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Evaluation of Essential and Toxic Elements, Polyphenol Content, and Antioxidant Activity in Cabbage (*Brassica oleracea* L.)

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Brassica oleracea (cabbage) is a widely consumed cruciferous vegetable known for its nutritional richness and health-promoting properties. This study aimed to evaluate the mineral composition, total polyphenol content (TPC), antioxidant activity (AA), and the presence of potentially toxic elements in selected cabbage varieties. Total polyphenol content ranged from 3,588 to 4,002 mg GAE.kg^{-1} DM, with corresponding antioxidant activity values between 8.01 and 13.0 mmol TE.kg^{-1} DM. Among the macronutrients, potassium (18,291–21,064 mg.kg^{-1} DM) was the most abundant, followed by calcium and phosphorus. Iron was the dominant microelement (24.5–28.7 mg.kg^{-1} DM), with considerable levels of manganese, zinc, and copper. Potentially toxic elements such as lead and cadmium were also detected in some samples, occasionally exceeding the EU maximum permissible limits on a FW basis. However, estimated dietary intake suggests that average cabbage consumption does not pose a significant health risk, remaining within acceptable provisional tolerable weekly intake (PTWI) levels. The study confirms that mineral and phytochemical composition in cabbage is significantly influenced by varietal differences and may also reflect environmental and post-harvest factors. These findings reinforce the nutritional and functional value of *Brassica oleracea* as a source of essential elements and bioactive compounds with potential health benefits.

Keywords: *Brassica oleracea*, cabbage, polyphenols, antioxidant activity, minerals

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Introduction

Brassica vegetables represent an important group of globally consumed crops that are valued not only for their nutritional content but also for their rich profile of bioactive compounds with potential health benefits. These vegetables are excellent sources of health-promoting phytochemicals, including polyphenols, carotenoids, selenium, glucosinolates, lipids, and vitamin C (Kumar and Andy, 2012; Vergun et al., 2017). Incorporation of *Brassica* vegetables into the daily diet provides a safe, cost-effective, and accessible strategy for reducing the risk of various non-communicable diseases. A distinguishing feature of *Brassica* species is their high content of sulfur-containing compounds, which contribute to their characteristic pungent aroma and flavor and are primarily responsible for their elevated glucosinolate levels (Higdon et al., 2007). Upon tissue disruption, glucosinolates undergo enzymatic hydrolysis by the endogenous enzyme β-thioglucosidase (myrosinase), resulting in the formation of biologically active breakdown products such as isothiocyanates and indoles. These metabolites have been associated with multiple health-promoting effects, including antioxidant activity, modulation of detoxification enzymes, immune system stimulation, and inhibition of cancer cell proliferation (Sanlier and Guler Saban, 2018; Rakhmetov et al., 2018). In addition to glucosinolates, *Brassica* vegetables also contain a wide array of natural antioxidants such as vitamins C and E, carotenoids, and enzymatic antioxidants including catalase, superoxide dismutase (SOD), and peroxidase. Cabbage (*Brassica oleracea*), in particular, is known to be a rich source of anthocyanins, flavonoids, terpenes, S-methylcysteine sulfoxide, coumarins, and other secondary metabolites with demonstrated biological activity (Kapusta-Duch et al., 2012). Cabbage is also a rich dietary source of folate, a B-group vitamin that plays a crucial role in DNA synthesis and repair, fetal development, and the prevention of various chronic diseases, including cardiovascular and neurodegenerative disorders (Czarnowska and Gujska, 2012). Polyphenolic compounds, which are ubiquitous in the plant kingdom, contribute to the plant's defense mechanisms and are also recognized for their numerous health-promoting properties in humans. The Brassicaceae family contains a diverse array of polyphenols, including lignans, flavonoids, and simple phenolic compounds, which have been widely studied for their antioxidant, anti-inflammatory, and chemopreventive effects (Jahangir et al., 2009). Among flavonoids, flavonols such as quercetin, kaempferol, and isorhamnetin are particularly abundant in *Brassica* vegetables. Cabbage is noted for its high content of phenolic acids, with over 20 distinct compounds identified, including derivatives of hydroxycinnamic acids (Abu-Ghannam and Jaiswal, 2015). These compounds exhibit potent free radical scavenging activity and possess metal-chelating properties. Some, such as caffeic acid, have also been shown to enhance the activity of endogenous antioxidant enzymes, thereby contributing to the overall antioxidant defense system (Semiz et al., 2017). In addition to phytochemicals, cabbage provides essential minerals including iron (Fe), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and phosphorus (P), all of which are vital for maintaining human health and metabolic function (Singh et al., 2009).

