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Article

Effect of Organic Fertilization on Macro– and Microelement Contents in Leaves and Fruits of Red Currant (*Ribes rubrum* L.)

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Abstract

This study was conducted over a four–year period (2019–2022) in an experimental red currant (*Ribes rubrum* L.) orchard to examine the effect of organic fertilization on the contents of macroelements (C, N, P, K, Ca, Mg, S) and microelements (Fe, Mn, Cu, Zn, B) in the leaves and fruits. Two organic fertilizers were applied: well–decomposed cattle manure (CM) at 60 t ha^{-1}, and pelletized poultry manure (PPM, 'Italpollina', NPK 4:4:4) at 1.6 t ha^{-1}. The study evaluated nutrient balance using the Deviation from Optimum Percentage (DOP) index in two cultivars, 'Rolan' and 'Jonkheer van Tets'. In 2021, no differences in balance of macronutrient were observed between cultivars; however, in 2022, 'Rolan' exhibited a higher imbalance than 'Jonkheer van Tets'. 'Rolan' showed greater imbalance for micronutrients in 2021, whereas in 2022 the opposite trend was recorded, with 'Jonkheer van Tets' showing higher ΣDOP values. Fertilization treatment affected nutrient balance, with CM causing the highest macro- and micronutrient nutrient differences in 2022, while PPM promoted a more moderate and stable nutrient status. The greatest differences were observed in the R–CM treatment. The findings highlight the importance of selecting appropriate fertilizer to maintain nutrient balance and optimize red currant cultivation.

Keywords: cattle manure; macroelements; microelements; organic fertilization; pelletized poultry manure; red currant

1 Introduction

Red currant is a perennial berry fruit species of high nutritional value, which ranked third in global production among berry fruits, after strawberry and raspberry. In 2024, 98.2% of the world's currants were produced in Europe. Russia led with around 509,945 thousand tons, followed by Poland with 100,200 thousand tons and Ukraine with 23,800 thousand tons (FAOSTAT, 2024). The most common currants species that are grown for commercial use are black (*Ribes nigrum* L.), red (*Ribes rubrum* L.) and white currants (*Ribes rubrum* L. var. *album*). Currants are a source of mineral elements, especially potassium (K),

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phosphorus (P), calcium (Ca), magnesium (Mg), and iron (Fe), as well as vitamins, sugars, organic acids, and other biologically important compounds (Nour et al., 2014; Ersoy et al., 2018; Kierońska et al., 2024).

Nitrogen (N), phosphorus (P) and potassium (K) are macroelements that are essential for both plant growth and development (Sergio, 2005). Their content in the currants is influenced by climatic factors (such as temperature and precipitation), soil properties, irrigation water quality, applied agrotechnical measures, and the currant cultivar (Plessi et al., 2007; Milošević, 2018; Wolske et al., 2021; Kierońska et al., 2024), but also by storage and commercialization conditions. The use of plant nutrition products that contained N, P and K has a major impact on the both quality and quantity of fruits (Chu et al., 2007; Wang et al., 2024; Guo et al., 2021). In order to reduce the unnecessary amounts of their applications, the balanced amounts could be carefully determined and applied.

To ensure vegetative growth, form a large number of new branches and fruiting area, produce fruits of satisfactory nutritional and organoleptic quality, currants require regular application of only the necessary amount of nutrients and a balanced nutrition regime (Nikolić and Milivojević, 2015; Zdunić et al., 2016). The investigation of the timing, type, and fertilizer usage plan is a key research subject for many scientists today (Neilsen et al., 2009; Wang et al., 2024). Most authors suggest that the best period for fertilizer application is in the spring, before the growing season begins. In this way, sufficient time for mineralization and movement of individual nutrients into the root zone and to avoid unnecessary damage to the plant caused by the application of manure and mineral fertilizers during the summer and autumn can be provided (van Duijnen et al., 2021; Norberg and Aronsson, 2024; Zhang et al., 2025; Masaka, 2005). The use of organic fertilizers reduces the high costs of using mineral fertilizers and is therefore considered good agricultural practice (Al-Sheikh et al., 2024). This is also important based on the fact that there is an increase in the need for organic fruits production. In this regard, Hanč et al. (2008) note that organic fertilizer can replace the usually used mineral fertilizer, and in some cases, the yield of the biomass of the cultivated crop can be increased more than that which can be achieved with the use of mineral fertilizer. It should be mentioned that the importance of organic fertilizer is not based on the safety of the environment alone, but there is improvement in the physical and chemical properties of the soil, which makes it more fertile (Hopkins, 2001; Hu and Cao, 2007). Unlike mineral fertilizers, the addition of organic fertilizers increases the reserves of N, P and K in the soil (Mustatfa and Ahmed, 2023). Wójcik and Filipczak (2015) emphasized that organic fertilizers can be a complete or partial replacement for all nutrients. They concluded that P– and K–based fertilizers can be replaced by manure, which makes currants suitable for organic production. Manure is an important source of N, P, K and organic matter for currants, and its use can save 50% or more in the use of mineral N (Petrović et al., 2020). Dean et al. (2000) note that a few hours after application the application of solid chicken manure, 50% of the total nitrogen is in inorganic form. Moreover, organic cultivation practices enhance the levels of bioactive compounds in blackcurrants, with those from organic systems exhibiting significantly higher contents of vitamin C, total polyphenols, total phenolic acids, total flavonoids, and anthocyanins compared to conventionally grown ones (Rachtan-Janicka et al., 2021).

Research on the effects of organic fertilizers on red currants is very limited, especially regarding their impact on the mineral composition of leaves and fruits, yield, and bioactive compounds of red currants. Most existing studies have focused primarily on comparing macro– and micronutrient content across different currant cultivars (Niskanen, 2002; Nour et al., 2011; Petrisor et al., 2013; Ziobroń et al., 2021; Gacnik et al., 2024; Kierońska et al., 2024). For example, Pandelea et al. (2023) evaluated the effects of two types of organic compost (municipal sludge and vegetal-origin compost) on red currant quality, with particular focus on berry quality in the cultivar 'Jonkheer van Tets'. Their findings indicated that vegetal-origin compost significantly improved berry quality by increasing dry matter and vitamin C content.

Despite the increasing demand for currants on the Serbian market and favourable agroecological conditions for currants cultivation, production in the Republic of Serbia remains low, with an annual production of approximately 150 tons (Paunović et al., 2025). As early as the 1970s, they were commercially cultivated in the areas of Požega, Arilje, Guča, Čačak, Valjevo, Kosjerić, and Vlasina (Stanisavljević et al., 1999). Although in Western and Southern Serbia there are between 70 and 80 ha of modern plantations of black and red currants, currants are most often grown in home gardens as individual bushes (Nikolić et al., 2012; Keserović et al., 2014).

The aim of this study was to assess the effect of organic fertilization on the content of macroelements (C, N, P, K, Ca, Mg, S) and microelements (Fe, Mn, Cu, Zn, B) in the leaves and fruits of two red currant (*Ribes rubrum* L.) cultivars grown in western Serbia. The study also seeks to clarify the role of organic fertilizers in mineral accumulation, contributing to the development of nutritionally enhanced fruits and environmentally sustainable production systems.

2 Materials and Methods

2.1 Experimental Site and Environmental Conditions

The currant orchard was established in the spring of 2019 in bush training system at the village of Tijanje, Municipality of Lučani, western part of the Republic of Serbia (43°49′40.80″ N, 20°13′46.00″ E) at an altitude of 397 m a.s.l. using two-year-old plants, spaced 3 m between rows and 1.2 m within the row. This study included two red currant cultivars: 'Rolan' (developed in the Netherlands, producing large, light–red, sweet–tart berries in long mid–season–ripening clusters on a vigorous, upright bush) and 'Jonkheer van Tets' (developed in the Netherlands, producing large, early–ripening, purplish–red, slightly tart berries in medium–length clusters of 8–10 berries on a vigorous, upright bush) (Zdunić et al., 2016). Moreover, both 'Rolan' and 'Jonkheer van Tets' are officially recognized red currant (*R. rubrum*) cultivars in Serbia by the Ministry of Agriculture, Forestry and Water Management (https://sorte.minpolj.gov.rs/registar-priznatih-sorti). During the experimental period, the orchards were maintained following regular cultural and protective practices.

The regional climate is classified as mild continental, and the experimental site is south–east oriented. According to the data provided by the Republic Hydrometeorological Institute of Serbia (RHI, 2026) 2019 was the warmest year in Serbia since the beginning of meteorological observations. The average annual air temperature in the experimental region was 11.0 °C. The total annual precipitation was 859.2 mm, and the area had very rainy conditions. The summer of 2020 was the second wettest in Serbia since the beginning of meteorological records. The total annual precipitation in the experimental region was 808.3 mm and the average annual temperature was 10.6 °C. In 2021, the winter was warm and humid. It was also a very rainy year, with total annual precipitation reaching 922.1 mm. The average annual temperature dropped to 10.3 °C. The highest mean monthly temperature, 22.0 °C, occurred in July, which was particularly warm. Furthermore, 2022 was the second warmest year in Serbia since meteorological records began. It recorded the second hottest July at the measurement site and was very dry, with a high number of frost days. The vegetation period was marked by pronounced drought conditions. Total precipitation in the experimental area amounted to 544.8 mm, and the average annual temperature was 10.9 °C. Figure 1 summarizes the weather conditions recorded during the experimental period.

