

Article

Mineral Profile of Beetroot Ferments Enriched with Parsley Leaves

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Abstract

Fermented vegetable beverages are increasingly considered functional foods, yet the effect of fermentation and plant-based fortification on their mineral profile remains insufficiently described. This study aimed to evaluate the mineral composition of beetroot ferments enriched with parsley leaves, considering the technological form of the additive and fermentation time. Beetroot ferments were prepared without parsley addition (control) and with chopped or blended parsley leaves, and analyzed after 24, 48, 72, and 96 h of fermentation. The concentrations of Ca, K, Mg, Na, Fe, Mn, Zn, and Cu were determined using microwave plasma atomic emission spectrometry (MP-AES) after microwave-assisted digestion, and their contribution to dietary reference values was calculated. The results showed that potassium was the dominant macroelement, with the highest content observed in the sample with chopped parsley after 72 h. Parsley addition increased the levels of selected minerals, particularly Ca, Mg, and Mn, while Fe showed variable changes depending on fermentation time and parsley leaf form. Zinc showed the greatest variability during fermentation, while copper remained at relatively low levels. The findings indicate that parsley leaves can improve the mineral profile of beetroot ferments, and that fermentation time and additive fragmentation are important factors shaping their nutritional value.

Keywords: beetroot fermentation; parsley leaves; mineral profile; fermented vegetable beverages; macroelements; microelements

1. Introduction

The contemporary demand for functional foods and specific health-promoting methods is influencing the development of research on fermented plant products. Vegetable fermentation is one method of food preservation that can simultaneously enrich the product with bioactive substances, increase their bioavailability, enhance the sensory properties, and increase the shelf life of items like fruit and vegetables [1,2]. The procedure is based on anaerobic fermentation, in which suitable *Lactobacteriaceae* bacteria transform simple carbohydrates into lactic acid [3,4]. Particular importance is attached to fermented vegetable juices, which are increasingly perceived not only as traditional food products but also as an element of a health-promoting diet [5]. Despite their potent taste, consumers appreciate fermented vegetable juices because of their high nutritional content and the presence of polyphenols, flavonoids, antioxidants, and minerals [5].

Beetroot (*Beta vulgaris* L.), belonging to the family Amaranthaceae and the genus *Beta*, is a valuable plant material, rich in betalains, polyphenols, fibre, and minerals such as



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potassium, magnesium, calcium, and iron [6–8]. Due to its nutritional value and antioxidant properties, beets are widely used in food production, including the production of functional foods [9–11]. Beetroot fermentation can further enhance the biological value of the product through metabolic changes occurring under the influence of microorganisms available on the ingredients and the availability of minerals [12–14].

Studies show that beetroot fermentation liberates bound phenolic compounds from cell wall matrices through microbial enzymatic activity [15–17]. Due to this, the amount of phenolic compounds in the fermented beetroot juice increases, and new bioactive metabolites are formed [18–20]. However, too long a process can reduce the presence of bioactive compounds in fermented juice [21]. Most studies show a large increase in antioxidant capacity after fermentation despite variable changes in phenolics or betalains [14,15]. Also, the fermentation process leads to an increase in cytotoxic activity against human liver cancer [22].

Due to changes that occur during fermentation, fermented beetroot juice has been shown to have strong antioxidant, anti-inflammatory, anticancer, antibacterial, antidepressant, antihypertensive, hepatoprotective, hypocholesterolemic, immunomodulatory, and probiotic qualities [23–26].

Many studies show that during vegetable fermentation, minerals migrate from plant tissue into the surrounding brine, increasing mineral concentration in the liquid phase [27–29]. The increase in mineral content may be due to the decomposition of complex polyphenol-mineral due to fermentation, releasing polyphenols and minerals. Therefore, the fermented beetroot juice can be a source of not only polyphenols but also minerals such as magnesium, potassium, iron, and so on.

In the literature, there are many studies on the impact of lactic acid fermentation on the content of bioactive substances in beetroot juice. However, there is a lack of research on the effect of fermentation on the content of micro and macronutrients in beetroot juice.

Recently, increasing attention is being paid to the possibility of enriching fermented products with plant-based ingredients, which can enhance their nutritional value [30,31]. One of them is parsley (*Petroselinum crispum* (Mill.) Fuss), belonging to the family Apiaceae and the genus *Petroselinum*, which is a source of vitamins, antioxidants, and minerals, primarily iron, magnesium, and potassium [32–35]. However, in the literature, there are no studies on the effect of adding parsley on the content of micro and macroelements in fermented beetroot juice. Therefore, parsley addition may represent a promising approach to modifying the mineral profile and nutritional potential of beetroot ferments. In this context, parsley leaves were selected as a plant-based ingredient with a potentially valuable mineral profile. The comparison of chopped and blended parsley leaves was included to determine whether the degree of comminution affects mineral transfer and the final mineral profile of beetroot ferments.

