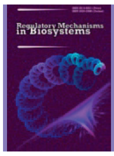

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Post-harvest application of biological residue decomposers and mulching: Effects on soil health and winter wheat yield

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Ensuring sustainable crop production while maintaining soil fertility is a critical challenge in the context of global climate change and increasing agricultural intensification. One promising approach involves the use of biological agents to accelerate the decomposition of plant residues and improve soil quality. This study explores the impact of post-harvest mulching combined with plant residue destructors on the decomposition rate of oilseed flax stubble, nitrogen availability, and the microbiological activity of arable soils. The research was conducted during the 2023–2024 growing season under rainfed conditions on middle-loamy dark chestnut soil using a systematic field experiment with four replications. Two experimental factors were considered: the application of various microbial cellulose destructors and the use or absence of surface mulching after flax harvest. Results showed that the combined application of biological destructors and mulching significantly enhanced the decomposition of plant biomass – by 202–289% relative to untreated control plots – due to the activity of cellulose-degrading microorganisms. This process led to improved nutrient cycling, with the content of mobile nitrogen compounds in the topsoil increasing by 62.2–78.9%. Concurrently, the biological activity of ammonifying microbial populations rose by 32.0–58.9%, indicating enhanced microbial-driven nitrogen transformation. A slight positive effect was also observed in plots where only water was applied to the stubble, attributed to temporary increases in humidity that stimulated native aerobic cellulose-degrading microbes. Importantly, the improved soil conditions resulting from this integrated approach contributed to a 4.1–9.8% increase in grain yield of the subsequent winter wheat crop. Among the tested microbial products, the most effective preparation included a synergistic blend of humic and fulvic acids, amino acids, phytoenzymes, and essential macro- and micronutrients. These findings highlight the potential of combining mulching and microbial biotechnology as a cost-effective and environmentally friendly agronomic practice to enhance soil health, accelerate nutrient turnover, and improve crop productivity in dryland farming systems.

Keywords: cellulose-decomposer; microbiological activity; mineralization of plant residues; soil fertility; steppe zone.

Introduction

Biologization of agriculture is essential for sustainable development. It seeks a comprehensive approach to improving existing agricultural practices in crop production to meet the demands of biodiversity preservation, natural resource conservation, rational environmental management, reduced ecological pressure, mitigation of climate-related risks and adverse impacts on agroecosystems, and to satisfy the growing demand for food alongside ensuring adequate economic efficiency (Hadzalo et al., 2024). To effectively address these challenges, the development of an integrated agrotechnological strategy is crucial. One of its components is the application of biological cellulose decomposers to enhance soil fertility and promote the efficient utilization of plant residues. This approach harnesses natural decomposition processes, accelerating the breakdown of cellulose-rich materials such as straw and stubble, thereby releasing essential nutrients back into the soil. Moreover, the application of these biological agents improves soil structure, water retention capacity, and microbial activity, contributing to a more resilient and productive agroecosystem.

Biological agents play a vital role in the decomposition of crop residues within biologized (biologically based) agriculture. Specific fungi and bacteria are employed to break down plant residues, converting them into valuable organic matter while reducing the carryover of plant pathogens. Fungi such as *Trichoderma* spp. and *Paecilomyces* spp. are commonly used for this purpose, often cultivated on agro-industrial residues as substrates for mass production (Das & Abdulhameed, 2020). Broadly, the primary groups of biological agents include Firmicutes, Proteobacteria, Bacteroidetes, Acidobacteria, and Actinobacteria. Representative genera such as *Pseudomonas*, *Delftia*, *Paenibacillus*, *Lysinibacillus*, *Arthrobacter*, and *Brevundimonas* frequently participate in straw degradation, with their predominance varying by decomposition stage and environmental conditions (Zhang et al., 2022; Sun et al., 2023). Key fungal decomposers include representatives of *Cephalotrichum*, *Sordariales*, *Coprinus*, *Schizothecium*, *Aspergillus*, and *Trichoderma*, whose activity is significantly influenced by soil salinity and straw type (Zhang et al., 2023). Scientific evidence shows that integrating biological agents with cover crops enhances soil structure, fertility, and microbial diversity, thereby supporting long-term soil health and sustainability (Pinales et al., 2023).