2.2 Experimental Design and Plant Material

The experiment was established as a randomized complete block design with three replications, including two cultivars and three fertilization treatments. Each cultivar × fertilization combination was represented by five plants per three replications (block), totalling 15 plants per combination. The experiment included two organic fertilization treatments: well–decomposed cattle manure (CM) and pelletized poultry manure (PPM, NPK 4:4:4) as well as a control treatment without fertilizer application. CM was applied at a rate 60 t ha^{-1} while PPM was applied at 1.6 t ha^{-1}.

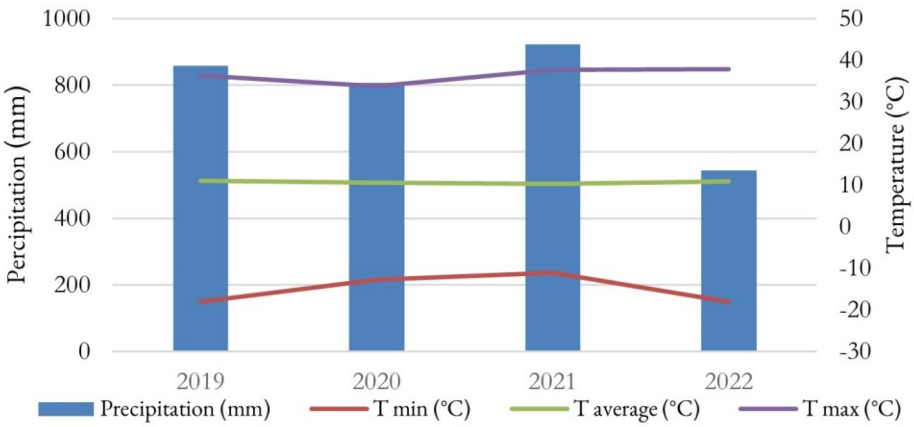

Figure 1. Weather parameters (precipitation; T_{min}, $T_{average}$ and T_{max} – minimum, average and maximum air temperature, respectively) during the experimental period.

The chemical composition of the CM was as follows: an average composition of 12.91% moisture, 1.95% total nitrogen (N_{tot}), 2.40% P_2O_5, and 1.83% K_2O. The total content of the microelements Cu, Mn, Fe, Zn, and B was 35.02 ppm, 428.29 ppm, 0.33 ppm, 93.81 ppm, and 8.73 ppm, respectively. The content of Ca, Mg, and C was 4.62%, 0.80%, and 16.53%, respectively. The carbon-to-nitrogen ratio (C/N) was 8.48. PPM is commercially available and is produced by 'Italpollina' SPA (Italy). According to the manufacturer, poultry manure serves as the primary raw material, supplemented with dehydrated feathers, fulvic acid, amino acids, and guano. Its declared composition is as follows: N_{tot} 4%, organic nitrogen 4%, 4 % P_2O_5, 4% K_2O, organic carbon 30%, and a C/N ratio of up to 10.

CM and PPM were applied to the soil surface in row bands before planting and incorporated into the soil by rotary tilling and hoeing. Fertilization was repeated annually before the beginning of the growing season. The experiment was conducted from 2019 to 2022.

Samples of leaves and fruits were collected over two consecutive years (2021 and 2022). Up to fifty leaves were sampled from the middle mature section on the lateral– and primocanes for each of the three replicates (Jones, 1998; Paunović et al., 2022), 120 days after full flowering. Fruit samples were harvested at optimal maturity, defined for each cultivar as the point when approximately 90% of the fruit surface was coloured (Đorđević et al., 2022). For each replicate, around 0.5 kg of fruit was collected, resulting in a total of 1.5 kg per treatment.

2.3 Chemical Properties of the Soil

Soil samples were collected from the top layer (0–30 cm). The samples were homogenized to form a composite sample, air–dried, ground, and sieved through a 2 mm mesh prior to further analysis, in accordance with ISO 18400. Soil analyses were conducted over four experimental years.

Soil pH was measured potentiometrically using a pH meter (Mettler–Toledo, Greinfensee, Switzerland) equipped with a glass electrode in soil suspensions prepared with distilled water and 1 M KCl (1:5, v/v), following the procedure described in SRPS EN ISO 10390:2022. Calcium carbonate ($CaCO_3$) content was determined volumetrically using the Scheibler method using five–position 'Scheibler'calcimeter (Many Agrovet, Belgrade, Serbia), according to SRPS ISO 10693:2005. The soil organic matter (SOM) content was estimated by multiplying the organic C concentration by a coefficient of 1.724 (Nelson and Sommers, 1996). Organic C content was determined according to SRPS ISO 10694:2005. The contents of plant available forms of P (P_2O_5) and K (K_2O) were determined by the Egner–Riehm method using an extraction procedure with an ammonium lactate (0.1 M) in acetic acid (0.4 M) solution at pH 3.7 (Riehm, 1958). Plant available K_2O concentration was measured using an FP 6440 Precise Perfect flame photometer

(Hinotek, Ningbo, China). In the extracts, plant available P_2O_5 concentration was determined spectrophotometrically using the molybdenum blue stannous chloride reducing agent method, on a UV–160A spectrophotometer (Shimadzu, Kyoto, Japan) at a wavelength of 580 nm.

2.4 Evaluation of Leaf and Fruit Macro – and Micronutrient Composition

Samples of leaf and fruit were air–dried and ground using a grinder (IKA 11 Basic Analytical Mill, IKA Werke GmbH & Co. KG, Staufen, Germany) prior to further analyses. To express element content on a dry mass basis, the moisture content of the plant tissue was determined on subsamples (Miller, 1998). Total N and C contents were measured by dry combustion using a CNS elemental analyzer (Vario EL III CHNOS Elemental Analyzer, Elementar Analyses System GmbH, Langenselbold, Germany) on air-dried samples. The results were expressed on a dry matter basis. The contents of macroelements (P, K, Ca, Mg, S) and microelements (Fe, Mn, Cu, Zn, B) were determined after digestion with concentrated nitric acid (65% HNO_3) and 30% hydrogen peroxide (H_2O_2) (Jones and Case, 1990), using inductively coupled plasma optical emission spectrometry (ICP–OES) with an iCAP 6300 Duo instrument (Thermo Scientific, Cambtidge, United Kingdom) and corrected to an absolute dry matter basis.

2.5 Deviation from Optimum Percentage (DOP Index)

For a more complete interpretation of the obtained results of the mineral composition of the leaves in relation to the reference values, the provision of currants with mineral elements is shown using the DOP (Deviation from Optimum Percentage) index (Montañés et al., 1991). The DOP index is calculated according to the formula:

$$DOP = \frac{C \text{ x } 100}{C_{ref}} - 100 \quad (1)$$

where C represents the content of a chemical element, and C_{ref} represents the optimal reference value of the content of an element in the leaf (Montañés et al., 1993). The most common value is taken from the literature, the authors of which are reputable world experts. In this case, the reference values given by Niskanen (2002) were used. The interpretation of results based on the DOP index value suggests that the security of plants is optimal if its DOP index is equal to zero; positive values of the DOP index suggest that there is an excess (+) of something, and negative values suggest that there is a lack of something (–).

ΣDOP represents the state of the leaf mineral supply with macro or microelements, or the total intensity of the imbalance of mineral nutrition. ΣDOP is obtained by simply adding the absolute values of the DOP index of all macro or microelements. If the value of ΣDOP is higher, then the intensity of the imbalance between nutrients is higher and vice versa.

2.6 Statistical Analysis

The obtained data were analysed using a two–way analysis of variance (ANOVA) to assess the effects of cultivar (A), fertilizer (B), and their interaction (A×B) on leaf and fruit micro– and macronutrient content. Differences among means were evaluated using the least significant difference (LSD) test at $p < 0.05$. The statistical software package Statgraphic18 (Manugistics, Inc., Rockville, MD, USA) was used for all statistical analyses.

