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# Macro- and Trace Elements in Fresh Fruits from the Reșița Agri-Food Market, Romania—Chemometric Analysis and Health Risk Assessment

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**Abstract**

Fruits are an important source of essential minerals, but can also contribute to the intake of potentially toxic elements. This study determined the moisture, macroelement (Na, K, Ca, Mg) and trace element (Cu, Mn, Fe, Cd, Pb, Zn, Cr) contents of 15 fruit species purchased from the agri-food market in Reșița, Romania, by flame and graphite furnace atomic absorption spectrometry. The data were evaluated by principal component analysis (PCA), k-means and hierarchical cluster analysis (HCA) and used to assess the health risk. Mean contents followed the orders K > Ca > Mg > Na and Fe > Zn > Mn > Cu > Cr > Pb > Cd, strawberry being the richest in most elements. The first three principal components explained over 93% of the variance and the samples clustered with literature data for the same species. Pb and Cd contents were well below EU and Codex Alimentarius limits. For daily intakes of 200 g (adults) and 175 g (children aged 6–9 years), all hazard quotients were below 1 and the margin of exposure indicated a low risk from Pb; thus, under the evaluated scenarios, the analysed fruits pose no health concern and are a valuable source of essential minerals.

**Keywords:** fruits; macroelements; trace elements; flame and graphite furnace atomic absorption spectrometry; principal component analysis; hierarchical cluster analysis; health risk assessment

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Academic Editor: Isabel Lara

Received: 1 October 2026
Revised: 3 November 2026
Accepted: 3 November 2026
Published: 5 November 2026

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## 1. Introduction

Fruits are an essential component of a healthy diet, providing water, dietary fibre, vitamins, polyphenols and mineral elements with a low energy content [1,2]. Prospective studies have shown that a higher intake of fruits and vegetables is associated with a lower risk of cardiovascular disease, cancer and all-cause mortality [3], whereas inadequate fruit and vegetable consumption was estimated to be responsible for 3.9 million deaths worldwide in 2017 [4]. For this reason, WHO/FAO recommend a daily intake of at least 400 g of fruits and vegetables [5].

Mineral elements are inorganic nutrients that cannot be synthesised by the human body and must therefore be supplied by the diet [6]. Although they are required in relatively

small amounts, they are indispensable for life: they are structural components of bones and teeth, maintain the osmotic pressure, the acid–base balance and the membrane potential of cells, act as cofactors or structural components of a large number of enzymes, hormones and transport proteins, and participate in nerve transmission, muscle contraction and the immune response [6,7]. According to the daily requirement, minerals are divided into macroelements (Na, K, Ca, Mg, P, Cl, S), required in amounts greater than 100 mg per day, and trace elements (Fe, Zn, Cu, Mn, I, Se, Mo), required in amounts of less than 100 mg per day [6,7]; Cr, traditionally included in this group, is discussed separately below, since its essentiality is uncertain. Both the deficiency and the excess of mineral elements can affect human health. Micronutrient deficiencies, also known as "hidden hunger", affect more than half of preschool-aged children and more than two-thirds of women of reproductive age worldwide [8], whereas an excessive intake of some elements or the presence of toxic elements in foods can cause adverse effects [9].

Fruits are an important dietary source of macroelements, particularly K, Mg and Ca, while their Na content is low, a composition that is favourable for the regulation of blood pressure [1,7]. K is the main intracellular cation, while Na is the main extracellular cation; the concentration gradient between them, maintained by the Na/K-ATPase pump, determines the distribution of fluids between the intracellular and extracellular compartments, the membrane potential and the transmission of nerve impulses [7]. An increased K intake lowers blood pressure and the risk of stroke, whereas an excessive Na intake has the opposite effect [10]. More than 99% of body Ca is found in bones and teeth, where it provides structural support; the remaining Ca is involved in blood coagulation, muscle contraction, nerve transmission and hormone secretion, and an adequate Ca intake is associated with a lower risk of osteoporosis and hypertension [11]. Mg, about half of which is stored in bones, participates in over 600 enzymatic reactions involved in energy metabolism, protein and nucleic acid synthesis, muscle contraction and the regulation of vascular tone, and Mg deficiency has been associated with cardiovascular disease, type 2 diabetes and osteoporosis [12].

Among the essential trace elements, Fe is a component of haemoglobin, myoglobin, cytochromes and numerous enzymes involved in oxygen transport and cellular respiration, and iron deficiency is the most common cause of anaemia worldwide, affecting especially children and women of reproductive age [13]. Zn acts as a catalytic, structural and regulatory cofactor for more than 300 enzymes and for numerous transcription factors, being essential for growth, immune function, reproduction and wound healing [14]. Cu is a component of several oxidoreductases, such as cytochrome c oxidase, ceruloplasmin and Cu/Zn superoxide dismutase, and is involved in iron metabolism, connective tissue formation and the functioning of the nervous system; Cu deficiency can lead to anaemia and bone abnormalities, whereas at high intakes Cu can promote oxidative damage to cells [15]. Mn is a cofactor of enzymes such as arginase, pyruvate carboxylase and Mn superoxide dismutase, being involved in the metabolism of amino acids, lipids and carbohydrates and in antioxidant defence; Mn deficiency is rare in humans, while excessive exposure has neurotoxic effects [16]. Cr was long considered an essential trace element, but its nutritional role in humans is now uncertain, since its essentiality is not supported by conclusive evidence; trivalent Cr, the form present in foods, is considered to have low toxicity [17].

Besides essential elements, fruits can also accumulate potentially toxic elements such as Cd and Pb, whose content depends on soil composition, the quality of irrigation water, the use of fertilisers and pesticides, and the proximity of industrial or mining areas [18–20]. These elements have no known biological function in the human body and accumulate over time in various tissues [9]. Cd accumulates mainly in the kidneys and liver, where it can cause renal dysfunction and bone demineralisation, and is classified by the International

Agency for Research on Cancer as carcinogenic to humans (Group 1) [9,21]. Pb affects the nervous system, kidneys and haematopoietic system, children being the most vulnerable group, since exposure can impair their neurological development [9]. Because these elements are toxic even at low doses and have a cumulative effect, their levels in foods are regulated, and the assessment of the health risk associated with their dietary intake is an important component of food safety [22–24].

The mineral composition of fruits depends on species, cultivar, degree of ripeness, soil and climatic conditions and agricultural practices, and has been evaluated in numerous studies for the fruit species considered in this work [25–40]. Since mineral elements are concentrated by water removal, dried fruits have considerably higher mineral contents per unit mass than fresh fruits; moreover, the drying method and commercial processing can further modify their elemental profiles [41]. For this reason, comparisons between fresh fruits, dried fruits and literature data are most meaningful when expressed on a dry weight basis. In addition, fruits contain organic acids and ascorbic acid, which increase the absorption of non-haem iron from the diet [6,13]. Nevertheless, data on the mineral composition of fruits marketed in south-western Romania remain scarce. To the best of our knowledge, no study has evaluated the essential and potentially toxic elements of fruits sold in the Reșița area, a region with a long history of metallurgical and mining activities, which may influence the trace element content of locally grown produce. Moreover, few studies have combined, for a large number of fruit species from the same market, the determination of macro- and trace elements with multivariate analysis and a health risk assessment based on current toxicological reference values.

The aim of this study was to determine the moisture content and the macroelement (Na, K, Ca, Mg) and trace element (Cu, Mn, Fe, Cd, Pb, Zn, Cr) contents of 15 fruit species belonging to five botanical families (Rosaceae, Vitaceae, Cucurbitaceae, Grossulariaceae and Ericaceae), purchased from the agri-food market in Reșița, Romania, using flame and graphite furnace atomic absorption spectrometry. The specific objectives were (i) to compare the obtained values with those reported in the literature for the same species and with the maximum levels set by the EU and the Codex Alimentarius; (ii) to identify the relationships between elements and the grouping of samples by principal component analysis (PCA), k-means clustering and hierarchical cluster analysis (HCA); and (iii) to assess the risk to human health associated with fruit consumption on the basis of the estimated daily intake (EDI), target hazard quotient (THQ), total target hazard quotient (TTHQ), margin of exposure (MOE) and carcinogenic risk (CR).

## 2. Materials and Methods

### *2.1. Reagents and Materials*

The reagents used for sample digestion were of ultrapure grade (Merck, Darmstadt, Germany): nitric acid ($HNO_3$, 65%) and hydrochloric acid (HCl, 37%). Acetylene with a purity of 99.6% (Linde, Timișoara, Romania) was used as the fuel gas for the flame. Ultrapure water (resistivity 18.2 MΩ·cm) was produced with a Milli-Q® EQ 7008/7016 water purification system (Merck) and was used for all dilutions.

### *2.2. Sample Collection and Preparation*

The fruit samples analysed in this study were purchased in July 2026 from the agri-food market in Reșița, Caraș-Severin County, Romania. The fruits were grown by local producers in the area surrounding Reșița. Since not all species were available from the same producer, each species was purchased from a single local producer, and fruits from different producers were not combined. The fruit species were selected based on how commonly they are consumed in western Romania. All fruits were at commercial (con-

sumption) maturity, i.e., ripe and ready to eat. The fruits were randomly selected from the same lot, ensuring a similar degree of maturity and the absence of visible defects. For each species, an aggregate sample of approximately 1 kg was collected, in line with the minimum aggregate sample mass recommended by Commission Regulation (EC) No 333/2007 for the determination of Pb and Cd in foodstuffs [42]; for watermelon and melon, three whole fruits were collected. The cultivars were not specified by the producers and could therefore not be reported. Fifteen fruit species belonging to five botanical families were evaluated: Rosaceae—plum (*Prunus domestica*), strawberry (*Fragaria* × *ananassa*), apple (*Malus domestica*), pear (*Pyrus communis*), peach (*Prunus persica*), apricot (*Prunus armeniaca*), sour cherry (*Prunus cerasus*) and sweet cherry (*Prunus avium*); Vitaceae—white and black grapes (*Vitis vinifera*); Cucurbitaceae—watermelon (*Citrullus lanatus*) and melon (*Cucumis melo*); Grossulariaceae—red currant (*Ribes rubrum*) and black currant (*Ribes nigrum*); and Ericaceae—highbush blueberry (*Vaccinium corymbosum*). The samples were coded F1*–F43* (Tables 1 and 2); the asterisk distinguishes them from the literature data used for comparison.

Upon arrival at the laboratory, the fruits were cleaned of adhering soil and plant debris and rinsed with ultrapure water (resistivity 18.2 MΩ·cm).

Only the edible portion of each fruit was analysed: stones, seeds, cores, stems and the strawberry calyx were removed, the peel was retained for fruits normally eaten with the peel (plum, apple, pear, peach, apricot, sour and sweet cherry, grapes, currants and blueberry), and the rind was removed from watermelon and melon. The aggregate sample of each species was divided into three independent samples, which were separately shredded with a polypropylene hand grater, thoroughly mixed and kept in porcelain containers; each sample was then subjected separately to mineralisation and instrumental analysis.

The moisture content was determined gravimetrically by oven drying. Portions of 100 g of each homogenised sample were weighed (±0.001 g) into porcelain dishes that had been previously cleaned and brought to constant mass, and were dried at 105 °C for 6 h in a laboratory oven (BINDER GmbH, Tuttlingen, Germany).

After drying, the dishes were allowed to cool in a desiccator and were weighed; the drying, cooling and weighing steps were repeated until two consecutive weighings differed by no more than ±0.001 g [43]. The moisture and dry matter contents were then obtained from Equations (1) and (2) [22,25]:

$$\mathrm{M}\ (\%) = \frac{m_1 - m_2}{m_1 - m_0} \times 100 \quad (1)$$

$$\mathrm{DM}\ (\%) = 100 - \mathrm{M} \quad (2)$$

where M is the moisture content (%), DM is the dry matter content (%), $m_0$ is the mass (g) of the empty dish, $m_1$ is the mass (g) of the dish with the sample before drying, and $m_2$ is the mass (g) of the dish with the sample after drying.

### *2.3. Dry and Wet Mineralisation*

#### 2.3.1. Dry Mineralisation

Dry ashing was carried out on 2 g of the dried material obtained from each fruit, weighed into porcelain crucibles. The crucibles were placed in a muffle furnace and the temperature was increased stepwise, first to 200–250 °C and then to 550 °C, where the samples were kept for 8 h until a white ash was obtained. The temperature was increased gradually in order to avoid ignition of the samples and to limit volatilisation losses of the more volatile elements. All porcelain crucibles and volumetric glassware were previously soaked in dilute $HNO_3$ and rinsed with ultrapure water, and reagent blanks were carried through the entire procedure (dry ashing, acid dissolution and dilution) together with the samples.

2.3.2. Wet Mineralisation

After cooling, the ash was treated with 10 mL of HCl and 5 mL of $HNO_3$, and the mixture was evaporated almost to dryness. The residue was then quantitatively transferred into a 100 mL volumetric flask and made up to volume with ultrapure water [22,25].

### *2.4. Determination of Macro- and Trace Elements*

Na, K, Ca, Mg, Cu, Mn, Fe and Zn were determined by flame atomic absorption spectrometry (FAAS) using a Varian SpectrAA 280 FS spectrometer (Varian Inc., Mulgrave, Australia) equipped with an air–acetylene flame and element-specific hollow cathode lamps. Owing to their low concentrations, Cd, Pb and Cr were determined by graphite furnace atomic absorption spectrometry (GFAAS) using the same spectrometer equipped with a GTA 120 graphite tube atomiser (Varian Inc.) with deuterium lamp background correction. Aliquots of 20 µL of the sample solution were injected with the autosampler, and the furnace temperature programmes (drying, pyrolysis, atomisation and cleaning steps) were those recommended by the manufacturer for each element.

Measurements were performed at 589.0 nm for Na, 766.5 nm for K, 422.7 nm for Ca, 202.6 nm for Mg, 324.8 nm for Cu, 279.5 nm for Mn, 248.3 nm for Fe, 228.8 nm for Cd, 217.0 nm for Pb, 213.9 nm for Zn and 357.9 nm for Cr.

