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Organic and mineral fertilizers improve nitrogen availability, yield formation, and carbon efficiency of spring barley in a typical chernozem

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ABSTRACT

Spring barley productivity and environmental performance depend on the synchronisation of nitrogen supply with crop demand, especially under variable hydrothermal conditions. A two-year field experiment was conducted in 2024–2025 on a typical chernozem in the right-bank forest-steppe of Ukraine to evaluate the fertilisation systems based on compost and vermicompost applied alone or in combination with mineral nitrogen. All fertilised treatments had a planned total nitrogen input equivalent to 50 kg N/ha; however, the organic amendments also supplied additional phosphorus and potassium, so the results are interpreted as fertilisation-system effects, rather than isolated nitrogen-source effects. The experiment included an unfertilised control, mineral nitrogen, full-rate compost, compost combined with mineral nitrogen, full-rate vermicompost, and vermicompost combined with mineral nitrogen. All fertilised treatments increased grain yield compared with the control, which averaged 5.72 t/ha. The highest two-year mean grain yield was obtained with vermicompost N_{25} + mineral N_{25}, reaching 7.01 t/ha, followed by full-rate compost with 6.80 t/ha. Compost mainly improved yield through increased spike density, whereas the vermicompost–mineral nitrogen combination promoted biomass accumulation and grain filling. Assessment of CO_2-equivalent emissions indicated that fertilised treatments reduced yield-scaled emissions compared with the control. The vermicompost–mineral nitrogen combination showed the lowest emission intensity, at 692.6 kg CO_2-eq/t of grain. These results suggest that partial substitution of mineral nitrogen with vermicompost may improve spring barley productivity and estimated carbon efficiency; however, longer-term studies with direct greenhouse gas and soil carbon measurements are needed to confirm the environmental effects.

Keywords: nitrogen, compost, emission, grain yield, yield structure.

INTRODUCTION

Spring barley (*Hordeum vulgare* L.) is an important cereal crop for food, feed, and malting purposes; however, its productivity is highly dependent on nutrient supply, soil moisture availability, and the formation of yield components during a relatively short growing season. Mineral nitrogen fertilisation can rapidly improve early crop growth, but its exclusive use may increase production costs and environmental pressure while contributing little to long-term soil organic matter restoration. Therefore, organic amendments, such as compost and vermicompost, are increasingly considered not only as nutrient sources, but also as soil-improving inputs with biostimulant-like effects mediated through organic carbon, humic substances, microbial activity, and gradual nutrient release (Oyege and Balaji Bhaskar, 2023; Salis et al., 2024). On the other hand, agriculture and food systems contribute substantially to global greenhouse gas emissions, while fertiliser production and use represent one of the most energy- and emission-intensive components of crop management. The production of synthetic nitrogen fertilisers is associated with high energy demand and CO_2 emissions, whereas field application may additionally contribute to nitrogen losses and indirect environmental impacts. Therefore, the assessment of fertilisation strategies should not be limited to yield response alone, but should also include carbon-related indicators (Fan et al., 2023).

In this context, organic amendments such as compost and vermicompost are increasingly considered as components of integrated nutrient management aimed at improving soil fertility and reducing dependence on mineral fertilisers. These amendments can supply nutrients in organically bound forms, contribute organic carbon to the soil, stimulate microbial activity, and improve soil physical properties. At the same time, organic amendments are not emission-free inputs, because their production, processing, storage, transportation, and field application are also associated with certain CO_2-equivalent emissions. Consequently, their agronomic efficiency should be evaluated together with their environmental efficiency, particularly when organic fertilisers are used to partially substitute mineral nitrogen (Albano et al., 2023).

Compost application can improve soil fertility by adding organic matter and supplying nutrients in organically bound forms, but its short-term agronomic efficiency depends strongly on amendment quality, mineralisation rate, soil temperature, and moisture conditions. Compost has been shown to improve barley growth and yield while enhancing soil chemical fertility, although mineral fertilisers often provide a faster but less persistent effect on soil fertility indicators (Salis et al., 2024). Similar cereal studies also indicate that compost and biostimulant-based strategies may partially replace mineral nitrogen without reducing productivity, especially when organic inputs are combined with mineral fertilisers to better synchronise nutrient release with crop demand (Abbas et al., 2022).