To determine the impact of varietal characteristics, environmental conditions, and post-harvest factors on the mineral and phytochemical composition of *Brassica oleracea* in order to evaluate its nutritional and functional value as a source of essential elements and bioactive compounds beneficial to human health

Material and Methodology

Plant Material

The researched samples of cabbage, cultivar Agressor F1, were obtained from different retailers in Slovakia.

Extract Preparation

25 g of fresh homogenized samples were extracted in 50 ml of 80% methanol for 12 hours and filtered through filtrating paper.

Total polyphenol content

Total polyphenol content was determined by the Folin-Ciocalteau colorimetric method (Lachman et al., 2003). Folin-Ciocalteu phenol reagent (Merck, Germany), 20% Na_2CO_3 (Sigma Aldrich, USA), and distilled water were used. 0.1 mL of extract was pipetted into a 50 mL volumetric flask. 0.85 mL of Folin-Ciocalteu reagent was added, and after 3 minutes, 5 mL of 20% Na_2CO_3 was added. The mixture was stirred, and the flask was filled with distilled water to the mark. Flasks were left for 2 hours at laboratory temperature and then measured against a blank solution at 765 nm, using a Shimadzu UV/VIS scanning spectrophotometer. Total polyphenol content was expressed as mg of gallic acid equivalent per 1 kg, based on the calibration curve.

Antioxidant Activity

Antioxidant activity was measured by DPPH radical scavenging assay (Brand Williams et al., 1995). DPPH•+ radical (2,2-diphenyl-1-picrylhydrazyl) (Sigma Aldrich, USA) and methanol (Sigma Aldrich, USA) were used to produce a working DPPH solution. 1 mL of extract was pipetted into 3.9 mL of working DPPH solution, stirred, and left in the dark. After 10 minutes, the solution was measured against a blank solution at nm, using a Shimadzu UV/VIS scanning spectrophotometer. Antioxidant activity was expressed at 130 as mmol of Trolox equivalent in 1 kg, based on the calibration curve.

Mineral Content

For analysis of macroelements, 1 g of homogenized dried sample was mineralized in a mixture of 10 ml of concentrated HNO_3 and 5 ml of concentrated HCLO using a closed microwave digestion system Mars Xpress 5 (CEM Corp., Matthews, NC, USA). After mineralization, cooled samples were filtered through quantitative filter paper Filtrak 390 (Munktell, GmbH, Bärenstein, Germany). For the K, Ca, Mg, and Na determination, 2 ml of filtered sample was diluted with redistilled water to a volume of 50 ml, and measured against a blank solution using an atomic absorption spectrophotometer VARIAN AASpectra DUO 240FS (Varian, Ltd., Mulgrave, VIC, AUS). For the P determination, 1 ml of filtered sample was diluted with 8 ml of solution $\left((C_6H_8O_6, H_2SO_4\ (NH_4)_2MoO_4,\text{ and } C_4H_4KO_7Sb, 0 \times 5\ \ H_2O)\right)$ and deionized water to the volume of 50 ml, and measured against blank solution using a UV/ Visible Scanning Spectrophotometer Shimadzu UV-1800 (Shimadzu, Kyoto, Japan).

