



**IN VITRO MINERAL BIOACCESSIBILITY AND CONTRIBUTION TO DIETARY MINERAL
INTAKE OF COMMERCIALY AVAILABLE BREAD TYPES IN TÜRKİYE**

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ABSTRACT

This study evaluated the mineral composition, in vitro mineral bioaccessibility and estimated contribution to dietary mineral intake of commonly consumed breads in Türkiye. Five bread types (white wheat, whole wheat, sourdough wheat, buckwheat and einkorn) were purchased from five independent commercial brands. Moisture, ash and protein were determined by standard methods, while K, Mg, Ca, Na, Fe, Mn and Zn were quantified by ICP-OES after microwave digestion. A modified static INFOGEST protocol was applied to assess in vitro gastrointestinal digestion and mineral bioaccessibility. Buckwheat and einkorn breads showed the highest Mg, Fe, Mn and Zn contents, whereas white wheat bread contained the highest Na. Sourdough bread exhibited the greatest bioaccessibility for Fe, Mn and Zn. Based on EFSA reference values, a 250 g portion of bread provided approximately 14-17% of the adequate intake for K, but $\leq 2\%$ of Ca and limited Zn, while sourdough and buckwheat breads substantially improved bioaccessible Fe and Mn supply.

Keywords: Bread, mineral composition, in vitro digestion, mineral bioaccessibility, INFOGEST

**TÜRKİYE'DE YAYGIN OLARAK TÜKETİLEN EKMEK ÇEŞİTLERİNİN İN VİTRO MİNERAL
BİYOERİŞİLEBİLİRLİĞİ VE DİYET MİNERAL ALIMINA KATKISI**

ÖZ

Bu çalışma, Türkiye'de yaygın olarak tüketilen ekmeklerin mineral kompozisyonu, in vitro mineral biyoerişilebilirliği ve önerilen günlük almaya katkısını değerlendirmeyi amaçlamıştır. Beyaz buğday, tam buğday, ekşi mayalı buğday, karabuğday ve siyez ekmekleri, her biri beş farklı ticari üreticiden temin edilmiştir. Nem, kül ve protein içerikleri standart yöntemlerle belirlenmiş; K, Mg, Ca, Na, Fe, Mn ve Zn konsantrasyonları mikrodalga destekli asit sindirimi sonrası ICP-OES ile analiz edilmiştir. Mineral biyoerişilebilirliğini belirlemek için ekmek matrisi için uyarlanan statik INFOGEST protokolü kullanılmıştır. Karabuğday ve siyez ekmekleri Mg, Fe, Mn ve Zn bakımından en zengin ürünler olurken, en yüksek Na içeriği beyaz buğday ekmeğinde saptanmıştır. Ekşi mayalı ekmek, özellikle Fe, Mn ve Zn için en yüksek biyoerişilebilirlik yüzdelerini göstermiştir. EFSA referans değerlerine göre 250 g ekmek porsiyonu potasyum yeterli alımının yaklaşık %14-17'sini karşılarken, kalsiyuma ve kısmen çinkoya sınırlı katkı sağlamaktadır.

Anahtar kelimeler: Ekmek, mineral içerik, in vitro sindirim, mineral biyoerişilebilirlik, INFOGEST



INTRODUCTION

Bread has historically been a staple food at the center of human life from both cultural and nutritional perspectives. In Türkiye, white wheat, whole wheat, einkorn, buckwheat and sourdough breads contribute substantially not only to daily energy intake but also to the coverage of mineral requirements. The diversification of these products arises not only from sensory preferences but also from the different nutritional effects of constituents such as minerals, dietary fibers and phytochemical compounds provided by different flour types (Frontela et al., 2011; Wang & Wang, 2024a). In particular, whole grain and sourdough products have attracted renewed interest in recent years because they are rich in minerals and fiber. However, it has been reported that even when the total mineral content of cereal-based products is high, the fraction that can be absorbed at the end of the digestive process, i.e. the bioaccessible fraction, is often limited (El Houssni et al., 2024; Gupta & Gangoliya, 2015).

Minerals such as iron (Fe), zinc (Zn), magnesium (Mg), calcium (Ca), potassium (K), manganese (Mn) and sodium (Na) play critical roles in fundamental physiological processes including oxygen transport, bone development and mineralization, enzyme activity, nerve conduction and energy metabolism. Deficiencies of these minerals are associated with numerous health problems, particularly in developing countries, such as anemia, growth retardation, impaired immune function and neurocognitive disorders (Etcheverry et al., 2012; Gupta & Gangoliya, 2015). The persistence of iron and zinc deficiencies in a substantial proportion of the world's population makes it necessary to evaluate not only the mineral content but also the bioaccessibility of minerals in cereal-based foods that are heavily consumed in the daily diet. Certain antinutritional compounds, particularly phytic acid (myo-inositol hexakisphosphate), which naturally occurs in cereals, form insoluble complexes with minerals and limit their absorption; this effect becomes more pronounced in breads produced from flours with a high bran content, such as whole wheat and einkorn (El Houssni et al., 2024; Frontela et al., 2011).

In the evaluation of mineral bioaccessibility in foods, *in vitro* digestion models have emerged as practical, ethical and reproducible approaches. The consortium-based INFOGEST protocol, which operates with parameters close to the physiological conditions of the human digestive system, is

regarded as a standardized method that enables comparative assessment across different food matrices (Brodkorb et al., 2019; Etcheverry et al., 2012; Minekus et al., 2014). Within this protocol, the bioaccessible (dialyzable/soluble) fraction is estimated by determining the soluble fraction of a mineral at the end of the simulated oral, gastric and intestinal phases; this value reflects *in vitro* bioaccessibility and may be interpreted only as a potential indicator of *in vivo* bioavailability. Here, bioaccessibility refers to the fraction released into gastrointestinal fluids, whereas bioavailability additionally encompasses intestinal absorption, metabolism, and tissue utilization. Recent studies have shown a significant relationship between such *in vitro* digestion models and Caco-2 cell models or human intervention studies (Bryszewska et al., 2019).

A wide range of technological and structural factors influence mineral bioaccessibility in breads. Among these, raw material composition, milling degree, fermentation type and duration, baking conditions and the phytate content of the product are particularly important. Frontela et al., (2011) reported that phytic acid levels in whole wheat and white breads decreased as fermentation time increased, and that this reduction particularly enhanced the dialyzable fractions of iron and zinc. Wang & Wang, (2024) demonstrated that sourdough fermentation markedly increased mineral solubility by disrupting phytate-mineral complexes through pH reduction and microbial phytase activity. Aslam et al., (2024) observed increased iron bioaccessibility associated with disruption of microstructural integrity in micronized wheat flours, but reported a more limited effect for zinc, thereby highlighting differences in the localization of minerals within cereal tissues. Some review studies have also shown that soaking, germination, fermentation and microbial phytase applications can reduce phytate content and thereby enhance mineral bioaccessibility (El Houssni et al., 2024; Gupta & Gangoliya, 2015).

This study provides a market-based comparison of mineral content and *in vitro* bioaccessibility across five commonly consumed bread categories in Türkiye using commercially available products. The current literature indicates that factors affecting mineral content and bioaccessibility in cereal-based products interact in a complex manner. However, there are limited studies in which bread types commonly consumed in the Turkish market (white wheat, whole wheat, einkorn, buckwheat and sourdough) have been comparatively evaluated in terms of

both total mineral contents and in vitro mineral bioaccessibility. Despite increasing consumer demand in Türkiye for breads such as einkorn, whole wheat and sourdough, data elucidating the actual nutritional contribution of these products remain insufficient. This study aims to comparatively determine the total contents and in vitro bioaccessibility levels of selected macro- and trace minerals (K, Mg, Ca, Na, Fe, Mn and Zn) in five commonly consumed bread types in Türkiye, using a modified INFOGEST protocol. The findings are expected to provide a basis for evaluating the potential contribution of different bread varieties to mineral nutrition and to support future product development and nutritional studies in this field.

MATERIALS AND METHODS

Materials

In this study, five different bread types commonly consumed in the Turkish market were evaluated: white wheat bread, buckwheat bread, sourdough wheat bread, whole wheat bread and einkorn bread. Bread samples were purchased as commercially available products from the retail market. Accordingly, the findings should be interpreted as a market-based comparison of selected products representing common bread categories rather than a nationally representative survey. For each bread type, products from five different producers/brands available on the market during the same period were purchased. Thus, five independent commercial samples ($n=5$) were obtained for each bread type, and each was considered a biological replicate in the statistical evaluation. The purchased products were transported at room temperature to the laboratory on the same day and stored in polyethylene bags with minimal air contact at refrigeration temperature ($+4^{\circ}\text{C}$) until analysis. Long-term storage was avoided, and all chemical analyses were completed within 48 hours following purchase. Before analysis, each bread sample, including both crust and crumb, was homogenized in a grinder equipped with stainless steel blades. The resulting homogeneous bread samples were then divided into subsamples for the determination of moisture, ash and protein contents, total mineral analysis and in vitro digestion experiments.

Methods

Moisture content

An amount of 5 g of homogenized bread sample was weighed into glass dishes that had been pre-dried at 105°C and

equilibrated in a desiccator. The samples were dried in a hot-air oven at $105\pm 2^{\circ}\text{C}$ to constant weight (at least 6 h), then cooled to room temperature in a desiccator and weighed. Moisture content was calculated from the difference between initial and final weights and expressed on a wet basis (%) (Cunniff & Washington, 1997).

Ash content

An amount of 3 g of homogenized bread was weighed into porcelain crucibles; the samples were first gently pre-ashed over a flame until the evolution of smoke ceased, and then the crucibles and contents were incinerated in a muffle furnace at $550\pm 25^{\circ}\text{C}$ for 6 h until a constant, light grey-white ash was obtained. After cooling in a desiccator, the crucibles were weighed, and ash content was calculated as percentage on a wet basis (Cunniff & Washington, 1997).

Protein content

The crude protein content of the bread samples was determined according to the Kjeldahl nitrogen determination method (Belc et al., 2021). An amount of 1.0 g of homogenized bread sample was weighed into a Kjeldahl flask, to which concentrated H_2SO_4 and a catalyst mixture ($\text{K}_2\text{SO}_4/\text{CuSO}_4$) were added, and the mixture was digested until the solution became clear green-blue. The cooled digest was diluted with distilled water and subjected to steam distillation under alkaline conditions (NaOH), and the released ammonia was trapped in a boric acid solution. The collected distillate was titrated with standard HCl solution to calculate the total Kjeldahl nitrogen. Crude protein content was obtained by multiplying the nitrogen value by the factor 6.25 and expressed as percentage on a wet basis.

Determination of elemental composition

The concentrations of calcium (Ca), iron (Fe), magnesium (Mg), manganese (Mn), sodium (Na), potassium (K) and zinc (Zn) in the bread samples were determined using inductively coupled plasma-optical emission spectrometry (ICP-OES). The sample preparation and microwave-assisted acid digestion steps were based on a previously described procedure applied to a vegetable matrix and were adapted for the bread matrix (Alhagri & Albeshry, 2023).

Microwave-assisted acid digestion

Homogenized bread samples (0.40 ± 0.01 g) were weighed into Teflon microwave digestion vessels. To each vessel, 6 mL of

65% (w/w) concentrated HNO₃ and 2 mL of 30% (w/w) H₂O₂ were added, and the vessels were left open for approximately 10 minutes to allow gas release before capping. The closed vessels were then subjected to digestion in a closed-system microwave digestion unit using a three-step program: In the first step, the temperature was raised to 170°C and held for 5 minutes; in the second step, the temperature was increased to 200°C and maintained for 15 minutes; in the final step, the system was cooled in a controlled manner to 50°C and held for 10 minutes, resulting in clear solutions.

At the end of digestion, the clear solutions were cooled to room temperature, passed through 0.45 µm filters and transferred

into polypropylene tubes, and the volume was adjusted to 10 mL with ultrapure water. The same procedure was applied to reagent blanks, and these blank values were taken into account in the ICP-OES measurements.

ICP-OES operating conditions

Element determinations were performed using an ICP-OES instrument equipped with an argon plasma source. The analytical emission lines were selected to minimize spectral interferences, and the selected wavelengths, calibration performance (regression model and R²), and method sensitivity parameters (LOD/LOQ) are summarized in Table 1. (Apaydin & Afşar, 2025).