Currently, the use of biodestructors faces several significant challenges. First is the variability in their effectiveness across different agroecological conditions. Their performance strongly depends on environmental factors, including soil type, pH, temperature, and moisture levels. This variability often results in inconsistent outcomes. Soil microbial communities are inherently complex and dynamic. Introducing external microorganisms may disrupt existing microbial balances, occasionally with unpredictable or even detrimental consequences, particularly under the current conditions of rapid climate change (Bardgett & Caruso, 2020). Therefore, modern biodestructors must demonstrate efficacy under both low and high temperature and humidity levels, and across various soil ecotypes (Boiko et al., 2024). In addition, results are often context-specific, depending on the cultivated crop. This was confirmed by Fomenko & Kaziuta (2023), who observed positive effects of biodestructors on soil humification in typical chernozem under cereal crops, while noting adverse effects under other crop types.

Another critical issue is that the introduced microorganisms in biodestructors must compete with native soil microbes for resources and adapt to the local soil environment. Many fail to survive or establish themselves in the soil, limiting their long-term impact on soil fertility and, in some cases, leading to neutral or negative results (Chen et al., 2024). Moreover, the efficacy and safety of biological products depend heavily on the quality of these preparations. Ensuring the high quality and integrity of bioproducts on the market is a challenge, necessary to prevent forgery and the introduction of potentially harmful biological agents (Rowińska et al., 2024). Given the considerable diversity of available biodestructors – based on different strains of bacteria, fungi, or other biologically active substances – rigorous safety and authenticity testing is especially important (Boiko et al., 2024).

In line with current agricultural science, it is essential to consider specific factors such as soil and climate conditions, agricultural management level, and crop rotation when applying biodestructors. Researchers highlight the need for a deep understanding of soil microbial ecology to optimize the use of these biological agents. Parameters such as soil pH, organic matter content, and the composition of native microbial communities significantly influence the efficacy of introduced organisms. Studies emphasize the need for targeted application of biodestructors, taking into account the nutrient requirements of crops and the specific properties of the soil. For example, the same biodestructor may yield different outcomes and efficiency levels when applied to cereal versus legume crops, as demonstrated in trials with spring barley and peas, where the agent performed significantly better under peas in terms of enhancing soil fertility. Furthermore, cultivation techniques – particularly tillage practices – must be considered, as they have a notable effect on the efficiency of biodestructors (Panfilova & Byelov, 2022).

In summary, while biodestructors offer a promising approach for improving soil fertility and crop productivity, several challenges must be addressed to ensure their successful and sustainable use. Despite the growing popularity of biological agents in agriculture, and biodestructors of crop residues, current scientific knowledge remains limited and necessitates further theoretical and practical research. Most studies conducted in southern Ukraine have produced encouraging results but still require deeper analysis and clarification (Panfilova, 2021).

Therefore, the objective of this scientific research was to study the effectiveness of modern plant residue biodestructors when applied post-harvest in oilseed flax crops, as well as their residual effect on the subsequent crop – winter wheat – through the analysis of major phenological, biometric, and microbiological indicators, alongside a set of quantitative and qualitative crop productivity evaluation criteria.

Materials and methods

The study was carried out by setting up a two-factor field experiment on the experimental field of the research farm "Pioneer" located in Beryslav district of Kherson region (47º27`13.4`` N 33º43`36.0`` E). The factor A was represented by the nomenclature of modern biological cellulose-destructors, the factor B – by the method of their application (without mulching and with mulching, respectively). The soil of the experimental plot was dark-chestnut middle-loamy, with a humus content of 2.3% in the arable layer (0–30 cm). The size of the first-order sowing plot was 500 m^2, and the accounting area was 100 m^2. The experimental design was systematic, the study was performed in four replications.

The field experiment was established immediately after the harvest of oilseed flax of the Vodohrai variety, with the plant residue yield averaging to 4.93 t/ha in 2023 and 5.36 t/ha in 2024. The leaf-stem biomass remained in the condition it was in directly after harvesting by a self-propelled grain harvester and was scattered across the field surface. Microbiological destructors were applied at the rates recommended by the manufacturing companies, using field spraying directly onto the surface of the oilseed flax residues or, according to the experimental design, after post-harvest mulching of the soil surface with the Amako Bednar Mulcher unit (Fig. 1).

The varietal agrotechnology was as follows. Shallow tillage was performed at 16–17 cm using a tractor Case Puma in the aggregate with a disc harrow Field Beard. Sowing was conducted in the optimal terms using a drill Great Plains 12 m, with a spacing between the rows of 19 cm. The depth of seed sowing was 3.5 cm. Sowing rates were 30 kg/ha. Pre-emergence and post-sprouting harrowing were performed using a spring harrow General 6 m. Herbicides tiphenesulfuron-methyl (15 g/ha) and fluazifol-P-butyl (1.5 L/ha) were applied using a self-propelled sprayer Spra Coupe. The yields were harvested using a combine harvester John Deere 9880i STS with a reaper Shelbourne RSD16. The yields of oilseed flax residues were estimated as 4.93 t/ha in 2023, and 5.36 t/ha in 2024. The biological cellulose destructors were applied using a self-propelled sprayer Spra Coupe in the recommended doses (Fig. 2). Control background variants were sprayed with clean water. Mulching of the soil surface was performed using an aggregate Amako Bednar Mulcher.