Calibration was performed with external standard solutions prepared by dilution of certified stock standard solutions (Merck, Darmstadt, Germany), with five calibration levels for each analyte, over the ranges 0.1–5.0 mg $L^{-1}$ (Na, Mg), 1–50 mg $L^{-1}$ (K), 0.5–10 mg $L^{-1}$ (Ca), 0.01–0.50 mg $L^{-1}$ (Cu, Mn, Zn) and 0.05–1.00 mg $L^{-1}$ (Fe) for FAAS, and 0.05–1.00 µg $L^{-1}$ (Cd), 0.5–10 µg $L^{-1}$ (Pb) and 5–100 µg $L^{-1}$ (Cr) for GFAAS. Linearity was satisfactory for all elements ($R^2 > 0.995$). Sample solutions with concentrations above the highest calibration level were diluted with ultrapure water to fall within the working range. The lowest calibration level of each element was taken as the limit of quantification (LOQ), i.e., the lower limit of the working range, and was converted to sample concentration by taking into account the sample mass (2 g d.w.) and the final volume (100 mL), resulting in LOQs of 0.005 g $kg^{-1}$ d.w. (Na, Mg), 0.05 g $kg^{-1}$ d.w. (K), 0.025 g $kg^{-1}$ d.w. (Ca), 0.5 µg $g^{-1}$ d.w. (Cu, Mn, Zn), 2.5 µg $g^{-1}$ d.w. (Fe), 0.0025 µg $g^{-1}$ d.w. (Cd), 0.025 µg $g^{-1}$ d.w. (Pb) and 0.25 µg $g^{-1}$ d.w. (Cr); concentrations below the LOQ are reported as "<LOQ". Reagent blank signals were subtracted from the sample signals, and a calibration check standard was measured at regular intervals during each analytical run. Recovery tests with spiked samples and the analysis of a certified reference material were not performed in this study. Therefore, possible losses of Cd and Pb by volatilisation during dry ashing at 550 °C could not be quantified, and the reported Cd and Pb contents may be underestimated; they should be regarded as indicative values, and the health risk estimates derived from them (Section 2.6) should be interpreted with caution.

Each of the three independent samples of each fruit was mineralised and analysed separately, and each sample was determined in triplicate. The results are reported as the arithmetic mean ± standard deviation (SD) of the three independent samples; since the three samples were prepared from fruits of the same lot, the SD reflects the variability between fruits within this lot together with the analytical variability, but not the variability between lots or producers. The results are expressed as g $kg^{-1}$ dry weight (d.w.) for macroelements and µg $g^{-1}$ d.w. for trace elements [22].

### *2.5. Statistical and Chemometric Analysis*

The differences between fruits are discussed descriptively, and the multivariate methods described below were used as exploratory tools.

When a data set contains a large number of correlated variables, it is advisable to reduce its dimensionality in order to obtain a clearer and more easily interpretable result. Principal component analysis (PCA) is well suited to such problems, since the data set can be described by a small number of principal components ordered according to the proportion of variance they explain. This allows the underlying structure of the data to be visualised and reveals the relationships between variables and samples.

PCA was applied separately to the macroelements (Na, K, Ca, Mg) and to the trace elements, using the samples from this study and samples from the literature listed in Tables 1 and 2. Missing literature values (not reported) were not imputed: only the samples with reported values for all elements of the respective data set were included, i.e., 41 samples for macroelements (F14, F15, F33 and F44 excluded) and 35 samples for trace elements (F8, F12, F14, F15, F18, F26, F29, F38, F41 and F44 excluded). Cd and Pb were not included in the multivariate analysis, since their contents were below the LOQ in most of the fruits analysed in this study; the PCA of trace elements was therefore performed on Cu, Mn, Fe, Zn and Cr. Values reported in the literature as not detected (n.d.) were entered as zero, and the Cr contents below the LOQ (F31*, F34*) as LOQ/2. The influence of this substitution and of the data source on the groupings was assessed by a sensitivity analysis, in which the analysis was repeated with the n.d. values replaced by half of the lowest value reported for the respective element and after excluding all samples containing n.d. values. The data were standardised (z-score) and PCA was performed on the correlation matrix, retaining the first three principal components. The two data sets were analysed independently, each with its own standardisation and correlation matrix, so that their different numbers of samples do not influence each other, and the results of the two analyses are not compared quantitatively. The loadings were expressed as correlation coefficients between the elements and the principal components (eigenvector coefficients multiplied by the square root of the corresponding eigenvalue); an absolute loading of at least 0.5, which means that at least 25% of the variance of the element is explained by the component, was considered a substantial contribution. The samples were grouped by k-means clustering of the PC1–PC3 scores (k-means++ initialisation, 50 random starts); the number of clusters was chosen between 2 and 5 on the basis of the silhouette score and of the agreement with HCA. To verify the stability of the groupings, hierarchical cluster analysis (HCA) was applied to the same standardised data, using the Euclidean distance and Ward's linkage method; the fidelity of the dendrograms was assessed by the cophenetic correlation coefficient, and their agreement with the k-means clusters by the adjusted Rand index (ARI). Since the literature data were obtained with different sample preparation and analytical methods and for fruits of different origins, the chemometric analysis was used as an exploratory, descriptive tool to compare the mineral profiles of the analysed fruits with published data for the same species, and not to infer causal or biological relationships.

Statistical analysis and graphical representations were performed using OriginPro 2026 SR1 (OriginLab Corporation, Northampton, MA, USA) [22].

### *2.6. Assessment of the Risk to Human Health*

Since Romanian legislation does not provide clear recommendations on the daily consumption of fresh fruits and no statistical data on this consumption are available, a daily intake of 200 g of fresh fruit was considered, representing half of the minimum daily amount of fruits and vegetables recommended by WHO/FAO [22,44,45]. The same exposure scenario was applied in our previous study on fresh vegetables [22], which allows a direct comparison of the dietary exposure associated with the two food groups. This value should be regarded as a hypothetical scenario of regular fruit consumption by an adult, rather than as an estimate of the average fruit consumption of the population.

The exposure of consumers to trace elements through fruit consumption was expressed as the estimated daily intake (EDI, μg $kg^{-1}$ $day^{-1}$), calculated with Equation (3) [20,22,23,45–47]:

$$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (3)$$

where C is the trace element concentration in the fruit (μg $g^{-1}$ fresh weight, obtained from the dry weight values in Table 2 and the moisture content of each sample), IR is the daily ingestion rate of fruit (200 g $day^{-1}$), EF is the exposure frequency (365 days $year^{-1}$), ED is the exposure duration (70 years), BW is the body weight of an adult (70 kg, the default value proposed by EFSA [48]) and AT is the averaging time (EF × ED, days). For samples with Cd, Pb or Cr contents below the LOQ, the LOQ was used as an upper-bound concentration. These upper-bound values account only for the limit of quantification and not for possible losses of Cd and Pb during dry ashing (Section 2.4).

The non-carcinogenic risk associated with each trace element was evaluated by the target hazard quotient (THQ), obtained as the ratio between the EDI and the oral reference dose (RfD) (Equation (4)) [20,22,23,46,47]:

$$THQ = \frac{EDI}{RfD} \quad (4)$$

The RfD values used were 70 (Cu, acceptable daily intake [49]), 140 (Mn), 700 (Fe), 1 (Cd, for dietary exposure [50]), 300 (Zn) and 1500 (Cr) μg $kg^{-1}$ $day^{-1}$ [24,51–53]. Since the provisional tolerable weekly intake of Pb has been withdrawn and no health-based guidance value is currently available for this element, the risk associated with Pb was characterised by the margin of exposure (MOE), calculated as the ratio between the $BMDL_{10}$ of 0.63 μg $kg^{-1}$ $day^{-1}$ for effects on the prevalence of chronic kidney disease, the most sensitive endpoint for adults, and the EDI; MOE values greater than 1 indicate that the risk is likely to be low, the risk decreasing as the MOE increases [54]. A THQ value below 1 indicates that adverse health effects are unlikely, even for sensitive population groups, whereas a THQ equal to or greater than 1 indicates a potential risk to consumer health.

To assess the cumulative effect of simultaneous exposure to several trace elements, the total target hazard quotient (TTHQ) was calculated as the sum of the individual THQ values of Cu, Mn, Fe, Cd, Zn and Cr (Equation (5)). Pb was not included in the TTHQ, since it was assessed separately by the margin of exposure approach; a TTHQ value above 1 indicates a potential health concern [20,22–24,46,47]:

$$TTHQ = THQ_{Cu} + THQ_{Mn} + THQ_{Fe} + THQ_{Cd} + THQ_{Zn} + THQ_{Cr} \quad (5)$$

The carcinogenic risk (CR), defined as the probability that an individual will develop cancer over a lifetime as a result of exposure to a carcinogenic element, was estimated only for Pb, using Equation (6) [20,22,23,46,47,55]:

$$CR = EDI \times SF \quad (6)$$

where EDI is the estimated daily intake of the element through fruit consumption (mg $kg^{-1}$ $day^{-1}$) and SF is the oral cancer slope factor. The SF value used for Pb was 0.0085 (mg $kg^{-1}$ $day^{-1}$)$^{-1}$ [56]. Although Cd is classified as carcinogenic to humans, no oral cancer slope factor has been established by the US EPA [50], and extrapolation of the inhalation potency to oral exposure is not considered appropriate; therefore, the risk associated with Cd was assessed only by the THQ. CR values below $10^{-6}$ indicate a negligible risk, values between $10^{-6}$ and $10^{-4}$ an acceptable risk, and values above $10^{-4}$ an unacceptable carcinogenic risk [46,55].

To account for a sensitive population group, the exposure was also assessed for children aged 6–9 years. For this group, a daily intake of 175 g of fresh fruit was considered,

corresponding to half of the minimum daily intake of fruits and vegetables of 350 g recommended by WHO for children of this age [57], and a body weight of 23.1 kg, the default value for children aged 3–10 years [48]. EDI, THQ and TTHQ were calculated as described above. For Pb, the MOE was calculated for the $BMDL_{01}$ of 0.50 µg $kg^{-1}$ $day^{-1}$ for developmental neurotoxicity, the critical effect of Pb in children [54]. The CR was not calculated for children, since it refers to lifetime exposure.

## 3. Results and Discussion

### *3.1. Macro- and Trace Element Concentrations in Fruits*

The moisture and macroelement contents determined in the fruit samples are presented in Table 1, together with values reported in the literature for the same fruit species.

**Table 1.** Macroelement and moisture contents of the 15 fruit samples analysed in this study and 30 literature data sets from different botanical families (g $kg^{-1}$ dry weight ± SD).

| Code | Fruit Sample | Moisture (%) | Na | K | Ca | Mg |
|---|---|---|---|---|---|---|
| | | | g $kg^{-1}$ d.w. | g $kg^{-1}$ d.w. | g $kg^{-1}$ d.w. | g $kg^{-1}$ d.w. |
| **Rosaceae** | | | | | | |
| **F1*** | **Plum (*Prunus domestica*)** | **81.24** | **0.080 ± 0.020** | **7.345 ± 0.880** | **1.425 ± 0.234** | **0.979 ± 0.122** |
| F2 | Plum (*Prunus domestica*) [25] | 87.23 [58] | 0.038 | 1.520 | 0.012 | 0.031 |
| F3 | Plum (*Prunus domestica*) [59] | 84.30 [59] | 0.010 | 7.260 | 0.771 | 0.494 |
| **F4*** | **Strawberry (*Fragaria × ananassa*)** | **89.90** | **1.070 ± 0.330** | **25.900 ± 1.700** | **1.860 ± 0.340** | **1.670 ± 0.320** |
| F5 | Strawberry (*Fragaria × ananassa*) [25] | 90.95 [58] | 0.062 | 1.670 | 0.011 | 0.047 |
| F6 | Strawberry (*Fragaria × ananassa*) [59] | 89.80 [59] | 0.030 | 8.770 | 1.630 | 1.070 |
| **F7*** | **Apple (*Malus domestica*)** | **85.71** | **0.460 ± 0.250** | **6.910 ± 0.830** | **0.450 ± 0.180** | **0.680 ± 0.190** |
| F8 | Apple (*Malus domestica*) [28] | 85.56 [58] | 0.008 | 28.300 | 0.241 | 0.244 |
| F9 | Apple (*Malus domestica*) [38] | 85.56 [58] | 0.042 | 9.680 | 0.391 | 0.475 |
| **F10*** | **Pear (*Pyrus communis*)** | **84.60** | **0.110 ± 0.050** | **6.800 ± 0.900** | **0.380 ± 0.120** | **0.470 ± 0.100** |
| F11 | Pear (*Pyrus communis*) [25] | 83.96 [58] | 0.048 | 0.830 | 0.010 | 0.028 |
| F12 | Pear (*Pyrus communis*) [29] | 83.96 [58] | 0.035 | 10.100 | 0.396 | 0.488 |
| **F13*** | **Peach (*Prunus persica*)** | **88.90** | **0.090 ± 0.030** | **8.950 ± 1.200** | **0.420 ± 0.110** | **0.780 ± 0.160** |
| F14 | Peach (*Prunus persica*) [35] | 88.87 [58] | — | 9.120 | 0.924 | 0.515 |
| F15 | Peach (*Prunus persica*) [58] | 88.90 [58] | — | 17.100 | 0.541 | 0.811 |
| **F16*** | **Apricot (*Prunus armeniaca*)** | **84.24** | **0.110 ± 0.040** | **18.900 ± 0.200** | **1.250 ± 0.320** | **0.920 ± 0.210** |
| F17 | Apricot (*Prunus armeniaca*) [25] | 86.35 [58] | 0.036 | 2.100 | 0.020 | 0.042 |
| F18 | Apricot (*Prunus armeniaca*) [58] | 86.40 [58] | 0.074 | 19.000 | 0.956 | 0.735 |
| **F19*** | **Sour cherry (*Prunus cerasus*)** | **84.80** | **0.180 ± 0.070** | **12.800 ± 0.600** | **0.920 ± 0.240** | **0.740 ± 0.160** |
| F20 | Sour cherry (*Prunus cerasus*) [25] | 86.13 [58] | 0.038 | 1.560 | 0.025 | 0.057 |
| F21 | Sour cherry (*Prunus cerasus*) [39] | 86.13 [58] | 0.858 | 11.400 | 1.870 | 0.678 |
| **F22*** | **Sweet cherry (*Prunus avium*)** | **82.90** | **0.160 ± 0.060** | **14.200 ± 0.400** | **0.780 ± 0.220** | **0.830 ± 0.180** |
| F23 | Sweet cherry (*Prunus avium*) [25] | 82.25 [58] | 0.031 | 1.180 | 0.012 | 0.023 |
| F24 | Sweet cherry (*Prunus avium*) [59] | 82.00 [59] | 0.006 | 7.060 | 0.650 | 0.357 |
| **Vitaceae** | | | | | | |
| **F25*** | **White grape (*Vitis vinifera*)** | **80.90** | **0.090 ± 0.040** | **13.600 ± 0.710** | **0.840 ± 0.220** | **0.760 ± 0.180** |
| F26 | White grape (*Vitis vinifera*) [60] | 80.54 [58] | 0.015 | 3.920 | 0.036 | 0.065 |
| F27 | White grape (*Vitis vinifera*) [59] | 86.60 [59] | 0.016 | 7.100 | 0.716 | 0.413 |
| **F28*** | **Black grape (*Vitis vinifera*)** | **79.80** | **0.110 ± 0.050** | **15.200 ± 0.900** | **0.920 ± 0.240** | **0.840 ± 0.200** |
| F29 | Black grape (*Vitis vinifera*) [60] | 80.54 [58] | 0.015 | 3.560 | 0.034 | 0.080 |
| F30 | Black grape (*Vitis vinifera*) [59] | 83.70 [59] | 0.006 | 8.900 | 0.644 | 0.430 |
| **Cucurbitaceae** | | | | | | |
| **F31*** | **Watermelon (*Citrullus lanatus*)** | **93.00** | **1.250 ± 0.380** | **14.800 ± 2.100** | **0.950 ± 0.180** | **1.620 ± 0.310** |
| F32 | Watermelon (*Citrullus lanatus*) [25] | 91.45 [58] | 0.074 | 1.000 | 0.023 | 0.059 |
| F33 | Watermelon (*Citrullus lanatus*) [61] | 91.45 [58] | — | — | — | — |
| **F34*** | **Melon (*Cucumis melo*)** | **89.80** | **0.850 ± 0.250** | **18.500 ± 1.100** | **0.720 ± 0.180** | **1.350 ± 0.270** |
| F35 | Melon (*Cucumis melo*) [25] | 90.15 [58] | 0.094 | 1.310 | 0.017 | 0.036 |
| F36 | Melon (*Cucumis melo*) [59] | 91.00 [59] | 0.973 | 10.500 | 0.406 | 0.528 |