Table 1. ICP-OES analytical wavelengths, calibration performance (regression model, R²), limits of detection (LOD) and quantification (LOQ), and for the determination of minerals in digested bread samples.

Element	Wavelength (nm)	Regression model	R ²	LOD (mg/L)	LOQ (mg/L)
Ca	317.933	Linear	0.996	0.006	0.019
Fe	259.94	Linear	0.997	0.03	0.099
K	766.49	Linear	0.997	0.012	0.04
Mg	279.553	Linear	0.996	0.02	0.065
Mn	257.61	Linear	0.995	0.005	0.017
Na	588.995	Linear	0.996	0.014	0.047
Zn	213.856	Linear	0.995	0.015	0.049

Limits of detection (LOD) and quantification (LOQ) were estimated from repeated measurements of blank solutions and the slope of the external calibration curve (m), using the widely applied calibration-curve approach (LOD=3σ/m and LOQ=10σ/m, where σ is the standard deviation of the blank response). The resulting LOD and LOQ values for each element are reported in Table 1 (AOAC, 2016).

Calibration curves were constructed using diluted standards prepared from a multi-element stock standard solution (Merck, Item No: 1.11355, Darmstadt, Germany). Standards and sample solutions were prepared in a solution containing 5% (v/v) HNO₃ to ensure matrix compatibility, and at least a five-point calibration range was used for each element. During measurements, a calibration standard and a blank were analyzed

after every 10 samples to monitor signal stability and potential drift.

Calculation of results

The results obtained from the ICP-OES instrument were read as mg/L (C solution) and converted to the elemental concentration of the bread samples (C sample, mg/kg fresh bread) using the following equation:

$$C_{\text{sample}} (\text{mg/kg}) = \frac{C_{\text{solution}} \left(\frac{\text{mg}}{\text{L}}\right) \times V_{\text{final}} (\text{mL})}{m_{\text{sample}} (\text{g})} \times DF \times \frac{1\text{L}}{1000\text{mL}} \times \frac{1000\text{g}}{1\text{kg}} \quad \text{Eq 1.}$$

Here, V_{final} denotes the solution volume (mL) after digestion, m_{sample} is the weight of the bread sample (g), and DF represents the additional dilution factor, if applied. The final results were reported in mg/kg for the bread samples.

Determination of in vitro gastrointestinal digestion and mineral bioaccessibility

To evaluate the mineral bioaccessibility of the bread samples, the static in vitro digestion protocol proposed by the INFOGEST consortium was used as a basis, with certain adaptations considering the solid bread matrix and the dynamics of mineral release (Brodkorb et al., 2019; Minekus et al., 2014). The types of enzymes used, pH values and incubation temperature were kept consistent with INFOGEST recommendations, while the duration of the intestinal phase was extended to better capture the slower release of mineral ions.

Sample preparation and gastric phase

For each digestion trial, 2.5 g of homogenized (mechanically pre-disintegrated) bread was weighed into 50 mL sterile polypropylene tubes. To obtain a digestible food bolus from the solid matrix, an appropriate volume of ultrapure water was added to form a homogeneous suspension, and the tube contents were mixed using a vortex mixer. At the beginning of the gastric phase, the pH of the suspension was adjusted to $\text{pH } 2.0 \pm 0.1$ using 0.1 N HCl. In line with the INFOGEST approach, a fresh pepsin solution was prepared immediately before digestion: 0.2 g pepsin (Sigma-Aldrich, P-7000) was dissolved in 5 mL 0.1 N HCl. From this solution, 0.5 mL was added to each tube to ensure a constant pepsin dose across all digestions. In accordance with the INFOGEST framework, digestive enzyme additions are defined in terms of target activities (e.g., porcine pepsin at 2,000 U/mL in the final gastric mixture); therefore, the supplier-declared activity specifications of the enzyme batch used in this study are reported and considered when describing the digestion conditions. The tubes were incubated at 37°C in a shaking water bath at 100 rpm for 2 h. This step was intended to mimic protein hydrolysis under gastric conditions and the transfer of minerals from the food matrix into the soluble phase (Brodkorb et al., 2019; Etcheverry et al., 2012; Minekus et al., 2014).

Intestinal phase

After completion of the gastric phase, the pH of the tube contents was gradually increased to the range of pH 6.8-7.0 using 1 M NaHCO_3 solution. Subsequently, freshly prepared enzyme solutions were added to simulate pancreatic and bile secretions:

- Pancreatin solution: 0.4 g pancreatin (Sigma-Aldrich,

P-1750) was dissolved in 10 mL ultrapure water.

- Bile salt solution: 0.25 g bile extract (Sigma-Aldrich, B-8631) was dissolved in 10 mL ultrapure water.

Each tube received 1.0 mL of the pancreatin solution and 1.0 mL of the bile salt solution. Following INFOGEST, pancreatin addition in the intestinal phase was defined on a trypsin activity basis (target 100 U/mL in the final intestinal mixture). The pancreatin amount was calculated using the supplier-provided activity information for the commercial preparation used (supplier and catalog number provided), and the same preparation was used throughout the experiments. Nevertheless, batch-to-batch variability in enzyme activities remains a limitation that may affect absolute digestion intensity (Brodkorb et al., 2019).

The samples were incubated at 37°C at the same shaking speed (100 rpm) for 4 h. Compared with the classical 2 h intestinal phase of the INFOGEST protocol, this extended duration was based on previous findings indicating that the solubility of polyvalent cations (particularly Ca, Fe, Zn and Mg) proceeds more slowly in cereal-based matrices with high fiber and phytate contents (Etcheverry et al., 2012; Faria et al., 2018).

Post-digestion processing and collection of the bioaccessible fraction

At the end of the intestinal phase, the contents of each tube were brought up to 50 mL with ultrapure water to standardize the dilution effect among samples. The tubes were then centrifuged at $15,100 \times g$ for 20 min at room temperature.

Following centrifugation, the supernatant was carefully collected and passed first through Whatman No. 1 filter paper and then through 0.45 μm syringe filters to remove all residual particulates. The resulting clear supernatant was considered the bioaccessible (dialyzable/soluble) fraction containing soluble mineral species released during in vitro digestion. The filtrates were stored at 4°C to minimize precipitation and possible chemical transformations and were subjected to mineral analysis within 24 h at the latest. Before analysis, the solutions were vortexed again. The results obtained were compared with the total mineral contents of the same bread samples prior to digestion and the concentrations of the soluble fraction after digestion, and the in vitro bioaccessibility percentage for each element was calculated using the following equation:

$$\text{Bioaccessibility (\%)} = \frac{C_{\text{diaziable}}}{C_{\text{Total}}} \times 100$$

Eq 2.

All digestion experiments were carried out on at least three independent commercial samples for each bread type; for each sample, the digestion and ICP-OES measurements were performed in triplicate, and the results were reported as mean \pm standard deviation.

Statistical Analysis

Univariate statistical analyses were performed using IBM SPSS Statistics. Data are presented as mean \pm standard deviation (SD). Differences among bread types were evaluated by one-way analysis of variance (ANOVA), and when significant, group comparisons were performed using Duncan's multiple range test. Statistical significance was set at $P < 0.05$.

Principal Component Analysis (PCA) was used as an exploratory multivariate approach to visualize similarities among bread samples based on their mineral profiles. PCA was performed separately for (i) total mineral contents (mg/kg) and (ii) mineral bioaccessibility percentages, using the replicate-level dataset (5 bread types \times 3 biological replicates; $n=15$). Prior to PCA, variables were autoscaled (mean-centered and divided by the standard deviation) to account for the different magnitude of macro- and trace minerals. Score plots (PC1 vs PC2) and loading plots were used to interpret sample grouping and the minerals contributing most to separation (Sezer et al., 2022).

RESULTS AND DISCUSSION

Moisture, ash and protein contents of the breads

The moisture, ash and protein values of the five bread types are given in Table 2.

Table 2. Moisture, ash and protein contents of bread samples (% , fresh weight basis)

Bread Type	Moisture (%)	Ash (%)	Protein (%)
White wheat	41.70 \pm 0.70 ^a	1.80 \pm 0.15 ^b	11.61 \pm 0.34 ^c
Buckwheat	38.53 \pm 1.77 ^{ab}	2.10 \pm 0.24 ^a	13.38 \pm 0.35 ^b
Sourdough (wheat)	37.70 \pm 1.69 ^b	1.90 \pm 0.10 ^{ab}	10.50 \pm 0.23 ^d
Whole wheat	38.83 \pm 1.49 ^{ab}	1.77 \pm 0.12 ^{bc}	11.85 \pm 0.60 ^c
Einkorn bread	36.45 \pm 0.88 ^b	1.51 \pm 0.08 ^c	14.20 \pm 0.14 ^a

Values are expressed as mean \pm standard deviation ($n=5$). Different lowercase letters in the same column indicate significant differences among bread types ($P < 0.05$).

Moisture contents ranged between 36.45 \pm 0.88 and 41.70 \pm 0.70%. The highest moisture was measured in white wheat bread (41.70 \pm 0.70%), whereas the lowest moisture was found in einkorn bread (36.45 \pm 0.88%). Buckwheat, whole wheat and sourdough breads were at intermediate levels, with moisture values of approximately 37-39%. This distribution appears to be consistent with the generally higher hydration applied in white bread formulations to achieve greater water-holding capacity and loaf volume. The moisture levels of 38-42% reported for conventional white wheat breads are of similar magnitude to the values obtained in the present study

(Dewettinck et al., 2008). Some studies on buckwheat breads likewise report moisture contents in the 35-40% range and indicate that increasing the proportion of hulled cereal in the formulation enhances water retention (Alkay et al., 2023; Mohajan et al., 2019).

Ash contents ranged between 1.51 \pm 0.08 and 2.10 \pm 0.24%, with the highest ash content determined in buckwheat bread (2.10 \pm 0.24%) and the lowest in einkorn bread (1.51 \pm 0.08%). The ash values of white wheat, whole wheat and sourdough breads were very similar, at approximately 1.77-1.90%. The

high ash level in buckwheat bread is consistent with the relatively high concentrations of minerals such as Mg, Fe, Mn and Zn shown in the previous section and is in line with studies reporting that buckwheat flour is a mineral-rich ingredient (Alkay et al., 2023; Mohajan et al., 2019). It has previously been reported that the ash content increases in breads produced from whole grain flours or flours with a high bran proportion, corresponding to an enrichment of the mineral fraction, especially in K, Mg, P and trace elements (Dewettinck et al., 2008; Păucean et al., 2024). Although buckwheat bread showed the highest ash content and generally higher levels of several minerals (e.g., Mg, Fe, Mn, and Zn), ash did not exhibit a strictly linear relationship with the total mineral content across all bread types. This is expected because ash represents the total inorganic residue after incineration and therefore integrates not only the target elements quantified by ICP-OES but also other inorganic constituents and salts present in the matrix. Moreover, ash content is widely used as an indicator of flour extraction rate and the contribution of outer kernel layers, but differences in formulation (particularly salt level) can increase ash without proportionally increasing intrinsic grain-derived minerals. Consequently, in commercially available breads, ash may serve as a general quality/composition marker, yet it should not be interpreted as a direct linear proxy for total mineral content (Fayaz et al., 2021; Nargesi & Kheiralipour, 2025).

Protein contents showed a more pronounced variation among bread types; the highest protein level was measured in einkorn bread, at $14.20 \pm 0.14\%$, followed by buckwheat bread with $13.38 \pm 0.35\%$. Whole wheat and white wheat breads had similar protein levels of approximately 11.6-11.9%, whereas sourdough wheat bread had the lowest protein content, at $10.50 \pm 0.23\%$. The high protein level determined in einkorn bread is consistent with studies reporting that einkorn flour contains more protein than conventional bread wheat and that this difference becomes more evident when wholemeal flour is used (Brandolini et al., 2023; Keçeli et al., 2021). Similarly, buckwheat breads are frequently reported in the literature as being rich in protein, and it is emphasized that when fortification or full buckwheat flour substitution is applied, the protein content can reach higher levels than those of conventional wheat breads (Bhavsar et al., 2013; Mohajan et al., 2019).