The mineral composition of fermented vegetable products is an important determinant of their nutritional value, as macro- and microelements play a key role in numerous physiological and metabolic processes in the human body, including electrolyte balance, enzyme activity, and the proper functioning of biological systems [36]. Therefore, the assessment of mineral content may provide valuable insights into the nutritional potential of fermented beetroot-based beverages enriched with plant-derived additives and their possible application in everyday diets.

The aim of this study was to analyze the mineral profile of beetroot ferments enriched with parsley leaves, taking into account the influence of parsley leaf comminution form and fermentation time. The study included the determination of selected macro- and microelements and the calculation of their contribution to dietary reference values (PRI/AI).

2. Materials and Methods

2.1. Materials

The experimental material consisted of laboratory-produced beetroot ferments prepared from beetroot (*Beta vulgaris* L., cv. Zeppo) obtained from a farm located in the Wielkopolska region (Poland). Fresh parsley leaves (*Petroselinum crispum*) and traditional rye sourdough bread were used as additional ingredients. Prior to processing, the beetroots were washed, peeled, and cut into cubes of approximately 1 cm. Parsley leaves were washed and incorporated into the formulations in two technological forms: chopped and blended. In this study, “chopped parsley” refers to parsley leaves mechanically cut into visible fragments, whereas “blended parsley” refers to parsley leaves subjected to more intensive mechanical comminution using a blender to obtain a finer and more homogeneous plant material.

Three fermentation variants were prepared: a control beetroot ferment without parsley addition (C), a beetroot ferment with chopped parsley leaves (PCH), and a beetroot ferment with blended parsley leaves (PBL). The control formulation consisted of approximately 50 g of beetroot, 85 mL of boiled water, and 5 g of rye sourdough bread. The parsley-enriched variants were prepared using approximately 50 g of beetroot, 20 g of fresh parsley leaves, 85 mL of boiled water, and 5 g of rye sourdough bread.

The ferments were prepared in glass jars previously scalded with boiling water and dried. The ingredients were weighed into the jars according to the formulation, and boiled water at 35 °C was added. Rye sourdough bread was used as a natural source of lactic acid bacteria to support the fermentation process. The jars were covered with aluminum foil to limit light exposure and left to ferment in a dark place at room temperature for 24, 48, 72, or 96 h. After each fermentation period, the liquid fraction of each beetroot ferment was collected and subjected to mineral composition analysis. A total of 12 samples differing in the degree of parsley leaf fragmentation and fermentation time were prepared and analyzed.

2.2. Methods

The concentrations of selected macro- and microelements, including calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu), were determined using microwave plasma atomic emission spectrometry (MP-AES), according to the approach described by Rybicka and Gliszczynska-Świąto [37], with modifications.

Prior to analysis, the liquid fraction of each beetroot ferment was collected and homogenized. Approximately 0.5 g of the homogenized liquid sample was subjected to wet mineralization with 10 mL of 65% nitric acid (HNO₃) using a MARS 6 microwave digestion system (CEM, Matthews, NC, USA). The mineralization process was conducted at 210 °C for 15 min, followed by a 15 min holding time. The microwave power ranged from 900 to 1080 W, and the maximum pressure was 800 psi. After digestion, the samples were cooled, quantitatively transferred to 50 mL volumetric flasks, and diluted to volume with distilled water. Calibration curves were prepared using nine standard solutions, with concentration ranges adjusted to the expected levels of individual minerals in the analyzed samples. Spectroscopic measurements were performed at the following wavelengths: Zn, 213.9 nm; Cu, 324.8 nm; Na, 330.2 nm; Mg, 383.8 nm; Fe, 371.9 nm; Mn, 403.1 nm; K, 404.4 nm; and Ca, 616.2 nm. All analyses were performed in triplicate. The obtained results were expressed as mg/100 g fresh matter.

The percentage contribution of 100 g of the liquid fraction of beetroot ferments to the daily reference intake of selected macro- and microelements was calculated based on the

determined mineral content and the Population Reference Intake (PRI) or Adequate Intake (AI) values established for adults.

All analyses were performed in triplicate, and the results are expressed as mean $\pm$ standard deviation. Statistical analyses were performed using Statistica 13.3 software. Statistical analysis was performed separately for each mineral. One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was used to assess significant differences between sample variants at the same fermentation time and between fermentation times within the same sample variant. Different uppercase letters indicate significant differences between sample variants within the same fermentation time, whereas different lowercase letters indicate significant differences between fermentation times within the same sample variant. In addition, two-way ANOVA was applied to evaluate the main effects of parsley addition form, fermentation time, and their interaction on the mineral composition of beetroot ferments. Effect size was expressed as partial eta squared. Differences were considered statistically significant at $p < 0.05$.

3. Results

Table 1 presents the content of macroelements (Ca, K, Mg and Na) in beetroot sourdoughs without additive and with the addition of chopped and blended parsley leaves, depending on fermentation time. The results indicate that parsley addition and the degree of parsley leaf comminution affected the mineral profile of most analyzed macroelements, although the magnitude and significance of these effects depended on the element.