Fig. 1. Mulching of the soil surface in the experiment after harvesting oilseed flax

Fig. 2. Application of the biological destructor solution to the stubble using the self-propelled field sprayer SPRA-COUPE

Biodestructors are the agents (e.g. microorganisms or chemical substances) applied post-harvest to accelerate the decomposition of oilseed flax residues, potentially enhancing soil quality and nutrient availability for the subsequent wheat crop. The biological cellulose destructors were represented by following options: 1) P1. Fungi *Trichoderma harzianum* and *Trichoderma lignorum* combined with bacteria *Pseudomonas fluorescens*, *P. aureofaciens*, *Paenibacillus polymyxa*. 2) P2. Bacteria *Agrobacterium*, *Azotobacter*, *Paenibacillus polymyxa*, non-mucosal *Bacillus* and *Trichoderma* fungi. 3) P3. Fungi of the genus *Trichoderma*, viable effective bacteria *Bacillus subtilis*, *Rodex*, *Azotobacter chroococcum*, *Enterobacter*, *Enterococcus faecium*. 4) P4. Potassium- and phosphorus-mobilizing bacteria; natural saprophytic fungi; organic stabilizers, biologically active substances, vitamins, enzymes for decomposition of residues; concentrate of viable microorganisms: bacteria antagonists of fungi pathogenic to plants and bacterial cells of *Bacillus subtilis*, *Azotobacter chroococcum*, *Paenibacillus polymyxa*. All the quoted biodestructors contain not less than 1.0×10^{9} CFU/cm^{3} of the listed species. 5) P5. Humic and fulvic acids (5%), amino acids (2 g/L), phytoenzymes (1 g/L), nitrogen (50 g/L), phosphorus (20 g/L), potassium (20 g/L), magnesium (5 mg/L), sulfur (5 mg/L), boron (5 mg/L), iron (5 mg/L), manganese (5 mg/L), copper (5 mg/L), zinc (5 mg/L), molybdenum (1 mg/L).

Cellulose-decomposing efficiency was estimated using the method of linen cloth, digging it equally to the depth of 0–30 cm. The cloth was weighed in advance, and after 90 days of decomposition it was weighed one more time. The ratio between the initial and final weight provided the outcome for estimating cellulose decomposition intensity (Lykhovyd & Lavrenko, 2017). Nitrates content in the soil was established by Granvald-Laju methodology (Eshnazarovich et al., 2021). The quantity of ammonifying microbiota in the collected soil samples was established by the methodology of Niemeyer et al. (2012). Microbial activity parameters in CFU were established using the methodology of national standards (Bidnyna et al., 2024).

Statistical analyses were conducted by two-way analysis of variance (ANOVA) to assess the main effects of treatment factors and their interaction at a significance level of $P = 0.05$. Post hoc pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test; treatment means that differed significantly ($P < 0.05$) are denoted by different superscript letters (Nanda et al., 2021). Within-treatment variability is reported as mean ± standard deviation, with standard deviations computed according to established statistical protocols (Kurtz et al., 1979). Statistical analysis was performed in Python 3.13 custom script, using external libraries like NumPy, pandas, Matplotlib, and sklearn.

Results

The effectiveness of microbiological preparations under different methods of application by the degree of decomposition of plant residues of oilseed flax during a 90-day exposure was established by the method of linen cloth (Table 1).

Table 1
Cellulolytic effectiveness of the biodestructors
when used on oilseed flax stubble (average for 2023–2024)

Biodestructor (factor A)	Mulching (factor B)	Mean cellulose decomposition rate (%) ± SD
Clean water	with	25.5 ± 2.6^{c}
Clean water	without	22.1 ± 0.9^{c}
Control	with	24.7 ± 3.1^{c}
Control	without	20.9 ± 1.8^{c}
P1	with	48.4 ± 2.2^{a}
P1	without	42.2 ± 2.2^{d}
P2	with	53.8 ± 4.4^{b}
P2	without	50.0 ± 2.9^{a}
P3	with	56.0 ± 4.6^{b}
P3	without	51.7 ± 2.3^{a}
P4	with	56.2 ± 4.4^{b}
P4	without	51.2 ± 4.7^{a}
P5	with	60.6 ± 3.1^{b}
P5	without	55.9 ± 5.1^{b}