3 Results and Discussion

3.1 Chemical Properties of the Soil

For successful cultivation of currants, deep, moderately heavy, well-structured, well-drained, and slightly acidic soils (pH 5.5–7.0) are most suitable. Such soils should be rich in humus and essential nutrients, particularly potassium and phosphorus (Milivojević, 2022). Based on the soil analysis results presented in Table 1, the soil of the experimental orchard is suitable for currant cultivation. Namely, soil pH ranged from slightly acidic to near neutral (6.23–7.10 in H_2O; 5.33–6.12 in KCl), with slightly lower values under organic fertilization (CM, PPM). The $CaCO_3$ was below detection limits, consistent with the pH values. Available K_2O and P_2O_5 were generally well supplied; PPM increased both nutrients, while CM increased P_2O_5 in all years and K_2O from 2021. In contrast, nutrient levels in the control declined to medium supply by 2022 (Manojlović et al., 1969). SOM was at a medium level but increased over time, particularly under organic treatments, indicating accumulation effects (Hanč et al., 2008; Al-Sheikh et al., 2024).

Table 1. Basic agrochemical characteristics of the soil.

Year	Treatment	Parameter					
		pH (H_2O)	pH (KCl)	Carbonate content	Plant-available K_2O, (mg 100 g^{-1})	Plant-available P_2O_5, (mg 100 g^{-1})	SOM (%)
2019	Control	6.94	5.85	<LOD	79.00	22.80	3.29
	CM	6.43	5.37	<LOD	77.30	26.60	3.90
	PPM	6.42	5.71	<LOD	102.60	36.70	4.19
2020	Control	7.10	6.12	<LOD	77.30	19.60	3.67
	CM	6.72	5.61	<LOD	70.55	33.65	4.31
	PPM	6.88	5.98	<LOD	103.90	41.25	4.22
2021	Control	6.95	5.87	<LOD	62.95	15.90	2.72
	CM	6.23	5.33	<LOD	80.70	24.15	3.80
	PPM	6.64	5.56	<LOD	99.65	30.40	3.71
2022	Control	6.64	5.65	<LOD	60.85	15.05	3.22
	CM	6.53	5.55	<LOD	74.80	30.30	4.38
	PPM	6.62	5.60	<LOD	97.15	38.55	4.29

< LOD – Values below the limit of detection (limit of detection 0.04%); SOM – soil organic matter; CM – cattle manure; PPM – pelletized poultry manure.

3.2 Mineral Composition of Red Currant Leaves

The genetic yield potential of a species or genotype can be fully expressed only under conditions of optimal supply of essential mineral nutrients. The concentrations of the analysed macroelements (C, N, P, K, S, Ca, and Mg) in red currant leaf samples across treatments and years are presented in Table 2.

Content of C, N, and P in leaf samples did not differ significantly between the cultivars, suggesting a similar capacity of cultivars 'Jonkheer van Tets' and 'Rolan' to accumulate these macronutrients. However, K and Ca contents showed significant differences between tested cultivars, with higher content in the 'Rolan'. Significant differences in S content between the examined cultivars were observed in 2022, while Mg content varied significantly only in 2021 showing higher content in 'Jonkheer van Tets'.

There were no significant differences in the contents of C, N, and S among the different fertilizers, possibly due to the fact that fertilizer application had little effect on content of these macronutrients in the leaves. In contrast, leaf P and Ca concentrations differed significantly among fertilizer treatments, with higher values in the control than in fertilized plants. This can be explained by the antagonistic effect of elevated K on Ca uptake, as well as by the possible immobilization or reduced availability of P in organically amended soils. Additionally, when phosphorus fertilizers are applied, only a small fraction is taken up by plants, while the remainder reacts with soil constituents to form less soluble compounds (Sundara et al., 2002). The K content in leaves did not differ statistically among fertilizers in 2021, but differences were significant in 2022. In 2022, the control exhibited higher K content compared to CM and PPM, suggesting no clear effect of fertilizer application on leaf K concentration. Leaf Mg content did not differ significantly among fertilizer treatments in 2021, whereas a significant treatment effect was observed in 2022. The higher Mg content in the leaves of the studied currant cultivars in 2022 under the CM treatment was most likely caused by the low K content, due to the competitive interaction between Mg^{2+} and K^{+} ions.

Table 2. Influence of cultivar and organic fertilizers treatment (CM and PPM) on the macroelement composition of red currant leaves.

Factor		C (%)		N (%)		P (%)		K (%)		S (%)		Ca (%)		Mg (%)	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Cultivar (A)	JVT	46.36 ± 1.05^{a}	46.43 ± 1.07^{a}	2.52 ± 0.06^{a}	2.77 ± 0.07^{a}	0.34 ± 0.01^{a}	0.47 ± 0.02^{a}	2.15 ± 0.03^{b}	2.32 ± 0.08^{b}	0.18 ± 0.00^{a}	0.19 ± 0.00^{a}	2.55 ± 0.08^{b}	3.24 ± 0.12^{b}	0.37 ± 0.00^{a}	0.39 ± 0.02^{a}
	R	46.94 ± 1.07^{a}	45.55 ± 1.07^{a}	2.42 ± 0.07^{a}	2.56 ± 0.06^{a}	0.40 ± 0.04^{a}	0.41 ± 0.02^{a}	2.40 ± 0.03^{a}	2.55 ± 0.03^{a}	0.18 ± 0.00^{a}	0.17 ± 0.00^{b}	2.75 ± 0.13^{a}	3.36 ± 0.15^{a}	0.35 ± 0.00^{b}	0.40 ± 0.01^{a}
Fertilizer (B)	CM	47.12 ± 1.35^{a}	46.42 ± 1.34^{a}	2.57 ± 0.08^{a}	2.76 ± 0.09	0.33 ± 0.00^{b}	0.41 ± 0.01^{b}	2.24 ± 0.03^{a}	2.39 ± 0.05^{b}	0.18 ± 0.00^{a}	0.18 ± 0.00^{a}	2.45 ± 0.04^{b}	3.34 ± 0.12^{a}	0.36 ± 0.00^{a}	0.45 ± 0.01^{a}
	PPM	46.24 ± 1.33^{a}	46.72 ± 1.33^{a}	2.48 ± 0.07^{a}	2.65 ± 0.09^{a}	0.32 ± 0.00^{b}	0.40 ± 0.02^{b}	2.33 ± 0.04^{a}	2.28 ± 0.09^{b}	0.18 ± 0.00^{a}	0.18 ± 0.00^{a}	2.44 ± 0.01^{b}	3.05 ± 0.19^{b}	0.37 ± 0.01^{a}	0.37 ± 0.01^{b}
	Control	46.58 ± 1.32^{a}	44.84 ± 1.30^{a}	2.35 ± 0.08^{a}	2.58 ± 0.09^{a}	0.46 ± 0.04^{a}	0.52 ± 0.01^{a}	2.26 ± 0.10^{a}	2.64 ± 0.02^{a}	0.18 ± 0.01^{a}	0.18 ± 0.01^{a}	3.06 ± 0.09^{a}	3.51 ± 0.14^{a}	0.35 ± 0.00^{a}	0.36 ± 0.01^{b}
Cultivar × Fertilizer (A × B)	JVT–CM	46.63 ± 2.09^{a}	46.93 ± 2.10^{a}	2.62 ± 0.12^{a}	2.86 ± 0.13^{a}	0.32 ± 0.00^{d}	0.43 ± 0.00^{c}	2.18 ± 0.01^{e}	2.29 ± 0.01^{d}	0.19 ± 0.00^{c}	0.19 ± 0.00^{b}	2.36 ± 0.01^{e}	3.27 ± 0.21^{c}	0.37 ± 0.00^{b}	0.47 ± 0.00^{a}
	JVT–PPM	45.69 ± 2.05^{a}	46.95 ± 2.11^{a}	2.48 ± 0.11^{a}	2.76 ± 0.12^{a}	0.31 ± 0.00^{e}	0.44 ± 0.00^{c}	2.23 ± 0.01^{d}	2.08 ± 0.01^{e}	0.19 ± 0.00^{b}	0.19 ± 0.00^{c}	2.43 ± 0.00^{d}	3.19 ± 0.35^{e}	0.39 ± 0.00^{a}	0.36 ± 0.00^{e}
	JVT–Control	46.76 ± 2.01^{a}	45.41 ± 2.04^{a}	2.45 ± 0.11^{a}	2.69 ± 0.12^{a}	0.38 ± 0.00^{b}	0.54 ± 0.00^{a}	2.05 ± 0.00^{f}	2.60 ± 0.01^{b}	0.17 ± 0.00^{f}	0.20 ± 0.00^{a}	2.87 ± 0.02^{b}	3.25 ± 0.11^{d}	0.36 ± 0.00^{c}	0.34 ± 0.00^{f}
	R–CM	47.60 ± 2.13^{a}	45.90 ± 2.06^{a}	2.52 ± 0.11^{a}	2.67 ± 0.12^{a}	0.34 ± 0.00^{c}	0.38 ± 0.00^{d}	2.29 ± 0.00^{c}	2.49 ± 0.01^{c}	0.18 ± 0.00^{d}	0.18 ± 0.00^{d}	2.54 ± 0.01^{c}	3.41 ± 0.14^{b}	0.35 ± 0.00^{d}	0.44 ± 0.00^{b}
	R–PPM	46.80 ± 2.10^{a}	46.49 ± 2.08^{a}	2.48 ± 0.11^{a}	2.54 ± 0.11^{a}	0.32 ± 0.00^{d}	0.36 ± 0.00^{e}	2.42 ± 0.01^{b}	2.48 ± 0.00^{c}	0.17 ± 0.00^{e}	0.17 ± 0.00^{e}	2.45 ± 0.00^{d}	2.90 ± 0.22^{d}	0.35 ± 0.00^{e}	0.39 ± 0.00^{c}
	R–Control	46.41 ± 2.08^{a}	44.27 ± 1.99^{a}	2.26 ± 0.10^{a}	2.47 ± 0.11^{a}	0.55 ± 0.00^{a}	0.50 ± 0.00^{b}	2.48 ± 0.03^{a}	2.69 ± 0.00^{a}	0.19 ± 0.00^{a}	0.17 ± 0.00^{f}	3.26 ± 0.01^{a}	3.77 ± 0.11^{a}	0.35 ± 0.00^{de}	0.38 ± 0.00^{d}
Mean		46.65 ± 0.73^{A}	45.99 ± 0.74^{A}	2.47 ± 0.05^{B}	2.66 ± 0.05^{A}	0.37 ± 0.02^{B}	0.44 ± 0.02^{A}	2.28 ± 0.04^{B}	2.44 ± 0.05^{A}	0.18 ± 0.00^{A}	0.18 ± 0.00^{A}	2.65 ± 0.08^{B}	3.34 ± 0.08^{A}	0.36 ± 0.00^{B}	0.39 ± 0.01^{A}
ANOVA															
A		ns	ns	ns	ns	ns	ns	*	*	ns	*	*	*	*	ns
B		ns	ns	ns	ns	*	*	ns	*	ns	ns	*	*	ns	*
A×B		ns	ns	ns	ns	*	*	*	*	*	*	*	*	*	*