**Table 1.** *Cont.*

| Code | Fruit Sample | Moisture (%) | Na | K | Ca | Mg |
|---|---|---|---|---|---|---|
| | | | g kg$^{-1}$ d.w. | g kg$^{-1}$ d.w. | g kg$^{-1}$ d.w. | g kg$^{-1}$ d.w. |
| **Grossulariaceae** | | | | | | |
| **F37*** | **Red currant (*Ribes rubrum*)** | **84.20** | **0.380 ± 0.120** | **16.400 ± 1.300** | **2.100 ± 0.420** | **1.320 ± 0.250** |
| F38 | Red currant (*Ribes rubrum*) [36] | 83.95 [58] | 0.014 | 12.300 | 1.600 | 1.430 |
| F39 | Red currant (*Ribes rubrum*) [39] | 83.95 [58] | 0.611 | 16.300 | 3.860 | 0.922 |
| **F40*** | **Black currant (*Ribes nigrum*)** | **81.96** | **0.110 ± 0.010** | **17.850 ± 0.890** | **3.050 ± 0.150** | **1.330 ± 0.070** |
| F41 | Black currant (*Ribes nigrum*) [36] | 81.96 [58] | 0.034 | 13.800 | 2.000 | 1.910 |
| F42 | Black currant (*Ribes nigrum*) [39] | 81.96 [58] | 0.621 | 14.600 | 4.600 | 1.090 |
| **Ericaceae** | | | | | | |
| **F43*** | **Blueberry (*Vaccinium corymbosum*)** | **84.50** | **0.070 ± 0.030** | **11.800 ± 1.000** | **0.520 ± 0.150** | **0.680 ± 0.180** |
| F44 | Blueberry (*Vaccinium corymbosum*) [37] | 84.21 [58] | — | 5.170 | 0.576 | 0.386 |
| F45 | Blueberry (*Vaccinium corymbosum*) [40] | 84.21 [58] | 0.308 | 5.880 | 0.868 | 0.315 |

Results are expressed as the arithmetic mean ± standard deviation of three independent samples of each fruit, prepared separately from fruits of the same lot, each determined in triplicate. Code (F1–F45): sample code. For each species, the first code, marked with an asterisk (F1*, F4*, F7*, F10*, F13*, F16*, F19*, F22*, F25*, F28*, F31*, F34*, F37*, F40*, F43*), represents the sample analysed in this study; the next two codes represent values reported in the literature for the same species, the source being indicated in square brackets after the fruit name. The samples analysed in this study are shown in bold. —, not reported. All values are expressed on a dry weight basis; literature values reported on a fresh weight basis were converted to dry weight using the moisture content reported in the respective study or, when this was not reported, the moisture content given in the USDA FoodData Central database for the same species [58].

The moisture content of the 15 fruit samples analysed in this study ranged from 79.80% (black grape, F28*) to 93.00% (watermelon, F31*), with an average of 85.10%, and was close to the values reported for the same species in the literature (80.54–91.45%) [58,59].

The Na contents ranged from 0.07 (blueberry, F43*) to 1.25 g kg$^{-1}$ d.w. (watermelon, F31*), with an average of 0.34 g kg$^{-1}$ d.w.; relatively high values were also found in strawberry (F4*) and melon (F34*). The literature data for the same species vary widely (0.0055–0.973 g kg$^{-1}$ d.w.) [25,29,38–40,59], reflecting the strong influence of growing conditions on the Na content of fruits.

The K contents ranged from 6.80 (pear, F10*) to 25.9 g kg$^{-1}$ d.w. (strawberry, F4*), with an average of 14.0 g kg$^{-1}$ d.w., and were generally within or slightly above the range reported for the same species in most studies (7.06–19.0 g kg$^{-1}$ d.w.) [29,35,36,38,39,58,59], whereas markedly lower values were reported in Latvia, Turkey and Timișoara [25,37,60]. K was the predominant macroelement in all fruits, and the K/Na ratio ranged from about 12 (watermelon) to 172 (apricot), confirming the favourable mineral profile of fruits for blood pressure regulation [10].

The Ca contents ranged from 0.38 (pear, F10*) to 3.05 g kg$^{-1}$ d.w. (black currant, F40*), with an average of 1.11 g kg$^{-1}$ d.w. The currants had the highest Ca contents, a feature also reported for these species in Serbia and Romania (1.60–4.60 g kg$^{-1}$ d.w.) [36,39], while the values for the other fruits were generally within the range reported in the literature (0.391–1.63 g kg$^{-1}$ d.w.) [29,35,37,38,59].

The Mg contents ranged from 0.47 (pear, F10*) to 1.67 g kg$^{-1}$ d.w. (strawberry, F4*), with an average of 1.00 g kg$^{-1}$ d.w., in agreement with the literature data for the same species (0.357–1.91 g kg$^{-1}$ d.w.) [35,36,39,58,59].

Overall, the average macroelement contents decreased in the order K > Ca > Mg > Na.

The trace element contents determined in the fruit samples are presented in Table 2, together with values reported in the literature for the same fruit species.

**Table 2.** Trace element contents of the 15 fruit samples analysed in this study and 30 literature data sets, together with the maximum permitted levels (EU and Codex Alimentarius) (μg $g^{-1}$ dry weight, mean ± SD).

| Code | Fruit Sample | Cu | Mn | Fe | Cd | Pb | Zn | Cr |
|---|---|---|---|---|---|---|---|---|
| | | **μg $g^{-1}$ d.w.** | **μg $g^{-1}$ d.w.** | **μg $g^{-1}$ d.w.** | **μg $g^{-1}$ d.w.** | **μg $g^{-1}$ d.w.** | **μg $g^{-1}$ d.w.** | **μg $g^{-1}$ d.w.** |
| **Rosaceae** | | | | | | | | |
| **F1*** | **Plum (*Prunus domestica*)** | **8.90 ± 0.90** | **3.00 ± 0.40** | **20.30 ± 0.90** | **<0.0025** | **0.135 ± 0.072** | **6.10 ± 0.70** | **0.613 ± 0.080** |
| F2 | Plum (*Prunus domestica*) [25] | 1.50 | 1.05 | 0.53 | n.d. | 0.100 | 0.20 | n.d. |
| F3 | Plum (*Prunus domestica*) [59] | 3.18 | 8.92 | 33.80 | — | — | 7.64 | 0.637 |
| **F4*** | **Strawberry (*Fragaria × ananassa*)** | **26.50 ± 1.20** | **65.90 ± 0.90** | **67.40 ± 0.30** | **0.010 ± 0.004** | **0.029 ± 0.010** | **40.20 ± 0.60** | **0.860 ± 0.420** |
| F5 | Strawberry (*Fragaria × ananassa*) [25] | 2.05 | 2.15 | 1.07 | 0.005 | 0.350 | 0.70 | n.d. |
| F6 | Strawberry (*Fragaria × ananassa*) [59] | 2.94 | 48.00 | 52.90 | — | — | 13.70 | 0.980 |
| **F7*** | **Apple (*Malus domestica*)** | **3.08 ± 0.61** | **2.80 ± 0.77** | **24.10 ± 6.20** | **0.005 ± 0.002** | **<0.025** | **16.10 ± 1.90** | **1.400 ± 0.500** |
| F8 | Apple (*Malus domestica*) [28] | 3.18 | 1.30 | 2.82 | — | — | 1.57 | — |
| F9 | Apple (*Malus domestica*) [38] | 3.39 | 4.00 | 28.30 | 0.230 | 0.140 | 4.15 | 1.830 |
| **F10*** | **Pear (*Pyrus communis*)** | **3.40 ± 0.80** | **2.10 ± 0.60** | **15.80 ± 0.20** | **0.004 ± 0.002** | **<0.025** | **8.70 ± 1.10** | **0.420 ± 0.150** |
| F11 | Pear (*Pyrus communis*) [25] | 2.70 | 0.90 | 0.45 | n.d. | 0.050 | 0.35 | n.d. |
| F12 | Pear (*Pyrus communis*) [29] | 3.55 | — | 26.60 | 0.024 | 0.141 | 4.30 | 0.686 |
| **F13*** | **Peach (*Prunus persica*)** | **3.70 ± 0.80** | **3.90 ± 0.90** | **21.40 ± 0.70** | **0.003 ± 0.001** | **<0.025** | **9.10 ± 0.60** | **0.550 ± 0.180** |
| F14 | Peach (*Prunus persica*) [35] | 2.29 | 2.47 | 32.80 | — | — | 89.70 | — |
| F15 | Peach (*Prunus persica*) [58] | 6.13 | 5.50 | 22.50 | — | — | 15.30 | — |
| **F16*** | **Apricot (*Prunus armeniaca*)** | **4.10 ± 0.90** | **5.30 ± 1.20** | **24.80 ± 1.60** | **<0.0025** | **<0.025** | **11.20 ± 0.80** | **0.380 ± 0.120** |
| F17 | Apricot (*Prunus armeniaca*) [25] | 1.25 | 1.15 | 0.58 | n.d. | 0.100 | n.d. | n.d. |
| F18 | Apricot (*Prunus armeniaca*) [58] | 5.74 | 5.66 | 28.70 | — | — | 14.70 | — |
| **F19*** | **Sour cherry (*Prunus cerasus*)** | **3.60 ± 0.80** | **6.80 ± 0.50** | **18.70 ± 0.40** | **<0.0025** | **<0.025** | **10.40 ± 0.30** | **0.450 ± 0.140** |
| F20 | Sour cherry (*Prunus cerasus*) [25] | 1.70 | 1.30 | 0.65 | n.d. | 0.150 | n.d. | n.d. |
| F21 | Sour cherry (*Prunus cerasus*) [39] | 18.70 | 30.70 | 141.00 | 0.317 | 0.418 | 54.10 | 10.900 |
| **F22*** | **Sweet cherry (*Prunus avium*)** | **4.20 ± 1.00** | **7.30 ± 0.80** | **22.60 ± 0.40** | **<0.0025** | **<0.025** | **11.80 ± 0.70** | **0.480 ± 0.150** |
| F23 | Sweet cherry (*Prunus avium*) [25] | 0.80 | 0.80 | 0.40 | 0.010 | 0.250 | 0.35 | n.d. |
| F24 | Sweet cherry (*Prunus avium*) [59] | 3.33 | 5.00 | 66.70 | — | — | 4.44 | 0.167 |
| **Vitaceae** | | | | | | | | |
| **F25*** | **White grape (*Vitis vinifera*)** | **3.50 ± 0.80** | **4.70 ± 1.10** | **19.40 ± 1.60** | **<0.0025** | **<0.025** | **8.90 ± 1.10** | **0.310 ± 0.100** |
| F26 | White grape (*Vitis vinifera*) [60] | 1.22 | 0.72 | 3.67 | — | — | 1.49 | — |
| F27 | White grape (*Vitis vinifera*) [59] | 21.60 | 8.96 | 21.60 | — | — | 3.73 | 0.149 |
| **F28*** | **Black grape (*Vitis vinifera*)** | **4.30 ± 1.00** | **5.80 ± 1.30** | **22.80 ± 1.10** | **<0.0025** | **<0.025** | **10.70 ± 1.40** | **0.360 ± 0.120** |
| F29 | Black grape (*Vitis vinifera*) [60] | 1.46 | 0.50 | 5.91 | — | — | 0.67 | — |
| F30 | Black grape (*Vitis vinifera*) [59] | 1.23 | 3.68 | 38.00 | — | — | 4.29 | 0.307 |
| **Cucurbitaceae** | | | | | | | | |
| **F31*** | **Watermelon (*Citrullus lanatus*)** | **0.80 ± 0.20** | **1.10 ± 0.30** | **28.10 ± 0.70** | **<0.0025** | **<0.025** | **1.45 ± 0.42** | **<0.25** |
| F32 | Watermelon (*Citrullus lanatus*) [25] | 4.05 | 0.90 | 0.45 | n.d. | 0.100 | 0.65 | n.d. |
| F33 | Watermelon (*Citrullus lanatus*) [61] | 3.52 | 13.40 | 97.30 | 0.130 | 0.050 | 12.20 | 0.775 |
| **F34*** | **Melon (*Cucumis melo*)** | **1.20 ± 0.30** | **1.80 ± 0.40** | **22.40 ± 1.10** | **<0.0025** | **<0.025** | **5.80 ± 1.40** | **<0.25** |