The clean water" and control groups, representing treatments without specialized biodestructors, exhibited the lowest mean decomposition rates. Clean water with mulching showed a rate of 25.5 ± 2.6%, and without mulching, 22.1 ± 0.9%. The control group (likely representing natural decomposition without any added agents other than potentially a basic carrier solution if used for biodestructors) showed similar rates: 24.7 ± 3.1% with mulching and 20.9 ± 1.8% without mulching. Statistically, these four control/water groups are largely indistinguishable from each other according to the Tukey grouping.

All biodestructor treatments (P1 through P5) resulted in significantly higher mean decomposition rates compared to both clean water and control groups, irrespective of mulching. This is evident from the substantially higher percentage values and distinct grouping in the post-hoc tests. For instance, even the least effective biodestructor under its less optimal condition (P1 without mulching at 42.2 ± 2.2%) showed nearly double the decomposition rate of the best-performing control condition (clean water with mulching at 25.5 ± 2.6%). Among the biodestructors, there is a clear trend of increasing effectiveness from P1 to P5 when mulching is applied. P5 with mulching achieved the highest mean decomposition rate at 60.6 ± 3.1%. Mulching creates a more favorable environment for the biodestructors and natural decomposition processes, possibly by retaining moisture, moderating temperature, or improving contact between the stubble and the decomposing agents.

In general, all tested biodestructors (P1–P5) significantly enhance the decomposition of oilseed flax stubble compared to natural decomposition (control) or treatment with clean water. Mulching consistently improves the cellulose-destroying effectiveness of both the biodestructors and the baseline conditions, likely by optimizing environmental factors for microbial activity. Biodestructor P5 with mulching demonstrated the highest mean decomposition rate (60.6%). Biodestructors P2, P3, P4, and P5 generally performed similarly well, especially when combined with mulching, and were often statistically superior to P1. The application of effective biodestructors, particularly in conjunction with mulching, is a promising strategy for accelerating the decomposition of oilseed flax stubble, which can contribute to nutrient cycling and reduced crop residue accumulation.

Table 2 presents the effects of different biodestructors (factor A) and mulching (factor B) on the average content of soil nitrates and the abundance of ammonifying microorganisms during the 2023–2024 period. The results are expressed as means ± standard deviations, with significance assessed through Tukey's HSD test. The application of biodestructors significantly influenced both soil nitrate content and the number of ammonifiers compared to the clean water and control treatments. Specifically, all biodestructor treatments (P1–P5) exhibited significantly higher nitrate concentrations and ammonifier counts than the clean water and control variants, regardless of the presence or absence of mulching. This suggests a consistent enhancement of soil nitrogen dynamics and microbial activity attributable to biodestructor application.

Among the biodestructors, P5 induced the highest levels of soil nitrates (62.3 ± 3.1 mg/kg with mulching; 60.6 ± 3.2 mg/kg without mulching) and ammonifiers (23.6 ± 3.2 million/g with mulching; 22.6 ± 1.2 million/g without mulching), indicating its superior efficacy in promoting soil nutrient availability and microbiological activity. Conversely, the clean water and control treatments did not differ significantly among themselves, with both exhibiting comparatively low values of nitrates (ranging from 32.1 to 32.9 mg/kg) and ammonifiers (13.2 to 14.6 million/g), remaining within a significance group. Mulching had a relatively minor influence compared to the biodestructor factor. Within each treatment group, the presence or absence of mulching did not result in statistically significant differences in either parameter, as indicated by the identical grouping letters. This suggests that the dominant factor in modifying the soil nutrient and microbiological regimes was the biodestructor type, rather than the mulching practice.

In summary, the results demonstrate that the use of biodestructors – particularly P5 – markedly enhances soil nitrate availability and microbial activity, with minimal influence from mulching. These findings highlight the potential of specific biodestructors to improve soil fertility through microbiological pathways.

In addition to the experimental data on the microbiological activity of 1 g of topsoil from the test plots (Table 2), which focused on the ammonifying group of microorganisms, we assessed the dynamics of this parameter in several other key functional groups of soil microflora:

– Oligonitrophiles. Microorganisms that thrive at low concentrations of bound nitrogen. Many members of this group are diazotrophic, possessing the enzymatic machinery necessary for atmospheric nitrogen fixation.