JVT – 'Jonkheer van Tets', R – 'Rolan'; CM – cattle manure, PPM – pelletized poultry manure. Means followed by different lowercase letters differ significantly among cultivars, fertilizers and interactions (cultivar×fertilizer), while means followed by different uppercase letters differ significantly among years according to the LSD test ($p < 0.05$).
n.s. – not significant; * – significant according (ANOVA, $p < 0.05$).

Cultivars showed consistent C and N content across all interaction combinations. This can be attributed to the fact that the assimilation of these essential elements is primarily regulated by intrinsic physiological mechanisms rather than by fertilization. According to Kresović and Ličina (2003), nitrogen in soil is primarily present in organic form, and its availability to plants becomes possible only after the mineralization process is completed. In contrast, the cultivar × fertilizer interaction had a significant effect on P, K, S, Ca and Mg content in leaves. Cultivar 'Rolan' exhibited the highest P concentration in the control, indicating a strong inherent capacity to accumulate P even without fertilization, while K content was also significantly higher in the control in both experimental years. On the other hand, cultivar 'Jonkheer van Tets' in the control exhibited the highest values of P among the interaction combinations in 2022. In contrast, in 2021, the treatments with CM and PPM showed a negligible increase in K content compared to control. Moreover, significant effect of interactions between cultivar and fertilization were detected with respect to S, Ca, and Mg contents.

The comparison of mean values between years showed that C and S contents remained stable, with no significant differences observed. By comparison, leaf concentrations of N, P, K, Ca, and Mg were significantly higher in 2022 than in 2021, indicating the influence of climatic conditions and plant maturity on nutrient accumulation. In 2021, nearly twice as much precipitation was recorded compared to 2022, which most likely resulted in more vigorous vegetative growth and consequently a dilution effect, leading to lower concentrations of mineral elements per unit of plant dry mass. The mineral element content in leaves depends on a wide range of biotic and abiotic factors, as well as on species and cultivar-specific characteristics. The results indicate that cultivar had a significant effect on the content of all the analysed micronutrients (Fe, Mn, B, Zn, and Cu), with the exception of Fe in 2022, where no significant difference between cultivars was found (Table 3). The cultivar 'Jonkheer van Tets' exhibited the highest contents of B and Zn in both years, indicating a strong capacity for the accumulation of these micronutrients in the leaves, while its Fe content was the highest in 2021 and comparable to that of 'Rolan' in 2022.The cultivar 'Rolan' had higher Cu content compared to 'Jonkheer van Tets' in both years. The Mn content varied among the cultivars and the years, reaching significantly higher content in 'Jonkheer van Tets' in 2021, and in 'Rolan' in 2022.

Table 3. Influence of cultivar and organic fertilizers (CM and PPM) on the microelement composition of red currant leaves.

Factor		Fe (ppm)		Mn (ppm)		B (ppm)		Zn (ppm)		Cu (ppm)	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Cultivar (A)	JVT	196.97 ± 9.01 ^{a}	185.35 ± 3.88 ^{a}	48.54 ± 3.41 ^{a}	56.50 ± 4.06 ^{b}	31.55 ± 0.24 ^{a}	21.59 ± 0.67 ^{a}	10.43 ± 0.25 ^{a}	12.56 ± 0.15 ^{a}	2.31 ± 0.04 ^{b}	2.28 ± 0.03 ^{b}
	R	131.95 ± 1.54 ^{b}	191.93 ± 15.82 ^{a}	39.91 ± 2.28 ^{a}	63.27 ± 4.20 ^{a}	28.72 ± 1.10 ^{b}	20.73 ± 0.31 ^{b}	8.90 ± 0.35 ^{b}	9.67 ± 0.28 ^{b}	2.56 ± 0.02 ^{a}	2.78 ± 0.05 ^{a}
Fertilizer (B)	CM	172.31 ± 19.33 ^{a}	170.42 ± 4.19 ^{b}	55.35 ± 2.98 ^{a}	75.69 ± 1.86 ^{a}	31.11 ± 0.11 ^{a}	20.12 ± 0.07 ^{b}	8.85 ± 0.51 ^{b}	10.58 ± 0.70 ^{c}	2.34 ± 0.08 ^{b}	2.47 ± 0.12 ^{b}
	PPM	171.54 ± 19.17 ^{a}	167.57 ± 3.61 ^{b}	40.31 ± 1.69 ^{b}	48.21 ± 1.39 ^{c}	27.81 ± 1.55 ^{b}	20.24 ± 0.01 ^{b}	10.17 ± 0.57 ^{a}	10.82 ± 0.72 ^{b}	2.49 ± 0.01 ^{a}	2.43 ± 0.09 ^{c}
	Control	149.53 ± 5.11 ^{a}	227.93 ± 12.20 ^{a}	37.02 ± 1.24 ^{b}	55.76 ± 1.63 ^{b}	31.49 ± 0.43 ^{a}	23.11 ± 0.52 ^{a}	9.99 ± 0.05 ^{a}	11.95 ± 0.53 ^{a}	2.47 ± 0.07 ^{a}	2.68 ± 0.13 ^{a}
Cultivar × Fertilizer (A × B)	JVT–CM	214.41 ± 0.35 ^{b}	175.64 ± 0.17 ^{d}	43.99 ± 0.77 ^{c}	45.24 ± 0.90 ^{a}	31.26 ± 0.08 ^{b}	20.23 ± 0.01 ^{c}	11.43 ± 0.00 ^{a}	12.42 ± 0.01 ^{b}	2.46 ± 0.01 ^{c}	2.23 ± 0.01 ^{e}
	JVT–PPM	160.96 ± 0.00 ^{c}	200.65 ± 0.68 ^{b}	39.78 ± 0.22 ^{d}	52.12 ± 0.21 ^{a}	32.46 ± 0.10 ^{a}	24.27 ± 0.01 ^{a}	9.87 ± 0.01 ^{d}	13.13 ± 0.02 ^{a}	2.30 ± 0.00 ^{d}	2.40 ± 0.00 ^{d}
	JVT–Control	215.53 ± 0.38 ^{a}	179.76 ± 0.65 ^{c}	61.85 ± 1.13 ^{a}	72.14 ± 1.13 ^{a}	30.95 ± 0.14 ^{bc}	20.26 ± 0.01 ^{c}	9.99 ± 0.01 ^{c}	12.14 ± 0.01 ^{c}	2.17 ± 0.00 ^{e}	2.20 ± 0.00 ^{f}
	R–CM	128.67 ± 0.19 ^{e}	159.50 ± 0.16 ^{f}	36.63 ± 0.35 ^{e}	51.18 ± 0.11 ^{a}	24.35 ± 0.30 ^{d}	20.25 ± 0.01 ^{c}	8.90 ± 0.01 ^{e}	9.22 ± 0.01 ^{e}	2.51 ± 0.01 ^{b}	2.63 ± 0.01 ^{c}
	R–PPM	138.10 ± 0.29 ^{d}	255.21 ± 0.28 ^{a}	34.25 ± 0.21 ^{f}	59.39 ± 0.05 ^{a}	30.53 ± 0.01 ^{c}	21.96 ± 0.05 ^{b}	10.11 ± 0.01 ^{b}	10.77 ± 0.01 ^{d}	2.63 ± 0.01 ^{a}	2.97 ± 0.00 ^{a}
	R–Control	129.09 ± 0.23 ^{e}	161.09 ± 0.46 ^{e}	48.84 ± 0.95 ^{b}	79.24 ± 1.88 ^{a}	31.27 ± 0.10 ^{b}	19.97 ± 0.07 ^{d}	7.70 ± 0.02 ^{f}	9.02 ± 0.00 ^{f}	2.52 ± 0.01 ^{b}	2.73 ± 0.01 ^{b}
Mean		164.46 ± 9.04 ^{B}	188.64 ± 7.94 ^{A}	44.22 ± 2.25 ^{B}	59.89 ± 2.95 ^{A}	30.14 ± 0.65 ^{A}	21.16 ± 0.37 ^{B}	9.67 ± 0.28 ^{B}	11.12 ± 0.38 ^{A}	2.43 ± 0.04 ^{B}	2.53 ± 0.07 ^{A}
ANOVA											
A		*	ns	*	*	*	*	*	*	*	*
B		ns	*	*	*	*	*	*	*	*	*
A×B		*	*	*	ns	*	*	*	*	*	*