The relatively low protein percentage observed in sourdough wheat bread may be related to the flour extraction rate used

in the formulation and the addition of sourdough. Although sourdough fermentation does not chemically reduce the absolute amount of protein, the starter, sugar or other ingredients added to the overall dough formulation may dilute the protein proportion on a percentage basis. Studies reporting protein values of approximately 9-11% in sourdough wheat breads point to a similar order of magnitude to the results of the present study (Hayta & Hendek Ertop, 2018; Navarro et al., 2025).

These findings indicate that the technological and nutritional properties of breads are closely related not only to their mineral contents but also to their total ash and protein levels. Buckwheat and einkorn breads exhibit a richer profile in terms of both ash and protein, thereby supporting the high mineral content findings. On the other hand, white wheat and sourdough breads, with their higher moisture contents, occupy a different position with respect to shelf life and textural properties. However, since the levels of salt, sugar and fat in the formulations were not standardized in this study (marketed breads were used), it should be kept in mind that some of the differences observed in the proximate composition may have been influenced not only by the raw materials but also by variations in the recipes. The relatively high standard deviations observed for moisture, ash, and protein contents are primarily attributed to inter-product variability among independent commercial samples within each bread category rather than analytical imprecision. Market-based sampling inevitably captures differences in formulation and processing conditions across producers, and surveys of commercially available breads have likewise reported noticeable between-brand variation in proximate composition. Moreover, ash content is closely related to flour extraction rate/bran incorporation and can also be affected by differences in added salt, both of which may vary among products. Moisture variability is similarly sensitive to recipe-dependent water binding (especially in fiber-rich formulations) and post-baking moisture loss during shelf life (Begum et al., 2023; Bodor et al., 2025; Fayaz et al., 2021; Renzetti et al., 2021).

Mineral composition of the breads

The mineral contents determined in the five bread types are summarized in Table 3.

Table 3. Mineral composition of commonly consumed bread types in Türkiye (mg/kg, fresh weight basis)

	White wheat	Buckwheat	Sourdough (wheat)	Whole wheat	Einkorn bread
K	4056.47±203.75 ^a	3987.15±609.59 ^a	3558.24±449.2 ^a	4325.33±318.78 ^a	4243.79±350.09 ^a
Mg	229.88±25.92 ^c	529.96±48.3 ^a	271.3±48.15 ^c	287.71±14.6 ^c	379.75±19.31 ^b
Ca	103.91±10.71 ^d	126.79±6.24 ^{cd}	285.29±24.83 ^a	150.8±5.93 ^c	197.97±27.15 ^b
Na	5298.59±553.24 ^a	2444.13±382.56 ^{bc}	2907.68±101.09 ^{bc}	3387.98±710.03 ^b	1887.36±74.07 ^c
Fe	14.69±2.67 ^b	111.18±17.09 ^a	96.79±28.14 ^a	34.1±5.7 ^b	19.82±1.53 ^b
Mn	1.1±0.37 ^d	18.81±3.75 ^b	11.06±3.03 ^c	1.6±0.11 ^d	44.5±4.82 ^a
Zn	1.33±0.34 ^c	17.57±3.82 ^{ab}	15.6±3.01 ^b	17.3±1.59 ^{ab}	22.96±2.62 ^a

Values are expressed as mean ± standard deviation (n=5). Different lowercase letters in the same row indicate significant differences among bread types ($P<0.05$).

Potassium was the predominant macro element in all bread types, ranging from 3558.24±449.20 mg/kg (sourdough) to 4325.33±318.78 mg/kg (whole wheat). Buckwheat, einkorn, white and whole wheat breads had statistically similar K levels, and sourdough wheat bread was also included in the same group. Therefore, no significant difference was found between bread types in terms of potassium content ($P>0.05$). This finding is consistent with studies reporting that K is the main mineral in wheat and pseudocereals and is particularly concentrated in the bran fraction (Ciudad-Mulero et al., 2021; Ruibal-Mendieta et al., 2005). The K content of 372-444 mg/100 g reported by Latha Rani et al., (2022) for hulled buckwheat grains is similar in magnitude to the value of approximately 3990 mg/kg found for buckwheat bread in the present study.

Marked differences were observed between bread types in terms of magnesium ($P<0.05$). The highest Mg content was detected in buckwheat bread, at 529.96±48.30 mg/kg, followed by einkorn bread with 379.75±19.31 mg/kg. White wheat, sourdough and whole wheat breads were in a lower and statistically similar range, between 229.88 and 287.71 mg/kg. This is in agreement with the characterization of buckwheat as a pseudocereal rich in Mg in the literature (Bonafaccia et al., 2003; Latha Rani et al., 2022). Higher Mg contents have also been reported in spelt and other hulled wheats compared with modern wheat varieties, with particularly significant increases in Mg concentration in whole grain or bran fractions (Piergiovanni et al., 1997; Ruibal-Mendieta et al., 2005). The high Mg level observed in einkorn bread indicates that einkorn wheat has a

mineral profile similar to that of this “ancient wheat” group. Calcium content showed a more pronounced differentiation among bread types. The highest Ca level was found in sourdough wheat bread, at 285.29±24.83 mg/kg, followed by einkorn bread with 197.97±27.15 mg/kg. Whole wheat (150.80±5.93 mg/kg) and buckwheat (126.79±6.24 mg/kg) breads had intermediate levels, while white wheat bread had the lowest Ca content, at 103.91±10.71 mg/kg ($P<0.05$). Recent studies have reported that sourdough fermentation can partially hydrolyse phytic acid and thereby promote the binding of cations such as Ca within the dough matrix, leading to relatively higher Ca levels in the baked product (Alkay et al., 2024; El Houssni et al., 2024). However, the literature also indicates that Ca content in bread may vary substantially depending not only on flour type but also on the inclusion of milk powder, calcium salts or fortifying ingredients in the formulation (Dewettinck et al., 2008; Lucretia Ifeoma & Nkechi Juliet T., 2021). Therefore, the high Ca levels observed in sourdough bread should be considered potentially related not only to the type of fermentation but also to the raw materials used and possible added ingredients.

With regard to sodium content, the highest value was determined in white wheat bread, at 5298.59±553.24 mg/kg, followed by whole wheat bread with 3387.98±710.03 mg/kg. Buckwheat (2444.13±382.56 mg/kg) and sourdough (2907.68±101.09 mg/kg) breads had moderate Na contents, whereas einkorn bread had the lowest Na concentration, at 1887.36±74.07 mg/kg ($P<0.05$). Since sodium content essentially reflects the

amount of salt in the bread formulation, these results suggest that different salt levels are applied in different bread types. In the literature, Na contents in traditional white breads are often reported to reach 1.5-2.0 g/100 g, which constitutes an important contribution to hypertension risk (Adrogué & Madias, 2007; Dewettinck et al., 2008; Lucretia Ifeoma & Nkechi Juliet T., 2021). In this context, the lower Na levels of einkorn and buckwheat breads may be regarded as a favourable feature in terms of mineral composition.

When trace elements are examined, it is evident that iron content is markedly higher in buckwheat and sourdough breads. Fe was determined as 111.18 ± 17.09 mg/kg in buckwheat bread and 96.79 ± 28.14 mg/kg in sourdough bread; these two products were in the same statistical group and showed significantly higher Fe contents than white wheat (14.69 ± 2.67 mg/kg), whole wheat (34.10 ± 5.70 mg/kg) and einkorn (19.82 ± 1.53 mg/kg) breads ($p < 0.05$). Studies reporting higher Fe contents in buckwheat grains than in wheat, and particularly marked enrichment of Fe, Zn and Mn in the bran fraction, support these findings (Alvarez-Jubete et al., 2010; Bonafaccia et al., 2003; Przybylski & Gruczyńska, 2009). Similarly, various genotype comparison studies have shown that Fe content is higher in hulled wheats such as spelt and emmer than in modern bread wheats (Bálint et al., 2001; Ruibal-Mendieta et al., 2005). These literature data support the high Fe levels observed in buckwheat bread in the present study.

The Mn and Zn results also highlight the advantage of whole grain and ancient wheat varieties in terms of trace elements. Mn content reached the highest level in einkorn bread, at 44.50 ± 4.82 mg/kg, while buckwheat bread ranked second with 18.81 ± 3.75 mg/kg. Sourdough bread contained an intermediate amount of Mn (11.06 ± 3.03 mg/kg), whereas Mn contents in white and whole wheat breads were quite low, at around 1-2 mg/kg ($P < 0.05$). In terms of Zn, einkorn bread again ranked first, with 22.96 ± 2.62 mg/kg; buckwheat (17.57 ± 3.82 mg/kg) and whole wheat (17.30 ± 1.59 mg/kg) breads exhibited statistically similar levels. Sourdough bread contained 15.60 ± 3.01 mg/kg Zn at an intermediate level, whereas white wheat bread had the lowest Zn content, at 1.33 ± 0.34 mg/kg. It has been reported that spelt and other hulled wheats are rich in Zn and Mn, and that Zn in the bran fraction can reach levels of 18-26 mg/kg

(Ruibal-Mendieta et al., 2005; Żuk-Golaszewska et al., 2022). The Mn levels of 2.6-3.3 mg/100 g and Zn levels of 3.3-4.3 mg/100 g (approximately 26-43 mg/kg Zn) reported by Latha Rani et al., (2022) in buckwheat bread varieties are also of the same order of magnitude as the values obtained in this study for buckwheat and einkorn breads.

Overall, the mineral composition results show that white wheat bread has the highest Na content but is the poorest product in terms of trace elements such as Fe, Mn and Zn, whereas buckwheat and einkorn breads provide a richer profile in Mg, Fe, Mn and Zn. These findings are consistent with literature reports that breads produced from whole grain or high-bran flours are richer in minerals, while white breads provide a more limited contribution particularly with respect to trace elements (Bonafaccia et al., 2003; Ciudad-Mulero et al., 2021; Dewettinck et al., 2008; Lucretia Ifeoma & Nkechi Juliet T., 2021). However, parameters such as the amount of salt in the bread formulation, possible mineral fortification and the extraction rate of the flours used act as confounding variables in these comparisons and should be regarded as one of the limitations of the present study.

In vitro mineral bioaccessibility of the breads

The in vitro bioaccessibility percentages of the selected minerals in the five bread types are presented in Table 4. The overall bioaccessibility patterns across minerals and bread types are summarized in Figure 1. For a direct comparison between total mineral levels and the corresponding dialyzable fractions (mg/kg), see Figure 2. For potassium, bioaccessibility values ranged between 54.19 ± 3.12 and $57.42 \pm 3.31\%$, and no statistically significant difference was detected among bread types ($P < 0.05$). This result indicates that potassium behaves quite similarly across bread types in terms of both total content and soluble fraction after digestion. In all breads, K generally fell into the group of minerals with the highest bioaccessibility. This is consistent with the fact that K is largely present in a free or weakly bound form in the cereal matrix and is less retained by antinutritional compounds such as phytate compared with Ca, Fe and Zn (Frontela et al., 2011; Magallanes-López et al., 2017).