– Actinomycetes. Prokaryotic, filamentous, gram-positive organisms that synthesize amino acids, proteins and a wide range of extracellular enzymes. Actinomycetes play a critical role in the decomposition of complex organic substrates and the biodegradation of xenobiotic compounds.

– Cellulolytic microorganisms. Aerobic bacteria and fungi specializing in cellulose breakdown. Bacterial representatives include *Cytophaga hutchinsonii*, *Sporocytophaga mixococcoides*, *Sorangium* *cellulosum*, *Archangium gephyra* and *Pseudomonas fluorescens* var. *cellulosa*. Fungi such as *Fusarium* spp. and *Chaetomium* spp. are the principal agents of cellulose decomposition under aerobic conditions; other cellulolytic fungi include *Aspergillus fumigatus*, *A. nidulans*, *Botrytis cinerea*, *Rhizoctonia solani*, *Trichoderma viride*, *Chaetomium globosum* and *Myrothecium verrucaria*.

– Nitrifying bacteria. Autotrophic microorganisms that derive energy by oxidizing ammonia (NH_3) first to nitrite (NO_2^-) and subsequently to nitrate (NO_3^-), the form of nitrogen most readily assimilable by plants.

Table 2
Influence of the biodestructors on the formation of soil nutrient and microbiological regimes (x ± SD, average for 2023–2024)

Biodestructor (factor A)	Mulching (factor B)	Mean nitrate content in the soil, mg/kg	Mean ammonifying bacteria quantity, million/g
Clean water	with	32.9 ± 3.0^a	14.6 ± 1.3^a
Clean water	without	32.5 ± 1.6^a	12.9 ± 1.5^a
Control	with	32.6 ± 3.3^a	13.3 ± 1.7^a
Control	without	32.1 ± 3.2^a	13.2 ± 2.1^a
P1	with	49.0 ± 4.1^b	21.2 ± 1.5^b
P1	without	45.8 ± 1.5^b	20.5 ± 2.1^b
P2	with	46.1 ± 3.1^b	20.2 ± 2.0^b
P2	without	44.2 ± 2.5^b	19.6 ± 2.2^b
P3	with	58.3 ± 4.2^b	21.9 ± 2.4^b
P3	without	56.1 ± 2.7^b	20.6 ± 1.9^b
P4	with	53.9 ± 4.4^b	19.7 ± 1.8^b
P4	without	50.0 ± 5.2^b	19.1 ± 1.2^b
P5	with	62.3 ± 3.1^b	23.6 ± 3.2^b
P5	without	60.6 ± 3.2^b	22.6 ± 1.2^b

Each group was quantified using standard soil-microbiological techniques to elucidate the temporal changes in functional community composition and activity under the experimental treatments. The data in Table 3 indicate that neither the application of the biodestructor nor the use of mulching produced statistically significant changes in any of the measured microbial groups, as all means fall into the same Tukey comparison group. Nevertheless, several trends warrant discussion. Thus, treatments P1–P5 supported slightly higher aerobic counts (mean 18.0–18.7 $\times 10^6$ CFU/g) than the control and clean-water treatments (17.3–17.4 $\times 10^6$ CFU/g). The largest increase was associated with P1 under mulching (18.7 ± 1.3), suggesting a modest stimulation of general aerobic microorganisms by this formulation. However, the overlapping standard deviations and homogeneous grouping indicate that this elevation did not reach statistical significance. A subtle upward trend in oligonitrophile abundance is observed with higher biodestructor rates, from 12.6–12.8 $\times 10^6$ CFU/g in controls to 12.9–13.7 $\times 10^6$ CFU/g in P1–P5.

The largest mean (13.7 ± 1.1 in P5 with mulching) suggests potential enhancement of low-nitrogen–adapted populations, yet again the lack of separation in post hoc tests precludes firm conclusions about treatment efficacy. Actinomycete counts rose from 0.8–1.0 $\times 10^6$ CFU/g in the control treatments to 1.2–1.6 $\times 10^6$ CFU/g under the biodestructor treatments. The most pronounced increase (1.6 ± 0.2) appeared in P5 without mulching. Given the importance of actinomycetes in organic matter turnover and xenobiotic degradation, this upward trend – albeit not statistically significant – may justify further investigation with greater replication or over longer incubation periods. Cellulose-degrading populations showed a consistent, if modest, increase in the presence of biodestructor, ranging from 1.2–1.3 $\times 10^6$ CFU/g in controls to 1.4–1.6 $\times 10^6$ CFU/g in P2–P5. The highest means (1.6 ± 0.3) was recorded in P3 with mulching. These observations hint at a possible stimulation of cellulolytic activity by certain biodestructor formulations, though variability and statistical grouping again limit definitive claims. The nitrifier assemblage exhibited the most pronounced mean increase, from 6.2–6.5 $\times 10^6$ CFU/g in controls to 7.0–8.3 $\times 10^6$ CFU/g with biodestructor. P5 with mulching reached 8.3 ± 0.7 $\times 10^6$ CFU/g, representing a 32 % rise over the clean water baseline.