Table 1. Content of macroelements in beetroot sourdoughs without and with the addition of parsley leaves, depending on fermentation time and the form of their comminution.

Macroelement (mg/100 g f.m.)	Sample	Fermentation Time (h)			
		24	48	72	96
Ca	C	6.89 $\pm$ 1.09 ^{Ba}	4.46 $\pm$ 1.92 ^{Ba}	3.10 $\pm$ 0.26 ^{Bb}	1.95 $\pm$ 1.33 ^{Cb}
	PCH	13.09 $\pm$ 0.05 ^{Aa}	17.32 $\pm$ 1.65 ^{Aa}	18.15 $\pm$ 1.59 ^{Aa}	19.37 $\pm$ 4.47 ^{Aa}
	PBL	9.22 $\pm$ 0.27 ^{Aa}	10.20 $\pm$ 5.50 ^{Bb}	18.32 $\pm$ 2.33 ^{Aa}	20.19 $\pm$ 5.50 ^{Bb}
K	C	35.17 $\pm$ 2.25 ^{Cd}	99.59 $\pm$ 1.46 ^{Cc}	156.04 $\pm$ 1.76 ^{Cb}	188.42 $\pm$ 1.8 ^{Ba}
	PCH	73.96 $\pm$ 0.64 ^{Bd}	165.30 $\pm$ 1.95 ^{Ac}	221.85 $\pm$ 4.17 ^{Aa}	204.83 $\pm$ 4.5 ^{Ab}
	PBL	111.53 $\pm$ 5.03 ^{Ac}	149.48 $\pm$ 0.82 ^{Bb}	196.51 $\pm$ 1.74 ^{Ba}	202.65 $\pm$ 1.95 ^{Aa}
Mg	C	4.76 $\pm$ 0.01 ^{Cd}	6.87 $\pm$ 0.04 ^{Cc}	7.34 $\pm$ 0.15 ^{Cb}	10.05 $\pm$ 0.12 ^{Ba}
	PCH	5.27 $\pm$ 0.01 ^{Bd}	9.45 $\pm$ 0.13 ^{Ac}	11.16 $\pm$ 0.07 ^{Ab}	11.61 $\pm$ 0.06 ^{Aa}
	PBL	7.04 $\pm$ 0.32 ^{Ac}	7.18 $\pm$ 1.92 ^{Bc}	8.98 $\pm$ 0.13 ^{Bb}	12.20 $\pm$ 0.01 ^{Ba}
Na	C	12.86 $\pm$ 1.24 ^{Ac}	23.01 $\pm$ 2.17 ^{Ab}	38.64 $\pm$ 3.32 ^{Ab}	61.55 $\pm$ 3.66 ^{Aa}
	PCH	12.47 $\pm$ 1.92 ^{Ac}	20.66 $\pm$ 2.13 ^{Ac}	35.76 $\pm$ 3.14 ^{Ab}	61.92 $\pm$ 0.22 ^{Aa}
	PBL	16.57 $\pm$ 5.44 ^{Ab}	29.04 $\pm$ 2.05 ^{Ab}	46.71 $\pm$ 2.71 ^{Aa}	66.11 $\pm$ 1.56 ^{Aa}

Mean values followed by different uppercase letters within the same column and element are significantly different between sample variants at $p < 0.05$. Mean values followed by different lowercase letters within the same row are significantly different between fermentation times at $p < 0.05$. f.m.—fresh matter; C—control beetroot ferment without parsley addition; PCH—beetroot ferment with chopped parsley leaves; PBL—beetroot ferment with blended parsley leaves.

In the case of calcium (Ca), parsley addition increased the content of this element compared with the control sample. The control variant showed a gradual decrease in Ca content during fermentation, whereas the PCH variant exhibited a systematic increase from 13.09 mg/100 g after 24 h to 19.37 mg/100 g after 96 h. The PBL variant also showed

higher Ca levels than the control, particularly after 72 and 96 h of fermentation. These results indicate that parsley enrichment improved the calcium profile of beetroot ferments, although the effect depended on both the form of parsley leaves and fermentation time.

Potassium (K), which was the dominant macroelement in all samples, generally increased with fermentation time, although the pattern differed depending on the formulation variant. In the control sample and in the variant with blended parsley leaves (PBL), the highest K content was recorded after 96 h of fermentation, reaching 188.42 and 202.65 mg/100 g, respectively. In contrast, in the variant with chopped parsley leaves (PCH), the maximum potassium concentration was observed after 72 h of fermentation (221.85 mg/100 g), followed by a slight decrease after 96 h. The addition of parsley leaves, particularly in chopped form, was associated with higher potassium content compared with the control, indicating that parsley enrichment may improve the mineral profile of beetroot ferments.

A similar tendency was observed for magnesium (Mg). Magnesium content increased during fermentation in all variants, although the magnitude of changes depended on the formulation. Parsley-enriched samples generally contained more Mg than the control, and the highest value was recorded in the PBL variant after 96 h of fermentation (12.2 mg/100 g). This may suggest that greater comminution of parsley leaves was associated with a higher Mg content in the fermented product.

