Final formulations of waste biomass-based fertilizers: evaluation in plant trials

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Keywords: waste biomass, biofertilizers, germination tests, pot tests
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Organic fertilizers contribute substantially to sustainable agricultural practices. The application of such preparations improves soil fertility and supports the soil microbiome by improving soil structure, increasing its sorption capacity and stimulating microbial activity (Bhatt et al., 2019). Studies show that applying organic fertilizers reduces nitrogen leaching from the soil by several to tens of percent compared to mineral fertilizers (Wei et al., 2021). The use of organic fertilizers significantly reduces the environmental footprint of fertilization, lowering CO_2 and other greenhouse gas emissions by up to 50% (Krause et al., 2024). Research suggests that, as a result, the use of biofertilizers also leads to improved crop quality, increasing the nutrient content of produce and lowering the level of harmful nitrates (Ye et al., 2020). Given their multiple agronomic and environmental benefits, organic fertilizers represent a promising tool for sustainable agriculture.

In this study, three formulations of ecological fertilizers based on waste biomass dedicated to the cultivation of cereals (F1), protein crops (F4) and vegetables (F8) were designed The fertilizers were characterized by elevated levels of organic matter (C_{org}: 25.6±2.6 - 33.6±3.6%), nitrogen (N_{total}: 2.54±0.25 - 2.42±0.34%), phosphorus (P_2O_5: 1.42±0. 28 - 3.85±0.77%), potassium (K_2O: 4.02±0.80 - 5.18±1.04%), and micronutrients from the group of B, Cu, Mn, Fe and Zn at a level of 2 - 3% total. Each formulation complied with the regulatory criteria for organic fertilizers.

The effectiveness of the developed formulations was evaluated in germination tests under controlled laboratory conditions on model plants (cucumber, lupin, corn). The fertilizers were tested at three doses (75%, 100% = recommended rate, 150%) against a reference fertilizer and an unfertilized control. After 14 days, germination rate and plant biometric parameters—including fresh and dry weight, stem length, root system metrics (length, volume, area), and chlorophyll content—were assessed (Table 1).

Table 1. Selected biometric parameters of plants fertilized with F4 and F8 formulations.

Group/Dose	Chlorophyll (*mg/m²*)	Stem length (*cm*)	Root length (*cm*)	Fresh mass (*g*)	Germ. power (*%*)
			Lupin		
F4/75	549±46[a]	10.9±0.3[a,b,c,d,e,f]	38.3±4.0[a,b]	4.71	96
F4/100	373±50[a,b,c,d,e,f]	9.45±0.28[a,g,h]	31.0±4.0[a,c,d,e,f]	4.63	100
F4/150	477±43[b]	9.08±0.27[b,i,j]	39.0±3.1[c,g]	4.28	96
REF/75	504±56[c]	8.60±0.49[c,k]	38.4±4.5[d,h]	4.07	100
REF/100	502±52[d]	9.13±0.92[d,l,m]	39.5±3.7[e,i]	4.47	100
REF/150	470±65[e]	7.72±0.88[e,g,i,l]	19.7±3.7[b,f,g,h,i]	3.40	96
Control	540±47[f]	7.43±0.21[f,h,j,k,m]	34.8±4.5	2.78	96
			Cucumber		
F8/75	467±51	3.88±0.39[a,b]	40.7±6.9[a,b]	3.88	96
F8/100	503±68[a]	4.05±0.39[c,d,e]	39.0±5.1[c,d]	4.07	96
F8/150	414±78[a,b,c]	3.78±0.21[f]	19.4±2.8[a,c,e,f,g]	3.63	92
REF/75	521±31[b]	3.33±0.38[c,g]	41.4±4.3[e,h]	3.38	92
REF/100	508±15[c]	3.67±0.18[h]	38.4±5.4[f,i,j]	3.51	100
REF/150	490±16	3.25±0.33[a,d]	21.5±5.8[b,d,h,i,k]	3.34	96
Control	499±37	2.75±0.24[b,e,f,g,h]	47.6±2.1[g,j,k]	2.58	92

All tested formulations provided high seed germination (92 - 100%), comparable to the reference fertilizer and the control. Biometric analysis confirmed a favorable effect of the new organic fertilizers, with the most promising results observed for groups treated with F4 and F8. The application of F4 fertilizer at a dose of 75% resulted in an increase in the fresh mass of sprouts by about 16% compared to the reference object, while for F8 fertilizer at a dose of 100% it increased by about 15% (Table 1). The highest chlorophyll content was observed for F4 at 75% (549±46 mg/m²), exceeding the value for the reference fertilizer (504±56 mg/m²). Analogous effects were found for cucumber. The highest chlorophyll content was recorded in the group fertilized with a 100% dose of the F8 formulation (503±68 mg/m²), reaching higher contents compared to the control group (499±37 mg/m²) and similar levels compared to the reference product (508±15 mg/m²).

In the next stage, three-month pot tests were conducted on the same plant species. The dosage was selected based on germination test results. The results confirmed the new formulations' effectiveness in stimulating plant growth. The application of F1, F4, and F8 significantly increased the fresh weight of plants compared to the control. F1 and F8 increased the fresh weight of plants by 13% and 12%, respectively, compared to the group fertilized with the reference product. Root system parameters in most groups did not differ significantly between fertilizers, with a few cases where the object with the reference fertilizer tended to have higher values. The dry mass of the plants was subjected to mineralization and analysis of the content of selected elements. In most cases, plants treated with the new fertilizers showed higher micronutrient content than those treated with the reference product, indicating improved nutrient uptake and yield (Table 2), and supporting the efficacy of the new fertilizers in delivering bioavailable micronutrients relevant to plant performance.

Table 2. Content of micronutrients in plants fertilized with F1 formulation.

Elements	F1/50%	F1/75%	F1/100%	REF/100%	Control
B *(mg/kg)*	6.2±0.93	<1.50±0.23	<1.50±0.23	<1.50±0.23	<1.50±0.23
Cu *(mg/kg)*	8.01±1.2	5.44±0.82	8.34±1.25	5.7±0.85	13.1±2
Fe *(mg/kg)*	101±15	64.2±9.6	64±9.6	75.1±11.3	73.5±11
Mn *(mg/kg)*	27±4.1	23.1±3.5	28.4±4.3	24.4±3.7	18.4±2.8
Zn *(mg/kg)*	38.8±5.8	29.3±4.4	32.6±4.9	28.6±4.3	27.2±4.1

Analysis of the element content relationship in the soil-plant system (transfer factor) showed that as the application rate increases, nutrient transfer decreases. Higher soil concentrations may cause saturation, reducing nutrient uptake by plants. In addition, high concentrations of fertilizers can cause competition between elements, soil acidification or reduced solubility, which reduces the transfer of ingredients to plants.

The results indicate that the developed organic fertilizers improved early plant growth and nutrient uptake. Both germination and pot tests have shown that the new formulations can have higher efficacy compared to the reference fertilizer, increasing fresh plant weight and improving micronutrient content in biomass. The nutrient composition, bioavailability, and lack of phytotoxicity suggest that the developed formulations are suitable for application in organic and sustainable agriculture.

Acknowledgements
This work was financed by the National Centre for Research and Development under project no. LIDER13/0290/2022 entitled: "Innovative comprehensive ecological fertilizers based on waste biomass".

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