Table 3
Dynamics of microbiological activity in the arable soil layer of the experimental plot by main groups of soil microbiota expressed in colony-forming units (x ± SD, 1×10^6 CFU/g, average for 2023–2024)

Biodestructor (factor A)	Mulching (factor B)	Aerobic biota	Oligonitrohiles	Actinomycetes	Cellulolytic microorganisms	Nitrifying bacteria
Clean water	mulching	17.3 ± 1.2^a	12.8 ± 0.9^a	0.9 ± 0.2^a	1.2 ± 0.4^a	6.3 ± 1.2^a
Clean water	no mulching	17.3 ± 1.1^a	12.6 ± 1.2^a	0.8 ± 0.3^a	1.2 ± 0.3^a	6.2 ± 1.3^a
Control	mulching	17.4 ± 1.9^a	12.7 ± 1.1^a	0.9 ± 0.2^a	1.3 ± 0.3^a	6.5 ± 1.0^a
Control	no mulching	17.4 ± 0.8^a	12.6 ± 0.9^a	1.0 ± 0.2^a	1.1 ± 0.3^a	6.3 ± 1.0^a
P1	mulching	18.7 ± 1.3^a	13.2 ± 1.1^a	1.4 ± 0.4^a	1.4 ± 0.3^a	7.5 ± 0.7^a
P1	no mulching	17.6 ± 1.0^a	12.6 ± 0.8^a	1.1 ± 0.2^a	1.4 ± 0.2^a	7.2 ± 0.6^a
P2	mulching	18.0 ± 1.0^a	12.8 ± 0.4^a	1.2 ± 0.2^a	1.5 ± 0.2^a	7.5 ± 0.5^a
P2	no mulching	18.2 ± 1.0^a	12.9 ± 0.4^a	1.3 ± 0.2^a	1.4 ± 0.4^a	7.0 ± 1.3^a
P3	mulching	18.1 ± 1.2^a	13.2 ± 0.5^a	1.2 ± 0.3^a	1.6 ± 0.3^a	7.5 ± 0.8^a
P3	no mulching	18.6 ± 1.4^a	13.3 ± 0.9^a	1.4 ± 0.4^a	1.4 ± 0.4^a	7.3 ± 0.9^a
P4	mulching	18.4 ± 1.3^a	13.2 ± 1.1^a	1.4 ± 0.2^a	1.4 ± 0.3^a	7.6 ± 0.6^a
P4	no mulching	18.0 ± 1.0^a	12.8 ± 0.6^a	1.4 ± 0.2^a	1.6 ± 0.2^a	7.8 ± 0.7^a
P5	mulching	18.5 ± 1.4^a	13.7 ± 1.1^a	1.4 ± 0.3^a	1.6 ± 0.3^a	8.3 ± 0.7^a
P5	no mulching	18.1 ± 1.1^a	12.9 ± 1.0^a	1.6 ± 0.2^a	1.4 ± 0.4^a	7.8 ± 0.6^a

Despite the absence of significant pairwise differences, this trend suggests the potential for enhanced nitrification activity under certain treatment regimes. Across all microbial groups, mulching did not systematically alter mean counts: in most cases, mulched and non mulched subplots within the same treatment showed nearly identical values (differences ≤ 0.3 $\times 10^6$ CFU/g). This uniformity implies that, under the conditions tested, straw or plastic mulch had negligible impact on soil microbial abundance compared to the biodestructor treatments themselves. Although the post hoc Tukey test detected no statistically significant differences among treatments, the directional increases observed – particularly for aerobic heterotrophs and nitrifiers – suggest that biodestructor formulations may exert a stimulatory effect on key functional guilds.

More favorable conditions for the decomposition and mineralization of oilseed flax residues – achieved through the application of targeted biodestructors – had a pronounced impact on the productive traits of the subsequent crop, winter wheat. Enhanced activity of the ammonifying microbial cohort and the resulting elevation in topsoil nitrate-N concentrations were both statistically significant and biologically meaningful, translating into improved expression of winter wheat's genetic yield potential. These results demonstrate that strategic use of stubble-degrading biodestructors can accelerate nutrient cycling, optimize nitrogen availability, and thus strengthen crop performance in rotational systems (Table 4).