For analysis of microelements, 1 g of dried homogenised sample was mineralised in 5 mL of HNO_3 Suprapur® (Merck, Darmstadt, Germany) and 5 mL of deionised water (0.054 µS cm^{-1}), using a Mars Xpress 5 closed micro wave digestion system (CEM Corp., Matthews, NC, USA) at 160 °C for 15 minutes and maintaining it at constant temperature for 10 min. After digestion, samples were filtered through Filtrak 390 quantitative filter paper (Munktell, GmbH, Bärenstein, Germany) and filled to a volume of 50 mL with deionised water. The obtained filtrates were processed by Flame atomic absorption spectrophotometry (AAS) for Fe, Mn, Zn, Cu, Co, Ni, and Cr using a Varian AASpectra DUO 240FS system and a Graphite Furnace AAS method for Cd and Pb using a Varian AASpectra DUO 240Z system (Mulgrave, VIC, AUS).

Statistical analysis

Statistical analysis was performed using XLSTAT (Lumivero, 2025). Analysis of variance was conducted to find statistically significant information about differences among the tested samples ($p < 0.05$).

Results and Discussion

Total Polyphenol Content and Antioxidant Activity

The chemical composition of *Brassica* vegetables, including their mineral content and secondary metabolites, is influenced by a wide range of factors, such as cultivar, harvest period, storage conditions, processing and cooking methods, as well as agrochemical applications, biotic stresses, and environmental conditions (Sanlier and Guler Saban, 2018; Yue et al., 2024). According to Statilko et al. (2024), genetic background is the predominant determinant of phytochemical profiles in *Brassica* species. Among them, cabbage is recognized as an excellent source of polyphenolic compounds, which exhibit notable antioxidant properties linked to the mitigation of oxidative stress and the prevention of diseases associated with free radical damage (Abu-Ghannam and Jaiswal, 2015).

The total polyphenol content (TPC) and antioxidant activity (AA) were evaluated on both a fresh weight (FW) and dry matter (DM) basis for three cabbage samples. Sample 3 exhibited the highest TPC and AA values, with 502 ±14.7 mg GAE.kg^{-1} FW and 1.70 ±0.03 mmol TE.kg^{-1} FW, corresponding to 3,840 ±113 mg GAE.kg^{-1} DM and 13.0 ±0.24 mmol TE.kg^{-1} DM, respectively. These results were significantly higher ($p < 0.05$) than those of Sample 2, which had the lowest TPC and AA

Table 1 Total polyphenol content and antioxidant activity of the samples

Sample	TPC (mg GAE.kg^{-1} FW)	AA (mmol TE.kg^{-1} FW)	TPC (mg GAE.kg^{-1} DM)	AA (mmol TE.kg^{-1} DM)
A	445 ±8.88^{b}	1.40 ±0.04^{ab}	4,002 ±79.9^{b}	12.6 ±0.33^{ab}
B	422 ±12.6^{a}	0.94 ±0.01^{a}	3,588 ±107^{a}	8.01 ±0.07^{a}
C	502 ±14.7^{c}	1.70 ±0.03^{b}	3,840 ±113^{b}	13.0 ±0.24^{b}

Notes: Values marked with different letters are significantly different ($p < 0.05$)

values across both FW and DM bases. Sample 1 showed intermediate values but was statistically similar to Sample 3 in terms of TPC and AA on a DM basis. The trend indicates a strong positive relationship between polyphenol content and antioxidant activity, supporting the role of phenolic compounds as major contributors to the antioxidant capacity of cabbage. The phenolic profile and content, particularly flavonoids, are strongly associated with the antioxidant capacity of *Brassica* species, as phenolic compounds have demonstrated greater antioxidant activity than vitamins and carotenoids (Cartea et al., 2010). The antioxidant potential of flavonoids and phenolic acids is largely determined by their chemical structure, especially the number and position of hydroxyl groups. Consequently, antioxidant activity is influenced not only by the total phenolic content but also by the specific composition and structural characteristics of the individual phenolic compounds present.