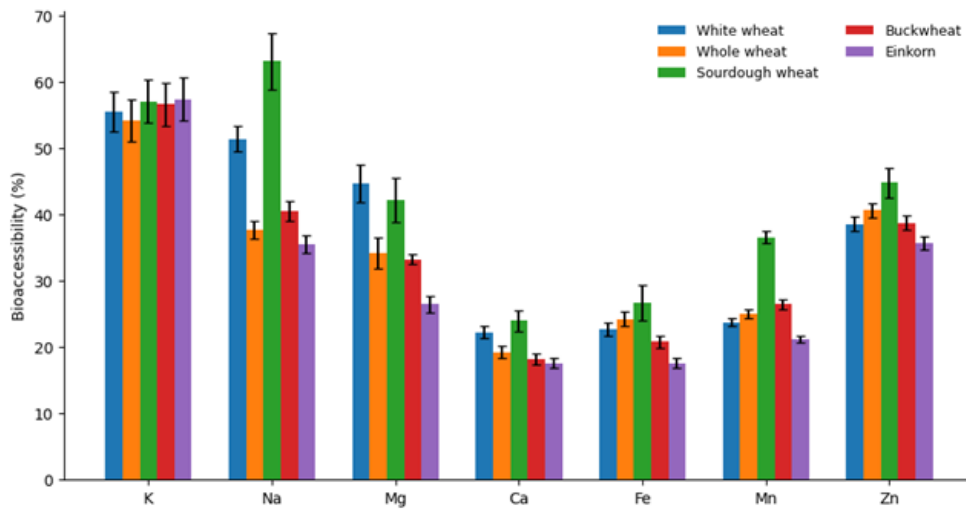


Figure 1. In vitro mineral bioaccessibility (%) of K, Na, Mg, Ca, Fe, Mn and Zn in five bread types. Bars indicate mean \pm SD (n=5)

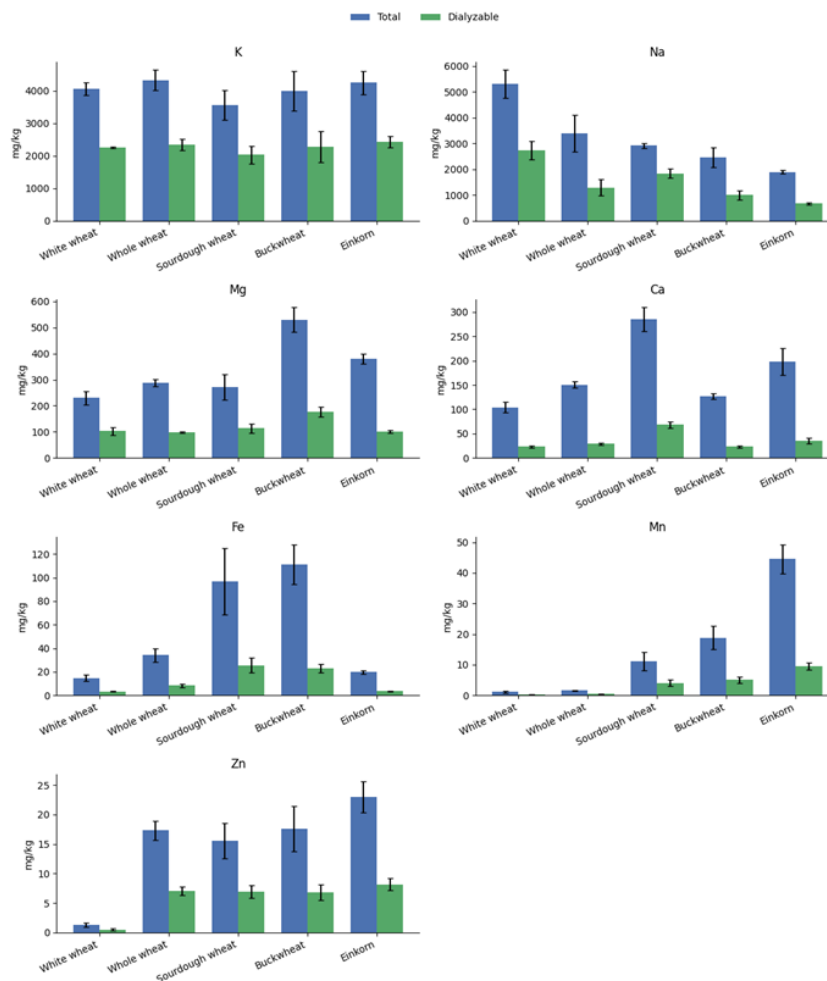


Figure 2. Total mineral content (mg/kg) and dialyzable fraction (mg/kg) after in vitro digestion for each mineral across bread types. Bars indicate mean \pm SD (n = 5)

Table 4. In vitro mineral bioaccessibility of minerals in different bread types (% of total mineral content)

	White wheat	Buckwheat	Sourdough (wheat)	Whole wheat	Einkorn bread
K	55.5±2.94 ^{aA}	56.65±3.26 ^{aA}	57.09±3.17 ^{aA}	54.19±3.12 ^{aA}	57.42±3.31 ^{aA}
Mg	44.67±2.77 ^{aB}	33.24±0.73 ^{aC}	42.26±3.33 ^{bBC}	34.22±2.37 ^{bC}	26.48±1.22 ^{cC}
Ca	22.26±0.97 ^{aD}	18.18±0.79 ^{bE}	23.98±1.63 ^{aD}	19.28±0.84 ^{bE}	17.56±0.77 ^{bD}
Na	51.4±1.93 ^{bA}	40.47±1.52 ^{cB}	63.1±4.18 ^{aA}	37.69±1.41 ^{cBC}	35.45±1.33 ^{cB}
Fe	22.69±0.95 ^{bD}	20.81±0.87 ^{bE}	26.72±2.67 ^{aD}	24.26±1.02 ^{abD}	17.55±0.74 ^{cD}
Mn	23.76±0.65 ^{dD}	26.48±0.72 ^{bD}	36.56±0.91 ^{aC}	25.08±0.68 ^{bCD}	21.19±0.58 ^{dD}
Zn	38.57±0.62 ^{bcC}	38.71±0.63 ^{bcB}	44.78±1.32 ^{aB}	40.61±0.66 ^{bB}	35.64±0.58 ^{cB}

Values are expressed as mean ± standard deviation (n = 5). Different lowercase letters in the same row indicate significant differences among bread types for a given mineral ($P < 0.05$). Different uppercase letters in the same column indicate significant differences among minerals within the same bread type ($P < 0.05$).

For magnesium, bioaccessibility was highest in white wheat and buckwheat breads, at 44.67±2.77% and 33.24±0.73%, respectively; sourdough and whole wheat breads exhibited intermediate levels, while einkorn bread, with 26.48±1.22%, fell into the lowest group ($P < 0.05$). In the statistical evaluation, Mg generally appeared in a lower statistical group than K and Na in most breads and displayed a moderately bioaccessible macromineral profile. Calcium bioaccessibility ranged from 17.56±0.77% to 23.98±1.63%, with the highest values observed in sourdough wheat and white wheat breads ($P < 0.05$). Ca bioaccessibility in buckwheat, whole wheat and einkorn breads was significantly lower and mostly clustered in the lowest statistical group. This pattern is in line with the general consensus that Ca forms strong complexes with phytic acid in cereal products and therefore has a more limited bioaccessible (dialyzable) fraction relative to its total content (Frontela et al., 2011).

Sodium bioaccessibility ranged between 35.45±1.33% and 63.10±4.18%, with the highest value found in sourdough bread ($p < 0.05$). White wheat bread ranked second in terms of Na, whereas bioaccessible Na levels in whole wheat, buckwheat and einkorn breads were significantly lower. In both white wheat and sourdough breads, K and Na were the macrominerals with

the highest post-digestive accessibility. Iron bioaccessibility ranged from 17.55±0.74% to 26.72±2.67%, with the highest Fe bioaccessibility determined in sourdough bread, followed by whole wheat bread. Buckwheat and white wheat breads showed moderate Fe bioaccessibility, whereas einkorn bread had the lowest level in statistical terms ($p < 0.05$). This finding indicates that although total Fe content is high in buckwheat bread, einkorn bread provides a more limited contribution in terms of both total Fe content and Fe bioaccessibility.

A similar pattern was observed for manganese and zinc. Mn bioaccessibility was highest in sourdough bread (36.56±0.91%), followed by buckwheat and whole wheat breads. White wheat and einkorn breads fell into statistically lower groups with respect to Mn bioaccessibility ($P < 0.05$). For Zn, the highest bioaccessibility was detected in sourdough bread (44.78±1.32%), with whole wheat bread ranking second; white wheat and buckwheat breads showed intermediate levels, whereas einkorn bread remained at a relatively lower level (35.64±0.58%). In sourdough and whole wheat breads, Zn was classified in the second-highest bioaccessible mineral group after K and Na.

Overall, the in vitro digestion model results indicate that K and Na are the minerals with the highest bioaccessibility in all bread types, while Ca, Fe and Mn are present in the bioaccessible

(dialyzable) fraction at lower percentages. This pattern is consistent with previous studies reporting that, among macrominerals in cereal-based products, Na and K, and among trace elements, especially Zn, generally exhibit relatively higher bioaccessibility (El et al., 2024; Etcheverry et al., 2012; Fărcaș et al., 2022; Frontela et al., 2011; Ting & Loh, 2016).

Studies on *in vitro* mineral bioaccessibility in breads and similar cereal products report a wide range of values depending on processing conditions and formulation. Frontela et al., (2011) showed that the dialyzable fractions of Fe, Ca and Zn in bakery products subjected to different processing steps vary markedly depending on the phytic acid content of the formulation and fermentation conditions. Lopez et al., (2003) reported that, in breads produced from whole wheat flour, sourdough fermentation increases the *in vitro* bioaccessibility of Mg, Fe and Zn compared with yeast-leavened breads, explaining this effect by phytase activity and pH reduction. In some more recent semi-dynamic INFOGEST applications, it has also been noted that, although sourdough and yeast breads may have similar total mineral contents, the soluble fractions after digestion can differ, and that acidity, organic acid profile and the degree of protein degradation are among the main reasons for this (Comunian et al., 2024; Etcheverry et al., 2012).

In the present study, the fact that sourdough wheat bread exhibited the highest bioaccessibility percentages for Fe, Mn and Zn is consistent with these literature findings and suggests that sourdough fermentation can partially disrupt mineral-phytate complexes and thereby increase the soluble fraction of trace elements. By contrast, einkorn bread, despite presenting a rich profile in terms of total mineral content, showed lower percentages particularly for Fe and Ca bioaccessibility. This indicates that, although ancient wheat varieties may be rich in minerals, they do not necessarily provide higher bioaccessibility, potentially due to a higher phytate load and bran proportion as reported for such matrices, and it underscores the limitation of inferring nutritional contribution solely from total mineral content (Ferruzzi et al., 2020; Magallanes-López et al., 2017).

Despite their relatively high total mineral contents, einkorn and buckwheat products may exhibit lower mineral bioaccessibility because mineral release during digestion is strongly modulated by matrix components that bind divalent cations (e.g., phytate, dietary fibre, and phenolics), rather than by total mineral

concentration alone. Whole-grain flours from ancient wheat species, particularly einkorn, can contain higher mineral levels but also higher phytic acid contents with comparable endogenous phytase activity, which can limit mineral liberation unless processing conditions promote phytate degradation (e.g., long proofing/sourdough) (Longin et al., 2023).

Similarly, in buckwheat-based breads, the whole-grain fraction increases minerals and fibre, yet higher mineral bioaccessibility has been reported for formulations containing refined buckwheat flour compared with whole-grain buckwheat flour, indicating that inhibitors associated with the outer layers and phenolic-rich matrix may restrict mineral release despite higher totals (Brites et al., 2022; Klepacka et al., 2020). Therefore, the lower bioaccessibility observed in einkorn and, for some minerals, in buckwheat breads can be interpreted as a matrix-driven effect (binding/complexation) rather than a contradiction to their higher total mineral contents (Klepacka et al., 2020).

Although phytate concentration and the inositol phosphate profile were not quantified in the present study, the comparatively higher bioaccessibility observed for some trace minerals in sourdough bread can be plausibly explained by fermentation-driven modifications of the cereal matrix (Alkay et al., 2023; Echavarría et al., 2024; Nsabimana et al., 2024; Ögünç et al., 2026; Tokarczyk & Koch, 2025; Wang & Wang, 2024b). Recent evidence indicates that sourdough fermentation lowers dough pH and promotes phytate hydrolysis through activation of endogenous cereal phytases and microbial phytases, which reduces the mineral-binding capacity of IP6 by converting it into lower inositol phosphates (Wang & Wang, 2024b). This process becomes particularly effective under acidic conditions (commonly reported when pH falls below ~4.6) and has been associated with substantial decreases in phytic acid in whole-grain sourdough systems. In parallel, the accumulation of organic acids (mainly lactic and acetic acids) may increase mineral solubility and stabilize soluble mineral-ligand complexes during gastrointestinal digestion, thereby increasing the dialyzable fraction in static *in vitro* models (Tokarczyk & Koch, 2025). Beyond phytate, fermentation-associated proteolysis can release low-molecular-weight peptides and free amino acids; such compounds have been discussed as potential metal-chelating ligands that may help maintain Fe/Zn in soluble forms and partially counteract re-complexation

or precipitation under intestinal conditions (Nsabimana et al., 2024). Collectively, these biochemical changes provide a mechanistic framework supporting the higher bioaccessibility of selected trace minerals in sourdough bread observed in our dataset, while also highlighting that the magnitude of the effect may vary across minerals and bread matrices.