Sodium (Na) content increased during fermentation in all analyzed samples, with the highest values recorded after 96 h. At this stage, Na content reached 61.55 mg/100 g in the control sample, 61.92 mg/100 g in the PCH variant, and 66.11 mg/100 g in the PBL variant. Although the numerically highest value was observed in the PBL sample, differences between formulation variants were not statistically significant. This indicates that fermentation time was the main factor affecting Na content, whereas parsley addition had no significant effect.

Figure 1 complements the numerical data presented in Table 1 by illustrating changes in macroelement contents depending on sample variant and fermentation time.

Table 2 presents the content of microelements (Fe, Mn, Zn and Cu) in beetroot sourdoughs without additive and enriched with chopped and blended parsley leaves, analyzed at successive stages of fermentation. The results indicate that fermentation time and parsley addition affected the levels of individual microelements; however, the direction and statistical significance of these changes varied depending on the element.

In the case of iron (Fe), the highest numerical content was recorded in the sourdough with blended parsley leaves (PBL) after 72 h of fermentation (0.69 mg/100 g). However, differences between sample variants at individual fermentation times were not statistically significant; therefore, the effect of parsley addition on Fe content should be interpreted with caution. In the control sample, Fe content decreased during fermentation, from 0.50 mg/100 g after 24 h to 0.32 mg/100 g after 96 h. In parsley-enriched samples, Fe levels showed greater variability, with temporary increases observed at selected fermentation stages, particularly after 72 h. These results suggest that fermentation time and parsley leaf form may influence Fe content, although this relationship requires further confirmation.

Manganese (Mn) content remained relatively stable in all variants, with slightly higher values observed in the samples enriched with parsley leaves. The highest Mn concentrations were obtained after 72 h of fermentation in both the PCH and PBL samples (0.15 mg/100 g). The addition of parsley leaves, regardless of their form, favoured the maintenance of a higher level of this element compared with the control, although the differences were moderate.

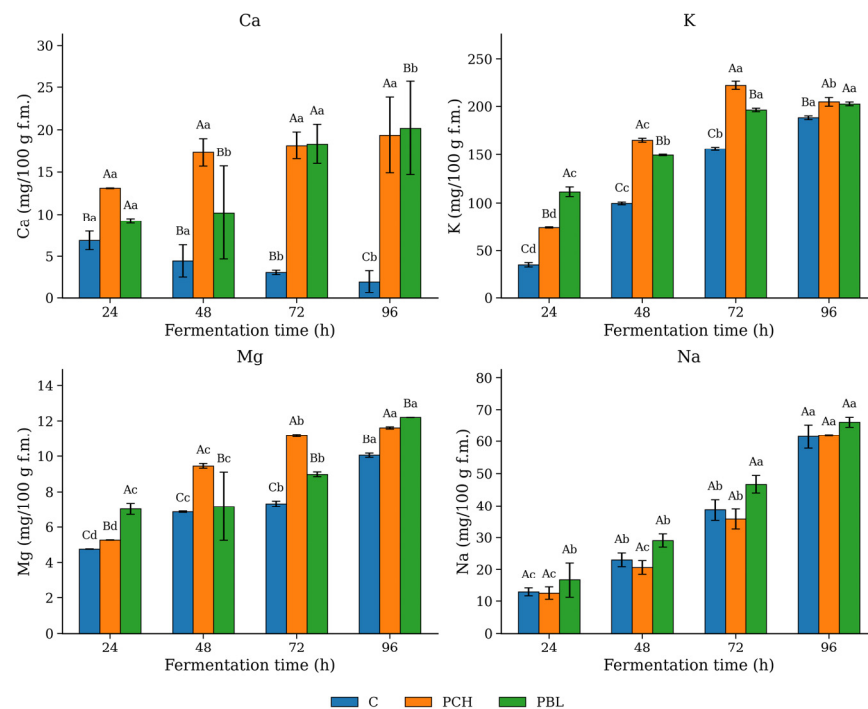


Figure 1. Changes in macroelement contents in beetroot ferments depending on parsley form and fermentation time. Values are presented as mean $\pm$ standard deviation. Different uppercase letters indicate significant differences between sample variants at the same fermentation time and element, whereas different lowercase letters indicate significant differences between fermentation times within the same sample variant and element; $p < 0.05$. C—control beetroot ferment without parsley addition; PCH—beetroot ferment with chopped parsley leaves; PBL—beetroot ferment with blended parsley leaves; f.m.—fresh matter.

Table 2. Content of microelements in beetroot sourdoughs without and with the addition of parsley leaves, depending on fermentation time and the form of their comminution.