JVT – 'Jonkheer van Tets', R – 'Rolan'; CM – cattle manure, PPM – pelletized poultry manure. Means followed by different lowercase letters differ significantly among cultivars, fertilizers and interactions (cultivar×fertilizer), while means followed by different uppercase letters differ significantly among years (LSD test, $p < 0.05$). n.s. – not significant; * – significant according (ANOVA, $p < 0.05$).

Fertilizer application had a significant effect on most of the analyzed micronutrients in red currant leaves (Mn, B, Zn, and Cu), with the exception of Fe in 2021 (Table 3). Mn accumulation was consistently highest under the CM treatment in both 2021 and 2022, whereas the PPM treatment and the control resulted in lower Mn concentrations. CM and the control showed similar values in 2021, whereas in 2022, the control treatment presented slightly higher B content than CM and PPM. In 2021, the highest Zn and slightly higher Cu values were observed under PPM and the control, whereas in 2022, the control exhibited slightly higher Zn and moderately higher Cu contents compared to CM and PPM.

The interaction between cultivar and fertilizer significantly affected most analysed leaf micronutrients except Mn in 2022. Significant differences in Fe content were observed among cultivar/fertilizer combinations, with the highest values recorded for 'Jonkheer van Tets' under control in 2021 and 'Rolan' under PPM fertilization in 2022. In 2021, 'Jonkheer van Tets' accumulated more Mn across all treatments than 'Rolan', with the highest values observed in the control, whereas in 2022, Mn content was higher in 'Rolan', particularly in the control. In 2021, the highest B concentration was recorded in 'Jonkheer van Tets' treated with PPM, while 'Rolan' exhibited lower B values across treatments. Similarly, B accumulation in 2022 was highest in 'Jonkheer van Tets' under PPM treatment, with all other cultivar/fertilizer combinations showing lower values. These results indicate that B accumulation strongly depends on the combination of cultivar and fertilizer. Regarding the Zn content, the highest concentration was recorded in 'Jonkheer van Tets' under CM application in 2021, whereas 'Rolan' exhibited lower Zn values across all treatments. Zn accumulation in 2022 was highest in 'Jonkheer van Tets' under PPM treatment, while 'Rolan' in all fertilization treatments had considerably lower Zn concentrations. Across both experimental years, 'Rolan' consistently exhibited higher Cu concentrations in leaves compared to 'Jonkheer van Tets', particularly under PPM treatment, indicating a greater capacity of this cultivar to accumulate Cu in leaf tissue.

3.3 Mineral Composition of Red Currant Fruits

The macroelement content of the collected red currant fruits is presented in Table 4. Effect of cultivar on the macroelement concentration was significant for most elements, except for C in both years and K in 2021. Across both experimental years, N content was higher in 'Rolan' and P content in 'Jonkheer van Tets'. K content did not differ among treatments in 2021, whereas in 2022 the cultivar 'Rolan' accumulated significantly higher K content. In both years, S content was higher in the cultivar 'Jonkheer van Tets' than in 'Rolan'. Ca accumulation was slightly higher in 'Rolan', whereas Mg content was consistently higher in 'Jonkheer van Tets' during both experimental years.

Fertilizer application significantly enhanced most of the analyzed macroelements content in red currant fruits, with the exception of C, K, and Mg in 2021. N content was higher under PPM application in 2021 and under CM in 2022 compared to the control. CM application slightly increased S content in 2021, while its effect on P was minimal; however, in 2022, differences in S and P among fertilizer treatments were less pronounced. In 2022, K content differed slightly with highest value in PPM application. Ca content remained relatively stable in both years across all fertilizer treatments, while Mg content was generally similar across treatments in 2021, while in 2022, fertilizer application (CM or PPM) slightly increased Mg compared to the control. These findings suggest that the choice of fertilizer influences the macroelement composition of red currant fruits and could be an important factor in optimizing their nutritional quality.

The interaction between cultivar and fertilizer significantly influenced the contents of N, P, S, Ca, and Mg in both 2021 and 2022, and K only in 2021, indicating that nutrient accumulation depended on the specific cultivar–fertilizer combinations. However, C content was not significantly affected by the interaction in either year. 'Jonkheer van Tets' showed the highest N content under CM, whereas in 'Rolan', N was highest under PPM in 2021 and with CM treatment in 2022. P content was highest in 'Jonkheer van Tets' under the control treatment in 2021, whereas in 2022 the highest values were recorded under the control and CM treatments for 'Jonkheer van Tets' and under the CM treatment for 'Rolan'. The highest S values were observed under CM treatment for both cultivars in 2021. In addition, 'Jonkheer van Tets' showed the highest S value under PPM in 2022 indicating that the interaction between cultivar and fertilizer indicates that the two cultivars respond similarly to fertilization, though slight differences were noted under control conditions in 2022. The year 2021 showed that Ca content was highest in the control for both cultivars, while the addition of CM and PPM reduced Ca. Meanwhile, in 2022, Ca content in 'Jonkheer van Tets' remained highest in the control and decreased with CM and PPM, whereas in 'Rolan', CM and PPM increased Ca, indicating a clear effect of cultivar/fertilizer interaction.

Table 4. Influence of cultivar and organic fertilizers (CM and PPM) on the macroelements composition of red currant fruits.