Kapusta-Duch et al. (2012) reported comparable values for total polyphenol content (TPC). The TPC values obtained in our study are in agreement with those reported by Jakobek et al. (2018), who observed similar concentrations ranging from 467 to 598 mg GAE.kg^{-1}. Voca et al. (2018) presented comparable values for different cabbage varieties, with TPC ranging from 247.6 to 603.6 mg GAE.kg^{-1}. In contrast, Liang et al. (2019) reported higher TPC values in white cabbage, ranging from 866 to 1,255 mg GAE.kg^{-1}, while Podsedek et al. (2006) reported lower TPC values, ranging from 208.1 to 297.1 mg GAE.kg^{-1}.

Jakobek et al. (2018) reported comparable antioxidant activity values in cruciferous vegetables, ranging from 0.6 to 1.2 mmol TE.kg^{-1}, which are in line with the results obtained in our study. In contrast, the antioxidant activity of the cabbage varieties analyzed in our research was lower than that reported by Rokayya (2013). Multescu et al. (2021) reported an antioxidant activity value of 2.53 mmol TE.kg^{-1}. Similarly, Mariani et al. (2023) characterized cabbage as a vegetable with considerable antioxidant potential. The variability observed among studies may be attributed to several factors, including differences in growing conditions, postharvest handling, storage, and processing methods, all of which can significantly influence the antioxidant activity of *Brassica* vegetables.

Mineral Content

Cruciferous vegetables represent an important dietary source of essential mineral elements. These minerals play a critical role in supporting physiological functions and regulating various biochemical processes in the human body. The consumption of cruciferous vegetables can contribute significantly to the intake of key minerals, including potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) (Wang et al., 2022).

Analysis of mineral content revealed that potassium was the most abundant mineral in cabbage, with concentrations ranging from 18,291 to 21,064 mg.kg^{-1} dry matter (DM). In addition, cabbage was found to be a rich source of calcium (2,495–5,595 mg.kg^{-1} DM)

Table 2 Content of biogenic and risk elements in the samples

Sample	K	Ca	P	Na	Mg	Fe	Mn
A	20,678^{ab}	5,595^{b}	2,174^{ab}	594^{a}	557^{b}	28.7^{b}	12.6^{a}
SD	1,742	247	111	19	21	1.6	0.7
B	18,291^{a}	2,650^{ab}	2,036^{a}	734^{b}	410^{a}	24.5^{a}	15.1^{b}
SD	1,057	115	121	44	22	1.3	0.8
C	21,064^{b}	2,495^{a}	3,087^{b}	579^{b}	448^{a}	27.7^{ab}	19.1^{c}
SD	1,744	178	169	31	18	1.5	0.7
Sample	**Zn**	**Cu**	**Ni**	**Co**	**Cr**	**Pb**	**Cd**
A	12.5^{b}	1.7^{a}	0.7^{b}	0.5^{b}	0.2^{a}	1.5^{b}	0.5^{c}
SD	0.8	0.1	0.03	0.03	0.01	0.11	0.02
B	9.5^{a}	1.8^{a}	0.4^{a}	0.4^{a}	0.1^{a}	0.4^{a}	0.2^{a}
SD	0.5	0.08	0.02	0.02	0.01	0.03	0.01
C	11.3^{b}	1.6a	1.0^{c}	0.6^{c}	0.2^{a}	0.4^{a}	0.4^{b}
SD	0.6	0.08	0.06	0.04	0.01	0.02	0.02

Notes: Values marked with different letters are significantly different ($p < 0.05$)

and phosphorus (2,036–3,078 mg.kg^{-1} DM). Our findings are consistent with those of Godlewska et al. (2021), who reported similar concentrations of potassium (K), calcium (Ca), and phosphorus (P) in *Brassica oleracea* L. Due to the low content of oxalic and phytic acids (compounds known to chelate calcium) in *Brassica* vegetables, the bioavailability of calcium from these plants is considered high (Sanlier and Guler Saban, 2018). Cabbage is also acknowledged as a good source of potassium and calcium by Heghedűș-Mîndru (2025). Similarly, Moyo et al. (2018) identified cruciferous vegetables as rich in K, Ca, and P, and their reported values are comparable to those found in our study.