Microelement (mg/100 g f.m.)	Sample	Fermentation Time (h)			
		24	48	72	96
Fe	C	0.50 $\pm$ 0.07 Aa	0.49 $\pm$ 0.07 Aa	0.39 $\pm$ 0.05 Aa	0.32 $\pm$ 0.05 Ab
	PCH	0.40 $\pm$ 0.01 Aa	0.48 $\pm$ 0.03 Aa	0.53 $\pm$ 0.20 Aa	0.24 $\pm$ 0.02 Aa
	PBL	0.60 $\pm$ 0.09 Aa	0.48 $\pm$ 0.03 Ab	0.69 $\pm$ 0.09 Aa	0.33 $\pm$ 0.05 Ab
Mn	C	0.10 $\pm$ 0.01 Cb	0.10 $\pm$ 0.03 Ab	0.07 $\pm$ 0.01 Bc	0.13 $\pm$ 0.03 Aa
	PCH	0.12 $\pm$ 0.01 Bb	0.11 $\pm$ 0.01 Ab	0.15 $\pm$ 0.04 Aa	0.12 $\pm$ 0.01 Ab
	PBL	0.14 $\pm$ 0.02 Ab	0.12 $\pm$ 0.02 Ac	0.15 $\pm$ 0.01 Aa	0.12 $\pm$ 0.01 Ac
Zn	C	1.77 $\pm$ 0.08 Cb	2.43 $\pm$ 0.07 Aa	0.12 $\pm$ 0.05 Bd	0.35 $\pm$ 0.03 Bc
	PCH	2.26 $\pm$ 0.11 Ba	0.57 $\pm$ 0.19 Bb	0.37 $\pm$ 0.05 Ac	0.41 $\pm$ 0.04 Ac
	PBL	2.70 $\pm$ 0.05 Aa	0.09 $\pm$ 0.02 Cc	0.41 $\pm$ 0.06 Ab	0.47 $\pm$ 0.02 Ab
Cu	C	0.06 $\pm$ 0.01 Bb	0.06 $\pm$ 0.01 Bb	0.08 $\pm$ 0.01 Aa	0.03 $\pm$ 0.01 Ac
	PCH	0.06 $\pm$ 0.01 Bc	0.10 $\pm$ 0.01 Aa	0.08 $\pm$ 0.01 Ab	0.02 $\pm$ 0.01 Bd
	PBL	0.11 $\pm$ 0.01 Aa	0.06 $\pm$ 0.02 Bb	0.08 $\pm$ 0.01 Ab	0.03 $\pm$ 0.01 Ac

Mean values followed by different uppercase letters within the same column and element are significantly different between sample variants at $p < 0.05$. Mean values followed by different lowercase letters within the same row are significantly different between fermentation times at $p < 0.05$. f.m.—fresh matter; C—control beetroot ferment without parsley addition; PCH—beetroot ferment with chopped parsley leaves; PBL—beetroot ferment with blended parsley leaves.

In the case of zinc (Zn), the greatest variability in content was observed during fermentation. The highest numerical value was recorded in the PBL sample after 24 h (2.70 mg/100 g), while in the control sample the maximum Zn content was observed after 48 h (2.43 mg/100 g). In parsley-enriched variants, Zn concentration decreased markedly after the initial fermentation stage, whereas in the control sample a sharp decrease was observed after 48 h. At the later stages of fermentation, Zn levels remained relatively low in all samples. These results indicate that Zn content was strongly affected by fermentation time, although the direction of changes depended on the formulation variant.

Copper (Cu) was present in relatively low amounts in all analyzed samples. The highest numerical value was recorded in the PBL sample after 24 h of fermentation (0.11 mg/100 g), while a relatively high Cu content was also observed in the PCH sample after 48 h (0.10 mg/100 g). In the later stages of fermentation, Cu levels were generally low and decreased after 96 h in all variants. Although some differences between samples were observed, the absolute Cu concentrations remained low, suggesting that beetroot ferments should not be considered a major source of this element.

Figure 2 complements the numerical data presented in Table 2 by illustrating changes in microelement contents depending on sample variant and fermentation time.