Factor		C (%)		N (%)		P (%)		K (%)		S (%)		Ca (%)		Mg (%)	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Cultivar (A)	JVT	49.76 ± 1.41^{a}	48.60 ± 1.68^{a}	1.55 ± 0.27^{b}	1.25 ± 0.19^{b}	0.34 ± 0.01^{a}	0.30 ± 0.01^{a}	2.23 ± 0.12^{a}	2.04 ± 0.04^{b}	0.11 ± 0.00^{a}	0.10 ± 0.00^{a}	0.17 ± 0.02^{b}	0.17 ± 0.01^{b}	0.10 ± 0.00^{a}	0.10 ± 0.00^{a}
	R	52.77 ± 1.47^{a}	51.30 ± 1.37^{a}	1.96 ± 0.23^{a}	1.43 ± 0.16^{a}	0.30 ± 0.00^{b}	0.27 ± 0.01^{b}	2.25 ± 0.03^{a}	2.21 ± 0.03^{a}	0.11 ± 0.00^{b}	0.09 ± 0.00^{b}	0.17 ± 0.01^{a}	0.18 ± 0.00^{a}	0.08 ± 0.00^{b}	0.09 ± 0.00^{b}
Fertilizer (B)	CM	52.80 ± 1.51^{a}	53.83 ± 1.53^{a}	1.00 ± 0.04^{c}	2.00 ± 0.06^{a}	0.33 ± 0.00^{a}	0.31 ± 0.00^{a}	2.18 ± 0.06^{a}	2.08 ± 0.07^{b}	0.13 ± 0.00^{a}	0.10 ± 0.00^{a}	0.14 ± 0.01^{c}	0.18 ± 0.01^{a}	0.09 ± 0.00^{a}	0.10 ± 0.00^{a}
	PPM	52.03 ± 2.29^{a}	48.77 ± 1.70^{b}	2.42 ± 0.12^{a}	1.15 ± 0.07^{b}	0.32 ± 0.02^{c}	0.26 ± 0.00^{b}	2.37 ± 0.16^{a}	2.15 ± 0.06^{a}	0.11 ± 0.00^{b}	0.10 ± 0.00^{a}	0.15 ± 0.00^{b}	0.17 ± 0.01^{b}	0.09 ± 0.00^{a}	0.09 ± 0.00^{b}
	Control	48.98 ± 1.46^{a}	47.25 ± 1.53^{b}	1.86 ± 0.34^{b}	0.86 ± 0.06^{c}	0.32 ± 0.01^{b}	0.28 ± 0.01^{c}	2.18 ± 0.01^{a}	2.14 ± 0.02^{a}	0.10 ± 0.00^{c}	0.09 ± 0.00^{b}	0.22 ± 0.00^{a}	0.18 ± 0.00^{a}	0.09 ± 0.00^{a}	0.09 ± 0.00^{b}
Cultivar × Fertilizer (A × B)	JVT–CM	53.19 ± 2.39^{a}	53.66 ± 2.41^{a}	2.63 ± 0.12^{a}	1.99 ± 0.09^{a}	0.33 ± 0.00^{b}	0.31 ± 0.00^{b}	2.21 ± 0.00^{a}	1.92 ± 0.00^{f}	0.13 ± 0.00^{a}	0.10 ± 0.00^{b}	0.12 ± 0.00^{f}	0.17 ± 0.00^{c}	0.10 ± 0.00^{b}	0.10 ± 0.00^{b}
	JVT–PPM	48.11 ± 2.16^{a}	46.55 ± 2.09^{a}	1.11 ± 0.05^{c}	1.01 ± 0.05^{a}	0.32 ± 0.00^{d}	0.26 ± 0.00^{c}	2.05 ± 0.00^{a}	2.01 ± 0.00^{e}	0.11 ± 0.00^{b}	0.11 ± 0.00^{a}	0.15 ± 0.00^{d}	0.15 ± 0.00^{e}	0.10 ± 0.00^{b}	0.09 ± 0.00^{c}
	JVT–Control	47.99 ± 2.15^{a}	45.59 ± 2.04^{a}	0.92 ± 0.04^{c}	0.75 ± 0.03^{a}	0.36 ± 0.00^{a}	0.31 ± 0.00^{b}	2.44 ± 0.36^{a}	2.18 ± 0.00^{c}	0.10 ± 0.00^{d}	0.10 ± 0.00^{c}	0.23 ± 0.00^{a}	0.19 ± 0.00^{a}	0.10 ± 0.00^{a}	0.10 ± 0.00^{b}
	R–CM	52.40 ± 2.35^{a}	54.01 ± 2.42^{a}	2.21 ± 0.10^{b}	2.00 ± 0.09^{a}	0.30 ± 0.00^{e}	0.31 ± 0.00^{a}	2.15 ± 0.01^{a}	2.25 ± 0.00^{b}	0.13 ± 0.00^{a}	0.10 ± 0.00^{d}	0.16 ± 0.00^{c}	0.19 ± 0.00^{b}	0.08 ± 0.00^{d}	0.11 ± 0.00^{a}
	R–PPM	55.95 ± 2.51^{a}	50.99 ± 2.29^{a}	2.60 ± 0.12^{a}	1.30 ± 0.06^{a}	0.32 ± 0.00^{c}	0.25 ± 0.00^{d}	2.31 ± 0.00^{a}	2.29 ± 0.00^{a}	0.11 ± 0.00^{c}	0.09 ± 0.00^{e}	0.14 ± 0.00^{e}	0.19 ± 0.00^{b}	0.09 ± 0.00^{c}	0.09 ± 0.00^{d}
	R–Control	49.97 ± 2.24^{a}	48.90 ± 2.19^{a}	1.07 ± 0.05^{c}	0.98 ± 0.04^{a}	0.29 ± 0.00^{f}	0.25 ± 0.00^{e}	2.30 ± 0.00^{a}	2.09 ± 0.00^{d}	0.10 ± 0.00^{cd}	0.09 ± 0.00^{f}	0.21 ± 0.00^{b}	0.16 ± 0.00^{d}	0.08 ± 0.00^{d}	0.09 ± 0.00^{d}
Mean		51.27 ± 1.05^{A}	49.94 ± 1.10^{A}	1.76 ± 0.18^{A}	1.34 ± 0.12^{B}	0.32 ± 0.01^{A}	0.28 ± 0.01^{B}	2.24 ± 0.06^{A}	2.12 ± 0.03^{A}	0.11 ± 0.00^{A}	0.10 ± 0.00^{B}	0.17 ± 0.01^{B}	0.18 ± 0.00^{A}	0.09 ± 0.00^{B}	0.10 ± 0.00^{A}
ANOVA															
A		ns	ns	*	*	*	*	ns	*	*	*	*	*	*	*
B		ns	*	*	*	*	*	ns	*	*	*	*	*	ns	*
A×B		ns	ns	*	*	*	*	ns	*	*	*	*	*	*	*

JVT – 'Jonkheer van Tets', R – 'Rolan'; CM –cattle manure, PPM – pelletized poultry manure.; Means followed by different lowercase letters differ significantly among cultivars, fertilizers and interactions (cultivar × fertilizer), while means followed by different uppercase letters differ significantly among years (LSD test, $p < 0.05$). n.s. – not significant; * – significant according (ANOVA, $p < 0.05$).

Cultivar, as a source of variation, as well as its interaction with fertilizer, significantly affected Mg content in red currant fruits. In both 2021 and 2022, Mg in 'Jonkheer van Tets' remained relatively stable across treatments, whereas in 'Rolan', Mg increased under CM compared to control and PPM in 2022. Magnesium is the fourth most abundant mineral and the second most abundant intracellular divalent cation and has been recognized as a cofactor for >300 metabolic reactions in the body (Volpe, 2013). Magnesium also plays a critical role in nerve transmission, cardiac excitability, neuromuscular conduction, muscular contraction, vasomotor tone, blood pressure, and glucose and insulin metabolism (Kolte et al., 2014; Gröber et al., 2015).

The mean nutrient content across cultivars and treatments showed clear trends during 2021 and 2022. C and K remained relatively stable, while N, P, and S decreased in 2022 compared to 2021. In contrast, Ca and Mg increased slightly in 2022.

Table 5 shows summarized results of the organic fertilizers (CM and PPM) effect on the microelement composition of red currant fruits. As can be seen, cultivar had a statistically significant effect on all elements except Mn in 2021. 'Jonkheer van Tets' showed higher Fe and Zn content in both years, whereas 'Rolan' contained higher Cu. The effect of cultivar on B depended on the year, with higher B in 'Rolan' in 2021, while 'Jonkheer van Tets' showed higher B in 2022. Mn content did not differ significantly between cultivars in 2021, but in 2022 higher Mn values were recorded in 'Jonkheer van Tets'. Manganese is an essential dietary element that functions primarily as a coenzyme in several biological processes. These processes include but are not limited to, macronutrient metabolism, bone formation, free radical defense systems, and, in the brain, ammonia clearance and neurotransmitter synthesis (Horning et al. 2015; Erikson and Aschner, 2019; Alharbi et al., 2024).

Table 5. Influence of cultivar and organic fertilizers (CM and PPM) on the microelement composition of red currant fruits.