Among the analyzed microelements, iron was the most abundant, with concentrations ranging from 24.5 to 28.7 mg.kg^{-1} dry matter (DM), followed by manganese (12.6–19.1 mg.kg^{-1} DM), zinc (9.5–12.5 mg.kg^{-1} DM), and copper (1.6–1.8 mg.kg^{-1} DM). Trace levels of nickel, cobalt, and chromium were also detected, each at concentrations of 1.0 mg.kg^{-1} DM or lower. According to Yue et al. (2024), potassium is the most abundant macronutrient in cabbage, while iron (Fe) represents the most abundant micronutrient. In their study, K and Fe accounted for over 39% and 80% of total macronutrient and trace element content, respectively, in four cabbage varieties. Czech et al. (2012) also described relatively high levels of Zn, Mn, and Fe in cabbage. According to Leahu et al. (2018), the most abundant trace elements in cabbage include copper, iron, zinc, manganese, and selenium, although their reported Cu, Zn, Mn, and Fe concentrations were slightly higher than those measured in our samples. Wang et al. (2022) reported slightly higher concentrations of Fe (46.90 mg.kg^{-1} DM) and Cu (4.25 mg.kg^{-1} DM) in cabbage compared to our findings.

In addition to biogenic elements, the content of potentially toxic elements was also assessed. Lead (Pb) concentrations ranged from 0.4 to 1.5 mg.kg^{-1} dry matter (DM), corresponding to 0.05–0.17 mg.kg^{-1} fresh weight (FW), while cadmium (Cd) levels ranged from 0.2 to 0.5 mg.kg^{-1} DM (0.02–0.06 mg.kg^{-1} FW). Although some samples exceeded the maximum permissible levels set by the Commission Regulation (EU) 2023/915 for Pb (0.1 mg.kg^{-1} FW) and Cd (0.04 mg.kg^{-1} FW), these concentrations are unlikely to pose a significant health risk to consumers, since the average weekly intake of cabbage remains below the provisional tolerable weekly intake (PTWI) thresholds established for lead and cadmium.

The content of nutrients, mineral elements, and antioxidant compounds in *Brassica* vegetables is influenced by a range of factors, including environmental conditions, agronomic practices, stage of maturity, post-harvest storage, and cultivar (Rokayya et al., 2013). *Brassica oleracea* is particularly valued for its potential role in the prevention of cancer and cardiovascular diseases, attributed to its rich nutritional profile, including glucosinolates, polyphenolic compounds, and other bioactive constituents.

Conclusions

The present study highlights the nutritional and functional value of *Brassica oleracea* samples, particularly in terms of their mineral composition, total polyphenol content (TPC), and antioxidant activity. Among the macronutrients, potassium was the most abundant, followed by calcium and phosphorus, while iron, manganese, zinc, and copper dominated the microelement profile. Although trace levels of potentially toxic elements such as lead and cadmium were detected, the estimated exposure through average cabbage consumption does not pose a significant health risk, remaining below the provisional tolerable weekly intake (PTWI) thresholds. The results also revealed variability in TPC and antioxidant activity among the studied samples. Given its rich content of essential minerals and bioactive compounds, *Brassica oleracea* remains a valuable dietary component with potential health benefits, including antioxidant, anti-inflammatory, and possibly chemopreventive properties. Future research should further investigate bioavailability, varietal differences, and processing effects to optimize the nutritional quality and functional food applications of cruciferous vegetables.

Conflict of Interest

The authors have no conflicts of interest to declare.

Ethical Statement

This article doesn't contain any studies that require an ethical statement.

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