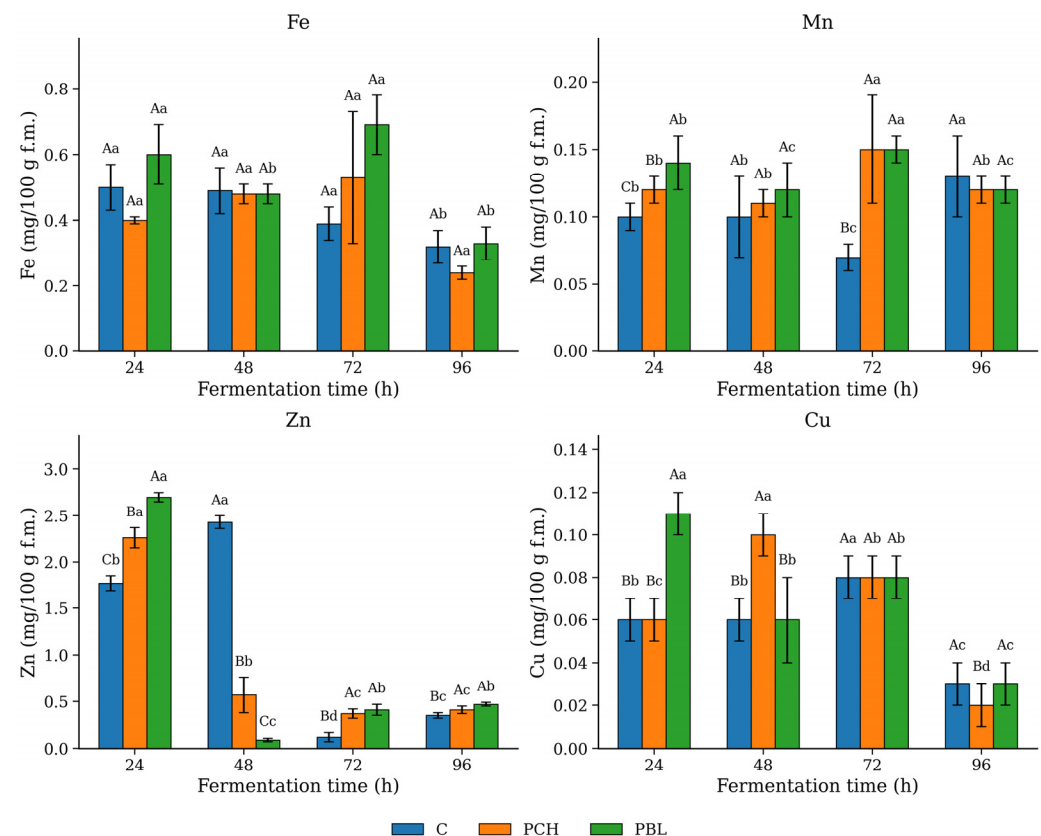


Figure 2. Changes in microelement contents in beetroot ferments depending on parsley form and fermentation time. Values are presented as mean $\pm$ standard deviation. Different uppercase letters indicate significant differences between sample variants within the same fermentation time and element at $p < 0.05$. Different lowercase letters indicate significant differences between fermentation times within the same sample variant and element at $p < 0.05$. C—control beetroot ferment without parsley addition; PCH—beetroot ferment with chopped parsley leaves; PBL—beetroot ferment with blended parsley leaves; f.m.—fresh matter.

The main and interaction effects of parsley addition form and fermentation time on the mineral composition of beetroot ferments are shown in Table 3. The results showed that the two-way interaction between parsley addition form and fermentation time had a

significant effect on most of the analyzed minerals, including Ca ($p < 0.001$), K ($p < 0.001$), Mg ($p < 0.001$), Fe ($p = 0.033$), Mn ($p < 0.001$), Zn ($p < 0.001$), and Cu ($p < 0.001$). In contrast, Na content was affected only by fermentation time ($p < 0.001$), while parsley addition form and the interaction between factors were not significant ($p > 0.05$). Among the significant effects, fermentation time exerted a stronger influence on Na, Fe, Zn, and Cu contents, whereas parsley addition form had a greater impact on Ca and Mn concentrations. For K and Mg, both factors showed comparably strong effects, as indicated by the high partial eta square values.

Table 3. Main and interactive effects of parsley addition form and fermentation time on the mineral composition of beetroot ferments.

	Variables	Parsley Addition Form	Fermentation Time	Parsley Addition Form × Fermentation Time
Ca	<i>p</i> -value	<0.001	0.021	<0.001
	Partial eta square	0.893	0.327	0.706
K	<i>p</i> -value	<0.001	<0.001	<0.001
	Partial eta square	0.990	0.998	0.971
Mg	<i>p</i> -value	<0.001	<0.001	<0.001
	Partial eta square	0.986	0.997	0.981
Na	<i>p</i> -value	0.333	<0.001	0.848
	Partial eta square	0.088	0.872	0.098
Fe	<i>p</i> -value	0.005	<0.001	0.033
	Partial eta square	0.357	0.662	0.412
Mn	<i>p</i> -value	<0.001	0.001	<0.001
	Partial eta square	0.885	0.468	0.888
Zn	<i>p</i> -value	<0.001	<0.001	<0.001
	Partial eta square	0.855	0.996	0.991
Cu	<i>p</i> -value	<0.001	<0.001	<0.001
	Partial eta square	0.508	0.910	0.869

Values indicate the results of two-way ANOVA. Effects were considered significant at $p < 0.05$. Partial eta square indicates the effect size. Interaction: parsley addition form × fermentation time.

Table 4 presents the contribution of macro- and microelements to meeting the daily reference intake requirements (PRI/AI) in 100 g of the liquid fraction of the analyzed beetroot ferments, taking into account parsley leaf addition, its technological form, and fermentation time. The results indicate that the liquid fraction of the investigated ferments may constitute a varied source of selected minerals, and that its mineral profile was determined by both the formulation variant and the duration of fermentation.

