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Response of organic and treated oats to steel slag, mineral and organo -mineral fertilizers use on acidic soil

Reakcija organskog i tretiranog ovsa na primenu čelične šljake, mineralnog i organo-mineralnog đubriva na kiselom zemljištu

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ABSTRACT

The research aimed to evaluate the significancy in variation in the biomass yield, physiological parameters (nitrogen balance index, chlorophyll, flavonoids, anthocyanins), macroelements (N, P, K), and trace elements (Fe, Mn, Zn, Ni), of the organic and treated oats, influenced by individual applications of mineral (MF) and organomineral (OMF) fertilizers, $CaCO_3$, steel slag (SS) and combination (MF+$CaCO_3$, OMF+$CaCO_3$, MF+SS, OMF+SS). The experiment in a greenhouse, in pots, was conducted from the fourth week of March to the fourth week of June 2025, using Eutric Cambisol, a soil characterized by a very acid reaction. Physiological parameters in both oat types were statistically most influenced ($P \leq 0.01$) by the treatment, macroelements - by the treatment and oat type, and all trace elements - mostly by the treatment, oat type, and their interaction. Individual parameters comparison in both oats indicated the most pronounced significant influence ($P < 0.05$) of OMF+SS, while the lowest values were determined in individual treatments. Slightly better results for biomass yield, but not so pronounced, were observed for treated oats. The highest values of all trace elements in both oats were determined in MF and MF+SS treatments, but far below the toxic values. For a better understanding of the present findings, further research in this area of study on larger soil areas could potentially make the oat production more acceptable from an ecological point of view.

Keywords: oats, biomass yield, physiological parameters, macroelements, trace elements, different fertilization practices

SAŽETAK

Cilj istraživanja bio je da se proceni značajnost u varijacijama prinosa biomase, fizioloških parametara (indeks azotnog bilansa, hlorofil, flavonoidi, antocijanini), makroelemenata (N, P, K) i mikroelemenata (Fe, Mn, Zn, Ni), organskog i tretiranog ovsa, pod uticajem individualnih primena mineralnih (MF) i organomineralnih (OMF) đubriva, $CaCO_3$, čelične šljake (SS) i njihovih kombinacija (MF+$CaCO_3$, OMF+$CaCO_3$, MF+SS, OMF+SS). Ogled je izveden u periodu od četvrte nedelje marta do četvrte nedelje juna 2025. godine, u saksijama u stakleniku u polukontrolisanim uslovima, na zemljištu tipa eutrični kambisol, koje karakteriše veoma kisela reakcija. Na fiziološke parametre obe vrste ovsa statistički najviše je uticao tretman ($P \leq 0,01$), na makroelemente - tretman i vrsta ovsa, a na mikroelemente - uglavnom tretman, vrsta ovsa i njihova interakcija. Poređenje pojedinačnih parametara kod obe vrste ovsa pokazalo je najizraženiji značajan uticaj ($P < 0,05$) zajedničke primene organomineralnog đubriva i šljake, dok su najniže vrednosti utvrđene u pojedinačnim tretmanima. Nešto bolji rezultati za prinos biomase, ali ne toliko izraženi, primećeni su kod tretiranog ovsa. Najviše vrednosti mikroelemenata obe vrste ovsa utvrđene su u tretmanima MF i MF+SS, ali su dobijene koncentracije daleko ispod toksičnih vrednosti. U cilju boljeg sagledavanja sadašnjih nalaza, dalja istraživanja u ovoj oblasti proučavanja na većim površinama zemljišta potencijalno bi mogla učiniti proizvodnju ovsa prihvatljivijom sa ekološke tačke gledišta.

Ključne riječi: ovas, prinos biomase, fiziološki parametri, makroelementi, mikroelementi, različite prakse đubrenja

INTRODUCTION

Oat (*Avena sativa* L.) is one of the most important self-fertilizing field plants belonging to the Poaceae family and, according to its origin, represents the youngest true cereal originating from wild forms. Oat has multiple uses, especially as a fodder plant. Products obtained by industrial processing of oat grains with high nutritional value and good digestibility (oat flakes, semolina, oat flour) are important for human nutrition. The high nutritional value of oats comes from their richness in amino acids. Vegetative biomass of oat (especially in a mixture with annual legumes) represents an excellent voluminous fodder, and contains 78% water, 2.7% total protein, 8.4% nitrogen-free extractable matter (NFEM), 0.7% oil, 2.7% cellulose and 1.4% mineral salts (Djurić et al., 2015). In traditional medicine, oat is also known as a medicinal plant, and for this purpose, the grains, water after cooking the grains, fresh biomass and straw after harvesting, are used. The importance of oats also lies in the fact that its requirements for external environmental conditions and agrotechnics are less than in other true cereals, so it can be grown even where other cereals would give incomparably lower biomass yields. Thanks to its well-developed root system, oat makes very good use of plant assimilates from less available forms. Of all the cereals, it tolerates less fertile, heavy and wet soils the best, manifesting a strong reaction to increased fertilization. It can also be grown on acidic soils, where it reacts well to calcification (Glamočlija, 2012).

Acidic soils are widespread and limit plant production all over the world, due to the constant increase in their surface area as a result of mostly intensive production technology, uncontrolled use of mineral fertilizers and the lack of organic fertilizers usage (Von Uexkull and Mutert, 1995). It is a similar situation in the Republic of Serbia, where the productivity of those soils is increasingly becoming a limiting factor in plant production (Pivić et al., 2011).

Cambisols generally make good agricultural soils and are used intensively. Eutric Cambisol belongs to the soil types of high ecological and productive value. Chemical properties vary depending on the intensity of use, degree of erosion, chemical properties of the parent material, and the level of development. The content of soil organic matter in these soils is in the range of 2 to 5%, and characterized by medium acid reaction and lack of carbonates (Hadžić et al., 2002). Intensification in the use of cambisols, in the manner of mineral fertilizers overuse, as well as the lack of organic, organo-mineral and biological fertilizers usage and of other soil amendments, causes their transformation into marginal, often acid soils. Amelioration of these soils' adverse properties, such as low pH, and it is the first step in creating favorable soil conditions for productive plant growth.