Vermicompost differs from compost by its finer structure, higher biological activity, and enrichment with humic compounds, enzymes, and plant-growth-promoting metabolites. Recent studies on barley have demonstrated that vermicompost can improve soil properties, increase biomass accumulation, and enhance grain yield, particularly under degraded or stress-prone soil conditions (Shen et al., 2022; Shilev et al., 2024). At the same time, the response to vermicompost is not always linear and depends on application rate, nutrient balance, and interaction with mineral fertilisation. For example, integrated application of vermicompost with mineral nitrogen has been reported to improve soil fertility, malt barley yield, and economic returns compared with unfertilised control and, in some cases, compared with mineral nitrogen alone (Terefe et al., 2024).

The effectiveness of compost and vermicompost may become particularly important under unstable hydrothermal conditions, when nutrient mineralisation and uptake are limited by moisture deficit or heat stress. Organic amendments can improve soil water retention, bulk density, and nutrient availability, which may support barley growth under reduced irrigation or drought stress (Khalifa et al., 2022). However, field evidence remains limited regarding how compost and vermicompost, applied alone or in combination with mineral nitrogen at an equivalent total nitrogen input, affect spring barley productivity under the conditions of the forest-steppe zone of Ukraine, where seasonal precipitation distribution and elevated temperatures can substantially modify nutrient release and crop response.

However, the environmental advantage of organic or organic–mineral fertilisation remains debated. Higher grain yield may reduce emission intensity per tonne of grain, whereas high application rates or carbon-intensive production and transportation of amendments may increase total emissions per hectare (Walling and Vaneeckhaute, 2020). Therefore, the most promising fertilisation strategy should combine stable productivity, improved soil nitrogen availability, and lower yield-scaled CO_2-equivalent emissions.

Therefore, the aim of this study was to evaluate the effect of compost and vermicompost, applied separately and in combination with mineral nitrogen, on biomass accumulation, soil mineral nitrogen dynamics, yield structure, grain yield and CO_2-equivalent emission efficiency of spring barley. It was hypothesised that organic–mineral combinations would provide a more balanced productivity and environmental response than single nutrient sources, while compost- and vermicompost-based treatments would differ in their pathways of yield formation and carbon efficiency through their effects on biomass accumulation, spike density, grain number, grain filling and yield-scaled emissions.

MATERIALS AND METHODS

Experimental plot location and soil conditions

Field trial was conducted during 2024 and 2025 vegetative season in a stationary field experiment by the Department of Plant Science at the Separate Division of the National University of Life and Environmental Sciences of Ukraine, "Agronomic Research Station" (village Pshenychne, Kyiv region), located in the northeastern part of the right-bank forest-steppe of Ukraine (49°46' N, 30°44' E).

The soil of experimental plot is Chernozem soil (CH), classified according to the FAO-UNESCO soil classification. The initial physicochemical characteristics of the experimental soil indicated favourable conditions for spring barley cultivation. The humus content in the 0–20 cm soil layer was 4.45% (Tyurin method). The soil had a porosity of 53.9%, particle density of 2.65 g/cm^3 and bulk density of 1.22 g/cm^3. The cation exchange capacity was 23.6 cmol/kg, indicating a relatively high nutrient retention capacity. The initial content of mineral nitrogen (Nmin) was 17.7 mg/100 g of soil (at autumn before amendment application), while available phosphorus and potassium amounted to 6.7 and 11.0 mg/100 g of soil, respectively.

Climate conditions

The weather conditions during the spring barley growing period in 2024 and 2025 differed from the long-term average in both temperature regime and precipitation distribution (Figure 1). In both years, mean monthly air temperatures from March to July were higher than the long-term values, particularly in June and July, indicating an increased thermal background during crop development. In terms of precipitation, 2024 was characterised by better moisture supply during the early growth stages, especially in March and May, whereas 2025 showed a pronounced precipitation deficit in March–April. In May 2025, precipitation exceeded both the 2024 level and the long-term average, which may have partly compensated for the early spring moisture deficit. However, in June–July, precipitation in both years was lower than the long-term average, especially in June, while temperatures remained elevated. These conditions could have intensified water and heat stress during active biomass accumulation, yield component formation, and grain filling.