**Table 2.** *Cont.*

| Code | Fruit Sample | Cu | Mn | Fe | Cd | Pb | Zn | Cr |
|---|---|---|---|---|---|---|---|---|
| | | **µg g$^{-1}$ d.w.** | **µg g$^{-1}$ d.w.** | **µg g$^{-1}$ d.w.** | **µg g$^{-1}$ d.w.** | **µg g$^{-1}$ d.w.** | **µg g$^{-1}$ d.w.** | **µg g$^{-1}$ d.w.** |
| F35 | Melon (*Cucumis melo*) [25] | 0.50 | 0.65 | 0.33 | 0.010 | 0.450 | 0.15 | n.d. |
| F36 | Melon (*Cucumis melo*) [59] | 0.22 | 3.33 | 24.40 | — | — | 10.00 | 0.111 |
| **Grossulariaceae** | | | | | | | | |
| **F37*** | **Red currant (*Ribes rubrum*)** | **1.90 ± 0.40** | **6.50 ± 1.20** | **24.30 ± 3.70** | **<0.0025** | **<0.025** | **5.80 ± 1.10** | **0.270 ± 0.070** |
| F38 | Red currant (*Ribes rubrum*) [36] | 6.85 | 19.90 | 124.00 | — | — | — | — |
| F39 | Red currant (*Ribes rubrum*) [39] | 12.50 | 15.30 | 55.20 | 0.243 | 0.181 | 26.20 | 4.170 |
| **F40*** | **Black currant (*Ribes nigrum*)** | **3.10 ± 0.70** | **12.80 ± 0.90** | **41.30 ± 1.80** | **0.003 ± 0.001** | **<0.025** | **9.80 ± 1.10** | **0.420 ± 0.120** |
| F41 | Black currant (*Ribes nigrum*) [36] | 7.21 | 16.60 | 85.90 | — | — | — | — |
| F42 | Black currant (*Ribes nigrum*) [39] | 7.37 | 24.00 | 80.90 | 0.188 | 0.200 | 29.90 | 5.600 |
| **Ericaceae** | | | | | | | | |
| **F43*** | **Blueberry (*Vaccinium corymbosum*)** | **2.20 ± 0.50** | **7.80 ± 1.60** | **28.60 ± 1.40** | **<0.0025** | **<0.025** | **6.40 ± 1.50** | **0.340 ± 0.100** |
| F44 | Blueberry (*Vaccinium corymbosum*) [37] | 1.65 | 36.10 | 29.80 | — | — | 6.33 | — |
| F45 | Blueberry (*Vaccinium corymbosum*) [40] | 1.90 | 23.50 | 51.10 | 0.168 | 1.870 | 21.30 | 0.149 |
| Codex CXS 193-1995 [62] mg kg$^{-1}$ f.w. | | N.E. | N.E. | N.E. | N.E. | 0.1 (0.2; 0.05) | N.E. | N.E. |
| EU 2023/915 (Cd, Pb) [63]; 396/2005, 2026/840 (Cu) [64,65] mg kg$^{-1}$ f.w. | | 5–100 | N.E. | N.E. | 0.020–0.030 | 0.050–0.20 | N.E. | N.E. |

Results are expressed as the arithmetic mean ± standard deviation of three independent samples of each fruit, prepared separately from fruits of the same lot, each determined in triplicate. <LOQ, below the limit of quantification (Cd 0.0025, Pb 0.025 and Cr 0.25 µg g$^{-1}$ d.w.; Section 2.4). Code (F1–F45): sample code. For each species, the first code, marked with an asterisk (F1*, F4*, F7*, F10*, F13*, F16*, F19*, F22*, F25*, F28*, F31*, F34*, F37*, F40*, F43*), represents the sample analysed in this study; the next two codes represent values reported in the literature for the same species, the source being indicated in square brackets after the fruit name. The samples analysed in this study are shown in bold. n.d., not detected; —, not reported. Maximum levels (mg kg$^{-1}$ f.w.) applicable to each fruit category: Pb—0.10 for pome fruits, stone fruits, grapes, strawberry and blueberry, 0.20 for currants and 0.050 for watermelon and melon (classified as fruiting vegetables), both in Regulation (EU) 2023/915 and in Codex CXS 193-1995; Cd—0.020 for pome fruits, stone fruits, watermelon and melon and 0.030 for grapes, strawberry, currants and blueberry (Regulation (EU) 2023/915), no Codex maximum level being set for Cd in these fruits. For Cu, the values are maximum residue levels for total copper resulting from the use of copper compounds as plant protection products (Regulation (EC) No 396/2005, as amended by Regulation (EU) 2026/840), and not maximum levels for contaminants: 5 for apricot and plum, 6 for apple and pear, 8 for peach, 10 for sweet cherry, watermelon and melon, 15 for strawberry, currants and blueberry and 100 for grapes. N.E., not established. All values are expressed on a dry weight basis; literature values reported on a fresh weight basis were converted to dry weight using the moisture content reported in the respective study or, when this was not reported, the moisture content given in the USDA FoodData Central database for the same species [58].

The Cu contents ranged from 0.80 (watermelon, F31*) to 26.5 μg $g^{-1}$ d.w. (strawberry, F4*), with an average of 4.97 μg $g^{-1}$ d.w. Except for strawberry, the values were within the range reported for the same species (0.222–21.6 μg $g^{-1}$ d.w.) [28,29,35,38,39,58,59]. Strawberry had the highest contents of Cu, Mn, Fe and Zn among the analysed fruits, which may reflect both species-specific accumulation and growing conditions.

The Mn contents ranged from 1.10 (watermelon, F31*) to 65.9 μg $g^{-1}$ d.w. (strawberry, F4*), with an average of 9.17 μg $g^{-1}$ d.w. The high Mn content of strawberry agrees with the value reported in Poland for the same species (48.0 μg $g^{-1}$ d.w.) [59], suggesting a high capacity of strawberry to accumulate Mn, whereas the values for the other fruits were within or below the range reported in the literature (4.00–36.1 μg $g^{-1}$ d.w.) [36–39,58].

The Fe contents ranged from 15.8 (pear, F10*) to 67.4 μg $g^{-1}$ d.w. (strawberry, F4*), with an average of 26.8 μg $g^{-1}$ d.w., and were similar to most literature data (21.6–66.7 μg $g^{-1}$ d.w.) [29,35,37,38,58,59], but lower than the values reported in Serbia and for currants in Romania (55.2–141 μg $g^{-1}$ d.w.) [36,39].

Cd was quantifiable in five of the analysed fruits, with contents ranging from 0.003 μg $g^{-1}$ d.w. (peach F13* and black currant F40*) to 0.010 μg $g^{-1}$ d.w. (strawberry F4*), while in the other ten fruits it was below the LOQ (0.0025 μg $g^{-1}$ d.w.). These values are similar to those reported for fruits from Timișoara, Romania (n.d.–0.0100 μg $g^{-1}$ d.w.) [25] and lower than most other literature data (0.0237–0.317 μg $g^{-1}$ d.w.) [29,38–40].

Pb was quantifiable only in plum (F1*, 0.135 μg $g^{-1}$ d.w.) and strawberry (F4*, 0.029 μg $g^{-1}$ d.w.), while in the other 13 fruits it was below the LOQ (0.025 μg $g^{-1}$ d.w.). These values are generally lower than the literature data for the same species (0.0500–1.87 μg $g^{-1}$ d.w.) [25,29,38–40].

The Zn contents ranged from 1.45 (watermelon, F31*) to 40.2 μg $g^{-1}$ d.w. (strawberry, F4*), with an average of 10.8 μg $g^{-1}$ d.w., within the range of most literature data (3.73–15.3 μg $g^{-1}$ d.w.) [29,37,38,58,59], except for strawberry, and lower than the values reported in Serbia and for peaches in Romania (26.2–89.7 μg $g^{-1}$ d.w.) [35,39].

The Cr contents determined in this work ranged from 0.27 to 1.40 μg $g^{-1}$ d.w., with an average of 0.53 μg $g^{-1}$ d.w. for the quantifiable values, the lowest value being recorded in the red currant sample (F37*) and the highest value in the apple sample (F7*); in watermelon (F31*) and melon (F34*), Cr was below the LOQ (0.25 μg $g^{-1}$ d.w.). These values are comparable to those reported in Poland, Greece and China (0.111–1.83 μg $g^{-1}$ d.w.) [29,38,59] and considerably lower than those reported in Serbia (4.17–10.9 μg $g^{-1}$ d.w.) [39].

Overall, the average trace element contents decreased in the order Fe > Zn > Mn > Cu > Cr > Pb > Cd.

Since the maximum levels presented in Table 2 are expressed on a fresh weight basis, the contents determined in this study were converted to fresh weight using the moisture content of each sample. The quantifiable Pb contents (0.003 mg $kg^{-1}$ f.w. in strawberry and 0.025 mg $kg^{-1}$ f.w. in plum) and Cd contents (0.0003–0.001 mg $kg^{-1}$ f.w.), as well as the LOQs converted to fresh weight for the samples below the LOQ (≤0.005 mg $kg^{-1}$ f.w. for Pb and ≤0.0005 mg $kg^{-1}$ f.w. for Cd), were well below the maximum levels applicable to each fruit category (Table 2): for Pb, 0.10 mg $kg^{-1}$ f.w. for most fruits, 0.20 mg $kg^{-1}$ f.w. for currants and 0.050 mg $kg^{-1}$ f.w. for watermelon and melon (Regulation (EU) 2023/915 and Codex Alimentarius) [62,63], and for Cd, 0.020 mg $kg^{-1}$ f.w. for pome fruits, stone fruits, watermelon and melon and 0.030 mg $kg^{-1}$ f.w. for grapes, strawberry, currants and blueberry (Regulation (EU) 2023/915) [63]. The Cu contents (0.056–2.68 mg $kg^{-1}$ f.w.) were also below the lowest maximum residue level for total copper set for the analysed fruits (5 mg $kg^{-1}$ f.w.) [64,65]; it should be noted, however, that these values are maximum residue levels for residues of copper-based plant protection products, since no maximum

level for Cu as a contaminant is set in the EU or by the Codex Alimentarius. Among the literature data, the Cd contents of apple F9 [38] (0.033 mg $kg^{-1}$ f.w.), sour cherry F21 (0.044 mg $kg^{-1}$ f.w.), red currant F39 (0.039 mg $kg^{-1}$ f.w.) and black currant F42 (0.034 mg $kg^{-1}$ f.w.) [39] exceeded the corresponding maximum levels (0.020 mg $kg^{-1}$ f.w. for apple and sour cherry and 0.030 mg $kg^{-1}$ f.w. for currants), and the Pb content of blueberry F45 [40] (0.30 mg $kg^{-1}$ f.w.) exceeded the maximum level of 0.10 mg $kg^{-1}$ f.w.

The differences between the values determined in this study and those reported in the literature can be attributed to differences in cultivar, degree of ripeness, cultivation conditions, soil composition, fertilisation methods, quality of the irrigation water and the analytical methods used.

### *3.2. Chemometric Analysis*

#### 3.2.1. Comparison of the Mineral Contents of the Analysed Fruits

The comparisons below are descriptive, since the SD values reported in Tables 1 and 2 reflect the variability within a single lot of each fruit and not the variability between lots or producers (Section 2.4).

Strawberry (F4*) had the highest K content (25.9 g $kg^{-1}$ d.w.), followed by apricot (F16*), melon (F34*) and black currant (F40*). The highest Na contents were found in watermelon (F31*, 1.25 g $kg^{-1}$ d.w.) and strawberry (1.07 g $kg^{-1}$ d.w.). Black currant (F40*) had the highest Ca content (3.05 g $kg^{-1}$ d.w.), followed by red currant (F37*, 2.10 g $kg^{-1}$ d.w.). The highest Mg contents were recorded in strawberry (1.67 g $kg^{-1}$ d.w.), watermelon (1.62 g $kg^{-1}$ d.w.) and black currant (1.33 g $kg^{-1}$ d.w.), with similar values. Pear (F10*) and apple (F7*) were among the fruits with the lowest K, Ca and Mg contents, while the lowest Na content was recorded in blueberry (F43*, 0.07 g $kg^{-1}$ d.w.).

Among the trace elements, strawberry (F4*) had the highest contents in Cu (26.5 µg $g^{-1}$ d.w.), Mn (65.9 µg $g^{-1}$ d.w.), Fe (67.4 µg $g^{-1}$ d.w.) and Zn (40.2 µg $g^{-1}$ d.w.), and also had the highest Cd content (0.010 µg $g^{-1}$ d.w.). Black currant (F40*) ranked second for Mn and Fe, plum (F1*) for Cu, and apple (F7*) for Zn. Plum had the highest Pb content (0.135 µg $g^{-1}$ d.w.) and apple the highest Cr content (1.40 µg $g^{-1}$ d.w.). Watermelon (F31*) had the lowest contents of most trace elements (Cu, Mn, Cd, Pb, Zn and Cr). For Cd and Pb, the values of most fruits were very similar and very low (0.001–0.010 µg $g^{-1}$ d.w. for Cd and 0.008–0.135 µg $g^{-1}$ d.w. for Pb).

#### 3.2.2. Principal Component Analysis (PCA)

Principal component analysis (PCA) was performed separately for the macroelements (Na, K, Ca, Mg; Table 1) and for the trace elements Cu, Mn, Fe, Zn and Cr (Table 2), as described in Section 2.5. Only samples with complete data were included (41 samples for macroelements and 35 for trace elements). The data were standardised (z-score) and PCA was carried out on the correlation matrix, retaining the first three principal components. Sample groupings were identified by k-means clustering of the PC1–PC3 scores, with the number of clusters selected on the basis of the silhouette score and of the agreement with HCA, and are delimited in the 3D score plots by wireframe spheres enclosing the core of each cluster. Since the data set combines the results of this study with literature data obtained under different analytical conditions, the groupings are interpreted as descriptive similarities between mineral profiles.

##### Variance Explained by the Principal Components

Before interpreting the groupings, it is essential to analyse the variance explained by each principal component and the contribution of each mineral element to these components (Figure 1). The loadings are expressed as correlation coefficients between the elements and

the principal components, and an absolute loading of at least 0.5 (i.e., at least 25% of the variance of the element explained by the component) was considered a substantial contribution. The loadings describe the contribution of each element to the multivariate patterns of the data set and do not, by themselves, provide evidence of biological or physiological relationships between the elements.

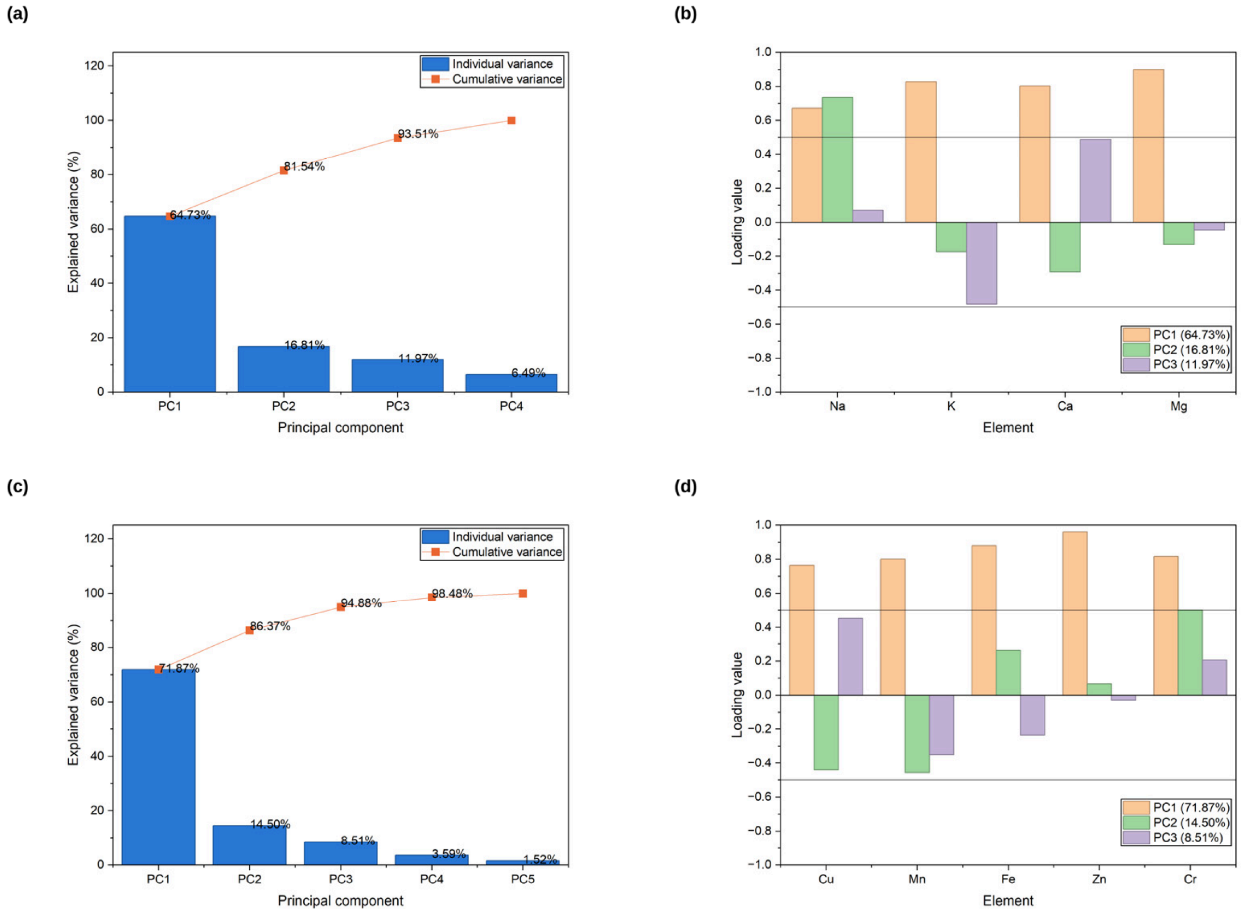



**Figure 1.** Scree plots and loadings on PC1–PC3 for macroelements (**a**,**b**) and trace elements (**c**,**d**). The loadings are correlation coefficients between the elements and the principal components; the horizontal lines at ±0.5 mark the threshold of substantial contribution.