Proper growth and development of plants in the soil requires a balanced content of nutrient elements in it, and it is not enough to determine the content of certain elements in the soil, but also their presence in the plants. Applying different fertilization systems (mineral, organic, organo-mineral) can achieve high biomass yields of good quality (Bogdanović et al., 2011). Mineral fertilizers are widely used in agriculture to optimize agricultural production. When mineral fertilizers are used excessively and inadequately, they will manifest a negative impact on the soil (Zamanian and Yazdandoost, 2021). The negative effects are different, but mostly they are reduced to changes in soil reactions, disorders of the soil structure and biological quality, while harmful substances accumulate in the cultivated plants. If mineral fertilizers are applied rationally, they represent an excellent way to intensify agricultural production by providing plants with nutrients and by their decomposition in the soil they are quickly transformed into readily available plant nutrients (Popadić, 2016).

In addition to the controlled application of mineral fertilizers, other types of nutrients originating from organic and organo-mineral fertilizers and other soil amendments (liming materials) can be added to potentially fertile soil as well as to soil with a low pH. Organic fertilizers play a significant role in increasing soil fertility, by improving the structural, water-physical and microbi-

ological properties of the soil, providing cultivated plants with nutrients (Nurmalasari et al., 2024). Organic fertilizers, unlike mineral fertilizers, have a prolonged effect on the chemical properties of the soil and therefore on the biomass yields of cultivated plants several years after the application (Ferguson et al., 2005; Gutser et al., 2005). Organo-mineral fertilizers were created by combining organic and mineral substances and are considered to have many advantages in application. Mineral substances are bound into organo-mineral complexes, and thus their fixation is prevented (Makinde, 2007). Applying organo-mineral fertilizers combines slow and fast release patterns of organic feedstock and mineral fertilizer, respectively, in order to reduce reliance on the latter. The nutrient composition of organic feedstock is usually imbalanced (N:P ratio, for example), where application based on one nutrient will cause under-application of the other. In an organo-mineral fertilizer, this is where the mineral part tackles nutrient imbalance, making it a balanced fertilizer product. Organo-mineral fertilizer provides balanced plant nutrition for a longer period of time because the mineral part is very quickly available to plants, while the organic part, due to the mineralization process, is available to plants for a longer period of time, simultaneously improving the physical and chemical structure of the soil (Sakrabani, 2024). Džamić and Stevanović (2000) stated that the application of these fertilizers increases the biomass yield by 2-10% compared to the application of equivalent amounts of the pure mineral fertilizers. Apart from plant nutrients, there are substances that, when supplied to an acid soil as liming material, also promote plant growth without themselves participating in the construction of plant material. These are substances that improve the environmental conditions of the plant insofar as they involve the soil. Several authors (Goulding, 2016; Holland et al., 2018) reported that application of liming material can increase the soil pH, availability of essential plant nutrients, crop biomass yields and prevent solubility of manganese and aluminum. In practice, the pursuance should be made to combine fertilizers and soil improvers since they supplement each other (FAO, 2017).

Along with traditional liming materials, such as calcite or slaked lime, present in Serbia, and regarding its alkaline nature, steel slag can be of great importance. Physico-chemical properties of steel slag offer a high potential for its utilization in agriculture, although significant amounts of steel slag are generated as waste material every day from steel industries. During their regular processes, the steel industries can produce various residues. Some of them can be successfully utilized in agricultural activities, as in the case of steel slag. Steel slag is considered to have made an important contribution to agricultural production (Deus et al., 2019). Nevertheless, developing new technologies in utilization of steel slag as resource materials is particularly important regarding decreasing the soil used for slag disposal, reducing environmental pollution, promoting the continuous and highly efficient development of steel industry (Annunziata Branca and Colla, 2012), and offering significant cost advantages over commercially produced limestone (Tozsin and Oztas, 2023), not only in the World, but also in Serbia. According to Ito (2015), the increase in slag use in different fields of application, such as agriculture, represents an indispensable way in sustainable development. Appropriate and effective use of slag in agriculture leads to neutralization of soil acidity, since steel slag contains fertilizer components CaO, SiO_2, and MgO. In addition to these three components, it also contains components such as FeO, MnO, and P_2O_5. A correction of acidity with slag occurs similarly to the use of limestone. Thus, the slag's alkaline property remedies soil acidity (Huang et al., 2012). In that regard, slag can improve crop productivity, mitigate greenhouse gas emissions, and stabilize heavy metals in contaminated soils, becoming a high-value-added product in sustainable agriculture. Tozsin and Oztas (2023) reported slag contribution to the structural development of the soil due to its content of Ca, Mg, and Fe and significantly decrease of fungal infections. In addition to the decrease in acidity levels, by using steel slag, Ca and Mg supply could also be added to the soil, with positive effects on crops such as black oats, potatoes, alfalfa, rice, beans, soybeans, and coffee, making steel slag a source capable of being used instead of lime-

stone (Deus et al., 2019). This particularly occurs when traditional limestone ($Ca(OH)_2$) or $CaCO_3$) is combined with different fertilization practices. Proper usage of steel slags in agriculture contributes to higher crop production, demonstrating that these residues bring benefits to the chemical soil properties, as follows: increase of pH in acidic soils; increase in the nutrient content of phosphorus, calcium, and magnesium; increase in the content of the beneficial element silicon (Torkashvand and Sedaghathoor, 2007; Nolla et al., 2013; Deus et al., 2014). The main restriction in the steel slag application is the presence of high levels of heavy metals in its composition, which can become toxic and limit its use in agricultural activities. Due to the different processes in their obtaining, the steel slags' chemical composition is very variable, where heavy metal levels in the slags, such as copper, iron, manganese, zinc, cadmium, nickel, lead, chrome, and mercury, agree with the values which are considered tolerable for soil application (Deus et al., 2019). The presence of these elements in the slag's composition in non-toxic contents was due to the soil pH increase, which contributed to avoiding toxicity by heavy metals (Corrêa et al., 2008). Deus et al. (2014) reported no changes in soil heavy metals content in steel slag long-term application as soil acidity correctives at the dose necessary to raise the initial soil saturation to 70%, when the soil was analysed 12 and 23 months after slag application. In the study of Islam et al. (2022), when a large amount of steel slag (above 1%) was added to the soil, mineral uptake by the plants decreased, but with a lower amount of steel slag (0.2% to 1%) added to the soil, mineral uptake of Ca, Mg, and Fe, and plant growth increased. However, monitoring the amount of heavy metals added to the soil along with the use of steel slag is considered absolutely required (Tozsin and Oztas, 2023).