Since compost and vermicompost were applied in autumn, the transformation of organically bound nutrients started before spring barley sowing and continued throughout the growing season. Soil moisture was one of the key factors controlling the mineralisation of organic nitrogen, the mobilisation of phosphorus and potassium, and the activity of soil microbiota. Better moisture availability during the early growth period in 2024 may have promoted a more gradual release of nutrients from compost and vermicompost and their uptake by plants at the initial stages of crop development.

Experimental design and crop management

The field experiment included five fertilisation treatments (and a control) differing in the source and combination of nitrogen inputs (Table 1). The

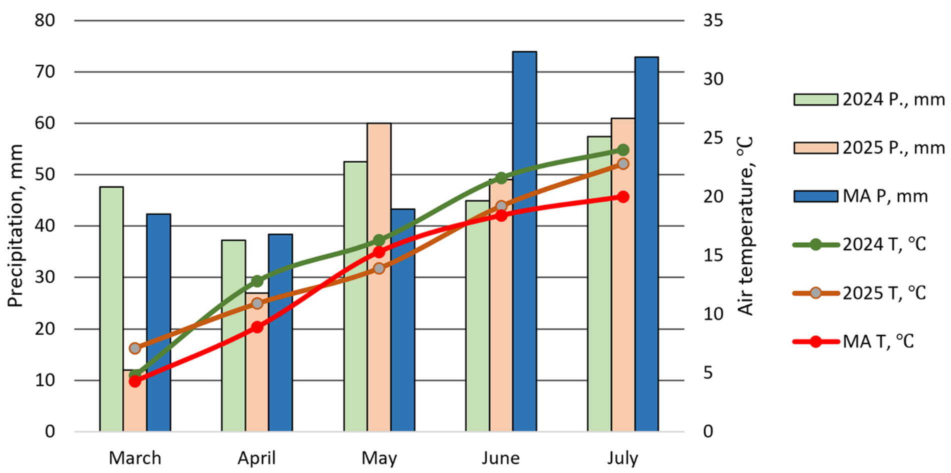

Figure 1. Weather conditions in 2024 and 2025 compared to multiannual parameters

Table 1. Characteristics of treatments and the amendment compound

Treatment	Mineral compound	Organic compound		
	N rate, kg/ha	N rate, kg/ha	P_2O_5, kg/ha*	K_2O, kg/ha*
T1. N_0 (control)	–	–	–	–
T2. N_{50} (mineral)	50	–	–	–
T3.N_{50} (compost)**	–	50	62.6	50.0
T4. N_{25} (compost) + N_{25} (M)	25	25	31.3	25.0
T5. N_{50} (vermicompost)	–	50	35.7	37.7
T6. N_{25} (VC) + N_{25} (M)	25	25	17.9	18.8

Note: * The contents of P_2O_5 and K_2O differed by no more than 5% between the study years. ** Full rate of compost – 5.5 t/ha, full rate of vermicompost – 3.6 t/ha.

treatments comprised an unfertilised control, a mineral N control at a rate of 50 kg N/ha, full-rate compost or vermicompost application equivalent to 50 kg N/ha, and combined organic–mineral treatments in which organic and mineral N were applied at a 1:1 ratio. Thus, the total planned N input in all fertilised treatments was 50 kg N/ha. The experiment was designed primarily to compare practical fertilisation systems at an equal planned nitrogen input, not to isolate the independent effects of phosphorus and potassium. Because compost and vermicompost had their own nutrient value, the treatments differed in the additional P_2O_5 and K_2O supplied with the organic amendments. Therefore, the results are interpreted as fertilisation-system performance.

The same types of bio-amendments, with similar origin and chemical composition, were used in both experimental years. Compost was produced through aerobic fermentation of cattle manure from the animals fed a typical regional diet, with cereal straw used as bedding material. Vermicompost was obtained from the activity of *Eisenia fetida* on a substrate consisting mainly of agricultural waste, including vegetable, fruit, and similar plant residues. Basic characteristics of soil amendments are presented in Table 2.