Among the macroelements, potassium (K) showed the greatest contribution to meeting nutritional reference values. Its contribution generally increased during fermentation, although the maximum value depended on the formulation variant. The highest level was recorded in the sourdough with chopped parsley leaves (PCH) after 72 h of fermentation, where 100 g of the product covered 6.34% of the AI for this element.

In the case of calcium (Ca) and magnesium (Mg), the addition of parsley leaves increased the contribution to nutritional reference values compared with the control sample. The highest contribution of calcium was found in the PBL sample after 96 h of fermentation (2.02% PRI), while for magnesium, the highest value was also recorded in PBL after 96 h

(3.87% PRI). These results indicate that parsley enrichment, particularly in blended form, may improve the mineral profile of beetroot ferments in terms of selected macroelements.

Table 4. Percentage contribution of 100 g of the liquid fraction of beetroot ferments to the daily reference intake (PRI/AI) of selected macro- and microelements, depending on fermentation time and parsley leaf comminution method.

Element	PRI/AI (mg/day)	Sample	Fermentation Time (h)			
			24	48	72	96
Ca	1000	C	0.69	0.45	0.31	0.19
		PCH	1.31	1.73	1.81	1.94
		PBL	0.92	1.02	1.83	2.02
K	3500	C	1.00	2.85	4.46	5.38
		PCH	2.11	4.72	6.34	5.85
		PBL	3.19	4.27	5.61	5.79
Mg	315	C	1.51	2.18	2.33	3.19
		PCH	1.67	3.00	3.54	3.69
		PBL	2.23	2.28	2.85	3.87
Na	1500	C	0.86	1.53	2.58	4.10
		PCH	0.83	1.38	2.38	4.13
		PBL	1.10	1.94	3.11	4.41
Fe	18	C	2.78	2.72	2.17	1.78
		PCH	2.22	2.67	2.94	1.33
		PBL	3.33	2.67	3.83	1.83
Mn	1.8	C	5.56	5.56	3.89	7.22
		PCH	6.67	6.11	8.33	6.67
		PBL	7.78	6.67	8.33	6.67
Zn	8	C	22.13	30.38	1.50	4.38
		PCH	28.25	7.13	4.63	5.13
		PBL	33.75	1.13	5.13	5.88
Cu	0.9	C	6.67	6.67	8.89	3.33
		PCH	6.67	11.11	8.89	2.22
		PBL	12.22	6.67	8.89	3.33

Sodium (Na) contribution increased gradually during fermentation, reaching the highest values after 96 h. The highest value was recorded in the PBL sample (4.41% AI), although differences between formulation variants were small. Despite this increase, the contribution of sodium to the AI remained moderate.

The analysis of microelements showed that zinc (Zn), manganese (Mn), and copper (Cu) made the greatest contribution to meeting nutritional reference values. Particularly high values were recorded for Zn in the initial stages of fermentation, especially in the sample with blended parsley leaves (33.75% PRI after 24 h). However, at later stages of fermentation, a marked decrease in the contribution of this element was observed in parsley-enriched variants, while in the control sample the highest value was recorded after 48 h. These results indicate that Zn contribution was strongly dependent on fermentation time and formulation variant.

Manganese was characterized by a relatively stable profile in all variants, with sourdoughs enriched with parsley leaves generally showing more favourable values than the control. The highest level of AI fulfilment for Mn was achieved after 72 h of fermentation in both parsley-enriched variants (8.33%), indicating that parsley leaf addition may increase the contribution of beetroot ferments to manganese intake.

Copper concentrations in the analyzed beetroot ferments were relatively low, ranging from 0.02 to 0.11 mg/100 g f.m. Consequently, the contribution to the daily reference intake (PRI) varied between 2.22% and 12.22%. Although the highest percentage values were observed in selected samples, the absolute differences in Cu content between most fermentation variants were small. Therefore, the nutritional significance of beetroot ferments as a source of copper should be interpreted with caution. The relatively high percentage contribution to PRI results primarily from the low dietary requirement for this element rather than from its high concentration in the product.

In summary, beetroot ferments, particularly those enriched with parsley leaves, showed a favourable mineral profile and may be considered a potential dietary source of selected macro- and microelements. The form of the additive and fermentation time played a key role in shaping the mineral composition of the product, with favourable effects generally observed for parsley-enriched variants and longer fermentation times.

4. Discussion

Although the effects of lactic acid fermentation on the bioactive composition of beetroot have been extensively described in the literature [3–5,14–16], previous studies have focused predominantly on changes in polyphenols, betalains, and antioxidant activity. In contrast, limited attention has been paid to the mineral composition of beetroot ferments, particularly those enriched with plant-based additives such as parsley leaves. In this context, the present results provide additional insight into the changes in macro- and microelement profiles during beetroot fermentation and show that both parsley addition and fermentation time may influence the nutritional value of the final product.

Most earlier investigations merely indicate the potential migration of minerals into the liquid phase during fermentation [27–29], without providing detailed quantitative data or considering the effect of fermentation time. The present study demonstrates dynamic, element-specific changes in both macro- and microelement concentrations across successive fermentation stages (24–96 h), enabling more precise identification of the fermentation time required to obtain the most favourable mineral profile.