Principal component analysis (PCA) was applied to autoscaled data matrices to visualize multivariate differences among bread types based on (i) total mineral content (mg/kg) and (ii) mineral bioaccessibility (%). For total mineral content, the first two components explained 70.97% of the variance (PC1 46.35%,

PC2 24.62%) (Figure 3-A,B). PC1 primarily contrasted Na with Zn/Mn/Mg contributions, indicating that sodium-rich profiles were separated from profiles characterized by higher trace and divalent minerals. PC2 was mainly associated with K versus Ca/Fe loadings, providing a secondary axis of discrimination. For bioaccessibility (%), PC1 and PC2 explained 82.27% of the variance (PC1 66.27%, PC2 16.00%) (Figure 3-C,D). PC1 reflected an overall bioaccessibility pattern across most minerals (except K), while PC2 was dominated by K bioaccessibility, highlighting element-specific variability in the dialyzable fraction across bread types.

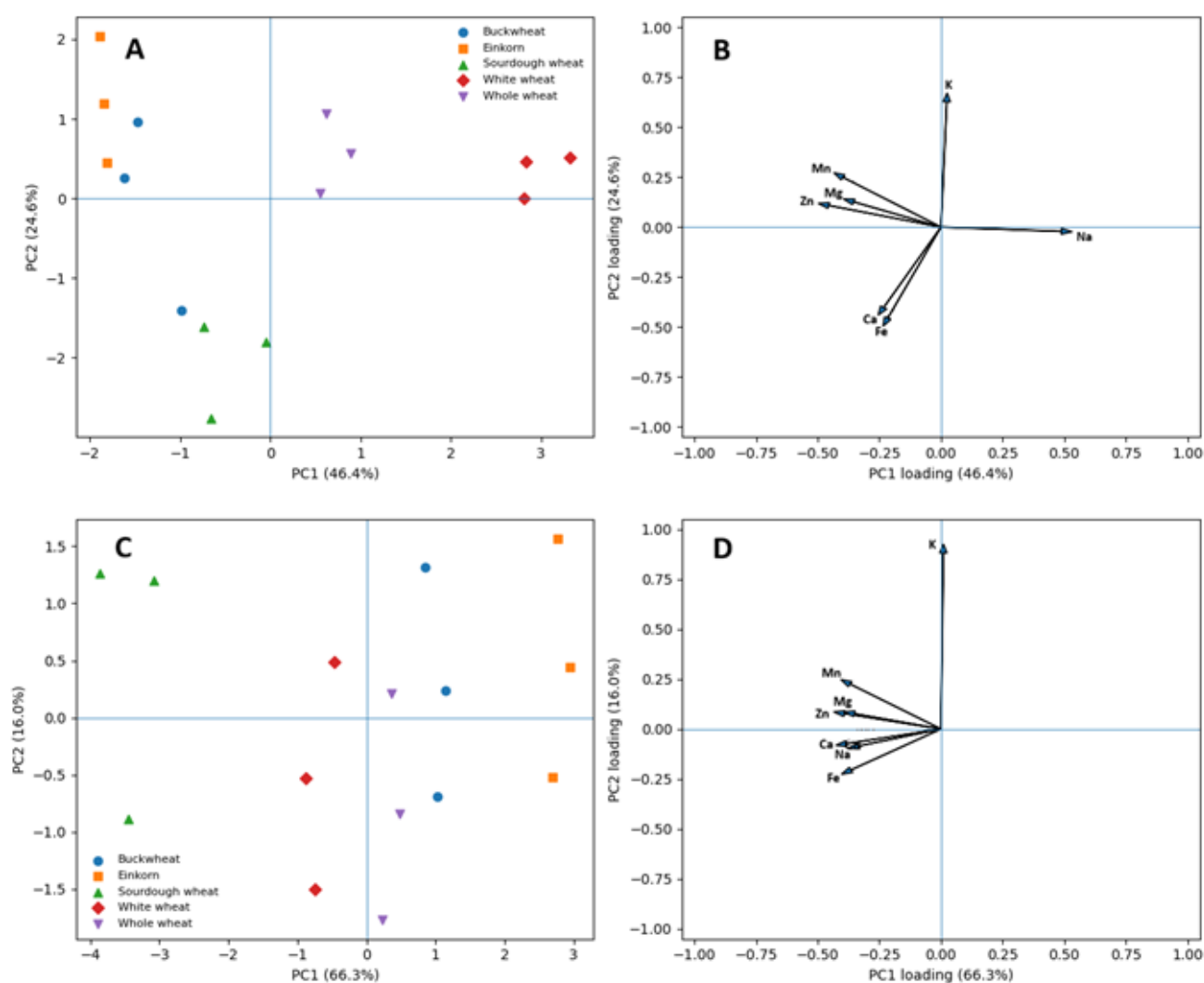


Figure 3. Principal component analysis (PCA) of mineral profiles in bread samples. (A) Score plot based on total mineral content (mg/kg). (B) Loading plot for the PCA model based on total mineral content (mg/kg). (C) Score plot based on mineral bioaccessibility (%). (D) Loading plot for the PCA model based on mineral bioaccessibility (%). Scores are shown at the replicate level ($n=5$ per bread type), and variables were autoscaled prior to PCA

Finally, the bioaccessibility percentages obtained in this study are of the same order of magnitude as those reported for vegetables, legumes and by-products using similar static in vitro digestion models. For example, Fărcaș et al., (2022) reported generally 30-70% bioaccessibility for macrominerals and a wider range for microminerals, depending on the element, in brewer's spent grain by-products; Apaydin & Afşar, (2025) also reported high percentages for K and Na and moderate levels for Fe and Zn in an in vitro mineral bioaccessibility study on vegetables. This similarity suggests that the modified INFOGEST protocol used here provides a suitable comparison basis for cereal-based foods and that the values obtained are consistent with the literature. Nevertheless, since this study relies solely on static in vitro models, it does not fully reflect true bioavailability, and the results should be supported by data from Caco-2 cell models or human studies; this should be regarded as an important methodological limitation (de Souza Scherrer Medeiros et al., 2024; Etcheverry et al., 2012; Ruan et al., 2024)

Evaluation of Mineral Bioaccessibility of Bread Types in Relation to RDI Values

Table 5 lists the mineral intake values recommended by the European Food Safety Authority (EFSA) for an average adult individual (approximately 70 kg, male or female) (RDI - Recommended Daily Intake) (Bresson et al., 2015; EFSA, 2013, 2015, 2016, 2017, 2019; Morrissey et al., 2020). In this study, the extent to which the in vitro bioaccessible mineral amounts determined according to the INFOGEST protocol in five bread types commonly consumed in Türkiye meet the EFSA recommended daily intake values for adults was evaluated. The evaluation was based on the reference values reported for adult men and women weighing 70 kg, and one serving of bread was assumed to be 250 g. In this context, EFSA's recommended daily intake levels for potassium (K), magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), manganese (Mn) and zinc (Zn) were taken as the basis.

Table 5. EFSA dietary reference values for selected minerals in adults (\approx 70 kg)

Mineral	EFSA RDI - men	EFSA RDI - women
K	3500 mg (AI) (EFSA, 2016; Morrissey et al., 2020)	3500 mg (AI) (EFSA, 2016; Morrissey et al., 2020)
Mg	350 mg (AI) (EFSA, 2015)	300 mg (AI) (EFSA, 2015)
Ca	950 mg (PRI) (EFSA, 2017)	950 mg (PRI) (EFSA, 2017)
Na	2000 mg (AI; \approx 5 g salt) (EFSA, 2019; Morrissey et al., 2020)	2000 mg (AI; \approx 5 g salt) (EFSA, 2019; Morrissey et al., 2020)
Fe	11 mg (PRI; men/postmenopausal women) (Bresson et al., 2015)	16 mg (PRI; premenopausal women) (Bresson et al., 2015)
Mn	3 mg (AI) (EFSA, 2013)	3 mg (AI) (EFSA, 2013)
Zn	9.4-16.3 mg (PRI range) (EFSA, 2017)	7.5-12.7 mg (PRI range) (EFSA, 2017)

AI: adequate intake; PRI: population reference intake. Values are given for healthy adults (\approx 70 kg) according to EFSA opinions. For zinc, PRI is expressed as a range depending on the phytate content of the diet.

According to the values indicated in Table 5, the adequate intake for adults is approximately 3500 mg/day for potassium, 350 mg/day for magnesium in men and 300 mg/day in women, a population reference intake (PRI) of 950 mg/day for calcium, an adequate intake of 2000 mg/day for sodium, 11 mg/day for iron in men and 16 mg/day in premenopausal women, 3

mg/day for manganese, and approximately 7.5-12.7 mg/day for zinc depending on the phytate content of the diet. These references were used as the basis for interpreting the coverage ratios calculated for the different bread types below. In addition, the mineral fraction that can be absorbed as a result of in vitro digestion for 1 portion (250 g) of bread is given in Table 6.

Table 6. Amount of bioaccessible minerals in a 250 g portion of bread (mg per portion)

Mineral	White wheat	Buckwheat	Sourdough	Whole wheat	Einkorn
K	561.88±5.51 ^a	567.90±117.63 ^a	507.48±68.43 ^a	585.41±45.26 ^a	608.14±43.46 ^a
Mg	25.73±3.79 ^b	44.07±4.64 ^a	28.51±4.25 ^b	24.55±0.58 ^b	25.12±1.32 ^b
Ca	5.78±0.63 ^c	5.76±0.43 ^c	17.08±1.53 ^a	7.28±0.59 ^{bc}	8.72±1.49 ^b
Na	682.03±91.94 ^a	248.13±46.53 ^{cd}	459.25±44.12 ^b	320.53±78.10 ^c	167.34±11.39 ^d
Fe	0.83±0.13 ^b	5.78±0.89 ^a	6.38±1.53 ^a	2.07±0.34 ^b	0.87±0.10 ^b
Mn	0.07±0.02 ^c	1.25±0.28 ^b	1.01±0.26 ^b	0.10±0.01 ^c	2.36±0.28 ^a

Values are expressed as mean ± standard deviation (n=5). Different lowercase letters in the same row indicate significant differences among bread types ($P<0.05$).

As shown in Table 7, the percentage contribution of a 250 g bread portion to EFSA dietary reference values was calculated using the bioaccessible mineral amounts. The contribution differed markedly by bread type and mineral, with particularly

notable variation for Fe and Mn, while Ca contribution remained limited across all samples. Zn is reported as a range reflecting the EFSA reference value range and, consequently, a range in calculated contribution.

Table 7. Percentage contribution (%) of a 250 g portion of bread to EFSA dietary reference values (men/women), calculated from bioaccessible mineral amounts

Mineral	White wheat	Buckwheat	Sourdough	Whole wheat	Einkorn
K	16.05/16.05	16.23/16.23	14.5/14.5	16.73/16.73	17.38/17.38
Mg	7.35/8.58	12.59/14.69	8.15/9.5	7.01/8.18	7.18/8.37
Ca	0.61/0.61	0.61/0.61	1.8/1.8	0.77/0.77	0.92/0.92
Na	34.1/34.1	12.41/12.41	22.96/22.96	16.03/16.03	8.37/8.37
Fe	7.55/5.19	52.55/36.12	58/39.88	18.82/12.94	7.91/5.44
Mn	2.33/2.33	41.67/41.67	33.67/33.67	3.33/3.33	78.67/78.67
Zn	0.80-1.38/1.02-1.73	10.43-18.09/13.39-22.67	10.67-18.51/13.70-23.20	10.80-18.72/13.86-23.47	12.58-21.81/16.14-27.33

Values are expressed as % contribution of a 250 g bread portion to EFSA adult dietary reference values and were calculated as: (bioaccessible amount in 250 g portion / EFSA reference value) × 100. Values are presented as men / women (separated by '/'). For Zn, results are shown as ranges because EFSA reference values are provided as ranges; therefore, the calculated % contribution is also expressed as a range. Percentages are based on the bioaccessible mineral amounts reported in Table 6.