Table 2. Basic characteristic of soil amendment

Characteristics	Compost	Vermicompost
Basic rate, t/ha (full rate)	5.5	3.6
DM content	88.3±1.4	55±2.4
Total N content, % (in presented moisture)	0.91±0.03	1.39±0.07
P_2O_5	1.14±0.04	0.99±0.03
K_2O	0.91±0.03	1.05±0.04
pH KCl	7.8	7.4
Organic matter content	70.3±2.4	58±3.6

The preceding crop was winter wheat. The field experiment was arranged as a randomised complete block design with six fertilisation treatments and three replications. A uniform basal application of 46 kg/ha P_2O_5 and 60 kg/ha K_2O as complex fertiliser was made before ploughing in all treatments to maintain a common background supply of phosphorus and potassium and to avoid P or K deficiency as a limiting factor for spring barley growth. This design was selected because the main hypothesis concerned the substitution of mineral nitrogen by organic nitrogen sources under practical fertilisation systems. The additional P and K supplied with compost or vermicompost were not compensated for by reducing the basal P and K rate; therefore, the P and K differences are treated as an inherent property and limitation of the tested fertilisation systems. After harvesting the preceding crop, the soil was ploughed to a depth of 22–24 cm. Disk harrowing was carried out to a depth of 6–8 cm in spring (March 15th 2024 and 17th March 2025). Compost and vermicompost were applied in autumn at calculated rates based on their nitrogen content, whereas ammonium nitrate containing 34.4% N was applied in spring before pre-sowing cultivation. Pre-sowing cultivation was conducted to a depth of 8–10 cm on 1 April 2024 and 24 March 2025. Sowing was performed using a 12-row seed drill with 12.5 cm row spacing and a working width of 1.5 m. The two-row spring barley cultivar 'Fontane' was sown at a rate of 350 viable seeds/m^2. The accounting plot area was 15 m^2, while the total plot area was 30 m^2.

No chemical plant protection products were applied during the growing season. Disease and pest incidence were monitored throughout crop development to assess their possible influence on productivity. During the two years of the experiment, disease symptoms were observed only on individual plants, while pest abundance remained at a minimal level.

Soil and plant sampling

Soil samples were collected from two soil layers, 0–20 and 20–40 cm. In each plot, at least ten individual soil samples were taken using a zigzag sampling pattern within the plot area, excluding border zones. The individual samples from each layer were combined to form one composite sample per plot and soil depth.

The soil samples for the determination of the main nutrient status were collected before fertiliser application in autumn. Additional soil sampling was carried out before sowing and after harvesting to assess changes in the content of mineral nitrogen during the growing season. Soil sampling was performed according to ISO 18400-102:2017 (2017), and sample preparation for chemical analysis was carried out according to ISO 11464:2006 (2006). Because the pre-sowing soil mineral nitrogen pool may also reflect initial field heterogeneity and nutrient transformation before crop establishment, especially in the first experimental year, these data were interpreted as an indicator of soil N availability before sowing rather than as direct treatment effects alone.

Mineral nitrogen (Nmin) was determined in field-moist soil samples after extraction with 1 mol/L KCl according to ISO 14256-2:2005. The result was expressed as the sum of ammonium and nitrate nitrogen (NH^{4+}–N + NO^{3-}–N), without separate presentation of these fractions.

Fresh aboveground biomass of spring barley was determined at 30, 60, and 90 days after emergence (DAE). Biomass was sampled from an area of 1 m^2, consisting of eight 1-m-long rows, excluding border rows. The fresh biomass was weighed immediately after cutting.

At 30 and 60 DAE, a 100 g subsample was taken from each treatment and dried in the laboratory at 62 °C for 48 h, or longer if required, until a stable weight was reached. At 90 DAE, the entire sample was collected and dried under ambient conditions. Dry matter content was determined using the thermogravimetric method at 105 °C separately for straw and grain. The measured moisture content was used to adjust the 90 DAE biomass and grain yield values to a standard moisture content of 14%.

The 90 DAE sample was also used to determine the number of stems. A subsample of 30 stems per sample was used to determine grain weight per spike, number of grains per spike, and thousand-grain weight. At full maturity, grain yield was accounted for from the central 15 m_2 accounting area of each plot after excluding border rows. Plants were harvested, threshed using a stationary threshing unit, and the grain was cleaned and weighed. Plot grain yield was converted to t/ha and recalculated to a standard grain moisture content of 14% and to a clean-grain basis.

Carbon emission assessment

The environmental assessment of spring barley production was based on the calculation of carbon dioxide equivalent emissions (CO_2-eq) associated with the main technological operations and fertiliser inputs. The assessment included the baseline emissions of the typical spring barley cultivation technology and additional emissions related to the production and application of mineral and organic fertilisers. The results were expressed as total CO_2-equivalent emissions per hectare, emission intensity per tonne of grain yield, and emissions per additional tonne of grain obtained compared with the unfertilised control.