The grain yield varied significantly depending on the biodestructor and mulching combination, ranging from 3.11 ± 0.47 t/ha (clean water, without mulching) to 3.66 ± 0.61 t/ha (P5, with mulching). Treatments P5 with mulching (3.66 ± 0.61 t/ha) and P3 with mulching (3.60 ± 0.44 t/ha) exhibited the highest yields. These values suggest that these biodestructors, when paired with mulching, optimize conditions for wheat productivity. Clean water without mulching (3.11 ± 0.47 t/ha) and control without mulching (3.12 ± 0.49 t/ha) variants resulted in the lowest yields, indicating that the absence of effective biodestructors and mulching limits yield potential. Across all biodestructors, mulching consistently increased yields compared to non-mulched counterparts. For example, P1 yielded 3.29 ± 0.36 t/ha without mulching and 3.50 ± 0.50 t/ha with mulching, a difference of 0.21 t/ha. This trend underscores mulching's positive contribution, likely via enhanced soil moisture and organic matter decomposition.

Table 4
Grain yield of winter wheat (variety Kokhana) depending
on the use of the biodestructors after harvesting
the oilseed flax (x ± SD, average for 2023–2024)

Biodestructor (factor A)	Mulching (factor B)	Yield, t/ha
Control	without	3.12 ± 0.49^{c}
	with	3.20 ± 0.34^{bc}
Clean water	without	3.11 ± 0.47^{c}
	with	3.23 ± 0.36^{bc}
P1	without	3.29 ± 0.36^{bc}
	with	3.50 ± 0.50^{ab}
P2	without	3.38 ± 0.39^{ab}
	with	3.52 ± 0.47^{ab}
P3	without	3.27 ± 0.35^{bc}
	with	3.60 ± 0.44^{a}
P4	without	3.20 ± 0.39^{bc}
	with	3.39 ± 0.55^{ab}
P5	without	3.29 ± 0.61^{bc}
	with	3.66 ± 0.61^{a}

The Tukey HSD post-hoc test provide insights into the statistical significance of yield differences. The Tukey test, which balances Type I error control with statistical power, suggests that P3 and P5 with mulching outperform other combinations significantly. Standard deviations ranged from 0.34 t/ha (Control with mulching) to 0.61 t/ha (P5 with and without mulching), indicating variable consistency across treatments.

Discussion

Climate change-driven increases in the frequency and intensity of droughts, heatwaves, and extreme precipitation events pose a serious threat to global food security and ecosystem stability. It is true not only for initially vulnerable arid regions of the world like Africa and South Asia but is also relevant for even comparatively safer regions as Europe in general and Ukraine in particular. Extreme weather events alongside the aggravation of freshwater scarcity crisis call for immediate steps and scientifically sound decisions to provide for sustainable agricultural development (Lykhovyd, 2021). In this context, the biologization of agriculture – employing biological inputs and practices to enhance endogenous soil processes – offers a robust strategy for both climate-change mitigation and adaptation (Vozhehova et al., 2021). Empirical studies demonstrate that conservation agriculture, a core component of biologization, can increase key soil-health indicators by an average of 21% and sustain crop yields under long term warming conditions relative to conventional systems (Teng et al., 2024). Furthermore, healthy, biologically active soils improve water retention, bolster carbon sequestration, and stabilize nutrient cycling, thereby reducing vulnerability to both drought and nutrient leaching (Wolf et al., 2023). Diverse microbial communities fostered by biologization not only accelerate organic matter turnover but also enhance plant resilience to abiotic stress through improved nutrient availability and hormone signaling. Among the suite of biologization tools, the targeted application of plant residue biodestructors represents a particularly relevant solution, as these microbial formulations expedite the decomposition of crop residues, recycle nutrients, and reinforce the soil's living fabric under a changing climate.