Potassium

The bioaccessible potassium content in a 250 g portion of bread ranged between 507 and 608 mg across bread types. Einkorn bread provided the highest amount, with 608 mg, whereas sourdough wheat bread showed the lowest level at approximately 507 mg. When these values are evaluated against EFSA's adequate intake of 3500 mg/day for potassium, it is seen that a 250 g bread portion covers approximately 14-17% of the potassium RDI. The differences among bread types are relatively limited, and all breads make a similar contribution to potassium requirements. Thus, bread provides a meaningful but limited contribution to daily potassium intake; the majority of the requirement must still be met from other sources such as vegetables, fruits and legumes. When this result is evaluated together with findings on the importance of potassium in cardiovascular health and blood pressure control (for example, nutritional studies demonstrating the association between the sodium/potassium ratio and cardiometabolic risk in adults), it further underscores the need to increase the consumption of vegetables and fruits in the overall diet (Morrissey et al., 2020).

Magnesium

Magnesium shows marked differences among the breads. According to EFSA, the adequate intake for magnesium is 350 mg/day for men and 300 mg/day for women. In this study, the bioaccessible magnesium amount in a 250 g bread portion ranged between 24.6 and 44.1 mg. The highest value was found in buckwheat bread (44.1 mg), followed by sourdough bread (28.5 mg) and einkorn (25.1 mg); in white and whole wheat breads, the bioaccessible Mg content was around 24-26 mg. These findings show that one portion of buckwheat bread can cover approximately 13% of the magnesium RDI in men and 15% in women, while the other breads generally cover about 7-10%. Therefore, consumption of whole grain and particularly buckwheat-based breads may provide a meaningful contribution to daily magnesium intake, but it is not sufficient on its own. The literature reports that sourdough fermentation enhances magnesium absorption by degrading phytic acid and that sourdough whole wheat bread is particularly advantageous in terms of Mg bioaccessibility (Lopez et al., 2003). The findings of the present study are consistent with these reports, given the relatively high bioaccessible Mg levels observed in sourdough wheat bread.

Calcium

EFSA recommends a population reference intake of approximately 950 mg/day for calcium. In the present study, the bioaccessible calcium content in a 250 g bread portion was approximately 5.8 mg in white and buckwheat breads, 7.3 mg in whole wheat bread, 8.7 mg in einkorn bread and 17.1 mg in sourdough bread.

When these values are compared with the RDI, it is evident that even sourdough bread alone covers only about 2% of the daily calcium requirement, while the other breads provide well below 1%. The results clearly demonstrate that bread consumption plays a very limited role in meeting calcium requirements. This finding is in line with many studies indicating that calcium content in bread is low and that the presence of phytate restricts calcium absorption (Ting & Loh, 2016).

In whole wheat and einkorn breads, calcium content may be slightly higher than in white bread due to the whole-grain structure, but components such as phytate may partially hinder calcium absorption. It has been reported that sourdough fermentation, unlike its effect on iron and zinc, does not have a marked impact on calcium absorption (Lopez et al., 2003). Therefore, foods such as milk and dairy products and leafy green vegetables should be the primary sources of calcium, which is critical for bone health, and bread consumption can provide only a minor contribution to calcium requirements (Emkey & Emkey, 2012; Pravina et al., 2013). From a public health perspective, the prevention of calcium deficiency should focus on the consumption of other calcium-rich sources independently of bread.

Sodium

EFSA defines an adequate intake for sodium of 2000 mg/day (approximately 5 g of table salt) for adults and notes that long-term intakes above this value may increase cardiovascular risks (EFSA, 2019). The bioaccessible sodium content in a 250 g bread portion ranged between 167 and 682 mg depending on the bread type.

In white wheat bread, a 250 g portion provided approximately 682 mg sodium, covering about 34% of EFSA's recommended daily intake; sourdough bread provided approximately 459 mg, corresponding to 23%; whole wheat bread about 321 mg (16%); buckwheat bread about 248 mg (12%); and einkorn

bread about 167 mg (8%). These results show that, particularly for white wheat and sourdough breads, bread consumption makes a substantial contribution to daily salt intake, whereas einkorn and buckwheat breads provide a comparatively lower, but still non-negligible, sodium load per portion. The high sodium bioaccessibility in white bread is expected, as sodium chloride is highly soluble and is typically present as added salt rather than being bound to anti-nutritional ligands; therefore, a substantial proportion remains readily available in the soluble fraction during *in vitro* digestion. In public health terms, this supports bread-focused salt-reduction actions, since bread is a staple and a major contributor to population salt intake (Kugler et al., 2025).

From a public health standpoint, these findings indicate that both the type of bread and the portion size should be carefully considered when evaluating dietary sodium intake. Reducing the salt content of bread formulations and preferring lower-sodium bread varieties represent realistic strategies to decrease population sodium intake. Nutritional studies have consistently reported that a significant proportion of daily sodium intake in many populations originates from bread and similar processed products, and that a high sodium/potassium ratio is associated with hypertension and increased cardiovascular risk (Brown et al., 2009; Morrissey et al., 2020). Thus, salt-reduction strategies in bread production are critical, and should be implemented in parallel with efforts to preserve the contribution of bread to the intake of beneficial minerals.

Iron

Iron is a mineral whose deficiency is particularly common in the population (Lopez et al., 2016; Pasricha et al., 2021; Zimmermann & Hurrell, 2007). EFSA recommends an iron intake of 11 mg/day for adult men and 16 mg/day for premenopausal women (Bresson et al., 2015). In the breads examined, the bioaccessible iron amount per 250 g portion was 0.83 mg in white bread, 0.87 mg in einkorn bread, 2.07 mg in whole wheat bread, 5.78 mg in buckwheat bread and 6.38 mg in sourdough bread.

These values indicate that consumption of sourdough wheat bread can cover approximately 58% of the iron RDI for men and about 40% for women. Similarly, buckwheat bread can supply roughly 50% of the RDI for men and 35% for women. Whole wheat bread provides about 19% of the RDI for

men and 13% for women, whereas white and einkorn breads contribute only around 5-8%.

The literature shows that phytic acid severely limits iron absorption in breads made from whole grain flours, whereas sourdough fermentation significantly increases the bioavailability of iron by reducing phytate levels (Bálint et al., 2001). The high bioaccessible Fe amounts observed in sourdough bread in this study are consistent with these findings. However, it should be borne in mind that the data presented here are based on an *in vitro* digestion model and may not fully reflect actual human absorption.

Studies have shown that bread made with yeast and whole grain flour adversely affects iron absorption, whereas bread made with sourdough significantly increases iron absorption (Lopez et al., 2016). Consumption of whole grain and particularly sourdough breads may help prevent iron deficiency to some extent by increasing the bioavailability of dietary iron. From a public health perspective, the widespread use of sourdough in bread making and the preference for whole grain flours could enhance the bio-utilization of dietary iron and thereby contribute to reducing the risk of anemia (Bresson et al., 2015; Lopez et al., 2016; Lopez et al., 2003).

Manganese

For manganese, EFSA proposes an adequate intake of 3 mg/day for adults (EFSA, 2013). The bioaccessible manganese amount in a 250 g bread portion was determined as 0.07 mg in white bread, 0.10 mg in whole wheat bread, 1.01 mg in sourdough bread, 1.25 mg in buckwheat bread and 2.36 mg in einkorn bread.

According to these results, einkorn bread alone can cover approximately 75-80% of the manganese RDI, buckwheat bread around 40%, and sourdough bread about 30-35%. White and conventional whole wheat breads, on the other hand, make only a very limited contribution to manganese requirements (about 2-3%). These findings indicate that whole grains and especially ancient wheat types (einkorn) are extremely rich in manganese and that regular consumption can practically eliminate the risk of manganese deficiency. Overall, consumption of whole grain bread is an effective way to meet manganese requirements. Manganese is a trace element required for metabolism and is involved in the structure of antioxidant enzymes (Kippler & Oskarsson, 2024). Breads, particularly whole grain varieties, are

so rich in manganese that, with regular consumption, inadequate intake of this mineral is rarely observed in the population (Ainyanbhor et al., 2025; EFSA, 2017). This finding shows that whole wheat bread is an important source of manganese in the traditional Turkish diet and contributes positively to public health in this respect.

Zinc

Zinc is another trace mineral required for immune function and enzymatic reactions (Gibson et al., 2016). EFSA dietary reference values for zinc vary depending on dietary phytate exposure; therefore, the estimated contribution of bread to zinc intake is expressed as a range (Magallanes-López et al., 2017). In a 250 g bread portion, the bioaccessible zinc amount was 0.13 mg in white bread, 1.70 mg in buckwheat bread, 1.74 mg in sourdough bread, 1.76 mg in whole wheat bread and 2.05 mg in einkorn bread.

White bread contributes only about 0.8-1.38% (men) / 1.02-1.73% (women) of the zinc reference values, whereas buckwheat, sourdough, whole wheat and einkorn breads provide a higher contribution ranging approximately from ~10-27%, depending on the reference value assumed. As sourdough fermentation increases zinc absorption by degrading phytic acid, previous studies have noted that sourdough whole wheat bread is among the most favourable options in terms of zinc bioaccessibility (Lopez et al., 2016; Lopez et al., 2003; Ting & Loh, 2016).

Overall, although none of the bread types alone provides a high proportion of zinc, the bread type and preparation method have a major influence on the bioavailability of zinc. As with iron, sourdough whole grain bread is the most preferable option for zinc, and the zinc obtained from such bread may contribute up to about 10-15% of EFSA's average recommendation. This is several times higher than the contribution of white bread. Consequently, the combination of whole grains and sourdough may play a positive role in preventing zinc deficiency; however, foods rich in zinc such as red meat, nuts and legumes should still constitute the primary dietary sources, while bread should be considered a complementary source (Gibson et al., 2016; Lopez et al., 2016; Lopez et al., 2003; Magallanes-López et al., 2017; Ting & Loh, 2016).

CONCLUSION

This study provided a comparative evaluation of the mineral composition and in vitro mineral bioaccessibility of five bread types commonly consumed in Türkiye, namely white wheat, whole wheat, einkorn, buckwheat and sourdough wheat bread, using a modified INFOGEST static digestion model. The results showed that potassium was the predominant macromineral in all breads, while marked differences were observed for magnesium, calcium, sodium and trace elements. White wheat bread was characterized by the highest sodium content but the lowest levels of Fe, Mn and Zn, whereas buckwheat and einkorn breads exhibited a distinctly richer profile in Mg, Fe, Mn and Zn. Sourdough wheat bread showed intermediate or high total mineral contents for several elements and, more importantly, consistently favourable in vitro bioaccessibility values for Fe, Mn and Zn.

The in vitro digestion experiments demonstrated that K and Na were the most bioaccessible minerals across all bread types, while Ca, Fe and Mn were present in the soluble fraction at lower percentages. Sourdough bread, and to a lesser extent buckwheat and whole wheat breads, provided higher bioaccessible amounts of Fe and Zn than white and einkorn breads, underscoring the importance of both grain type and fermentation process for mineral bioaccessibility. At the same time, the comparison between total mineral content and bioaccessible fractions clearly indicated that a high mineral concentration in the raw product does not necessarily translate into a proportionally higher bioaccessible amount, as exemplified by einkorn bread, which is rich in several minerals but showed relatively modest bioaccessibility for some of them, particularly Ca and Fe. The integrated comparison of bioaccessibility (Figure 1) and total vs dialyzable mineral levels (Figure 2) provides a consolidated overview of these trends.

When the bioaccessible mineral contents were interpreted in relation to EFSA reference values for adults (assuming a 250 g bread portion), bread was found to make a modest contribution to daily K and Mg intakes, a negligible contribution to Ca intake, and a substantial contribution to Na intake, especially in the case of white wheat bread. Sourdough and buckwheat breads were able to supply a considerable proportion of the recommended daily intake for Fe, while whole grain and einkorn breads made meaningful contributions to Mn and

Zn. Nevertheless, for Ca and Zn in particular, bread should be regarded as a complementary rather than primary dietary source, and its potential benefits in terms of Fe, Mn and Zn must be weighed against the concurrent sodium load. From a public health perspective, these findings support strategies that promote whole grain and sourdough breads while simultaneously reducing salt levels in formulations.