Emission factors for fertiliser production were adopted from the commonly used life-cycle inventory approach for fertiliser-related greenhouse gas emissions (Kool et al., 2012). The following emission factors were used: 5.62 kg CO_2-eq/kg N for nitrogen fertiliser, 1.47 kg CO2-eq/kg P_2O_5 and 1.36 kg CO_2-eq/kg K_2O. For organic amendments, the assumed emission factors were 125 kg CO_2-eq/t for compost and 75 kg CO_2-eq/t for vermicompost. These values were used to estimate the carbon cost of fertiliser inputs in each treatment according to the actual rates of mineral nitrogen, compost, vermicompost, $P_2O_{5,}$ and K_2O applied.

The total CO_2-equivalent emissions per hectare were calculated as the sum of baseline emissions from the typical cultivation technology and emissions associated with fertiliser inputs. Yield-scaled emissions were calculated by dividing total CO_2-equivalent emissions by grain yield. Additional CO_2-equivalent emissions were calculated as the difference between the total emissions of each fertilised treatment and the unfertilised control. Emissions per additional tonne of grain were calculated by dividing the additional

CO_2-equivalent emissions by the additional grain yield relative to the control.

Assessment of CO_2-equivalent emissions was a comparative, literature-based screening calculation. Direct CO_2 or N_2O fluxes, changes in soil organic carbon, site-specific transport distances, storage losses, and operation-specific fuel consumption were not measured. Therefore, the carbon-related indicators are interpreted as estimated short-term emission intensity and carbon-efficiency indicators for the compared treatments, not as measured net greenhouse gas balances.

Statistical analysis

The effects of fertilisation treatment and year conditions were evaluated using analysis of variance. Year was represented in the ANOVA as a categorical fixed factor with two levels (2024 and 2025), i.e., as a factor (Year) in R, rather than as a continuous numerical covariate. Due to substantial differences between the 2024 and 2025 growing seasons and the relatively weak interaction between year and treatment for biomass formation, biomass data were analysed separately by year using one-way ANOVA. For the remaining traits, two-way ANOVA was applied with year and fertilisation treatment as fixed factors.

The differences between treatment means were assessed using Tukey's honestly significant difference test at $P < 0.05$. Correlation analysis (Pearson method) was used to evaluate relationships among soil mineral nitrogen, biomass accumulation, yield structure traits, and grain yield. Carbon emission indicators were calculated from grain yield and fertiliser input data and were used for comparative environmental assessment of the fertilisation treatments. All statistical analyses and graphical outputs were performed in the R software (version 4.3.1, Boston, USA) environment using the ggplot2 package.

RESULTS

Effect of treatments on aboveground biomass accumulation

Fertilisation treatments affected spring barley biomass accumulation, with significant differences between treatments becoming more pronounced from 60 days after emergence (DAE) onwards (Figure 2). The response pattern differed between the two experimental years, indicating that biomass formation was strongly influenced by year-specific growing conditions. All fertilised treatments in 2024 increased fresh biomass compared with the unfertilised control at 60 DAE. However, the combined application of compost and mineral nitrogen (T4) was the most effective treatment for stimulating fresh biomass accumulation. Between 30 and 60 DAE, the biomass increment in this treatment was approximately 20% higher than in the other fertilised variants. Although differences among treatments became less pronounced toward the end of the growing season, T4 remained the most favourable treatment in terms of fresh biomass production.

In 2025, the treatment response differed from that observed in 2024. The highest fresh biomass values were recorded in the vermicompost-based treatments, which significantly exceeded the other