The main objectives of the current study were to evaluate the effects of individual uses of commercial mineral [composite NPK (15:15:15)] and organo-mineral fertilizers, and their individual combination with steel slag and calcite on the physiological (nitrogen balance index - NBI, chlorophyll - Chl, flavonoids - Flv, anthocyanins - Ant), and chemical (nitrogen - N, phosphorus - P, potassium - K, iron - Fe, manganese - Mn, zinc - Zn, nickel - Ni) parameters in organic and treated oat aerial biomass and oats biomass yield. The research could provide insight into the type of soil treatment which can be used to improve the biomass yield and chemical and physiological parameters in organic and treated oat plants.

MATERIALS AND METHODS

Experimental design

The study was carried out from the 4th decade of March to the 4th decade of June in 2024, in the vegetative conditions of the Institute of Soil Science greenhouse, using plastic pots, each filled with 3.0 kg/pot of homogenized Eutric Cambisol type of soil (IUSS Working Group WRB, 2022). The soil was brought from the experimental field in Mladenovac town (grid reference: 44°24′ N, 20°40′ E), located about 55 km from Belgrade in the Republic of Serbia. Soil analysis was done in 2020. Soil properties were determined in our previous study (Latković et al., 2020), and accordingly, has very acid reaction (pH in H_2O 4.90, pH in 1M KCl 4.06), high available potassium (K_2O, 253 mg/kg), medium to high available phosphorus (P_2O_5, 157 mg/kg), and medium total nitrogen (N, 1.36 g/kg) and organic carbon (Corg, 21.9 g/kg) supply. Granulometric composition revealed its clay-loamy texture (fractions: sand 31.8%, clay 31%, silt 37.2%), having a relatively favorable particle size distribution for the cultivation of oats.

In each plastic pot, ten organic and ten treated oat seeds of the Vranac variety were sown on March 25th. Organic (untreated) oat seeds were produced in an organic cultivation system (without the use of chemical protection agents or mineral fertilizers), while treated oat seeds were produced in a conventional cultivation system. Oat plants were grown without the use of any plant protection means and with the standard growing methods (watering, regular manual weed control). Watering was carried out depending on the temperature and the needs of the plants, usually every other day with 200 ml of tap water per pot. Average temperatures during the study period ranged from 16.5 °C (March and

April), 19.1 °C (May), to 24.9 °C (June). The weather was mostly sunny with some clouds during the second half of April, the second half of May and the first half of June.

Designed treatments, set up in three replications, were as follows: commercial mineral NPK fertilizer 15:15:15 (MF); organo-mineral fertilizer (OMF); $CaCO_3$ (limestone, calcite); steel slag (SS); mineral NPK fertilizer 15:15:15+$CaCO_3$ (MF+$CaCO_3$); organo-mineral fertilizer+$CaCO_3$ (OMF+$CaCO_3$); mineral NPK fertilizer 15:15:15+steel slag (MF+SS); Organo-mineral fertilizer+steel slag (OMF+SS); Control (untreated soil, Ø). Mineral fertilizer (composite NPK 15:15:15) was applied as follows: nitrogen (N) fertilizer, in the form of urea with 46% N; phosphorus (P) fertilizer in the form of monoammonium phosphate with 52% of P in the form of P_2O_5 and 11% N; potassium (K) fertilizer in the form of potassium chloride with 40% in the form of K_2O. The studied commercial organo-mineral fertilizer was applied as a solid nutrient with 3.90% total N, 38,2% total carbon (C), 2.89% P_2O_5, and 2.66% K_2O, where the organic fertilizer is derived from chicken manure. The steel slag samples were taken during spring 2009 from the steel factory at different deposition sites of Hesteel Smederevo Steel Plant (previously US Steel), located about 65 km southeast of Belgrade. Its chemical properties were determined previously (Pivić et al, 2011), having the following properties: very alkaline reaction (pH in H_2O 12.48); calcium in oxide forms (CaO) from 33-45% (of which about 50% is easily soluble in 1 M ammonium acetate); magnesium (Mg) content mainly in the forms of MgO; nearly all the amount of P is in available forms for plants; high total iron (Fe) and manganese (Mn) content (15.34% and 1.80%, respectively), but with lower amounts in their soluble forms; low total zinc (Zn) content (14.60%); high total copper (Cu) content (228.80%).

Before sowing the oat seeds, the amount of fertilizers, $CaCO_3$ and slag, was measured according to the experimental design, recalculated as for 1 kg of soil, and mixed with a soil, as follows: NPK mineral fertilizer (15:15:15) = 0.36 g/kg; organo-mineral fertilizer = 0.13 g/kg; $CaCO_3$ = 2.21 g/kg; steel slag = 2.21 g/kg. Both $CaCO_3$ and steel slag with a granulation of 0.2 mm were used in the current study.

Plant preparation and analysis

The aerial oat biomass in the stage of the total ear formation was measured for obtaining the values of physiological parameters (chlorophyll, Chl; flavonoids, Flv; anthocyanins, Ant; nitrogen balance index, NBI - Chl/Flv Ratio), after which it was taken from each experimental variant and repetition, air-dried, measured for the oat biomass yield and expressed in g/pot. Physiological parameters were determined using a portable Dualex optical leafclip sensor (FORCE-A, Orsay, France). The biomass was dried additionally for 2 h at 105 °C ± 1 and weighed again for chemical analysis, using the method for the dry matter content determination in the plant tissue, gravimetrically (Miller, 1998). The content of N was analysed on an elemental CNS analyser, Vario model EL III, according to the standard method (SRPS ISO 13878:2005). Content of P was determined spectrophotometrically, and K - photometrically, both elements after the plant biomass was heated to boiling with a mixture of concentrated ammonium molybdate and stannous chloride (Djurdjević, 2014a, 2014b). Total forms of trace metals - Fe, Mn, Zn and Ni - were determined using inductively coupled plasma optical emission spectrometry (ICP-OES), after the plant extraction with aqua regia (ISO 22036:2024; SRPS ISO 11466:2004).