Methodologically, this work is constrained by the use of a static in vitro digestion model, which does not fully reflect in-vivo bioavailability (absorption and post-absorptive utilization), and by the fact that commercial breads with non-standardized formulations (e.g. salt level, use of milk powder or mineral fortification, flour extraction rate) were evaluated. The data therefore represent a realistic snapshot of the Turkish market rather than controlled formulations. Future studies should combine standardized formulations with Caco-2 cell models or human intervention trials to better elucidate the relationship between processing conditions, grain type, fermentation and true mineral bioavailability. Despite these limitations, the present results provide a useful reference framework for understanding the nutritional contribution of different bread types to mineral intake in the Turkish diet and highlight the potential role of product reformulation in improving mineral nutrition without increasing sodium exposure.

Additionally, phytate content and the inositol phosphate distribution were not measured; therefore, phytate-to-mineral molar ratios could not be computed and the contribution of phytate hydrolysis to mineral bioaccessibility could not be directly assessed. Also, detailed formulation and processing information (e.g., declared salt level, flour extraction/bran content, and fermentation conditions) was not consistently available for the purchased products, particularly for bakery-sold items; therefore, such parameters could not be systematically compiled in a comparative table. This lack of standardized formulation metadata is acknowledged as a study limitation and likely contributes to the observed within-category variability.

CONFLICTS OF INTEREST

The author declare that there is no conflict of interest

AUTHOR CONTRIBUTIONS

Hakan APAYDIN: Investigation, writing - original draft, review&editing, Methodology, validation.

REFERENCES

- Adrogué, H. J., Madias, N. E. (2007). Sodium and potassium in the pathogenesis of hypertension. *The New England Journal of Medicine*, 356(19), 1966-1978. <https://doi.org/10.1056/NEJMra064486>
- Ainyanbhor, I. E., Edo, G. I., Akpogheli, P. O., Owhero, J. O., Gaaz, T. S., Yousif, E., & Umar, H. (2025). A review on manganese and its effect on health and distribution in selected African countries. *Journal of Trace Elements in Medicine and Biology*, 91, 127707. <https://doi.org/10.1016/j.jtemb.2025.127707>
- Alhagri, I. A., Albeshry, M. (2023). Microwave-Assisted Digestion Using Dilute Nitric Acid and Hydrogen Peroxide for Multielement Determination in Wheat Flour by ICP-MS. *Journal of Chemistry*, 2023(1), 2349838. <https://doi.org/10.1155/2023/2349838>
- Alkay, Z., Alkay, R., Dertli, E., Kökten, K., Durak, M. Z. (2023). Rheological, Textural and Physicochemical Properties of Buckwheat Sourdough Bread Prepared With Different Lactic Acid Bacteria Strains. *Journal of Microbiology, Biotechnology and Food Sciences*, 12(5). <https://doi.org/10.55251/jmbfs.5643>
- Alkay, Z., Falah, F., Cankurt, H., Dertli, E. (2024). Exploring the Nutritional Impact of Sourdough Fermentation: Its Mechanisms and Functional Potential. *Foods*, 13(11). <https://doi.org/10.3390/foods13111732>
- Alvarez-Jubete, L., Arendt, E. K., Gallagher, E. (2010). Nutritive value of pseudocereals and their increasing use as functional gluten-free ingredients. *Trends in Food Science & Technology*, 21(2), 106-113. <https://doi.org/10.1016/j.tifs.2009.10.014>
- AOAC. (2016). Appendix F: Guidelines for standard method performance requirements. *AOAC Official Methods of Analysis*, 1-16.
- Apaydin, H., Afşar, A. S. (2025). Evaluation of In-Vitro Mineral Bioaccessibility of Commonly Consumed Vegetables. *Gıda*, 50(5), 713-722.
- Aslam, M. F., Arafsha, S. M., Berry, S. E., Bajka, B., Ellis, P. R., Latundada, G. O., & Sharp, P. A. (2024). Micronization of wholewheat flour increases iron bioavailability from hydrothermally processed wheat flour dough. *Food Research International*, 197(P1), 115149. <https://doi.org/10.1016/j.foodres.2024.115149>
- Bálint, A. F., Kovács, G., Erdei, L., Sutka, J. (2001). Comparison of the Cu, Zn, Fe, Ca and Mg contents of the grains of wild, ancient and cultivated wheat species. *Cereal Research Communications*, 29(3), 375-382. <https://doi.org/10.1007/BF03543684>

- Begum, R., Akter, S., Akter, S., Rahman, A., Alim, M. A. (2023). Physicochemical properties and storage stability of commercial breads available in Tangail, Bangladesh. *Food and Humanity*, 1, 1645-1651. <https://doi.org/10.1016/j.foohum.2023.11.014>
- Belc, N., Duta, D. E., Culetu, A., Stamatie, G. D. (2021). Type and Amount of Legume Protein Concentrate Influencing the Technological, Nutritional, and Sensorial Properties of Wheat Bread. *Applied Sciences*, 11(1). <https://doi.org/10.3390/app11010436>
- Bhavsar, G. J., Sawate, A. R., B. K. R., Chappalwar, V. M. (2013). Studies on Physico-Chemical Characteristics of Buckwheat and Its Exploration in Bread as Functional Food. *International Journal of Engineering Research and Technology*, 2(11), 3971-3980. www.ijert.org
- Bodor, K., Szilágyi, J., Incze, J., Ungvári, B., Bodor, Z. (2025). Examination of the physico-chemical parameters of some romanian breads. *Applied Food Research*, 5(1), 100744. <https://doi.org/10.1016/j.afres.2025.100744>
- Bonafaccia, G., Gambelli, L., Fabjan, N., Kreft, I. (2003). Trace elements in flour and bran from common and tartary buckwheat. *Food Chemistry*, 83(1), 1-5. [https://doi.org/10.1016/S0308-8146\(03\)00228-0](https://doi.org/10.1016/S0308-8146(03)00228-0)
- Brandolini, A., Lucisano, M., Mariotti, M., Estivi, L., Hidalgo, A. (2023). Breadmaking Performance of Elite Einkorn (*Triticum monococcum* L. subsp. *monococcum*) Lines: Evaluation of Flour, Dough and Bread Characteristics. *Foods*, 12(8). <https://doi.org/10.3390/foods12081610>
- Bresson, J. L., Burlingame, B., Dean, T., Fairweather-Tait, S., Heinonen, M., Hirsch-Ernst, K. I., & Willatts, P. (2015). Scientific Opinion on Dietary Reference Values for iron. *EFSA Journal*, 13(10), 1-117. <https://doi.org/10.2903/j.efsa.2015.4254>
- Brites, L. T. G. F., Rebellato, A. P., Meinhart, A. D., Godoy, H. T., Pallone, J. A. L., & Steel, C. J. (2022). Technological, sensory, nutritional and bioactive potential of pan breads produced with refined and whole grain buckwheat flours. *Food Chemistry: X*, 13, 100243. <https://doi.org/10.1016/j.fochx.2022.100243>
- Brodkorb, A., Egger, L., Alminger, M., Alvito, P., Assunção, R., Ballance, S., & Recio, I. (2019). INFOGEST static in vitro simulation of gastrointestinal food digestion. *Nature Protocols*, 14(4), 991-1014. <https://doi.org/10.1038/s41596-018-0119-1>
- Brown, I. J., Tzoulaki, I., Candeias, V., Elliott, P. (2009). Salt intakes around the world: implications for public health. *International Journal of Epidemiology*, 38(3), 791-813. <https://doi.org/10.1093/ije/dyp139>
- Bryszewska, M. A., Tomás-Cobos, L., Gallego, E., Villalba, M. P., Rivera, D., Taneyo Saa, D. L., & Gianotti, A. (2019). In vitro bioaccessibility and bioavailability of iron from breads fortified with microencapsulated iron. *Lwt*, 99(April 2018), 431-437. <https://doi.org/10.1016/j.lwt.2018.09.071>
- Ciudad-Mulero, M., Matallana-González, M. C., Callejo, M. J., Carrillo, J. M., Morales, P., & Fernández-Ruiz, V. (2021). Durum and Bread Wheat Flours. Preliminary Mineral Characterization and Its Potential Health Claims. *Agronomy*, 11(1). <https://doi.org/10.3390/agronomy11010108>
- Comunian, T. A., Freitas, D., Drouin, G., Maudhuit, A., Roelens, G., Poncelet, D., Drusch, S., & Brodkorb, A. (2024). Semi-dynamic in vitro digestion of sourdough bread enriched with flaxseed oil coacervates. *Food Structure*, 40, 100371. <https://doi.org/10.1016/j.foostr.2024.100371>
- Cunniff, P., Washington, D. (1997). Official methods of analysis of AOAC International. *J. AOAC Int*, 80(6), 127A.
- de Souza Scherrer Medeiros, L., Grancieri, M., Sant'Ana, C. T., de Araujo Santiago, M. C. P., da Silva, L. B., Glahn, R. P., & Costa, N. M. B. (2024). The lower content of mineral-complexing compounds favored the in vitro and in vivo iron bioavailability of biofortified cowpeas. *Journal of Functional Foods*, 123, 106601. <https://doi.org/10.1016/j.jff.2024.106601>
- Dewettinck, K., Van Bockstaele, F., Kühne, B., Van de Walle, D., Courtens, T. M., Gellynck, X. (2008). Nutritional value of bread: Influence of processing, food interaction and consumer perception. *Journal of Cereal Science*, 48(2), 243-257. <https://doi.org/10.1016/j.jcs.2008.01.003>
- Echavarría, J. A. C., El Hajj, S., Irankunda, R., Selmeçzi, K., Paris, C., Udenigwe, C. C., & Canabady-Rochelle, L. (2024). Screening, separation and identification of metal-chelating peptides for nutritional, cosmetics and pharmaceutical applications. *Food Funct*, 15(7), 3300-3326. <https://doi.org/10.1039/D3FO05765H>
- EFSA. (2013). Scientific Opinion on Dietary Reference Values for manganese. *EFSA Journal*, 11(11), 3419. <https://doi.org/10.2903/j.efsa.2013.3419>
- EFSA. (2015). *Dietary reference values: magnesium and phosphorus*.
- EFSA. (2016). Dietary reference values for potassium. *EFSA Journal*,