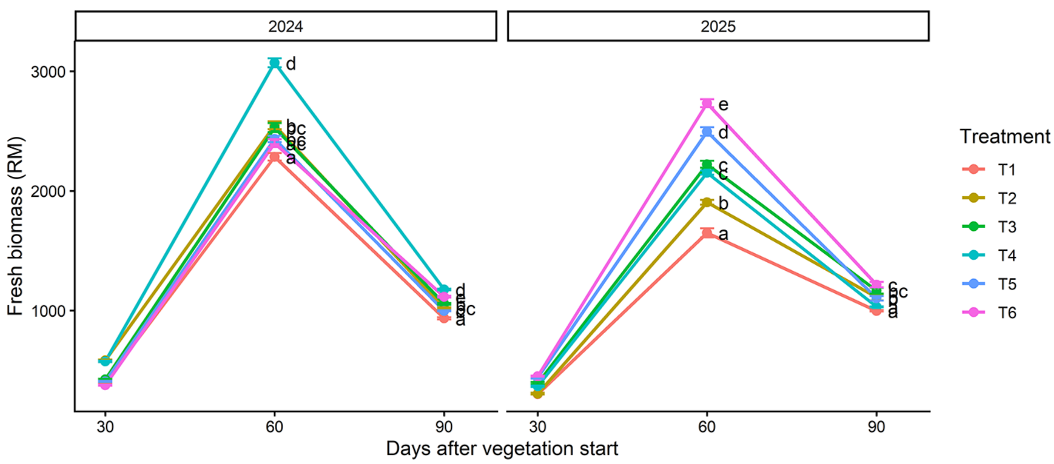

Figure 2. Fresh biomass accumulation (g/m^2) of spring barley depending on fertilisation treatment in 2024 and 2025

variants. At 60 DAE, the combined application of vermicompost and mineral nitrogen (T6) resulted in significantly higher fresh biomass than the full vermicompost treatment (T5). However, by the end of the growing season, the difference between these two treatments was no longer significant.

The dynamics of dry biomass (Figure 3) partly differed from those of fresh biomass, particularly at 60 DAE, which reflects differences in the moisture content of plant material.

In 2024, the combined application of vermicompost and mineral nitrogen (T6) provided the highest dry biomass during the second half of the growing season. Compared with the full-rate vermicompost treatment, the combination with mineral nitrogen increased dry biomass after flowering, resulting in greater biomass accumulation at harvest. At the final sampling, the other fertilised treatments formed a relatively similar group, but all of them significantly exceeded the control.

Dry biomass accumulation in 2025 generally followed the same pattern as fresh biomass, although some treatment-specific differences were observed. During the period from 30 to 60 DAE, compost-based treatments showed similar dynamics of dry matter accumulation. However, by harvest, the full compost treatment (T3) was more effective and approached the level of the best-performing treatments, whereas the combined compost and mineral nitrogen treatment (T4) remained close to the control. Overall, the results indicate that the effect of organic amendments on biomass accumulation depended on the year-specific conditions that influenced nutrient release and crop growth during the vegetation.

Effect of treatments on yield structure

The ANOVA results showed that the effects of year, fertilisation treatment, and their interaction differed among yield structure traits (Table 3). Year had no significant effect on spike density, indicating relatively stable stand formation between 2024 and 2025. However, year conditions strongly affected seed weight per spike, number of seeds per spike, thousand kernel weight, and grain yield, confirming the high sensitivity of barley productivity components to seasonal weather variability. Fertilisation treatment had a pronounced effect on all analysed traits, especially spike density and grain yield, which indicates that the source and combination of nitrogen inputs played an important role in yield formation. The year × treatment interaction was most evident for

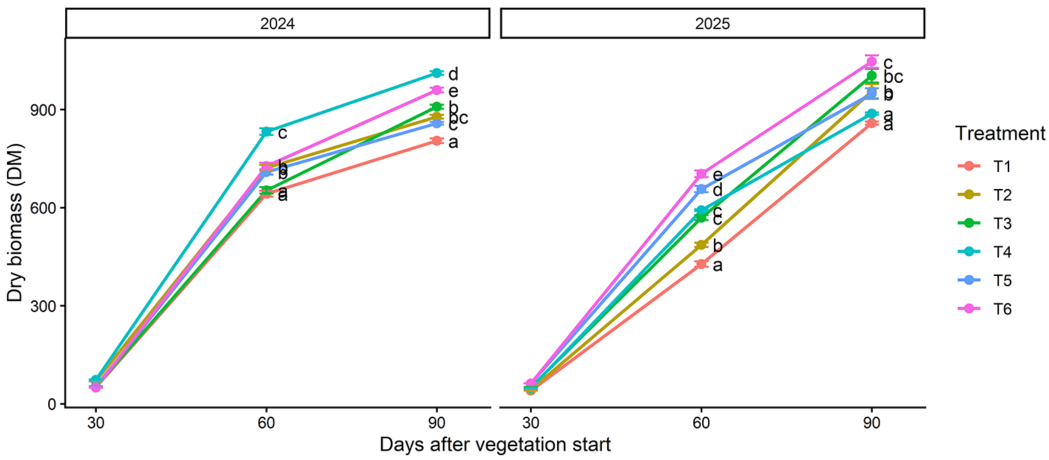

Figure 3. Dry biomass accumulation (g/m^2) of spring barley depending on fertilisation treatment in 2024 and 2025