Statistical analysis and graphical presentation

Analysis of variance (ANOVA, SPSS 22.0), followed by Duncan's multiple range tests (DMRT) at $P < 0.05$, was used to statistically analyse data relevant to the treatment effects on all plant parameters. For statistical analysis of the three factors influence (oat type, treatment, and their interactions), the ANOVA - F test was used. In providing a graphical data presentation regarding the significance of differences in oats biomass yield depending on the used treatment and comparisons of organic and treated oats biomass yield by treatments, the Excel program was used.

RESULTS

Physiological properties of oats

Statistical analysis of the oats physiological parameters (NBI, Chl, Flv, Ant) under influence of tested factors showed the following findings: highly significant ($P \leq 0.01$) differences for all parameters under influence of treatment (factor B); highly significant ($P \leq 0.01$) differences for anthocyanins under influence of oat type (factor A); highly significant ($P \leq 0.01$) differences for nitrogen balance index, chlorophyll and anthocyanins under influence of interaction of factors (A × B).

The influence of the factors on the parameters were absent ($P \geq 0.05$) for nitrogen balance index, chlorophyll and flavonoids influenced by the type of oat (factor A), and flavonoids influenced by the factors interaction (A × B), Table 1. The overall results revealed that the tested treatment and interaction of factors, rather than the type of oat, had the greatest influence on physiological parameters.

Statistical analysis of the differences between the treatments (factor B) for individual comparison of physiological parameters is presented in Table 2.

Table 1. F-values for observed factors for physiological parameters

Factors	Physiological parameters[1]			
	NBI	Chl (μ/cm²)	Flv (μ/cm²)	Ant (μ/cm²)
Type of oat (A)	1.188^{ns}	1.769^{ns}	0.145^{ns}	13.587**
Treatment (B)	116.00**	138.13**	32.970**	77.973**
A × B	11.426**	8.593**	1.698^{ns}	3.951**

[1] NBI - nitrogen balance index, Chl - chlorophyll, Flv - flavonoids, Ant - anthocyanins. Statistical significance levels: ** - significant at $P \leq 0.01$; ns - not significant at $P \geq 0.05$.

Table 2. Physiological parameters in oats depending on the treatment applied

Treatments[3]	Physiological parameters[1,2]							
	Organic oat				Treated oat			
	NBI	Chl	Flv	Ant	NBI	Chl	Flv	Ant
		μ/cm²				μ/cm²		
MF	33.32 ± 0.90^{d}	21.05 ± 1.83^{d}	0.59 ± 0.12^{de}	0.16 ± 0.01^{cd}	33.92 ± 1.67^{d}	22.95 ± 1.05^{d}	0.61 ± 0.10^{cd}	0.17 ± 0.01^{c}
OMF	34.57 ± 1.26^{d}	22.86 ± 1.37^{d}	0.62 ± 0.10^{cde}	0.15 ± 0.01^{de}	35.33 ± 0.83^{cd}	23.20 ± 0.92^{d}	0.62 ± 0.02^{cd}	0.17 ± 0.01^{c}
$CaCO_3$	28.44 ± 1.05^{e}	18.10 ± 1.63^{e}	0.52 ± 0.08^{e}	0.14 ± 0.01^{de}	29.14 ± 0.99^{e}	17.85 ± 0.89^{e}	0.55 ± 0.04^{d}	0.16 ± 0.01^{cd}
SS	28.14 ± 1.11^{e}	17.91 ± 1.03^{e}	0.50 ± 0.10^{e}	0.14 ± 0.01^{de}	29.74 ± 1.37^{e}	17.45 ± 0.87^{e}	0.56 ± 0.05^{d}	0.15 ± 0.01^{d}
MF + $CaCO_3$	35.06 ± 0.51^{cd}	27.14 ± 1.39^{c}	0.69 ± 0.06^{bcd}	0.17 ± 0.01^{c}	35.89 ± 0.61^{c}	27.86 ± 1.04^{c}	0.68 ± 0.03^{bc}	0.18 ± 0.01^{c}
OMF + $CaCO_3$	38.96 ± 3.28^{b}	30.50 ± 2.56^{b}	0.79 ± 0.03^{ab}	0.19 ± 0.01^{b}	38.18 ± 1.09^{b}	30.04 ± 1.01^{b}	0.75 ± 0.01^{b}	0.20 ± 0.02^{b}
MF + SS	38.18 ± 3.51^{bc}	27.53 ± 1.77^{c}	0.76 ± 0.05^{ab}	0.19 ± 0.02^{b}	38.88 ± 0.95^{b}	31.25 ± 1.51^{b}	0.76 ± 0.06^{b}	0.20 ± 0.02^{b}
OMF + SS	47.31 ± 1.53^{a}	34.93 ± 1.11^{a}	0.89 ± 0.06^{a}	0.21 ± 0.01^{a}	46.98 ± 0.32^{a}	35.53 ± 1.48^{a}	0.87 ± 0.02^{a}	0.22 ± 0.01^{a}
Control (untreated soil)	21.47 ± 2.33^{f}	14.70 ± 1.20^{f}	0.37 ± 0.05^{f}	0.11 ± 0.01^{f}	21.74 ± 0.55^{f}	15.07 ± 0.64^{f}	0.38 ± 0.05^{e}	0.11 ± 0.01^{e}

[1] Means ± STDEV (n = 3). [2,3] Abbreviations for designed treatments and physiological parameters are given in Chapter 2: Materials and methods. Duncan's test at $P < 0.05$: values followed by the same letter in a column are not significantly different.

The obtained results indicated a statistically significant effect ($P < 0.05$) of all applied treatments on physiological parameters in both oats in relation to untreated soil (organic oat: 21.47 NBI, 14.70 μ/cm² Chl, 0.37 μ/cm² Flv, 0.11 μ/cm² Ant; treated oat: 21.74 NBI, 15.07 μ/cm² Chl, 0.38 μ/cm² Flv, 0.11 μ/cm² Ant). The most pronounced significant effect ($P < 0.05$) on all physiological parameters in both oats compared to other tested treatments was determined in combined organo-mineral fertilizer and steel slag treatment (organic oat: 47.31 NBI, 34.93 μ/cm² Chl, 0.89 μ/cm² Flv, 0.21 μ/cm² Ant; treated oat: 46.98 NBI, 35.53 μ/cm² Chl, 0.87 μ/cm² Flv, 0.22 μ/cm² Ant), followed by combined organo-mineral fertilizer and $CaCO_3$. The lowest values of the tested parameters in both oats were determined in treatments where $CaCO_3$, steel slag, and mineral and organo-mineral fertilizers were applied individually.