Parsley has been described in the literature as a rich source of minerals, particularly calcium, iron, magnesium, and potassium [9,10]. However, its use as a fortifying ingredient in fermented beetroot products has not previously been investigated. The present results indicate that parsley addition not only increases the absolute content of selected minerals but also modifies their stability throughout fermentation, an effect that was especially pronounced for calcium and iron. To the best of our knowledge, such behaviour has not been previously reported. Moreover, there is a lack of comparative analyses of the impact of plant additive particle size on the mineral profile of fermented products. The results indicate that the technological form of parsley leaves (chopped vs. blended) affected the mineral content patterns of beetroot ferments. Chopped parsley was associated with a gradual increase in calcium content, whereas the blended form was associated with higher magnesium content and numerically higher iron values at selected fermentation stages. The blending and chopping process increases the degree of damage to plant tissues and the contact surface of parsley particles with the fermenting liquid matrix, which may facilitate the release and transfer of mineral ions into the liquid phase. Therefore, the observed differences between the chopped and blended parsley variants may result from both the

mineral composition of the parsley and the greater availability of minerals released from the more finely divided plant tissues during fermentation. To the best of our knowledge, the effect of parsley leaf comminution form on the mineral profile of beetroot ferments has not been previously described.

The literature generally suggests that fermentation enhances mineral bioavailability through the reduction in antinutritional factors, including the degradation of mineral complexes [12]. However, the present study shows that not all microelements respond uniformly to fermentation. In particular, zinc exhibited a marked decrease in concentration with prolonged fermentation time, contradicting the commonly assumed beneficial effect of fermentation on mineral availability. The marked changes in Zn content during fermentation may be associated with interactions between zinc and components of the fermentation matrix. However, this mechanism requires further investigation, including mineral bioaccessibility analysis. Microbial activity may also contribute to changes in mineral release, solubility, and distribution during fermentation. The production of organic acids, progressive acidification of the matrix, and microbial metabolism may affect the interactions between minerals and plant tissue components. However, microbial composition was not analyzed in the present study; therefore, the observed changes in mineral contents cannot be directly attributed to specific microbial taxa. Future studies should combine mineral profiling with microbiological analysis to better explain the relationship between microbial community shifts and mineral changes in beetroot ferments enriched with parsley leaves.

Previous studies on fermented beetroot juices rarely relate mineral composition to practical dietary reference values [11]. In the present work, fermented beetroot sourdoughs—especially those enriched with parsley—were shown to contribute meaningfully to the dietary intake of potassium, magnesium, manganese, and zinc. This approach enables a direct assessment of the functional and nutritional relevance of the product, representing an important applied value of the study.

Although parsley addition may also influence the flavour, aroma, and mouthfeel of beetroot ferments, sensory evaluation was not included in the present study. Therefore, future research should combine mineral profiling with sensory evaluation to determine whether parsley enrichment affects not only the nutritional value but also the sensory quality of beetroot ferments. Furthermore, fermentation time is often treated as a fixed parameter in the literature [14,15]. In contrast, the present results indicate that the most favourable mineral profile is typically achieved after 72–96 h of fermentation, while excessive prolongation may result in a decline in certain microelements. This highlights the need to balance fermentation intensity with mineral stability when optimizing fermented plant-based products. Although unfermented samples (0 h) were not the target product of this study, their inclusion in future research could provide an additional baseline for distinguishing changes related to the initial raw matrix from those occurring during fermentation.

5. Conclusions

The enrichment of beetroot ferments with parsley leaves represents a potential approach to modifying their mineral profile and improving their nutritional value. In the present work, this strategy was applied to determine whether parsley addition, its technological form, and fermentation time affect the content of selected macro- and microelements in beetroot ferments. The results show that both parsley enrichment and fermentation time influenced the mineral composition of the analyzed products.

Potassium was the dominant macroelement in all samples, and its content generally increased during fermentation, although the maximum value depended on the formulation variant. The addition of parsley leaves particularly affected the levels of calcium,

magnesium, iron, and manganese. The addition of chopped parsley leaves was associated with a gradual increase in calcium content and with the highest potassium content after 72 h of fermentation. Magnesium content generally increased during fermentation, with the highest value observed in the chopped parsley variant after 96 h. In contrast, the highest iron content was recorded in the sample with blended parsley leaves after 72 h of fermentation. Among microelements, zinc showed the greatest variability regardless of the parsley leaf processing method, with higher values recorded in the early stages of fermentation, followed by a marked decrease during prolonged fermentation.

The obtained results indicate that fermentation for 72–96 h may be favourable for shaping the mineral profile of parsley-enriched beetroot ferments. However, the most favourable fermentation time depended on the mineral considered. These findings may support the selection of fermentation parameters and parsley processing methods for the development of functional fermented vegetable beverages with improved nutritional value. In future research, it would be advisable to evaluate the sensory quality, consumer acceptability, and mineral bioaccessibility of the developed products.

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