Table 3. ANOVA results for spring barley yield components and grain yield

Effect	Spike density, spikes/m^2	Seed weight, g/spike	Seeds per spike, pcs	TKW, g	Seed yield, t/ha
Year (Y)	220.03ns	0.0268**	65.61**	41.28**	1.199**
Treatment (T)	7322.45**	0.0101**	2.7684**	10.93**	1.148**
Y*T	2817.03**	0.0044**	0.3073**	4.50**	0.225**

Note. ** – p<0.01; ns – p>0.05.

spike density, seed weight per spike, and thousand kernel weight, suggesting that the effectiveness of compost, vermicompost, and their combinations with mineral nitrogen depended on the specific conditions of each growing season.

Spring barley showed considerable yield-component plasticity, which was reflected in different pathways of grain yield formation depending on the fertilisation treatment and year conditions (Table 4 and Table 5). Across treatments, the highest stem density was obtained with full-rate compost application (T4) and the combined application of vermicompost with mineral nitrogen (T6). This effect was especially evident in 2025, when T3 produced the highest stem density among all treatments.

Grain weight per spike was slightly higher in 2025 than in 2024, although the absolute increase was moderate. In the two-year average, almost all fertilised treatments, except the full compost treatment (T3), increased grain weight per spike compared with the unfertilised control. The average value increased from 1.06 g/spike in the control to 1.13–1.14 g/spike in the mineral, combined and vermicompost-based treatments. This response resulted from changes in both grain number per spike and thousand kernel weight, but the contribution of these traits differed between treatments.

The number of grains per spike was strongly affected by year. In 2024, barley formed fewer grains per spike, averaging 25.46 grains/spike, whereas in 2025 this value increased to 28.16 grains/spike. In contrast, thousand kernel weight was higher in 2024, reaching 42.55 g compared with 40.41 g in 2025. This indicates a compensatory relationship between grain number and grain size: in 2025, a higher number of grains

Table 4. Effect of treatment and weather conditions on elements of grain yield structure (year x treatment)

Year	Treatment	Spike density, spikes/m^2	Seed weight, g/spike	Seeds per spike, pcs	TKW, g	Grain yield, t/ha
2024	T1	551.7^{ab*}	1.00^{a}	24.5^{a}	40.55^{ab}	5.49^{a}
	T2	561.7^{ab}	1.14^{bd}	25.6^{de}	44.59^{c}	6.40^{cd}
	T3	607.3^{cde}	1.08^{ce}	25.9^{dh}	41.77^{abd}	5.58^{ce}
	T4	617.3^{d}	1.08^{ce}	25.6^{ch}	40.97^{ab}	5.72^{cef}
	T5	554.0^{ab}	1.11^{bc}	25.1^{ae}	44.18^{c}	6.14^{bd}
	T6	513.7^{de}	1.08^{ce}	25.1^{ae}	43.22^{cd}	6.65^{cef}
2025	T1	539.7^{a}	1.10^{bc}	27.1^{bc}	40.66^{ab}	5.95^{b}
	T2	574.0^{abc}	1.15^{bd}	28.5^{fg}	40.19^{a}	6.58^{ce}
	T3	666.0^{f}	1.05^{e}	27.8^{bf}	37.84^{e}	7.01^{df}
	T4	547.3^{ab}	1.17^{d}	29.2^{g}	40.02^{a}	6.41^{cd}
	T5	580.3^{bce}	1.18^{d}	27.9^{f}	42.25^{bd}	6.85^{ef}
	T6	628.0^{d}	1.17^{d}	28.3^{f}	41.47^{abd}	7.37^{g}

Note: *Different letters within each column indicate significant differences between treatments according to Tukey's HSD test at $P < 0.05$.