Chemical properties of oats

The concentrations of the tested macroelements (N, P, K) and trace elements (Fe, Mn, Zn, Ni) in the aerial biomass of both oat types showed distinct responses under the influence of the type of oat (factor A), treatment (factor B), and their interaction factor (A × B). Experimental data for factors are presented in Tables 3 and 5, while statistical analysis of the differences in individual comparisons of chemical parameter values under the influence of treatments is presented in Tables 4 and 6.

Statistical analysis of the oats macroelements (N, P, K) under influence of tested factors indicated the following findings: highly significant ($P \leq 0.01$) differences for all parameters under influence of oat type (factor A) and treatment (factor B); highly significant ($P \leq 0.01$) differences for the content of K under influence of the factors interaction (A × B). Factor A × B did not show statistically significant effects ($P \geq 0.05$) on the content of N and P (Table 3). The overall results revealed that the tested treatments (factor B) and oat type (factor A), as opposed to their interaction, exhibited the strongest effect on macronutrient content.

Table 3. F-values for observed factors for macroelements

Factors	Macroelements (%)		
	N	P	K
Type of oat (A)	16.684**	158.24**	280.56**
Treatment (B)	79.738**	18.746**	195.38**
A × B	0.358ns	0.654ns	5.989**

Statistical significance levels:
** - significant at $P \leq 0.01$; ns - not significant at $P \geq 0.05$.

Statistical differences between the treatments (factor B) for individual comparison of the macroelements content are summarized in Table 4. The obtained data revealed a statistically significant effect ($P < 0.05$) of all treatments on the macroelements content in both oats in relation to untreated soil (organic oat: 2.09% N, 0.330% P, 3.35% K; treated oat: 2.18% N, 0.420% P, 3.64% K). The most highest and significant effect ($P < 0.05$) on all values of macroelements in both oats compared to other tested treatments was registered in the treatment where combined organo-mineral fertilizer and steel slag was used (organic oat: 2.88% N, 0.477% P, 4.59% K; treated oat: 2.97% N, 0.623% P, 4.83% K), followed by combined organo-mineral fertilizer and $CaCO_3$, and combined mineral fertilizer and $CaCO_3$. In general, individual applications of $CaCO_3$, steel slag, and mineral and organo-mineral fertilizers caused the lowest values of the tested parameters in both oats (Table 4).

Statistical analysis of the oats trace elements (Fe, Mn, Zn, Ni) under influence of tested factors indicated the following findings: highly significant ($P \leq 0.01$) differences for all parameters under influence of oat type (factor A) and treatment (factor B); highly significant ($P \leq 0.01$) differences for the content of Fe, Mn and Zn under influence of the factors interaction (A × B). Factor A × B did not show a statistically significant influence ($P \geq 0.05$) on the content of Ni (Table 5). The overall results revealed that all the tested factors (A, B, and A × B) for almost all trace elements exhibited the highest impact.

Table 4. Content of macroelements in oats depending on the treatment applied

Treatments[2]	Macroelements (% in dry biomass)[1]					
	Organic oat			Treated oat		
	N	P	K	N	P	K
MF	2.49 ± 0.04^{cd}	0.387 ± 0.06^{bc}	3.64 ± 0.16^{f}	2.55 ± 0.13^{cd}	0.490 ± 0.01^{f}	3.92 ± 0.02^{e}
OMF	2.57 ± 0.02^{c}	0.447 ± 0.04^{ab}	4.06 ± 0.07^{d}	2.67 ± 0.10^{bc}	0.523 ± 0.01^{e}	4.50 ± 0.04^{c}
$CaCO_3$	2.45 ± 0.02^{d}	0.447 ± 0.03^{ab}	3.87 ± 0.06^{e}	2.48 ± 0.06^{d}	0.546 ± 0.01^{d}	4.11 ± 0.02^{d}
SS	2.43 ± 0.05^{d}	0.457 ± 0.04^{ab}	3.98 ± 0.03^{de}	2.45 ± 0.10^{d}	0.542 ± 0.01^{d}	4.14 ± 0.02^{d}
MF + $CaCO_3$	2.72 ± 0.03^{b}	0.470 ± 0.05^{a}	4.39 ± 0.05^{b}	2.79 ± 0.10^{b}	0.566 ± 0.01^{bc}	4.76 ± 0.04^{b}
OMF + $CaCO_3$	2.82 ± 0.05^{a}	0.463 ± 0.03^{ab}	4.45 ± 0.04^{b}	2.95 ± 0.05^{a}	0.577 ± 0.01^{b}	4.88 ± 0.05^{a}
MF + SS	2.67 ± 0.08^{b}	0.457 ± 0.04^{ab}	4.22 ± 0.03^{c}	2.73 ± 0.06^{b}	0.556 ± 0.01^{cd}	4.65 ± 0.04^{b}
OMF + SS	2.88 ± 0.07^{a}	0.477 ± 0.05^{a}	4.59 ± 0.02^{a}	2.97 ± 0.03^{a}	0.623 ± 0.01^{a}	4.83 ± 0.04^{a}
Control (untreated soil)	2.09 ± 0.09^{e}	0.330 ± 0.04^{c}	3.35 ± 0.04^{g}	2.18 ± 0.02^{e}	0.420 ± 0.01^{g}	3.64 ± 0.18^{f}

[1] Means ± STDEV (n = 3). [2] Designed treatments and their abbreviations are given in Chapter 2: Materials and methods. Duncan's test at $P \leq 0.05$: values followed by the same letter in a column are not significantly different.

Table 5. F-values for observed factors for trace elements

Factors	Trace elements (%)			
	Fe	Mn	Zn	Ni
Type of oat (A)	185.77**	1130.9**	1221.4**	16.970**
Treatment (B)	714.87**	1017.6**	271.60**	38.958**
A × B	6.609**	68.410**	110.26**	1.088^{ns}

Statistical significance levels: ** - significant at $P \leq 0.01$; ns - not significant at $P \geq 0.05$.