For macroelements, the first three principal components explained 93.51% of the total variance (PC1 64.73%, PC2 16.81%, PC3 11.97%; Figure 1a,b). PC1 was positively correlated with all four elements (Mg 0.900, K 0.827, Ca 0.802, Na 0.672), reflecting the overall mineral content; PC2 was dominated by Na (0.735), while PC3 contrasted Ca (0.488) with K (−0.483), both loadings being close to the threshold of 0.5.

For trace elements, the first three principal components explained 94.88% of the total variance (PC1 71.87%, PC2 14.50%, PC3 8.51%; Figure 1c,d). PC1 was positively correlated with all five elements (Zn 0.961, Fe 0.880, Cr 0.817, Mn 0.801, Cu 0.765), expressing the overall trace element load; PC2 and PC3 explained a much smaller part of the variance and none of their loadings exceeded 0.5 in absolute value: PC2 contrasted Cr (0.499) and Fe (0.263) with Mn (−0.456) and Cu (−0.441), while PC3 contrasted Cu (0.452) with Mn (−0.350).

## PCA Using the Macroelement Content of the Evaluated Fruit samples as Input Data

k-means clustering identified four groups of samples (silhouette score 0.473, the highest among the solutions with 2–5 clusters; Figures 2–4): (1) a large group of 20 samples with intermediate mineral contents, comprising plum F1*, apple F7*, pear F10*, peach F13*,

apricot F16*, sour cherry F19*, sweet cherry F22*, grapes F25* and F28* and blueberry F43*, together with literature data for the same species; (2) a compact group formed by all ten samples from references [25,60], reflecting the low values reported in these sources; (3) Na-rich fruits (strawberry F4*, watermelon F31*, melons F34* and F36, sour cherry F21); and (4) Ca-rich currants (F37*, F38, F39, F40*, F41, F42). Within the clusters, the samples from this study were located next to the literature data for the same species, indicating that the obtained values are consistent with published data. The separation of the samples from references [25,60] into a distinct group shows, however, that part of the variability of the combined data set is related to the data source (analytical method, sample preparation and origin of the fruits), which is why the groupings are interpreted descriptively.

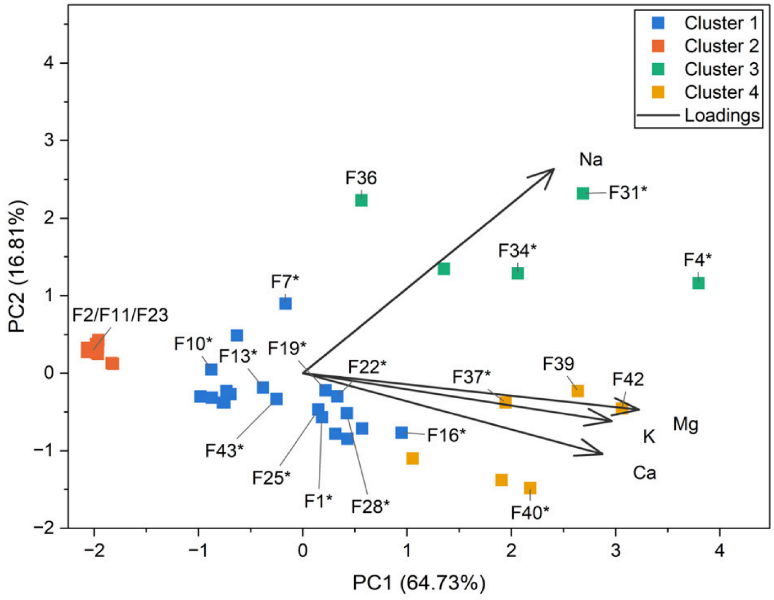



**Figure 2.** PCA biplot of macroelements (Na, K, Ca, Mg), PC2 vs. PC1 (PC1 = 64.73%, PC2 = 16.81%). samples are coloured by k-means cluster; samples from this study are marked with *; arrows represent the loadings (scaled ×3.58).

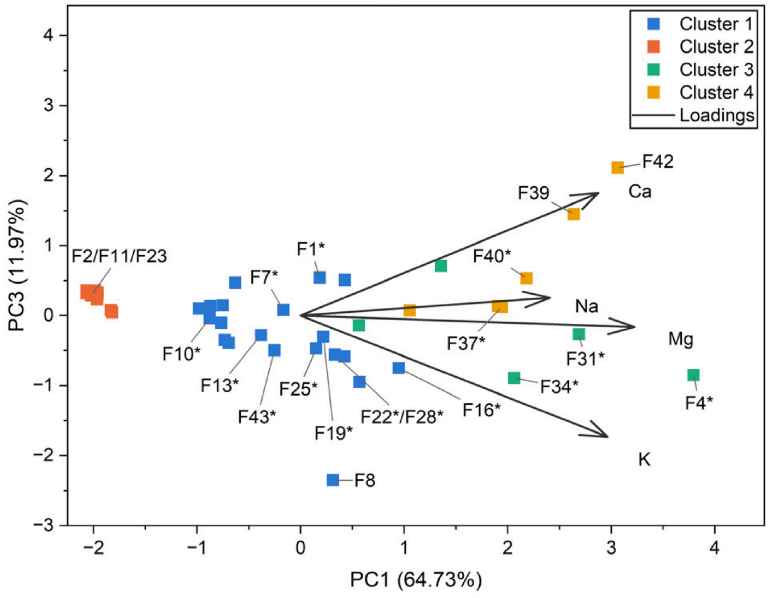



**Figure 3.** PCA biplot of macroelements, PC3 vs. PC1 (PC3 = 11.97%). Separation along PC3 is determined by the contrast between Ca and K. samples from this study are marked with *.

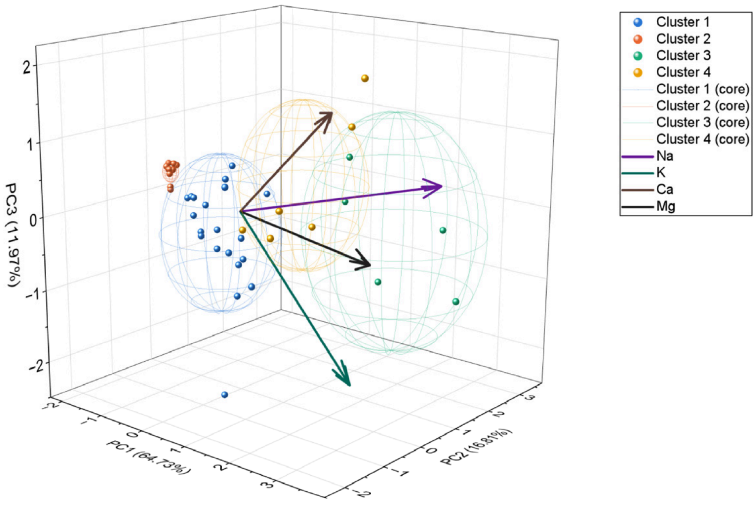



**Figure 4.** 3D PCA score plot of macroelements (PC1 = 64.73%, PC2 = 16.81%, PC3 = 11.97%; total = 93.51%). Wireframe spheres delimit the core of each k-means cluster (75% of samples); arrows represent the loadings of Na, K, Ca and Mg.

PCA Using the Trace Element Content of the Evaluated Fruit samples as Input Data

For trace elements, the silhouette score was highest for two clusters (0.686), but this solution only separated the two samples with the highest contents (F4* and F21) from all the others and showed a weak agreement with HCA (ARI = 0.594). Therefore, three clusters were retained (silhouette score 0.569; Figures 5 and 6), a solution in very good agreement with HCA (ARI = 0.884; Section 3.2.3). Cluster 1 (28 samples) comprised all samples from this study except strawberry, together with most literature data, forming a compact group with low and uniform trace element contents. Cluster 2 grouped strawberry F4* and sour cherry F21 [39], the samples with the highest PC1 scores, i.e., the highest overall trace element contents (Mn, Cu and Zn in strawberry; Fe, Zn and Cr in sour cherry). Cluster 3 (5 samples) included samples from the literature with high Fe, Mn and Zn contents: strawberry F6 [59], watermelon F33 [61], currants F39 and F42 [39] and blueberry F45 [40].

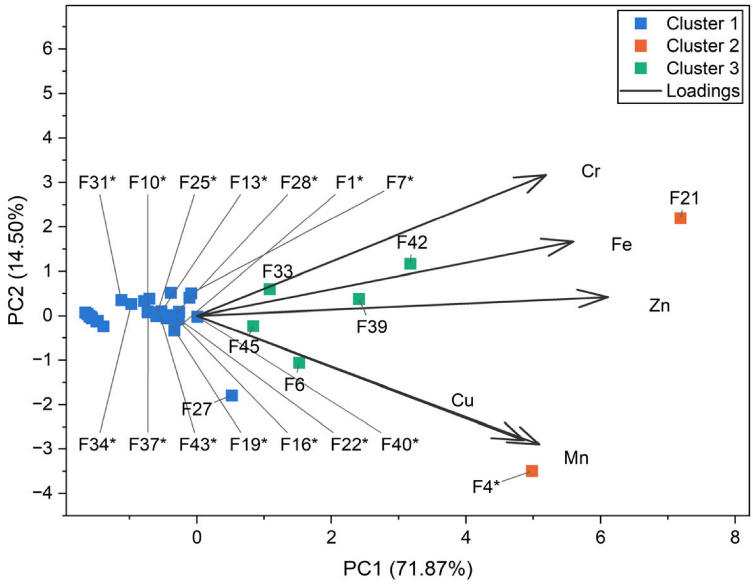



**Figure 5.** PCA biplot of trace elements (Cu, Mn, Fe, Zn, Cr), PC2 vs. PC1 (PC1 = 71.87%, PC2 = 14.50%). samples are coloured by k-means cluster; samples from this study are marked with *; arrows represent the loadings (scaled ×6.35).

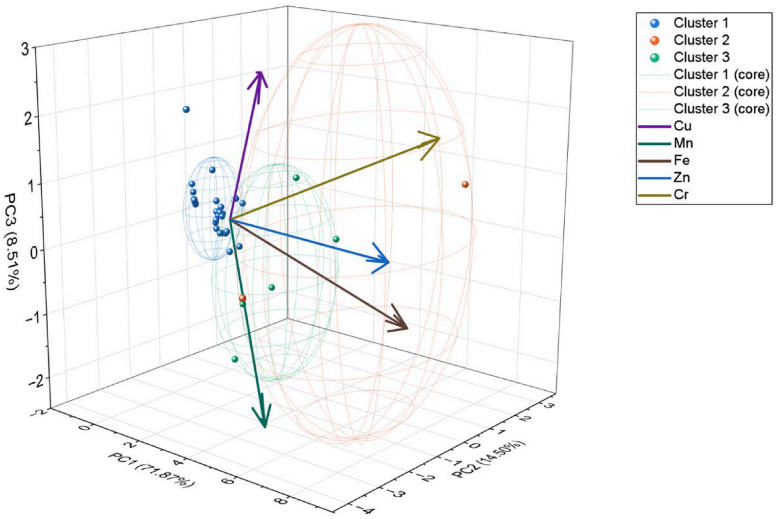



**Figure 6.** 3D PCA score plot of trace elements (PC1 = 71.87%, PC2 = 14.50%, PC3 = 8.51%; total = 94.88%). Wireframe spheres delimit the core of each cluster; arrows represent the loadings of the five elements.

To assess the influence of the treatment of the non-detected values and of the data source on these groupings, the trace element analysis was repeated with the n.d. values replaced by half of the lowest value reported for the respective element instead of zero, and after excluding the eight samples containing n.d. values, all of which originated from Reference [25]. The variance explained by the first three principal components changed only slightly (94.84% and 94.40%, respectively, compared with 94.88%), and the cluster membership of all samples was identical to that of the main analysis (ARI = 1.000); the same result was obtained when the LOQ instead of LOQ/2 was used for the Cr contents below the LOQ. Therefore, the reported groupings do not depend on the substitution of the non-detected values.

### 3.2.3. Hierarchical Cluster Analysis (HCA)

To verify the stability of the groupings obtained by PCA and k-means clustering, hierarchical cluster analysis (HCA) was applied to the same standardised (z-score) data sets, using the Euclidean distance and Ward's linkage method. The dendrograms were cut at the number of clusters retained in the PCA (four for macroelements and three for trace elements). The agreement between the two classifications was assessed by the adjusted Rand index (ARI), and the fidelity of the dendrograms to the original distances by the cophenetic correlation coefficient.

For macroelements (Figure 7), the cophenetic correlation coefficient was 0.766, and cutting the dendrogram at a linkage distance of 5.31 produced four clusters identical to those obtained by k-means clustering (ARI = 1.000). At the highest level, the dendrogram separated the Na-rich fruits and the Ca-rich currants from the fruits with low and intermediate mineral contents.

