*)', *Asian Journal of Research in Crop Science*, 4(4), 1-11, available: <https://doi.org/10.9734/ajrcs/2019/v4i430081>
- Stansluos, A.A.L., Öztürk, A., Türkoğlu, A., Kaymak, H.C. (2026) 'Influence of planting geometry on the quality criteria of sweet corn genotypes', *New Zealand Journal of Crop and Horticultural Science*, 54, e70034, available: <https://doi.org/10.1002/nzc2.70034>
- Syed, R.U., Moni, S.S., Break, M.K.B., Khojali, W.M.A., Jafar, M., Alshammari, M.D., Abdelsalam, K., Taymour, S., Alreshidi, K.S.M., Elhassan Taha, M.M., Mohan, S. (2023) 'Broccoli: a multi-faceted vegetable for health: an in-depth review of its nutritional attributes, antimicrobial abilities, and anti-inflammatory properties', *Antibiotics*, 12(7), 1157, available: <https://doi.org/10.3390/antibiotics12071157>
- Tripathi, S., Patel, J.M., Singh, N., Naik, J., Naik, V.R. (2020) 'Effect of different NPK levels on growth and yield attributes of broccoli (*Brassica oleracea* L.) under south Gujarat condition', *International Journal of Chemical Studies*, 8(3), 1335-1339, available: <https://doi.org/10.22271/chemi.2020.v8.i3r.9385>
- Yasmin, A., Hossain, M.M., Rahman, M.H. (2021) 'Growth and yield of broccoli (*Brassica oleracea* L. var. *italica*) impacted by seedling age and mulching materials', *Fundamental and Applied Agriculture*, 6(2), 134-143, available: <https://doi.org/10.5455/faa.67123>
- Zhang, Z., Bergan, R., Shannon, J., Slatore, C.G., Bobe, G., Takata, Y. (2018) 'The role of cruciferous vegetables and isothiocyanates for lung cancer prevention: current status, challenges, and future research directions', *Molecular Nutrition and Food Research*, 62(18), 1700936, available: <https://doi.org/10.1002/mnfr.201700936>