Statistical differences between the treatments (factor B) for individual comparison of the trace elements content are presented in Table 6. Statistical analysis of the results obtained indicates a statistically significant effect ($P < 0.05$) of all treatments on the trace elements content in both oats in relation to control soil (organic oat: 67.6% Fe, 47.9% Mn, 40.7% Zn, 7.7% Ni; treated oat: 84.2% Fe, 57.2% Mn, 43.0% Zn, 8.9% Ni). This result is somewhat expected considering that the soil in this variant was not treated. The most highest and significant impact ($P < 0.05$) on all values of trace elements in both oats in relation to other tested treatments was registered in the treatment where individual applications of mineral fertilizer was used (organic oat: 268.7% Fe, 101.6% Mn, 68.5% Zn, 16.3% Ni; treated oat: 311.5% Fe, 115.0% Mn, 68.5% Zn, 17.5% Ni), followed by combined mineral fertilizer and steel slag.

Table 6. Content of trace elements in oats depending on the treatment applied

Treatments[2]	Trace elements (% in dry biomass)[1]							
	Organic oat				Treated oat			
	Fe	Mn	Zn	Ni	Fe	Mn	Zn	Ni
MF	268.7 ± 15.97^{a}	101.6 ± 1.89^{a}	68.5 ± 0.62^{a}	16.3 ± 1.68^{a}	311.5 ± 1.15^{a}	115.0 ± 0.95^{a}	68.5 ± 1.25^{a}	17.5 ± 1.16^{a}
OMF	157.3 ± 8.69^{c}	71.7 ± 1.98^{e}	46.3 ± 1.11^{e}	11.8 ± 0.81^{c}	178.4 ± 0.60^{d}	73.0 ± 1.06^{g}	56.2 ± 1.12^{c}	12.0 ± 1.11^{cd}
$CaCO_3$	116.5 ± 1.28^{d}	64.6 ± 0.56^{f}	49.3 ± 1.01^{d}	12.2 ± 0.89^{c}	122.4 ± 1.89^{g}	88.4 ± 1.13^{f}	52.5 ± 0.50^{d}	13.1 ± 1.21^{bc}
SS	167.0 ± 8.19^{c}	96.2 ± 1.03^{b}	51.2 ± 1.33^{c}	14.0 ± 0.98^{b}	179.9 ± 1.65^{d}	95.4 ± 1.37^{e}	63.0 ± 0.91^{b}	14.2 ± 0.87^{b}
MF + $CaCO_3$	121.4 ± 2.17^{d}	90.3 ± 2.20^{c}	46.1 ± 0.90^{e}	8.27 ± 0.5^{d}	155.2 ± 1.32^{e}	101.7 ± 1.43^{c}	64.6 ± 1.27^{b}	10.1 ± 0.90^{de}
OMF + $CaCO_3$	113.6 ± 1.11^{d}	71.5 ± 0.79^{e}	43.0 ± 0.78^{f}	8.55 ± 0.96^{d}	143.4 ± 1.30^{f}	95.7 ± 0.55^{e}	56.9 ± 1.07^{c}	11.1 ± 0.59^{cd}
MF + SS	246.8 ± 9.48^{b}	98.1 ± 0.90^{b}	56.2 ± 1.37^{b}	10.6 ± 0.72^{c}	254.8 ± 7.45^{b}	109.5 ± 2.15^{b}	64.0 ± 1.15^{b}	11.8 ± 1.63^{cd}
OMF + SS	153.2 ± 9.87^{c}	82.5 ± 0.84^{d}	48.4 ± 1.02^{d}	10.5 ± 0.72^{c}	184.9 ± 0.92^{c}	98.8 ± 1.37^{d}	65.1 ± 0.95^{b}	11.7 ± 0.85^{cd}
Control (untreated soil)	67.6 ± 1.12^{e}	47.9 ± 1.01^{g}	40.7 ± 0.81^{g}	7.7 ± 1.12^{d}	84.2 ± 0.83^{h}	57.2 ± 1.07^{h}	43.0 ± 1.45^{e}	8.9 ± 0.95^{e}

[1] Means ± STDEV (n = 3). [2] Designed treatments and their abbreviations are given in Chapter 2: Materials and methods. Duncan's test at $P \leq 0.05$: values followed by the same letter in a column are not significantly different.

According to reference values of trace elements in plant material (Table 7), the results obtained in this research indicate normal concentrations for Mn and Zn, critical concentrations for Ni, and normal to critical concentrations for Fe (except in the NPK treatment for treated oat, where Fe concentrations were above the critical values). Nevertheless, the concentrations of the analyzed trace elements in the plant material of all treatments were far below the toxic values.

Table 7. Reference values of trace elements in plant biomass

Reference value	Fe	Mn	Zn	Ni
Normal	50-200[1]	15-100[3]	15-150[3]	0.1-5[3]
Critical	200-250[1]	100-150[2]	150[2]	5-20[2]
Toxic	600[2]	400[2]	200[2]	30[2]

Literature source:
[1]Schulze et al. (2005), [2]Kastori et al. (1997), [3]Kloke et al. (1984).

It was determined higher and statistically significant ($P < 0.05$) concentrations of Fe, Mn and Zn in both oats in the treatments where slag was applied individually and in combination with organo-mineral fertilizer compared to the individual application of $CaCO_3$ and in combination with organo-mineral fertilizer. However, reference values (Table 7) indicate normal concentrations of Fe, Mn and Zn, and critical content of Ni, in the plant material of both treatments. The obtained results showed that steel slag, similar to lime materials, can be used in plant production, most likely in increasing the pH value in acidic soils, leading to better soil conditions, plant nutrient uptake, development, and quality, despite the significant content of Fe and Mn in this industrial raw material.

Biomass yield and its comparison depending on the treatment and type of oat

By measuring the aerial biomass yields of both organic and treated oats it was determined the significance in differences in this parameter depending on the treatment used (Figure 1). Different applied treatments were the main factor in the statistical data analysis.