For trace elements (Figure 8), the cophenetic correlation coefficient was higher (0.899) and the agreement with k-means clustering was very good (ARI = 0.884). The dendrogram cut at a linkage distance of 6.93 produced the same three groups as k-means clustering, the only difference being the inclusion of sweet cherry F24 [59] in the group of samples from the literature with high Fe, Mn and Zn contents. At the highest level, strawberry F4* and sour cherry F21 [39] were separated from all other samples. Overall, HCA confirmed the main groupings identified by PCA and k-means clustering, showing that they do not depend on the clustering method used.

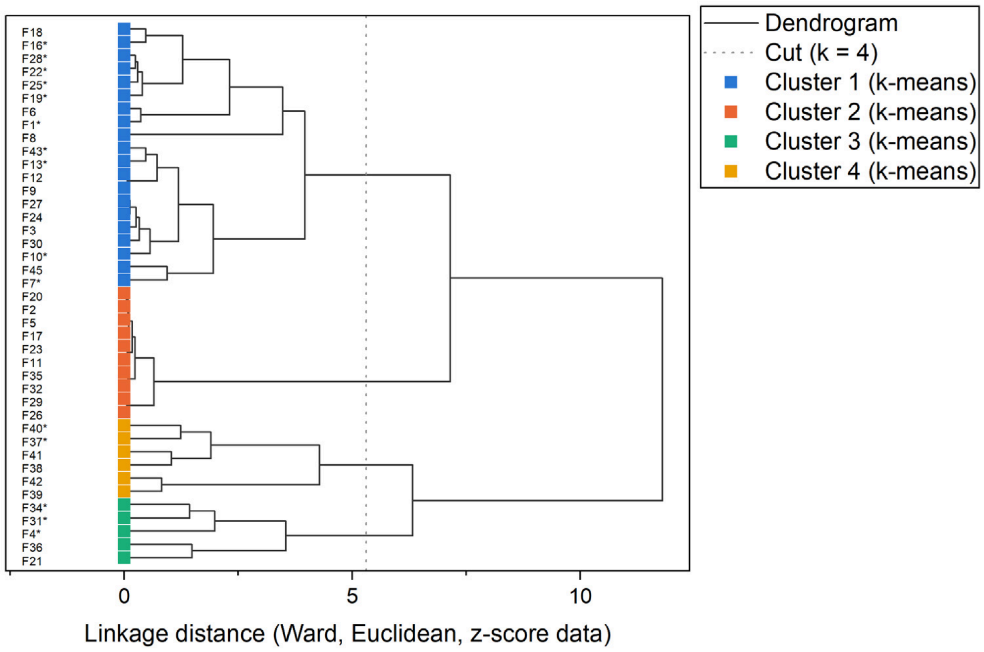



**Figure 7.** Dendrogram of the hierarchical cluster analysis of macroelements (Na, K, Ca, Mg; Ward linkage, Euclidean distance, z-score data). The dotted line marks the cut into four clusters; coloured squares show the k-means cluster of each sample. samples from this study are marked with *.

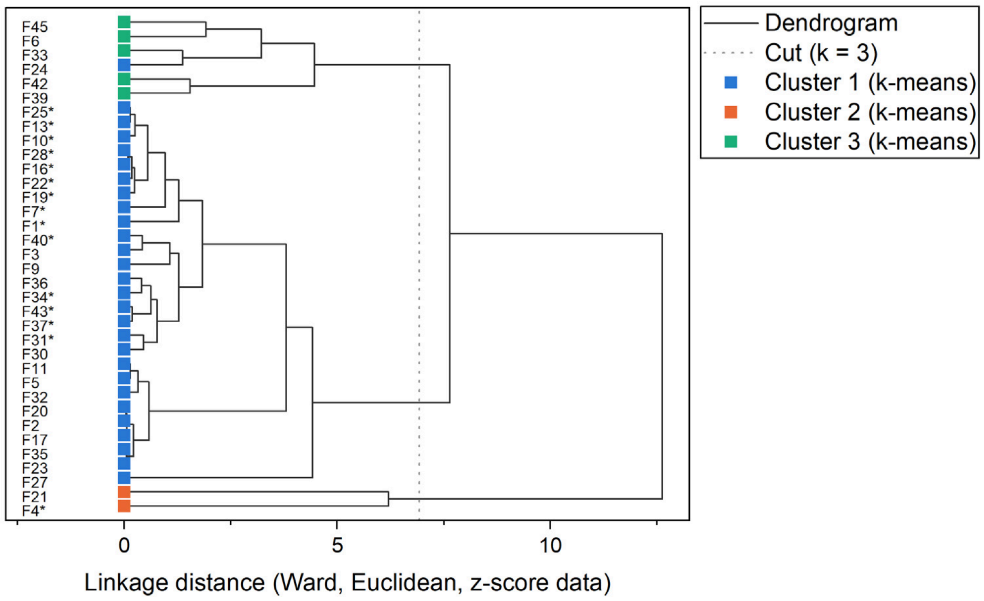



**Figure 8.** Dendrogram of the hierarchical cluster analysis of trace elements (Cu, Mn, Fe, Zn, Cr; Ward linkage, Euclidean distance, z-score data). The dotted line marks the cut into three clusters; coloured squares show the k-means cluster of each sample. samples from this study are marked with *.

### *3.3. Health Risk Associated with Fruit Consumption*

The risk to human health associated with the consumption of the fruits analysed in this study (F1*–F43*) was assessed on the basis of their trace element contents (Table 2), converted to a fresh weight basis using the moisture content of each sample (Table 1). The values obtained for EDI, THQ, TTHQ, MOE and CR are presented in Tables 3–5 for adults and in Table 6 for children aged 6–9 years.

**Table 3.** Estimated daily intake (EDI) of trace elements through the consumption of the analysed fruits (μg $kg^{-1}$ $day^{-1}$).

| Code | Fruit Sample | Cu | Mn | Fe | Cd | Pb | Zn | Cr |
|---|---|---|---|---|---|---|---|---|
| | | μg $kg^{-1}$ $day^{-1}$ | μg $kg^{-1}$ $day^{-1}$ | μg $kg^{-1}$ $day^{-1}$ | μg $kg^{-1}$ $day^{-1}$ | μg $kg^{-1}$ $day^{-1}$ | μg $kg^{-1}$ $day^{-1}$ | μg $kg^{-1}$ $day^{-1}$ |
| **Rosaceae** | | | | | | | | |
| F1* | Plum (*Prunus domestica*) | 4.77 | 1.61 | 10.90 | $<1.34 \times 10^{-3}$ | $7.24 \times 10^{-2}$ | 3.27 | 0.329 |
| F4* | Strawberry (*Fragaria* × *ananassa*) | 7.65 | 19.00 | 19.40 | $2.89 \times 10^{-3}$ | $8.37 \times 10^{-3}$ | 11.60 | 0.248 |
| F7* | Apple (*Malus domestica*) | 1.26 | 1.14 | 9.84 | $2.04 \times 10^{-3}$ | $<1.02 \times 10^{-2}$ | 6.57 | 0.572 |
| F10* | Pear (*Pyrus communis*) | 1.50 | 0.92 | 6.95 | $1.76 \times 10^{-3}$ | $<1.10 \times 10^{-2}$ | 3.83 | 0.185 |
| F13* | Peach (*Prunus persica*) | 1.17 | 1.24 | 6.79 | $9.51 \times 10^{-4}$ | $<7.93 \times 10^{-3}$ | 2.89 | 0.174 |
| F16* | Apricot (*Prunus armeniaca*) | 1.85 | 2.39 | 11.20 | $<1.13 \times 10^{-3}$ | $<1.13 \times 10^{-2}$ | 5.04 | 0.171 |
| F19* | Sour cherry (*Prunus cerasus*) | 1.56 | 2.95 | 8.12 | $<1.09 \times 10^{-3}$ | $<1.09 \times 10^{-2}$ | 4.52 | 0.195 |
| F22* | Sweet cherry (*Prunus avium*) | 2.05 | 3.57 | 11.00 | $<1.22 \times 10^{-3}$ | $<1.22 \times 10^{-2}$ | 5.77 | 0.235 |
| **Vitaceae** | | | | | | | | |
| F25* | White grape (*Vitis vinifera*) | 1.91 | 2.56 | 10.60 | $<1.36 \times 10^{-3}$ | $<1.36 \times 10^{-2}$ | 4.86 | 0.169 |
| F28* | Black grape (*Vitis vinifera*) | 2.48 | 3.35 | 13.20 | $<1.44 \times 10^{-3}$ | $<1.44 \times 10^{-2}$ | 6.18 | 0.208 |
| **Cucurbitaceae** | | | | | | | | |
| F31* | Watermelon (*Citrullus lanatus*) | 0.16 | 0.22 | 5.62 | $<5.00 \times 10^{-4}$ | $<5.00 \times 10^{-3}$ | 0.29 | <0.050 |
| F34* | Melon (*Cucumis melo*) | 0.35 | 0.53 | 6.53 | $<7.29 \times 10^{-4}$ | $<7.29 \times 10^{-3}$ | 1.69 | <0.073 |
| **Grossulariaceae** | | | | | | | | |
| F37* | Red currant (*Ribes rubrum*) | 0.86 | 2.93 | 11.00 | $<1.13 \times 10^{-3}$ | $<1.13 \times 10^{-2}$ | 2.62 | 0.122 |
| F40* | Black currant (*Ribes nigrum*) | 1.60 | 6.60 | 21.30 | $1.55 \times 10^{-3}$ | $<1.29 \times 10^{-2}$ | 5.05 | 0.216 |
| **Ericaceae** | | | | | | | | |
| F43* | Blueberry (*Vaccinium corymbosum*) | 0.97 | 3.45 | 12.70 | $<1.11 \times 10^{-3}$ | $<1.11 \times 10^{-2}$ | 2.83 | 0.151 |

EDI values were calculated for a daily intake of 200 g of fresh fruit and a body weight of 70 kg, using the trace element contents from Table 2 converted to fresh weight. For samples with contents below the LOQ, the LOQ was used as an upper-bound concentration; the resulting EDI values are upper-bound values (<). *, samples analysed in this study.

**Table 4.** Target hazard quotient (THQ) values of trace elements for the analysed fruits.

| Code | Fruit Sample | Cu | Mn | Fe | Cd | Zn | Cr |
|---|---|---|---|---|---|---|---|
| | | — | — | — | — | — | — |
| **Rosaceae** | | | | | | | |
| F1* | Plum (*Prunus domestica*) | $6.81 \times 10^{-2}$ | $1.15 \times 10^{-2}$ | $1.55 \times 10^{-2}$ | $<1.34 \times 10^{-3}$ | $1.09 \times 10^{-2}$ | $2.19 \times 10^{-4}$ |
| F4* | Strawberry (*Fragaria* × *ananassa*) | $1.09 \times 10^{-1}$ | $1.36 \times 10^{-1}$ | $2.78 \times 10^{-2}$ | $2.89 \times 10^{-3}$ | $3.87 \times 10^{-2}$ | $1.65 \times 10^{-4}$ |
| F7* | Apple (*Malus domestica*) | $1.80 \times 10^{-2}$ | $8.17 \times 10^{-3}$ | $1.41 \times 10^{-2}$ | $2.04 \times 10^{-3}$ | $2.19 \times 10^{-2}$ | $3.81 \times 10^{-4}$ |
| F10* | Pear (*Pyrus communis*) | $2.14 \times 10^{-2}$ | $6.60 \times 10^{-3}$ | $9.93 \times 10^{-3}$ | $1.76 \times 10^{-3}$ | $1.28 \times 10^{-2}$ | $1.23 \times 10^{-4}$ |
| F13* | Peach (*Prunus persica*) | $1.68 \times 10^{-2}$ | $8.83 \times 10^{-3}$ | $9.70 \times 10^{-3}$ | $9.51 \times 10^{-4}$ | $9.62 \times 10^{-3}$ | $1.16 \times 10^{-4}$ |
| F16* | Apricot (*Prunus armeniaca*) | $2.64 \times 10^{-2}$ | $1.70 \times 10^{-2}$ | $1.60 \times 10^{-2}$ | $<1.13 \times 10^{-3}$ | $1.68 \times 10^{-2}$ | $1.14 \times 10^{-4}$ |
| F19* | Sour cherry (*Prunus cerasus*) | $2.23 \times 10^{-2}$ | $2.11 \times 10^{-2}$ | $1.16 \times 10^{-2}$ | $<1.09 \times 10^{-3}$ | $1.51 \times 10^{-2}$ | $1.30 \times 10^{-4}$ |
| F22* | Sweet cherry (*Prunus avium*) | $2.93 \times 10^{-2}$ | $2.55 \times 10^{-2}$ | $1.58 \times 10^{-2}$ | $<1.22 \times 10^{-3}$ | $1.92 \times 10^{-2}$ | $1.56 \times 10^{-4}$ |
| **Vitaceae** | | | | | | | |
| F25* | White grape (*Vitis vinifera*) | $2.73 \times 10^{-2}$ | $1.83 \times 10^{-2}$ | $1.51 \times 10^{-2}$ | $<1.36 \times 10^{-3}$ | $1.62 \times 10^{-2}$ | $1.13 \times 10^{-4}$ |
| F28* | Black grape (*Vitis vinifera*) | $3.55 \times 10^{-2}$ | $2.39 \times 10^{-2}$ | $1.88 \times 10^{-2}$ | $<1.44 \times 10^{-3}$ | $2.06 \times 10^{-2}$ | $1.39 \times 10^{-4}$ |
| **Cucurbitaceae** | | | | | | | |
| F31* | Watermelon (*Citrullus lanatus*) | $2.29 \times 10^{-3}$ | $1.57 \times 10^{-3}$ | $8.03 \times 10^{-3}$ | $<5.00 \times 10^{-4}$ | $9.67 \times 10^{-4}$ | $<3.33 \times 10^{-5}$ |
| F34* | Melon (*Cucumis melo*) | $5.00 \times 10^{-3}$ | $3.75 \times 10^{-3}$ | $9.33 \times 10^{-3}$ | $<7.29 \times 10^{-4}$ | $5.63 \times 10^{-3}$ | $<4.86 \times 10^{-5}$ |
| **Grossulariaceae** | | | | | | | |
| F37* | Red currant (*Ribes rubrum*) | $1.23 \times 10^{-2}$ | $2.10 \times 10^{-2}$ | $1.57 \times 10^{-2}$ | $<1.13 \times 10^{-3}$ | $8.73 \times 10^{-3}$ | $8.13 \times 10^{-5}$ |
| F40* | Black currant (*Ribes nigrum*) | $2.28 \times 10^{-2}$ | $4.71 \times 10^{-2}$ | $3.04 \times 10^{-2}$ | $1.55 \times 10^{-3}$ | $1.68 \times 10^{-2}$ | $1.44 \times 10^{-4}$ |

**Table 4.** *Cont.*

| Code | Fruit Sample | Cu | Mn | Fe | Cd | Zn | Cr |
|---|---|---|---|---|---|---|---|
| | | — | — | — | — | — | — |
| **Ericaceae** | | | | | | | |
| F43* | Blueberry (*Vaccinium corymbosum*) | $1.39 \times 10^{-2}$ | $2.47 \times 10^{-2}$ | $1.81 \times 10^{-2}$ | $<1.11 \times 10^{-3}$ | $9.45 \times 10^{-3}$ | $1.00 \times 10^{-4}$ |

THQ values were calculated for a daily intake of 200 g of fresh fruit and a body weight of 70 kg, using the trace element contents from Table 2 converted to fresh weight. For samples with contents below the LOQ, the LOQ was used as an upper-bound concentration; the resulting THQ values are upper-bound values (<). THQ was not calculated for Pb, which was assessed by the margin of exposure approach (Table 5). *, samples analysed in this study.