- 14(10), e04592. <https://doi.org/10.2903/j.efsa.2016.4592>
- EFSA. (2017). Dietary Reference Values for nutrients Summary report. *EFSA Supporting Publications*, 14(12), e15121E. <https://doi.org/10.2903/sp.efsa.2017.e15121>
- EFSA. (2019). Dietary reference values for sodium. *EFSA Journal*, 17(9), e05778. <https://doi.org/10.2903/j.efsa.2019.5778>
- EL Houssni, I., Zahidi, A., Khedid, K., Hassikou, R. (2024). Review of processes for improving the bioaccessibility of minerals by reducing the harmful effect of phytic acid in wheat. *Food Chemistry Advances*, 4, 100568. <https://doi.org/10.1016/j.focha.2023.100568>
- El, I., Zahidi, A., Khedid, K., Hassikou, R. (2024). Review of processes for improving the bioaccessibility of minerals by reducing the harmful effect of phytic acid in wheat. *Food Chemistry Advances*, 4(December 2023), 100568. <https://doi.org/10.1016/j.focha.2023.100568>
- Emkey, R. D., Emkey, G. R. (2012). Calcium Metabolism and Correcting Calcium Deficiencies. *Endocrinology and Metabolism Clinics*, 41(3), 527-556. <https://doi.org/10.1016/j.ecl.2012.04.019>
- Etcheverry, P., Grusak, M. A., Fleige, L. E. (2012). Application of in vitro bioaccessibility and bioavailability methods for calcium, carotenoids, folate, iron, magnesium, polyphenols, zinc, and vitamins B(6), B(12), D, and E. *Frontiers in Physiology*, 3, 317. <https://doi.org/10.3389/fphys.2012.00317>
- Fărcaș, A. C., Socaci, S. A., Chiș, M. S., Martínez-Monzó, J., García-Segovia, P., Becze, A., Török, A. I., Cadar, O., Coldea, T. E., & Igual, M. (2022). In Vitro Digestibility of Minerals and B Group Vitamins from Different Brewers' Spent Grains. *Nutrients*, 14(17). <https://doi.org/10.3390/nu14173512>
- Faria, M. A., Araújo, A., Pinto, E., Oliveira, C., Oliva-Teles, M. T., Almeida, A., Delerue-Matos, C., & Ferreira, I. M. P. L. V. O. (2018). Bioaccessibility and intestinal uptake of minerals from different types of home-cooked and ready-to-eat beans. *Journal of Functional Foods*, 50, 201-209. <https://doi.org/10.1016/j.jff.2018.10.001>
- Fayaz, U., Dar, A. H., Kumar, N., Junaid, P. M., Shams, R., Khan, S. A. (2021). Formulations and quality characterization of low salt flat bread: Effects on functionality, rheological and sensory properties. *Applied Food Research*, 1(1), 100005. <https://doi.org/10.1016/j.afres.2021.100005>
- Ferruzzi, M. G., Kruger, J., Mohamedshah, Z., Debelo, H., Taylor, J. R. N. (2020). Insights from in vitro exploration of factors influencing iron, zinc and provitamin A carotenoid bioaccessibility and intestinal absorption from cereals. *Journal of Cereal Science*, 96, 103126. <https://doi.org/10.1016/j.jcs.2020.103126>
- Frontela, C., Ros, G., Martínez, C. (2011). Phytic acid content and “in vitro” iron, calcium and zinc bioavailability in bakery products: The effect of processing. *Journal of Cereal Science*, 54(1), 173-179. <https://doi.org/10.1016/j.jcs.2011.02.015>
- Gibson, R. S., King, J. C., Lowe, N. (2016). A Review of Dietary Zinc Recommendations. *Food and Nutrition Bulletin*, 37(4), 443-460. <https://doi.org/10.1177/0379572116652252>
- Gupta, R. K., Gangoliya, S. S. (2015). Reduction of phytic acid and enhancement of bioavailable micronutrients in food grains. 52(February), 676-684. <https://doi.org/10.1007/s13197-013-0978-y>
- Hayta, M., Hendek Ertop, M. (2018). Evaluation of microtextural properties of sourdough wheat bread obtained from optimized formulation using scanning electron microscopy and image analysis during shelf life. *Journal of Food Science and Technology*, 55(1), 1-9. <https://doi.org/10.1007/s13197-017-2823-1>
- Keçeli, A., Kaplan Evlice, A., Pehlivan, A., Şanal, T., Zencirci, N. (2021). Bread-making properties of einkorn wheat (*Triticum monococcum* ssp. *monococcum*) and its suitability for whole wheat bread production. *Cereal Research Communications*, 49(4), 625-637. <https://doi.org/10.1007/s42976-021-00146-0>
- Kippler, M., Oskarsson, A. (2024). Manganese - a scoping review for Nordic Nutrition Recommendations 2023. *Food & Nutrition Research*, 68. <https://doi.org/10.29219/fnr.v68.10367>
- Klepcka, J., Najda, A., Klimek, K. (2020). Effect of Buckwheat Groats Processing on the Content and Bioaccessibility of Selected Minerals. *Foods (Basel, Switzerland)*, 9(6). <https://doi.org/10.3390/foods9060832>
- Kugler, S., Hristov, H., Blaznik, U., Hribar, M., Hafner, E., Kušar, A., Pravst, I. (2025). Insights into the salt levels in bread offers in Slovenia: trends and differences. *Frontiers in Nutrition*, Volume 11-2024. <https://doi.org/10.3389/fnut.2024.1473362>
- Latha Rani, R., Kulkarni, U. N., Biradar, S. (2022). Essential mineral composition of buckwheat (*Fagopyrum esculentum*) varieties for nutrition security.
- Longin, C. F. H., Afzal, M., Pfannstiel, J., Bertsche, U., Melzer, T., Ruf, A., & Rodehutschord, M. (2023). Mineral and Phytic Acid Content as

- Well as Phytase Activity in Flours and Breads Made from Different Wheat Species. *International Journal of Molecular Sciences*, 24(3). <https://doi.org/10.3390/ijms24032770>
- Lopez, A., Cacoub, P., Macdougall, I. C., Peyrin-Biroulet, L. (2016). Iron deficiency anaemia. *The Lancet*, 387(10021), 907-916. [https://doi.org/10.1016/S0140-6736\(15\)60865-0](https://doi.org/10.1016/S0140-6736(15)60865-0)
- Lopez, H. W., Duclos, V., Coudray, C., Krespine, V., Feillet-Coudray, C., Messenger, A., Demigné, C., & Rémésy, C. (2003). Making bread with sourdough improves mineral bioavailability from reconstituted whole wheat flour in rats. *Nutrition (Burbank, Los Angeles County, Calif.)*, 19(6), 524-530. [https://doi.org/10.1016/s0899-9007\(02\)01079-1](https://doi.org/10.1016/s0899-9007(02)01079-1)
- Lucretia Ifeoma, B., Nkechi Juliet T., E. (2021). Physical Characteristics and Mineral Composition of Bread Produced from Blends of Wheat and Defatted/Undefatted Cashew Kernel Flours. *Asian Food Science Journal*, 20(2 SE-Original Research Article), 1-11. <https://doi.org/10.9734/afsj/2021/v20i230259>
- Magallanes-López, A. M., Hernandez-Espinosa, N., Velu, G., Posadas-Romano, G., Ordoñez-Villegas, V. M. G., Crossa, J., & Guzmán, C. (2017). Variability in iron, zinc and phytic acid content in a worldwide collection of commercial durum wheat cultivars and the effect of reduced irrigation on these traits. *Food Chemistry*, 237, 499-505. <https://doi.org/10.1016/j.foodchem.2017.05.110>
- Minekus, M., Alming, M., Alvito, P., Ballance, S., Bohn, T., Bourlieu, C., & Brodtkorb, A. (2014). A standardised static in vitro digestion method suitable for food-an international consensus. *Food and Function*, 5(6), 1113 - 1124. <https://doi.org/10.1039/c3fo60702j>
- Mohajan, S., Munna, M., Orchy, T., Hoque, M., Farzana, T. (2019). Buckwheat flour fortified bread. *Bangladesh Journal of Scientific and Industrial Research*, 54(4), 347-356. <https://doi.org/10.3329/bjsir.v54i4.44569>
- Morrissey, E., Giltinan, M., Kehoe, L., Nugent, A. P., McNulty, B. A., Flynn, A., & Walton, J. (2020). Sodium and Potassium Intakes and Their Ratio in Adults (18-90 y): Findings from the Irish National Adult Nutrition Survey. *Nutrients*, 12(4). <https://doi.org/10.3390/nu12040938>
- Nargesi, M. H., Kheiralipour, K. (2025). Estimating ash content in wheat flour using visible-near infrared hyperspectral imaging and machine learning methods. *LWT*, 234, 118591. <https://doi.org/10.1016/j.lwt.2025.118591>
- Navarro, J. L., López, M. S., Salvucci, E., León, A. E., Steffolani, M. E. (2025). Chemical and Nutritional Characterization of Sourdoughs Made with Sprouted and Unsprouted Whole-Wheat Flour and Their Effects on the Technological Quality of Bread. *Foods*, 14(16). <https://doi.org/10.3390/foods14162805>
- Nsabimana, S., Ismail, T., Lazarte, C. E. (2024). Enhancing iron and zinc bioavailability in maize (*Zea mays*) through phytate reduction: the impact of fermentation alone and in combination with soaking and germination. *Frontiers in Nutrition*, 11(December), 1-13. <https://doi.org/10.3389/fnut.2024.1478155>
- Öğünç, Y. T., Aytekin, Ö., Rakıcioğlu, N. (2026). Enhancing the nutritional profile of refined wheat bread with cereal and pulse flours: assessment of phytate content and mineral bioaccessibility. *European Food Research and Technology*, 252(2), 44.
- Pasricha, S.-R., Tye-Din, J., Muckenthaler, M. U., Swinkels, D. W. (2021). Iron deficiency. *The Lancet*, 397(10270), 233-248. [https://doi.org/10.1016/S0140-6736\(20\)32594-0](https://doi.org/10.1016/S0140-6736(20)32594-0)
- Păucean, A., Șerban, L.-R., Chiș, M. S., Mureșan, V., Pușcaș, A., Man, S. M., & Pop, A. (2024). Nutritional composition, in vitro carbohydrates digestibility, textural and sensory characteristics of bread as affected by ancient wheat flour type and sourdough fermentation time. *Food Chemistry: X*, 22, 101298. <https://doi.org/10.1016/j.fochx.2024.101298>
- Piergiovanni, A. R., Rizzi, R., Pannacciulli, E., Gatta, C. Della. (1997). Mineral composition in hulled wheat grains: a comparison between emmer (*Triticum dicoccon* Schrank) and spelt (*T. spelta* L.) accessions. *International Journal of Food Sciences and Nutrition*, 48(6), 381-386.
- Pravina, P., Sayaji, D., Avinash, M. (2013). Calcium and its role in human body. *International Journal of Research in Pharmaceutical and Biomedical Sciences*, 4(2), 659-668.
- Przybylski, R., Gruczyńska, E. (2009). A Review of Nutritional and Nutraceutical Components of Buckwheat. *The European Journal of Plant Science and Biotechnology*, 3(1), 10-22.
- Renzetti, S., Theunissen, M., Horrevorts, K. (2021). A Systematic Comparison of the Intrinsic Properties of Wheat and Oat Bran Fractions and Their Effects on Dough and Bread Properties: Elucidation of Chemical Mechanisms, Water Binding, and Steric Hindrance. *Foods*, 10(10). <https://doi.org/10.3390/foods10102311>
- Ruan, R., Shiroud Heidari, B., Chen, P., Gao, J., Chen, Z., Chen, L., & Zheng, M. (2024). Converting ocean nacre into bone mineral

matrix composite for bone regeneration- in vitro and in vivo studies. *Materials & Design*, 245, 113271. <https://doi.org/10.1016/j.matdes.2024.113271>

Ruibal-Mendieta, N. L., Delacroix, D. L., Mignolet, E., Pycke, J. M., Marques, C., Rozenberg, R., & Larondelle, Y. (2005). Spelt (*Triticum aestivum* ssp. *spelta*) as a source of breadmaking flours and bran naturally enriched in oleic acid and minerals but not phytic acid. *Journal of Agricultural and Food Chemistry*, 53(7), 2751-2759. <https://doi.org/10.1021/jf048506e>

Sezer, B., Ozturk, M., Ayvaz, H., Apaydın, H., Boyacı, I. H. (2022). Laser-induced breakdown spectroscopy as a reliable analytical method for classifying commercial cheese samples based on their cooking/stretching process. *Food Chemistry*, 390, 132946. <https://doi.org/10.1016/j.foodchem.2022.132946>

Ting, S. R., Loh, S. P. (2016). In vitro bioaccessibility of calcium, iron and zinc from breads and bread spreads. *International Food Research Journal*, 23(5).

Tokarczyk, J., Koch, W. (2025). Dietary Zn—Recent Advances in

Studies on Its Bioaccessibility and Bioavailability. *Molecules*, 30(13). <https://doi.org/10.3390/molecules30132742>

Wang, Z., Wang, L. (2024a). Grain & Oil Science and Technology Impact of sourdough fermentation on nutrient transformations in cereal-based foods : Mechanisms , practical applications , and health implications. *Grain & Oil Science and Technology*, 7(2), 124-132. <https://doi.org/10.1016/j.gaost.2024.03.001>

Wang, Z., Wang, L. (2024b). Impact of sourdough fermentation on nutrient transformations in cereal-based foods: Mechanisms, practical applications, and health implications. *Grain & Oil Science and Technology*, 7(2), 124-132. <https://doi.org/10.1016/j.gaost.2024.03.001>

Zimmermann, M. B., Hurrell, R. F. (2007). Nutritional iron deficiency. *The Lancet*, 370(9586), 511-520. [https://doi.org/10.1016/S0140-6736\(07\)61235-5](https://doi.org/10.1016/S0140-6736(07)61235-5)

Żuk-Golaszewska, K., Majewska, K., Tyburski, J., Golaszewski, J. (2022). Nutritional properties of organic spelt wheats in different growth stages and the resulting flours. *Journal of Elementology*, 27(3), 645-662.

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