Factor		Fe (ppm)		Mn (ppm)		B (ppm)		Zn (ppm)		Cu (ppm)	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Cultivar (A)	JVT	23.86 ± 1.92^{a}	24.03 ± 1.40^{a}	6.69 ± 0.24^{a}	10.06 ± 0.29^{a}	7.91 ± 0.05^{b}	8.88 ± 0.50^{a}	11.19 ± 0.26^{a}	10.50 ± 0.12^{a}	3.88 ± 0.06^{b}	3.15 ± 0.14^{b}
	R	14.50 ± 1.78^{b}	21.00 ± 0.61^{b}	6.77 ± 0.49^{a}	9.65 ± 0.32^{a}	8.68 ± 0.63^{a}	8.61 ± 0.42^{b}	10.84 ± 0.14^{b}	9.78 ± 0.14^{b}	4.18 ± 0.04^{a}	3.31 ± 0.10^{a}
Fertilizer (B)	CM	22.38 ± 1.42^{a}	19.64 ± 0.36^{c}	8.12 ± 0.21^{a}	9.87 ± 0.35^{a}	9.33 ± 0.69^{a}	10.03 ± 0.10^{a}	11.63 ± 0.20^{a}	10.16 ± 0.02^{a}	4.03 ± 0.05^{a}	2.78 ± 0.08^{c}
	PPM	16.65 ± 0.05^{c}	21.62 ± 0.22^{b}	5.76 ± 0.22^{c}	9.69 ± 0.56^{a}	7.18 ± 0.29^{c}	8.97 ± 0.43^{b}	10.78 ± 0.22^{b}	10.11 ± 0.39^{b}	3.99 ± 0.15^{a}	3.29 ± 0.01^{b}
	Control	18.51 ± 4.91^{b}	26.28 ± 1.46^{a}	6.30 ± 0.08^{b}	10.00 ± 0.17^{a}	8.38 ± 0.12^{b}	7.23 ± 0.15^{c}	10.64 ± 0.18^{b}	10.15 ± 0.07^{a}	4.07 ± 0.02^{a}	3.61 ± 0.02^{a}
Cultivar × Fertilizer (A × B)	JVT–CM	25.53 ± 0.00^{b}	20.46 ± 0.03^{e}	7.66 ± 0.00^{b}	9.09 ± 0.00^{c}	7.79 ± 0.00^{d}	9.81 ± 0.06^{c}	12.06 ± 0.00^{a}	10.20 ± 0.01^{c}	3.95 ± 0.00^{c}	2.61 ± 0.01^{f}
	JVT–PPM	16.55 ± 0.03^{d}	22.10 ± 0.02^{c}	6.26 ± 0.01^{cd}	10.94 ± 0.02^{a}	7.83 ± 0.01^{d}	9.93 ± 0.01^{b}	11.26 ± 0.00^{b}	10.99 ± 0.00^{a}	3.66 ± 0.00^{d}	3.26 ± 0.00^{d}
	JVT–Control	29.50 ± 0.01^{a}	29.53 ± 0.43^{a}	6.15 ± 0.01^{d}	10.16 ± 0.35^{b}	8.12 ± 0.02^{c}	6.89 ± 0.03^{f}	10.24 ± 0.00^{d}	10.31 ± 0.01^{b}	4.03 ± 0.00^{bc}	3.57 ± 0.01^{b}
	R–CM	19.22 ± 0.22^{c}	18.83 ± 0.01^{f}	8.59 ± 0.12^{a}	10.65 ± 0.00^{a}	10.87 ± 0.12^{a}	10.25 ± 0.03^{a}	11.19 ± 0.05^{b}	10.13 ± 0.01^{d}	4.11 ± 0.06^{b}	2.95 ± 0.00^{e}
	R–PPM	16.75 ± 0.02^{d}	21.13 ± 0.03^{d}	5.26 ± 0.04^{e}	8.45 ± 0.01^{d}	6.53 ± 0.07^{e}	8.01 ± 0.01^{d}	10.29 ± 0.03^{d}	9.23 ± 0.01^{f}	4.31 ± 0.05^{a}	3.31 ± 0.01^{c}
	R–Control	7.53 ± 0.03^{e}	23.04 ± 0.11^{b}	6.45 ± 0.11^{c}	9.85 ± 0.04^{b}	8.64 ± 0.02^{b}	7.57 ± 0.02^{e}	11.04 ± 0.02^{c}	9.99 ± 0.03^{e}	4.12 ± 0.01^{b}	3.66 ± 0.02^{a}
Mean		19.18± 1.70^{B}	22.52± 0.83^{A}	6.73± 0.26^{B}	9.85± 0.21^{A}	8.30± 0.32^{B}	8.74± 0.32^{A}	11.01±0.15^{A}	10.14±0.13^{B}	4.03± 0.05^{A}	3.23± 0.09^{B}
ANOVA											
A		*	*	ns	*	*	*	*	*	*	*
B		*	*	*	ns	*	*	*	*	*	*
A×B		*	*	*	*	*	*	*	*	*	*

JVT – 'Jonkheer van Tets', R– 'Rolan'; CM – cattle manure, PPM – pelletized poultry manure; Means by different lowercase letters differ significantly among cultivars, fertilizers and interactions (cultivar × fertilizer), while means followed by different uppercase letters differ significantly among years (LSD test, $p < 0.05$). n.s. – not significant; * – significant according (ANOVA, $p < 0.05$).

A statistically significant effect of fertilizer was observed for all microelements, except Mn in 2022. In 2021, the highest Fe content was recorded under CM treatment in cultivar 'Rolan', followed by PPM, with the lowest value in the control, whereas in 2022 the highest Fe content was observed in the control. In addition, for 'Jonkheer van Tets', in 2021, the highest Fe content was observed in the control, followed by CM, while PPM resulted in the lowest Fe values. In 2022, Fe content remained highest in the control, with lower values under CM and PPM. 'Jonkheer van Tets', Mn was highest under CM and lowest under control, while for 'Rolan', CM resulted in the highest Mn, PPM in the lowest, and control showed intermediate values. The B content showed that in 'Jonkheer van Tets' it was slightly higher in the control than in CM and PPM, whereas in 'Rolan' the highest values were observed under CM; however, B content in 'Jonkheer van Tets' was also higher under both PPM and CM compared to the control. Similarly, for 'Rolan', the highest B concentration was observed under CM, intermediate under PPM, and lowest in the control. Content of Zn was highest under CM for 'Jonkheer van Tets' in 2021 and under PPM in 2022, while for 'Rolan', the highest Zn concentration was observed under CM in both years. Content of Cu was highest in the control for 'Jonkheer van Tets' in both 2021 and 2022, whereas for 'Rolan', the highest Cu concentration was observed under PPM in 2021 and in the control in 2022.

Mean values across cultivars and fertilizer treatments showed clear year-dependent trends. Fe, Mn and B content were higher in 2022 than in 2021, whereas Zn and Cu were higher in 2021 compared to 2022.

The results obtained in this study show that the application of organic fertilizers influenced the concentration of both macro- and micronutrients in red currant leaves and fruits. However, the observed variations should be interpreted with caution, as the accumulation of elements in plant tissues is a complex process influenced by multiple interacting factors, including soil characteristics, climatic conditions, cultivar genotype, and agronomic practices (Plessi et al., 2007; Guo et al., 2021; Panfilova et al., 2024). Studies specifically addressing the effects of organic fertilization on red currant are scarce; therefore, comparisons are often made with related berry species regarding macro- and micronutrient content and fruit quality. Panfilova et al. (2024) demonstrated that foliar application of a Ca–organomineral suspension enhanced Ca content and total soluble solids in red currant fruits, while leaf Ca remained relatively stable. These findings highlight that nutrient accumulation in berries is highly dependent on ontogenetic stage, cultivar characteristics, and environmental conditions, which aligns with our results regarding the variability of mineral content between red currant cultivars under organic fertilization. Although Wójcik and Filipczak (2015) did not report specific macro- or micronutrient concentrations in leaves, the observed improvements in fruit quality and yield in black currant cultivar 'Tiben' (*R. nigrum*) highlight the role of nutrient supply in enhancing plant performance. They also suggested that pre-planting application of mineral P and K can be effectively replaced by solid swine manure without reducing yield. Research on related berry species such as blueberry (*Vaccinium spp.*) indicates that fruit macro- and micronutrient content varies among cultivars and fertilization treatments, with control plants sometimes showing higher macronutrients and mineral-fertilized plants higher microelements, reflecting complex genotype–fertilization interactions (Medvecký et al., 2014). These findings were based on six highbush blueberry (*Vaccinium corymbosum L.*) cultivars: 'Bluejay', 'Nelson', 'Bluecrop', 'Patriot', 'Berkeley', and 'Brigitta'. In addition, studies on strawberry have demonstrated that integrated fertilization strategies combining organic amendments such as poultry manure, vermicompost, and cow dung with mineral fertilizers significantly enhance nutrient uptake (N, P, K, S, Zn, and B), fruit yield, and quality (Quddus et al., 2025). In particular, poultry manure applied together with mineral fertilizers resulted in the highest nutrient accumulation and vitamin C content in strawberry fruits, highlighting the important role of organic inputs in improving nutrient availability, plant performance, and soil health. Sayğı (2022) also reported that organic fertilizers such as chicken manure, vermicompost, and farm manure improved leaf macro- and micronutrient contents in strawberry compared with chemical fertilizers, particularly enhancing N, P, K, Ca, Fe, Zn, and Cu concentrations, while providing comparable or superior yield and economic performance.

Direct comparisons of the obtained results with previously reported data are challenging. Nevertheless, the nutrient concentrations observed in this study are generally consistent with those reported for related berry species (Viljavuuspavelu 1997; Niskanen, 2002; Nour et al., 2011; Keller et al., 2015; Milošević and Milošević, 2017). For instance, Niskanen (2002) reported similar values in leaf samples from commercial black, red, and white currant fields in southern and central Finland. Moreover, the obtained results are comparable with those reported by Milošević and Milošević (2017), who noted similar results for black, red, and white currants, cultivated on heavy soils under minimal cultural practices, limited to pruning, fertilization with cattle manure, and herbicide-based weed control. According to Hegedűs et al. (2008), who studied elemental composition of several berry species (strawberry, raspberry, red and black currants) considerable variation exists among cultivars of the same species, with the red currant 'Jonkheer van Tets' exhibiting particularly high Fe concentrations. Similarly, significant differences were observed among the red currant cultivars fruits 'Rosu Timpuriu', 'Abundent', and 'Houghton Castle' in the mineral elements analysed in this study, including K, Ca, Mg, Fe, Al, Na, Mn, B, and Cu (Cosmulescu et al., 2015). The concentrations of elements observed in our study were also comparable with those reported by Karaagac et al. (2020), who found K to be the most abundant element, followed by Ca, Mg, Fe, Cu, Zn and Mn in decreasing order in red currant fruit (*R. rubrum* L. cv. 'Red Lake').