**Table 5.** Total target hazard quotient (TTHQ), margin of exposure (MOE) and carcinogenic risk (CR) for Pb for the analysed fruits.

| Code | Fruit Sample | TTHQ | MOE (Pb) | CR (Pb) |
|---|---|---|---|---|
| | | — | — | — |
| **Rosaceae** | | | | |
| F1* | Plum (*Prunus domestica*) | 0.108 | 8.7 | $6.15 \times 10^{-7}$ |
| F4* | Strawberry (*Fragaria* × *ananassa*) | 0.315 | 75.3 | $7.11 \times 10^{-8}$ |
| F7* | Apple (*Malus domestica*) | 0.065 | >61.7 | $<8.68 \times 10^{-8}$ |
| F10* | Pear (*Pyrus communis*) | 0.053 | >57.3 | $<9.35 \times 10^{-8}$ |
| F13* | Peach (*Prunus persica*) | 0.046 | >79.5 | $<6.74 \times 10^{-8}$ |
| F16* | Apricot (*Prunus armeniaca*) | 0.077 | >56.0 | $<9.57 \times 10^{-8}$ |
| F19* | Sour cherry (*Prunus cerasus*) | 0.071 | >58.0 | $<9.23 \times 10^{-8}$ |
| F22* | Sweet cherry (*Prunus avium*) | 0.091 | >51.6 | $<1.04 \times 10^{-7}$ |
| **Vitaceae** | | | | |
| F25* | White grape (*Vitis vinifera*) | 0.078 | >46.2 | $<1.16 \times 10^{-7}$ |
| F28* | Black grape (*Vitis vinifera*) | 0.100 | >43.7 | $<1.23 \times 10^{-7}$ |
| **Cucurbitaceae** | | | | |
| F31* | Watermelon (*Citrullus lanatus*) | 0.013 | >126.0 | $<4.25 \times 10^{-8}$ |
| F34* | Melon (*Cucumis melo*) | 0.024 | >86.5 | $<6.19 \times 10^{-8}$ |
| **Grossulariaceae** | | | | |
| F37* | Red currant (*Ribes rubrum*) | 0.059 | >55.8 | $<9.59 \times 10^{-8}$ |
| F40* | Black currant (*Ribes nigrum*) | 0.119 | >48.9 | $<1.10 \times 10^{-7}$ |
| **Ericaceae** | | | | |
| F43* | Blueberry (*Vaccinium corymbosum*) | 0.067 | >56.9 | $<9.41 \times 10^{-8}$ |

EDI, THQ, TTHQ and CR were calculated for a daily intake of 200 g of fresh fruit and a body weight of 70 kg, using the trace element contents from Table 2 converted to fresh weight. For samples with contents below the LOQ, the LOQ was used as an upper-bound concentration; the resulting TTHQ and CR values are upper-bound values (<) and the MOE values are lower-bound values (>). TTHQ, sum of the THQ values of Cu, Mn, Fe, Cd, Zn and Cr; MOE, margin of exposure calculated for the $BMDL_{10}$ of 0.63 µg $kg^{-1}$ $day^{-1}$ for nephrotoxicity [54]. *, samples analysed in this study.

The EDI values obtained for the analysed trace elements ranged from 0.16 to 7.65 µg $kg^{-1}$ $day^{-1}$ for Cu, 0.22 to 19.0 µg $kg^{-1}$ $day^{-1}$ for Mn, 5.62 to 21.3 µg $kg^{-1}$ $day^{-1}$ for Fe, $9.51 \times 10^{-4}$ to $2.89 \times 10^{-3}$ µg $kg^{-1}$ $day^{-1}$ for Cd and $8.37 \times 10^{-3}$ to $7.24 \times 10^{-2}$ µg $kg^{-1}$ $day^{-1}$ for Pb (quantifiable values; upper-bound values below $1.44 \times 10^{-3}$ µg $kg^{-1}$ $day^{-1}$ for Cd and $1.44 \times 10^{-2}$ µg $kg^{-1}$ $day^{-1}$ for Pb in the other fruits), 0.29 to 11.6 µg $kg^{-1}$ $day^{-1}$ for Zn and 0.122 to 0.572 µg $kg^{-1}$ $day^{-1}$ for Cr (upper-bound values below 0.050 and 0.073 µg $kg^{-1}$ $day^{-1}$ for watermelon and melon) (Table 3, Figure 9). The lowest EDI values were obtained for watermelon (F31*), while the highest values were obtained for Cu, Mn, Cd and Zn in strawberry (F4*), for Fe in black currant (F40*), for Pb in plum (F1*) and for Cr in apple (F7*). For all elements, the EDI values were well below the corresponding oral reference doses (RfD): the highest EDI represented 13.6% of the RfD for Mn, 10.9% for Cu, 3.9% for Zn, 3.0% for Fe, 0.29% for Cd and 0.04% for Cr.

All THQ values were below 1 (Table 4, Figure 10), ranging from less than $10^{-4}$ (Cr, watermelon and melon) to 0.136 (Mn, strawberry), which indicates that the consumption of the analysed fruits does not pose a non-carcinogenic risk to consumers. Based on the mean values, THQ followed the order $THQ_{Cu} > THQ_{Mn} > THQ_{Fe} > THQ_{Zn} > THQ_{Cd} > THQ_{Cr}$, Cu and Mn being the main contributors to the TTHQ. The TTHQ values ranged from 0.013 (watermelon, F31*) to 0.315 (strawberry, F4*) (Table 5, Figure 11) and were also below 1 for all fruits, indicating that the simultaneous intake of the six trace elements assessed by THQ through fruit consumption does not present a risk to human health. In the case of strawberry, Mn and Cu accounted for 43% and 35% of the TTHQ, respectively, in agreement with the high contents of these elements (Table 2).

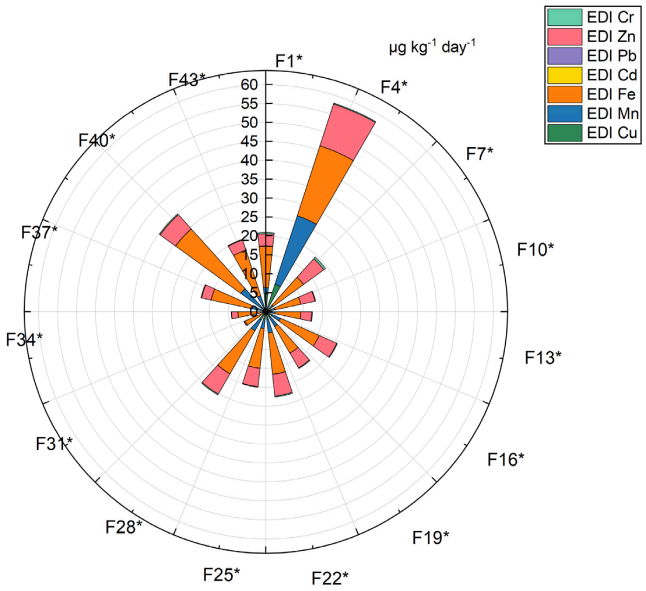



**Figure 9.** Graphical representation of the estimated daily intake (EDI) of trace elements for the analysed fruits (µg $kg^{-1}$ $day^{-1}$). The contributions of Cd and Pb are too small to be visible at this scale; the exact values are given in Table 3. samples from this study are marked with *.

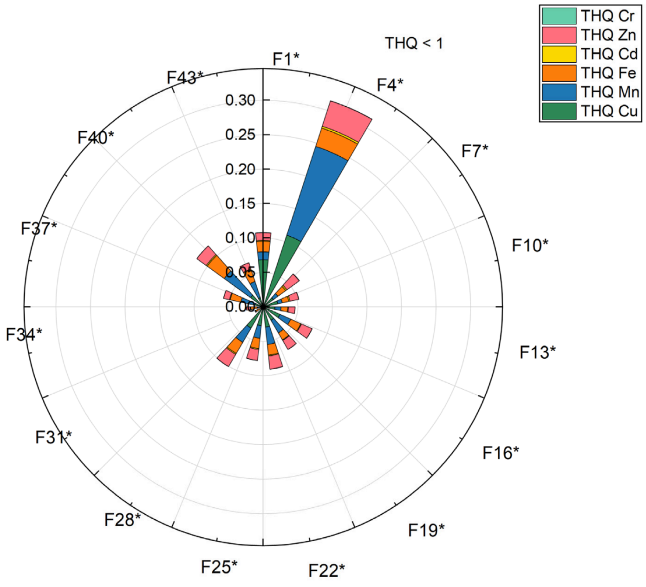



**Figure 10.** Graphical representation of the target hazard quotient (THQ) of trace elements for the analysed fruits. The contributions of Cd and Cr are too small to be visible at this scale; the exact values are given in Table 4. samples from this study are marked with *.

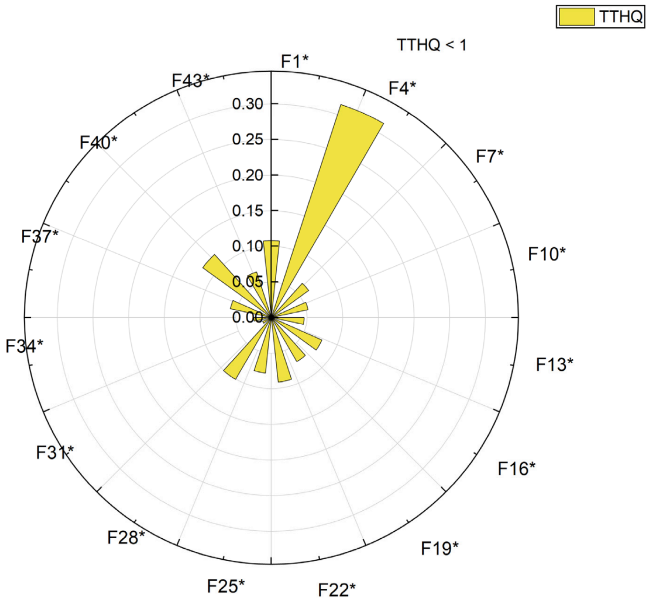



**Figure 11.** Graphical representation of the total target hazard quotient (TTHQ) for the analysed fruits. samples from this study are marked with *.

For Pb, the MOE values calculated for nephrotoxicity were 8.7 for plum (F1*) and 75.3 for strawberry (F4*), and above 43.7 for the other fruits (lower-bound values calculated with the LOQ) (Table 5, Figure 12); all values were above 1, indicating a low risk, and only plum had an MOE below 10. The carcinogenic risk associated with Pb was $6.15 \times 10^{-7}$ for plum and $7.11 \times 10^{-8}$ for strawberry, and below $1.23 \times 10^{-7}$ for the other fruits (upper-bound values), all below the negligible risk threshold of $10^{-6}$ (Table 5). These results show that, under the evaluated exposure scenario, the consumption of the analysed fruits is unlikely to pose a health risk associated with Pb, in agreement with the low Pb contents, well below the maximum levels set by the EU and the Codex Alimentarius (Section 3.1).

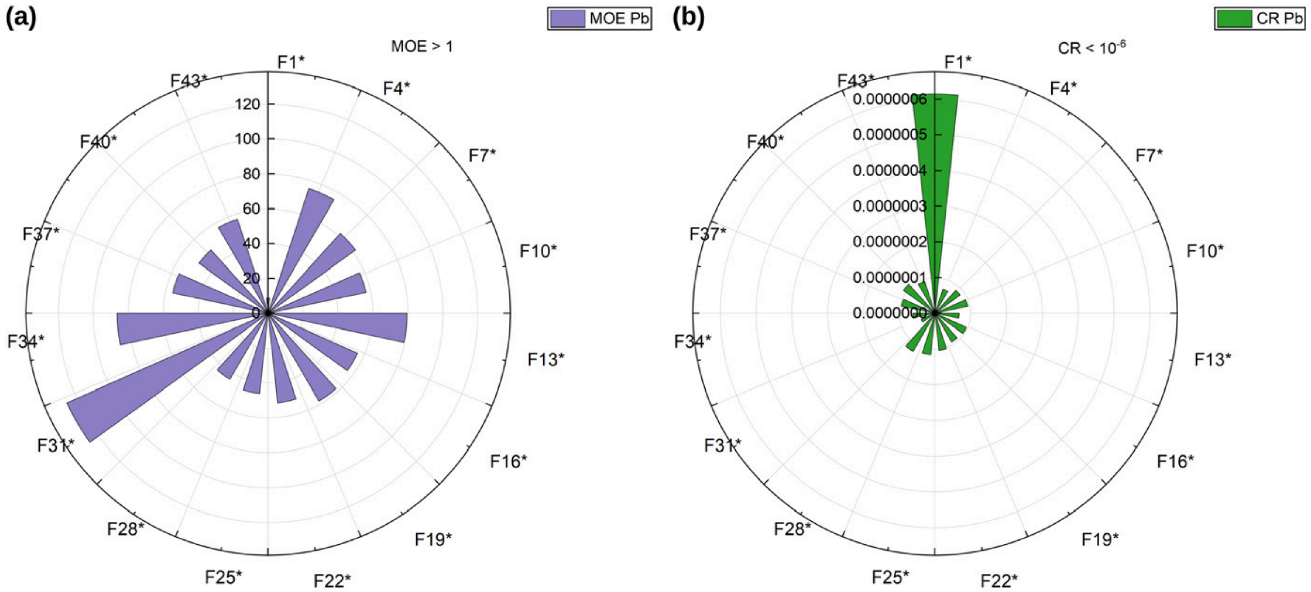



**Figure 12.** Graphical representation of (**a**) the margin of exposure (MOE) and (**b**) the carcinogenic risk (CR) for Pb for the analysed fruits. samples from this study are marked with *.

For children aged 6–9 years, the exposure per kg body weight was 2.65 times higher than that of adults (Table 6, Figure 13). All THQ values remained below 1, ranging from

less than $10^{-4}$ (Cr, watermelon and melon) to 0.360 (Mn, strawberry), and the THQ values for Cd did not exceed 0.008. The TTHQ values ranged from 0.035 (watermelon, F31*) to 0.834 (strawberry, F4*) and were below 1 for all fruits, Mn and Cu being again the main contributors. For Pb, the MOE values calculated for developmental neurotoxicity were 2.6 for plum (F1*) and 22.5 for strawberry (F4*), and above 13.1 for the other fruits (lower-bound values calculated with the LOQ); all values were above 1, indicating a low risk, but the narrow margin obtained for plum shows that children are the population group most sensitive to dietary Pb exposure, which supports the need for periodic monitoring of Pb in locally marketed fruits. Moreover, since possible losses of Pb during dry ashing could not be quantified (Section 2.4), the actual MOE values may be lower than those calculated; this is particularly relevant for plum, for which the margin obtained for children was the narrowest.