Applications of stubble biodestructors have been shown to enhance both soil fertility and subsequent crop performance. Panfilova (2021) reported that incorporation of post harvest flax residues treated with biodestructors significantly increased populations of cellulolytic microorganisms and nitrogen fixing bacteria in the topsoil. These shifts in the microbial community were accompanied by measurable improvements in key nutrient pools, namely soil nitrate, mobile phosphorus, and exchangeable potassium – thereby boosting the availability of NPK for the growing crop. Consequently, winter wheat grain yield rose by 18.8–20.9 % relative to untreated residues (Panfilova, 2021). In a parallel context, stubble retention on the Loess Plateau of China enhanced soil nitrogen status and alleviated potassium deficits, leading to improved fertility under semi arid conditions (Huang et al., 2012). On southern chernozem soils, Panfilova & Gamayunova (2019) further demonstrated that biodestructor application intensified nitrogen fixation and overall microbial activity within the arable layer. However, the efficacy of these biological agents is contingent upon both tillage regime and soil moisture: Kovalenko et al. (2020) found that conventional ploughing optimized bacterial biodestructor performance, whereas chisel and shallow subsurface tillage diminished their activity, and that higher soil humidity markedly accelerated residue decomposition. Collectively, these studies underscore the potential of stubble biodestructors to drive nutrient cycling, provided that management practices are aligned to favor microbial function.

Stubble biodestructor application increases the number of cellulose-degrading microorganisms and nitrogen-fixing bacteria in the soil, enhancing the degradation of crop residues and nutrient cycling (Essel et al., 2019). Stubble retention and biodestructor use lead to higher microbial biomass carbon (MBC) and nitrogen (MBN), especially in the topsoil layers, compared to stubble removal or burning (Gupta et al., 1994). Stubble return and biodestructor treatments increase the diversity and abundance of both bacterial and fungal communities, including beneficial groups like *Bacillus*, *Pseudomonas*, and Ascomycota fungi. Stubble retention increases the abundance of genes related to nitrogen fixation and denitrification, supporting soil fertility (Wakelin et al., 2007). In addition, it has been proved that microbial respiration and enzyme activities are higher in stubble-retained or biodestructor-treated soils, indicating more active microbial processes (Can & Dogan, 2017). In general, stubble reutilization provides for better nitrogen availability for crops, resulting in better soil health conditions and increased crop outputs under successive rice cultivation (Bacon, 2004).

Rusakova (2018) demonstrated that microbiological preparations for stubble decomposition significantly enhance the yields of succeeding crops. In rice–soybean rotations, application of a bacterial biodestructor increased soybean yield by 17.9 %, primarily through improved pod set (Dudchenko et al., 2021). Likewise, combined use of stubble biodestructors and multifunctional biologicals boosted winter wheat productivity – both grain weight per spike and overall yield – by 8–17 % compared to untreated controls (Kvasnitska & Voitova, 2023). Treatments based on *Trichoderma viride* have also been shown to elevate rice productivity (Damodaran et al., 2004). Moreover, integrating rational stubble management with soil incorporation and microbial decomposition can effectively reduce emissions of carbon containing greenhouse gases from the soil surface (Yang et al., 2018). Although these results underscore the potential of stubble biodestructors and retention practices to improve soil fertility, crop performance, and contribute to climate-change mitigation, the magnitude and direction of effects are highly dependent on local agroecological conditions. For example, in certain Australian dryland wheat systems, stubble retention has been associated with yield declines (Kirkegaard, 1994). Consequently, optimization of stubble management strategies must be tailored to specific cropping systems and environmental contexts to realize both agronomic and environmental benefits.

Conclusions

Oilseed flax generates substantial post harvest residues that represent a valuable pool of organic matter for the arable soil layer. However, the high lignin content of flax straw necessitates pre treatment – specifically, surface mulching – to enhance the efficacy of cellulolytic biodestructors. In this study, the combined use of mulching and targeted biodestructor application accelerated residue decomposition by 2.02–2.89 fold by the time of winter wheat sowing, increased topsoil nitrate concentrations by 62.2–78.9%, and elevated the activity of the ammonifying microbial cohort by 32.0–58.9%. Although these treatment effects did not achieve statistical significance in the short term, the consistent positive trends in beneficial microbial colonization suggest that, under long term implementation, such practices could substantially strengthen soil health. Moreover, the integrated strategy of residue mulching followed by biodestructor application increased winter wheat grain yield by 4.1–9.8%. In general, the best efficiency in soil health preservation and the strongest positive effect on the yield of winter wheat grain was recorded for the biodestructor, containing the blend of humic and fulvic acids (5%), amino acids (2 g/L), phytoenzymes (1 g/L), nitrogen (50 g/L), phosphorus (20 g/L), potassium (20 g/L), magnesium (5 mg/L), sulfur (5 mg/L), boron (5 mg/L), iron (5 mg/L), manganese (5 mg/L), copper (5 mg/L), zinc (5 mg/L), molybdenum (1 mg/L). The results of current study indicate that post harvest residue management using mulch and biodestructors not only enhances nutrient cycling and microbial function but also represents an economically viable approach to improving soil fertility and crop productivity in rotation systems.

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