3.4 Deviation from Optimum Percentage (DOP index)

The DOP index indicates deviations from optimal nutrient contents, reflecting both deficiencies and excesses, and provides insight into plant nutritional status and its relationship with soil conditions. The DOP and ΣDOP values in red currant leaves obtained in our study are presented in Table 6. Overall, N, P, K and Mg were generally found to being deficient (negative DOP values), whereas Ca was present in excess (positive DOP values). Generally, a smaller deficient of macroelements was observed in 2022 related to 2021. Furthermore, the most balanced N content in both cultivars was achieved under the CM treatment, indicating that organic fertilizer type has a strong influence on N concentration., The most balanced P content in both cultivars was observed in the control, while the most balanced K content was observed in the cultivar 'Rolan' also under the control during both years of the study, particularly in 2022. The best Mg balance was observed in the cultivar 'Rolan', under the control in 2021 and the PPM treatment in 2022, while 'Jonkheer van Tets' achieved the optimal Mg content under the PPM treatment in both years.

Table 6. DOP and ΣDOP for macroelements in red currant leaves across treatments.

Factor		N		P		K		Ca		Mg		ΣDOP	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Cultivar (A)	JVT	−8	1	−39	−15	−28	−23	46	80	−6	−3	128^{a}	126^{b}
	R	−12	−7	−27	−25	−20	−15	57	101	−12	0	128^{a}	147^{a}
Fertilizer (B)	CM	−7	−4	−40	−12	−25	−15	40	101	−9	−3	143^{b}	166^{a}
	PPM	−10	−2	−42	−20	−22	−18	39	100	−7	5	141^{b}	136^{b}
	Control	−14	−6	−16	−5	−25	−12	75	101	−11	−10	179^{a}	136^{b}
Cultivar × Fertilizer (A × B)	JVT –CM	−5	4	−42	−22	−27	−24	35	99	−7	16	117^{c}	168^{a}
	JVT –PPM	−10	−11	−43	−20	−26	−31	39	63	−2	−10	119^{c}	130^{c}
	JVT –Control	−11	−2	−31	−1	−32	−13	64	80	−11	−14	148^{a}	114^{d}
	R–CM	−8	−3	−37	−30	−24	−17	45	103	−12	9	126^{bc}	164^{a}
	R–PPM	−10	−7	−41	−35	−19	−17	40	79	−13	3	123^{bc}	142^{a}
	R–Control	−18	−10	−1	−9	−17	−10	86	122	1	−6	135^{b}	158^{a}
												146^{A}	128^{B}

JVT – 'Jonkheer van Tets', R – 'Roland'; CM – Cattle manure, PPM – 'Italpollina'; Means by different lowercase letters differ significantly among cultivars, fertilizers and interactions (cultivar × fertilizer), while means followed by different uppercase letters differ significantly between years (LSD test, $p < 0.05$).

The ΣDOP values (Table 6) indicate that all factors of variability (cultivar, fertilizer and their interaction) cause significant differences in macronutrient contents in red currant leaves, except cultivar in 2021. The highest macroelements imbalance was observed for the control for both cultivars, in 2021. In 2022, the highest imbalance was observed for the combinations of both cultivars with CM, indicating that the intensity of macroelement imbalance depended on the specific cultivar/fertilizer interaction.

The data presented in Table 7 summarize the DOP and ΣDOP values micronutrients (B, Cu, Fe, and Mn) in the fruit of two cultivars across organic fertilizer treatments during 2021-2022. Overall, B content showed a higher deficiency in 2022 for both cultivars. The most favourable Fe status was observed in 'Rolan' with CM fertilizer in 2022, indicating that CM can enhance Fe availability, particularly in 'Rolan', while both cultivars experienced Fe deficits under other fertilizer treatments. Also, Mn content was generally closer to optimal content in 2022 for both cultivars, with the most favourable status in 'Rolan' with CM fertilization. The values of DOP were similar across both cultivars and all fertilizer treatments suggesting Cu deficiency in leaves in both years.

Table 7. DOP and ΣDOP for microelements in red currant leaves.

Factor		B		Cu		Fe		Mn		ΣDOP	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Cultivar (A)	JVT	5	−28	−58	−59	−14	−19	−18	−4	98 ^{b}	125 ^{a}
	R	−4	−31	−54	−49	−42	−16	−32	7	136 ^{a}	120 ^{b}
Fertilizer (B)	CM	5	−23	−55	−51	−35	0	−37	−5	97 ^{c}	142 ^{a}
	PPM	4	−33	−57	−55	−25	27	−6	25	123 ^{b}	133 ^{b}
	Control	−7	33	−55	−56	−25	27	−32	18	132 ^{a}	92 ^{c}
Cultivar × Fertilizer (A × B)	JVT–CM	8	−19	−58	−56	−30	−12	−33	−12	74 ^{f}	136 ^{c}
	JVT–PPM	3	−32	−61	−60	−6	−22	5	22	91 ^{e}	139 ^{b}
	JVT–Control	4	−33	−55	−59	−6	−23	−25	−23	129 ^{c}	100 ^{e}
	R–CM	2	−27	−52	−46	−40	11	−42	1	119 ^{d}	148 ^{a}
	R–PPM	4	−33	−54	−50	−44	−30	−17	34	155 ^{a}	128 ^{d}
	R–Control	−19	−32	−54	−52	−44	−30	−38	−13	136 ^{b}	85 ^{f}
										117 ^{A}	123 ^{A}

JVT – 'Jonkheer van Tets', R – 'Rolan'; CM – Cattle manure, PPM – pelletized poultry manure; Means of ΣDOP followed by different lowercase letters differ significantly among cultivars, fertilizers and interactions (cultivar × fertilizer), while means followed by different uppercase letters differ significantly among years (LSD test, $p < 0.05$).

Analysis of variance ΣDOP of leaf micronutrient content indicated that no statistically significant differences were observed between cultivars in 2021 and 2022. However, PPM causing the best mineral leaf balance in 2021 while CM in 2022 was observed in cultivar 'Rolan'.

Higher ΣDOP values observed under certain fertilization treatments suggest that nutrient imbalance may result from interactions among elements rather than from the supply of individual nutrients alone. Antagonistic relationships among nutrients, such as the influence of P or Mn on Fe availability, can disrupt balanced uptake and internal nutrient distribution (Mengel et al., 2001; Hansen et al., 2006). In addition, the availability of micronutrients is closely related to soil pH, with higher pH values often limiting the uptake of elements such as Fe and Zn (Ebert, 2009). Furthermore, micronutrients such as B are essential for cell wall integrity, sugar transport and reproductive development, and their limited mobility within plants makes their balanced supply particularly important (Mengel et al., 2001).

4 Conclusions

The results of this study demonstrate that organic fertilization, using well-decomposed cattle manure (CM) and pelletized poultry manure (PPM), influenced the concentrations of both macro- and micronutrients in red currant (*R. rubrum*) leaves and fruits. Mineral composition varied according to cultivar and fertilizer treatment, indicating that both genotype and fertilization strategy significantly affected nutrient accumulation. In 2021, no differences between cultivars were observed, as both recorded the same ΣDOP value (state of the leaf mineral supply. However, in 2022, cultivar 'Rolan' exhibited a higher macronutrient imbalance compared to cultivar 'Jonkheer van Tets'. In 2021 cultivar 'Rolan' showed a higher total imbalance of microelements than 'Jonkheer van Tets', whereas in 2022 the opposite trend was observed, with 'Jonkheer van Tets' recording a higher ΣDOP value compared to cultivar 'Rolan'. In the second year of the study, CM caused the highest macronutrient concentrations (N, P, K, Ca and Mg) disbalance for both cultivars. In contrast, PPM showed a lower and more moderate disbalance, suggesting a more stable nutrient balance. Similarly, CM resulted in the highest average micronutrient (B, Cu, Fe and Mn) disbalance in the second year, whereas the greatest imbalance at the interaction content was recorded in the R–CM treatment. Future studies are needed to evaluate the long-term effects of organic fertilization on the mineral profile of red currant in both leaves and fruits, which could support more precise recommendations for optimal cultivation and enhanced sustainability.

Authors' Contributions

Conceptualization: MJ, GP, LBR, IG; Data curation: MJ, JP, JM; Formal analysis: MJ, JT, JP; Investigation: MJ, IG; Methodology: MJ, GP, LBR, IG; Project administration: MM; Supervision: MM, LBR, ASS; Validation: MM, RI; Visualization: MJ, JP, JT; Writing - original draft: MJ, JP, JT; Writing – review and editing: MJ, JP, JT, RI, MM.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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