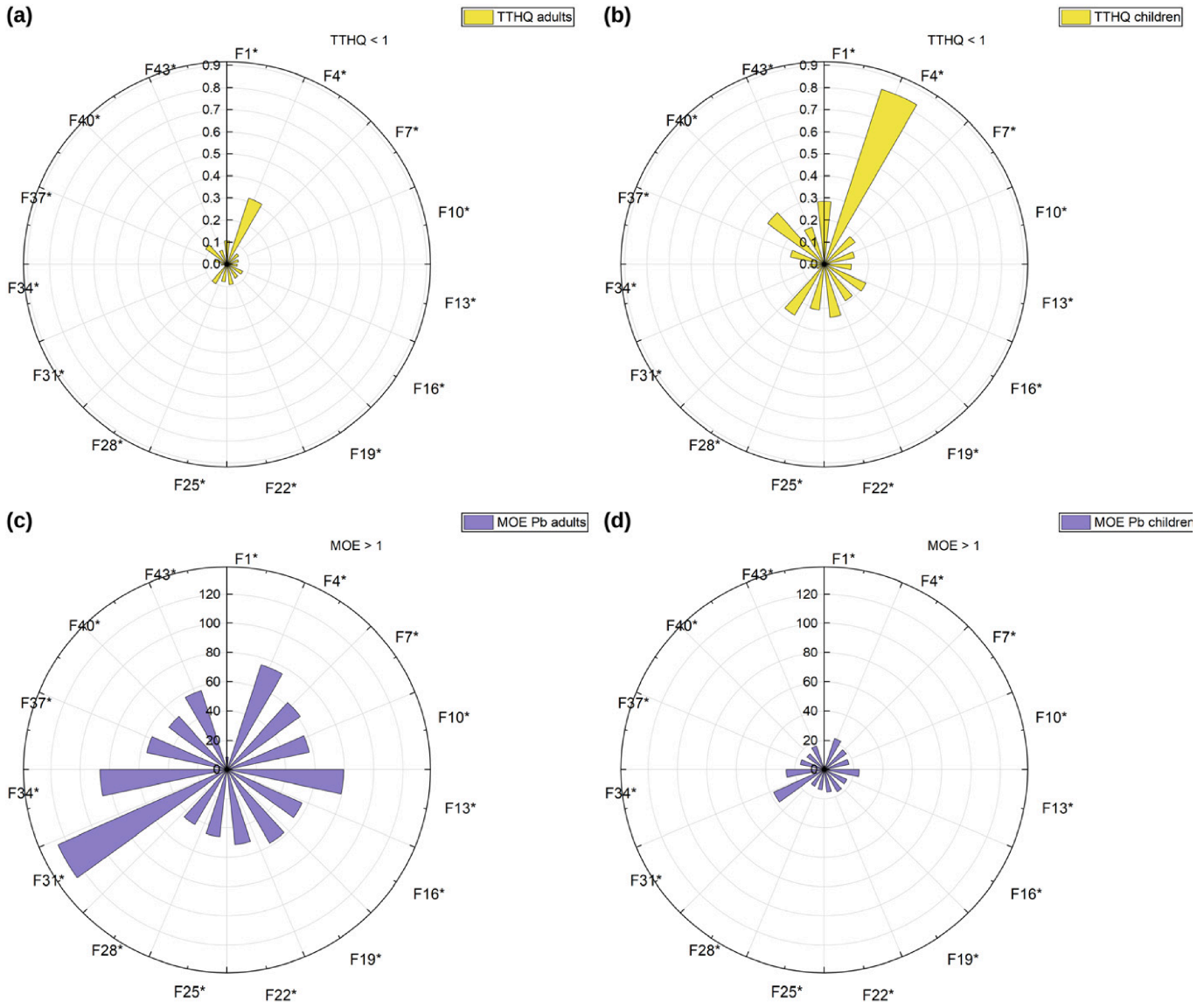



**Figure 13.** Comparison of the total target hazard quotient (TTHQ) for (**a**) adults and (**b**) children aged 6–9 years, and of the margin of exposure (MOE) for Pb for (**c**) adults and (**d**) children aged 6–9 years, for the analysed fruits. The same radial scale is used for adults and children; MOE values calculated with the LOQ are lower-bound values. samples from this study are marked with *.

**Table 6.** Target hazard quotient (THQ), total target hazard quotient (TTHQ) and margin of exposure (MOE) for Pb for children aged 6–9 years.

| Code | Fruit Sample | Cu | Mn | Fe | Cd | Zn | Cr | TTHQ | MOE (Pb) |
|---|---|---|---|---|---|---|---|---|---|
| | | THQ | THQ | THQ | THQ | THQ | THQ | — | — |
| **Rosaceae** | | | | | | | | | |
| F1* | Plum (*Prunus domestica*) | $1.81 \times 10^{-1}$ | $3.05 \times 10^{-2}$ | $4.12 \times 10^{-2}$ | $<3.55 \times 10^{-3}$ | $2.89 \times 10^{-2}$ | $5.81 \times 10^{-4}$ | 0.285 | 2.6 |
| F4* | Strawberry (*Fragaria* × *ananassa*) | $2.90 \times 10^{-1}$ | $3.60 \times 10^{-1}$ | $7.37 \times 10^{-2}$ | $7.65 \times 10^{-3}$ | $1.03 \times 10^{-1}$ | $4.39 \times 10^{-4}$ | 0.834 | 22.5 |
| F7* | Apple (*Malus domestica*) | $4.76 \times 10^{-2}$ | $2.17 \times 10^{-2}$ | $3.73 \times 10^{-2}$ | $5.41 \times 10^{-3}$ | $5.81 \times 10^{-2}$ | $1.01 \times 10^{-3}$ | 0.171 | >18.5 |
| F10* | Pear (*Pyrus communis*) | $5.67 \times 10^{-2}$ | $1.75 \times 10^{-2}$ | $2.63 \times 10^{-2}$ | $4.67 \times 10^{-3}$ | $3.38 \times 10^{-2}$ | $3.27 \times 10^{-4}$ | 0.139 | >17.1 |
| F13* | Peach (*Prunus persica*) | $4.44 \times 10^{-2}$ | $2.34 \times 10^{-2}$ | $2.57 \times 10^{-2}$ | $2.52 \times 10^{-3}$ | $2.55 \times 10^{-2}$ | $3.08 \times 10^{-4}$ | 0.122 | >23.8 |
| F16* | Apricot (*Prunus armeniaca*) | $6.99 \times 10^{-2}$ | $4.52 \times 10^{-2}$ | $4.23 \times 10^{-2}$ | $<2.98 \times 10^{-3}$ | $4.46 \times 10^{-2}$ | $3.02 \times 10^{-4}$ | 0.205 | >16.8 |
| F19* | Sour cherry (*Prunus cerasus*) | $5.92 \times 10^{-2}$ | $5.59 \times 10^{-2}$ | $3.08 \times 10^{-2}$ | $<2.88 \times 10^{-3}$ | $3.99 \times 10^{-2}$ | $3.45 \times 10^{-4}$ | 0.189 | >17.4 |
| F22* | Sweet cherry (*Prunus avium*) | $7.77 \times 10^{-2}$ | $6.75 \times 10^{-2}$ | $4.18 \times 10^{-2}$ | $<3.24 \times 10^{-3}$ | $5.10 \times 10^{-2}$ | $4.15 \times 10^{-4}$ | 0.242 | >15.4 |
| **Vitaceae** | | | | | | | | | |
| F25* | White grape (*Vitis vinifera*) | $7.23 \times 10^{-2}$ | $4.86 \times 10^{-2}$ | $4.01 \times 10^{-2}$ | $<3.62 \times 10^{-3}$ | $4.29 \times 10^{-2}$ | $2.99 \times 10^{-4}$ | 0.208 | >13.8 |
| F28* | Black grape (*Vitis vinifera*) | $9.40 \times 10^{-2}$ | $6.34 \times 10^{-2}$ | $4.98 \times 10^{-2}$ | $<3.83 \times 10^{-3}$ | $5.46 \times 10^{-2}$ | $3.67 \times 10^{-4}$ | 0.266 | >13.1 |
| **Cucurbitaceae** | | | | | | | | | |
| F31* | Watermelon (*Citrullus lanatus*) | $6.06 \times 10^{-3}$ | $4.17 \times 10^{-3}$ | $2.13 \times 10^{-2}$ | $<1.33 \times 10^{-3}$ | $2.56 \times 10^{-3}$ | $<8.84 \times 10^{-5}$ | 0.035 | >37.7 |
| F34* | Melon (*Cucumis melo*) | $1.32 \times 10^{-2}$ | $9.94 \times 10^{-3}$ | $2.47 \times 10^{-2}$ | $<1.93 \times 10^{-3}$ | $1.49 \times 10^{-2}$ | $<1.29 \times 10^{-4}$ | 0.065 | >25.9 |
| **Grossulariaceae** | | | | | | | | | |
| F37* | Red currant (*Ribes rubrum*) | $3.25 \times 10^{-2}$ | $5.56 \times 10^{-2}$ | $4.16 \times 10^{-2}$ | $<2.99 \times 10^{-3}$ | $2.31 \times 10^{-2}$ | $2.15 \times 10^{-4}$ | 0.156 | >16.7 |
| F40* | Black currant (*Ribes nigrum*) | $6.05 \times 10^{-2}$ | $1.25 \times 10^{-1}$ | $8.06 \times 10^{-2}$ | $4.10 \times 10^{-3}$ | $4.46 \times 10^{-2}$ | $3.83 \times 10^{-4}$ | 0.315 | >14.6 |
| **Ericaceae** | | | | | | | | | |
| F43* | Blueberry (*Vaccinium corymbosum*) | $3.69 \times 10^{-2}$ | $6.54 \times 10^{-2}$ | $4.80 \times 10^{-2}$ | $<2.94 \times 10^{-3}$ | $2.51 \times 10^{-2}$ | $2.66 \times 10^{-4}$ | 0.179 | >17.0 |

THQ, TTHQ and MOE were calculated for a daily intake of 175 g of fresh fruit and a body weight of 23.1 kg, using the trace element contents from Table 2 converted to fresh weight. For samples with contents below the LOQ, the LOQ was used as an upper-bound concentration; the resulting THQ values are upper-bound values (<) and the MOE values are lower-bound values (>). TTHQ, sum of the THQ values of Cu, Mn, Fe, Cd, Zn and Cr; MOE, margin of exposure calculated for the $BMDL_{01}$ of 0.50 µg $kg^{-1}$ $day^{-1}$ for developmental neurotoxicity [54]. *, samples analysed in this study.

## 4. Conclusions

This study evaluated the moisture, macroelement (Na, K, Ca, Mg) and trace element (Cu, Mn, Fe, Cd, Pb, Zn, Cr) contents of 15 fruit species belonging to five botanical families, purchased from the agri-food market in Reșița, Romania, using flame and graphite furnace atomic absorption spectrometry. The analysed fruits proved to be an important source of K, followed by Ca and Mg, while their Na content was low; the average macroelement contents followed the order K > Ca > Mg > Na, and the trace element contents the order Fe > Zn > Mn > Cu > Cr > Pb > Cd. Strawberry had the highest contents of K, Mg, Cu, Mn, Fe and Zn, black currant the highest Ca content and watermelon the highest Na content. The values obtained were comparable to those reported in the literature for the same species.

The exploratory chemometric analysis showed that the first three principal components explained more than 93% of the total variance for both macroelements and trace elements (Cu, Mn, Fe, Zn and Cr). For macroelements, k-means clustering of the PCA scores identified four groups of samples, determined mainly by the overall mineral content and by the Na and Ca contents, while for trace elements three groups were obtained: a large group with low and uniform contents, which included all the analysed fruits except strawberry, and two groups of samples with high Fe, Zn, Mn, Cu or Cr contents. The fruits analysed in this study were grouped together with the literature data for the same species, hierarchical cluster analysis confirmed the groupings obtained by PCA and k-means clustering, and the groupings were not affected by the treatment of the non-detected values.

The Pb and Cd contents of the analysed fruits were well below the maximum levels set by the EU and the Codex Alimentarius. For a daily intake of 200 g of fresh fruit, the estimated daily intake of all trace elements was well below the corresponding reference doses, and the THQ and TTHQ values were below 1 for all fruits, indicating no non-carcinogenic risk to consumers. The THQ and TTHQ values also remained below 1 for children aged 6–9 years consuming 175 g of fresh fruit per day. For Pb, the margin of exposure was above 1 for all fruits, for both adults and children, and the carcinogenic risk was below $10^{-6}$, indicating a low risk. Therefore, under the evaluated exposure scenarios, the consumption of the analysed fruits is unlikely to present a risk to human health, and these fruits can be considered a valuable source of essential mineral elements in the diet. Nevertheless, given the cumulative toxicity of Cd and Pb, periodic monitoring of their contents in fruits sold on local markets is recommended.

Since each fruit species was represented by a single lot from one local producer and market, the results may not be representative of other regions or seasons. Furthermore, recovery tests and certified reference material analysis were not performed; therefore, partial losses of the more volatile elements (Cd and Pb) during dry ashing cannot be completely excluded, and the reported Cd and Pb contents should be regarded as indicative; consequently, the EDI, THQ, MOE and CR values calculated for Cd and Pb may underestimate the actual exposure and should be interpreted with caution. Moreover, the health risk assessment was based on hypothetical exposure scenarios for adults and for children aged 6–9 years, and the conclusions on consumer safety apply only to the evaluated fruits and exposure conditions.

**Author Contributions:** Conceptualisation, R.C.H.-M., P.N., D.S.Ș., I.C., M.N., C.I.J. and G.H.-M.; validation, R.C.H.-M. and G.H.-M.; investigation, R.C.H.-M., P.N., I.C. and G.H.-M.; writing—original draft preparation, R.C.H.-M., D.S.Ș. and G.H.-M.; writing—review and editing, R.C.H.-M., P.N., D.S.Ș., I.C., M.N., C.I.J. and G.H.-M.; visualisation, R.C.H.-M., I.C., M.N. and G.H.-M.; supervision, R.C.H.-M., I.C. and G.H.-M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Acknowledgments:** The authors would like to thank the University of Life Sciences "King Mihai I" from Timișoara for the academic support and resources provided during the development of this research. During the preparation of this manuscript, the authors used M365 Copilot (based on the GPT-5 model) for language editing, rephrasing of certain passages, checking their clarity and coherence, and formatting the references and tables. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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