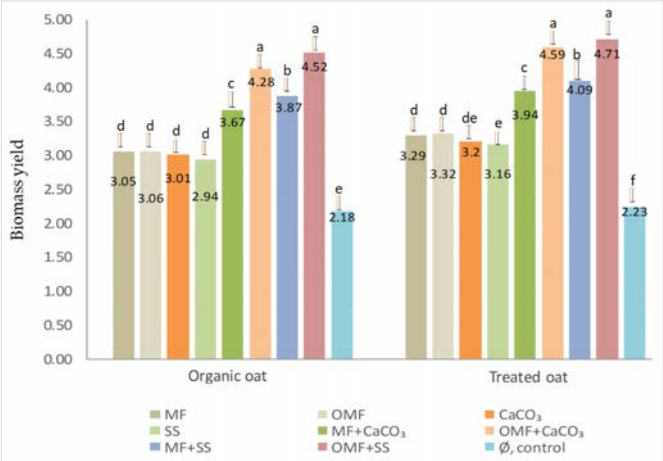


Figure 1. Effect of treatments on the average yield of aerial plant biomass (n = 3) depending on the oat type (designed treatments and their abbreviations are given in Chapter 2: Material and methods; Duncan's test at $P \leq 0.05$: values followed by the same letter are not significantly different)

There were significant differences ($P < 0.05$) in the biomass yield of both oats in treatments which included the combined use of organo-mineral fertilizer and steel slag (organic oat: 4.52 g/pot; treated oat: 4.71 g/pot), followed by the combined use of organo-mineral fertilizer and $CaCO_3$ (organic oat: 4.28 g/pot; treated oat: 4.59 g/pot) in relation to other treatments and untreated soil. The most inhibitory effect on the yield of both oats was manifested in untreated soil (organic oat: 2.18 g/pot; treated: 2.23 g/pot) in relation to all treated soils. The lowest biomass yields of both oats were found in treatments where $CaCO_3$, steel slag, and mineral and organo-mineral fertilizers were applied individually.

The obtained data on the aerial biomass yield average values indicated not so pronounced differences between organic and treated oat depending on the treatment applied. However, slightly better results for this parameter were noticed in treated oats in relation to organic ones (Figure 1).

DISCUSSION

The present data indicated distinct variation in values of increases and decreases in physiological parameters, macroelements and trace elements in both oat biomass and their biomass yield under the influence of the tested factors. The overall data on the three factors' influence (oat type, treatment, and their interactions) revealed that the significance of the treatment was most evident in terms of all parameters examined. Similar to this finding, Štrbanović et al. (2025) also reported a greater effect of the treatment factor on crimson clover seed weight after water absorption than the lot x factor, year x factor, and all factor interactions.

All treatments had a statistically significant effect on all tested parameters for both oats in relation to untreated soil. In general, treatments that included combined organo-mineral fertilizer and steel slag, combined organo-mineral and $CaCO_3$, and combined mineral fertilizer and $CaCO_3$, enhanced the biomass yield, physiological (NBI, Chl, Flv, Ant), and main chemical (N, P, K) parameters of organic and treated oats' aerial biomass. The examined properties of both oats had the lowest values in individual application of $CaCO_3$, steel slag and mineral and organo-mineral fertilizer treatments, respectively.

Many authors (Munn, 2005; Vieira da Silva et al., 2021; Tozsin and Oztas, 2023; Mao et al., 2024) emphasize a significant effect of using steel slag solely in plant cultivation, reporting an increase in the content of physiological parameters (primarily chlorophyll), essential elements (N, P, K), promotion of plant growth and increasing of crop biomass yields. This is not consistent with the current research, where the obtained results showed a better efficiency of the combined application of steel slag and organo-mineral, i.e., mineral fertilizer. Nevertheless, the current study can be supported by the statement of Kumar et al. (2025), that the slag can be applied to complement the conventional mineral fertilizers without causing any soil and plant toxicity. Accordingly, this helps to save on costs for NPK chemical fertilizers without any negative impact on the economic biomass yield and nutritional quality of vegetables. Mao et al. (2024) indicated that steel slag can improve soil and increase crop biomass yields because it contains high levels of calcium, magnesium, iron, silicon, and other trace metals. Islam et al. (2022) determined that low concentrations of steel slag (0.5% to 1%) in soil had positive effects on

plant growth, mineral uptake of plants, and bacterial biomass in organic short-term cultivation of *Brassica rapa* var. *periviridis* and *Spinacia oleracea* L. The authors suggested further studies regarding the long-term cultivation practice with repetitive application of slag. Similar results for slag in the present study were obtained for the use of commercial limestone (in the form $CaCO_3$), which is in accordance with previous studies. Chand et al. (2015) reported that slag can be safely and effectively used instead of limestone to neutralize soil acidity as a soil amendment in agriculture. Effects of steel slag and $CaCO_3$ on the growth of oat, wheat, corn and soybean were examined using acid soil in a 3-year greenhouse trial in the study of Munn (2005). The author determined that the steel slag and $CaCO_3$ applications significantly increased the biomass yield of all tested plants compared to untreated variants. Vieira da Silva et al. (2021) evaluated the effects of steel slag, wollastonite and calcined dolomite on physiological, biochemical and nutritional changes in soybean plants and determined significant increases in soybean biomass yield, greater production of fresh and dry leaf mass and stem fresh mass, increased leaf chlorophyll and K levels, with equal efficiency for all three liming materials.

Present study revealed the best effects of the integrated use of organo-mineral fertilizer and steel slag, that is, the integrated use of mineral fertilizer and steel slag, on physiological parameters and macroelements in oats. Significant results in the present study were also obtained using the treatment with combined usage of $CaCO_3$ and organo-mineral fertilizer. The results obtained are mostly in accordance with those obtained by Iren et al. (2016), where the use of organo-mineral fertilizer enhanced with lime in acid soil increased values of soil pH, available phosphorus, main nutrients (Ca, Mg, K), growth parameters and biomass yield of pumpkin relative to the control. Results of the present study showed that used steel slag in combination with organo-mineral fertilizer can be equally effective as the use of organo-mineral fertilizer combined with lime in acid soil, which is also confirmed in the study of Huang et al. (2012), where the correction of acidity with steel slag occurs similarly to the use of natural agricultural limestone. The superiority of the combined treatments compared to the control could be due to the increased availability of major plant nutrients and microbial activity as a result of the increase in soil pH (Asawalam and Onyegbule, 2009). Efficiency of organo-mineral fertilizer role in the treatment with slag or lime material in the form of $CaCO_3$ is reflected in reducing the rate of soil organic matter dehumification, optimization of the humus state in the soil, and increasing the biological soil activity. Moreover, in used organo-mineral fertilizer poultry compost provides organic matter and macro- and micronutrients, while mineral fertilizer adds available phosphorus, affecting the balance in plant nutrition and high biomass yield (Genrietta et al., 2022). Ayeni et al. (2012) also determined that organo-mineral fertilizers at low application levels could increase plant nutrients and maize production. Havryshko et al. (2017) reported a great increase of redox potential during the period of intensive growth and development of plants with the application of organo-mineral and mineral fertilizer systems, with the background of liming with $CaCO_3$.

The use of steel slag in acidic soils can improve the plant nutrient availability of not so fertile soils and be a cost-effective and environmentally friendly approach that helps reduce waste problems (Tozsin and Oztas, 2023), which also applies to slag combined with mineral fertilizer. In the study of Quang et al. (2022), the application of mineral fertilizer combined with steel slag enhanced soil nutrients and increased rice biomass yield. Accordingly, in field trial on acid soil, treatment with steel slag at a dosage of 3 tons/ha combined with mineral fertilizer showed a tendency to improve soil chemical properties (pH, soil organic matter - SOM, total and available P, exchangeable cations - K, Na, Mg), thus helping to increase the biomass yield and biomass yield components of rice compared to the control.

The data obtained in this study regarding the effect of treatments on the biomass yield of plants depending on the oat type indicated not so pronounced differences between organic and treated oat. These results are similar but not fully consistent with those obtained by

Ćurčić et al. (2022) on lettuce plants, where higher seed germination energy of treated oat than of organic (untreated) oat is determined. Accordingly, higher seed germination energy of any plant could potentially lead to better growth and development. Nevertheless, slightly better results were observed for the treated oat in relation to organic.

The presence of high concentrations of trace elements and metals in the composition of steel slag represents the main limitation in its use and has to be analysed before soil application. This action would likely significantly reduce plant toxicity, decreasing the absorption of metals by plants and their further transmission to animals and humans. Nevertheless, the positive effect of steel slag on plants can be explained by the proper content of Mg, Fe, Mn, Zn, and other trace metals important for plant development. According to reference values of trace elements in plant material, the results obtained in this research indicate normal concentrations for Mn and Zn, critical concentrations for Ni, and normal to critical concentrations for Fe (except in the NPK treatment for treated oat, where Fe concentrations were above the critical values). All tested trace elements showed the lowest values in the untreated soil (control), which could be somewhat expected considering that the soil in this variant was not treated. The obtained trace element values were below the toxic levels, differing from each other mainly depending on the treatment applied. The results obtained in this research are in accordance with the data from the study of Deus et al. (2019), where significant increases in trace elements and heavy metals in the plant tissue of black oats, soybean and beans, cultivated in the area where the slags were applied, were not observed. In the study of Munn (2005), very high levels of Fe in steel industry slags were not bio-available in the conditions where slags have been used as liming material in agriculture and for acid mine soil reclamation. This is in accordance with the current study, where iron was not found to be in excess in plant tissue in the treatments where slag was applied despite its high content in it. Munn (2005) also reported an increase in plant Ca and Mg, and a decrease in plant Al and Mn by application of slag. Pivić et al. (2011) did not find higher accumulation of Fe in barley in the treatments where steel slag alone and in combination with organic (manure) and mineral fertilizers was applied despite its significant content in slag. The combined application of industrial slag and NPK fertilizer in acidic soils increased soil pH (Pinto et al., 1995), thereby improving exchangeable Ca and Mg in the soil and reducing soil exchangeable Al, Mn, Cu and Zn (Besga et al., 1996), resulting in high biomass yields and nutrient concentrations in plants (Lopez et al., 1995). The results of the present research indicate the complete absence of toxic values of trace elements in both oats (Kloke et al., 1984; Kastori et al., 1997; Schulze et al., 2005). Statistical analysis in the study of Głodowska and Krawczyk (2017) revealed significantly higher concentrations of some trace metals in the conventionally grown vegetables than in the organically but added that their results were not conclusive.

Although the present study did not observe an increase in the level of trace elements in both plants, monitoring of the plant availability of these elements, added to the soil along with the steel slag, as well as the characterization of the slags to be used, is fundamental for the success of the slag residues used in agriculture.

CONCLUSIONS

The research data on the physiological parameters and macroelements in both oat types revealed that the influence of treatment was more evident than that of the oat type and their interactions. Estimated differences between the treatments for individual comparison of the tested parameters indicated distinct variation in increases and decreases in their values. The obtained data on the values of physiological parameter, macroelements, and biomass yield of organic and treated oats' aerial biomass have shown that the most pronounced significant influence was determined in the combined organo-mineral fertilizer and steel slag treatment, followed by the combined organo-mineral fertilizer and $CaCO_3$. Individual treatments with $CaCO_3$, steel slag, and mineral and organo-mineral fertilizers caused the lowest values of the tested parameters in both oats. Nevertheless, all

the treatments had a statistically significant effect on all tested parameters for both oats in relation to untreated soil (control). The differences in the biomass yield values between organic and treated oats, depending on the applied treatment, were not so pronounced, but with slightly better results determined in treated oats. The overall results for trace elements indicated the highest statistical effect of the treatment and oat type for Fe, Mn, Zn and Ni, and of their interaction for Fe, Mn and Zn. The statistically processed data on the values of the tested trace elements have shown the most pronounced influence of all treatments in both oats in relation to the control soil, as expected, considering that the control soil was not treated. In treatments where mineral fertilizer is applied simultaneously with steel slag, as well as mineral fertilizer alone, the highest values of all trace elements in both oats in relation to other treatments. Similar to commercial lime materials, it has been shown that steel slag of a specific composition can be used in plant production, most likely to increase the pH value in acidic soils, and thus for better soil conditions and plant nutrient uptake. According to the research in this paper, treatments with combined organo-mineral fertilizer and steel slag and combined organo-mineral fertilizer and $CaCO_3$ have shown the highest potential to be applied to acidic soils to improve plant growth without adverse effects. However, further research in this area of study needs to be conducted to provide insights into a better understanding of the current findings, especially on larger soil areas, making oat production potentially more acceptable from an ecological point of view.

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