Table 5. Effect of treatment and weather conditions on elements of grain yield structure

Factor	Variant of factor	Spike density, spikes/m^2	Seed weight, g/spike	Seeds per spike, pcs	TKW, g	Grain yield, t/ha
Year	2024	584^{a}	1.09	25.5^{a}	42.55^{a}	6.33^{a}
	2025	589^{a}	1.14	28.2^{b}	40.41^{b}	6.695^{b}
Treatment	T1	545.7^{a}	1.06^{a}	25.8^{a}	40.61^{a}	5.72^{a}
	T2	567.8^{ab}	1.14^{b}	27.1^{b}	42.39^{b}	6.49^{b}
	T3	636.7^{c}	1.07^{a}	26.9^{bc}	38.81^{a}	6.80^{cd}
	T4	582.3^{b}	1.13^{b}	27.9^{d}	40.50^{a}	6.56^{bc}
	T5	567.2^{ab}	1.14^{b}	26.5^{c}	43.22^{b}	6.49^{b}
	T6	620.8^{c}	1.13^{b}	26.7^{bc}	42.34^{b}	7.01^{d}

Note: *Different letters within each column indicate significant differences between variants of factor according to Tukey's HSD test at $P < 0.05$.

per spike was accompanied by lower thousand-kernel weight. All fertilisation treatments significantly increased the number of grains per spike compared with the control, with the combined application of compost and mineral nitrogen (T4) showing the most stable positive response in both years.

Grain yield was determined by the combined effect of stem density, grain number per spike, and grain weight per spike. All fertilisation treatments increased grain yield compared with the unfertilised control. The highest two-year average yield was obtained with the combined application of vermicompost and mineral nitrogen (T6), reaching 7.01 t/ha, followed by the full compost treatment (T3), with 6.80 t/ha. However, these treatments differed in the mechanism of yield formation. Full-rate compost mainly increased yield through higher stem density, whereas vermicompost-based and mineral nitrogen treatments contributed more strongly to grain filling and grain weight per spike. Thus, compost and vermicompost affected spring barley productivity through different yield-formation pathways.

Mineral nitrogen content before sowing and after barley harvesting

The content of mineral nitrogen in soil before sowing differed substantially among fertilisation treatments in both analysed soil layers (Table 6). The lowest Nmin values were recorded in the unfertilised control, reaching 29 mg/100 g in the 0–20 cm layer and 26 mg/100 g in the 20–40 cm layer. However, pre-sowing Nmin values represent the combined effect of baseline field heterogeneity, autumn transformation of organic amendments, spring mineral fertiliser application, and year-specific moisture conditions. Therefore, these values were used mainly to characterise the mineral N pool available before crop establishment; direct treatment effects on pre-sowing Nmin are more robustly inferred from the post-harvest comparison. The highest pre-sowing Nmin content was observed under the full compost and the full vermicompost treatments, especially in the 0–20 cm layer, while vermicompost showed the most pronounced increase in the deeper 20–40 cm layer.

After barley harvesting, mineral nitrogen content decreased in all treatments compared with the pre-sowing period, reflecting crop uptake and seasonal transformation of available nitrogen. However, fertilised treatments maintained significantly higher residual Nmin levels than the control. The combined application of compost and mineral nitrogen resulted in the highest post-harvest Nmin content in both soil layers, reaching 40 and 38 mg/100 g in the 0–20 and 20–40 cm layers, respectively. This suggests a more prolonged nitrogen release from compost when combined with mineral fertiliser. At the same time, higher post-harvest Nmin indicate an increased risk of nitrate leaching or other nitrogen losses if the remaining mineral N is not taken up by a subsequent crop. In contrast, mineral fertilisation alone and the combined vermicompost-based treatment showed lower residual Nmin levels, which may indicate more intensive crop uptake or faster depletion of readily available nitrogen during the growing season.

Correlation between plant productivity indicators and soil parameters

The pooled correlation matrix for 2024–2025 showed a clear relationship between soil mineral nitrogen status, biomass accumulation, and final productivity traits (Figure 4).

Table 6. Content of mineral nitrogen in soil, mg/100 g of soil (average by 2024–2025)

Treatment	Before sowing		After harvesting	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
T1 (c)	$29±0.29^d$	$26±0.51^e$	$21±0.43^e$	$18±0.33^f$
T2	$38±0.44^c$	$36±0.38^d$	$29±0.51^d$	$31±0.29^d$
T3	$46±0.54^a$	$42±0.34^b$	$33±0.33^c$	$34±0.46^c$
T4	$42±0.60^b$	$40±0.38^c$	$40±0.19^a$	$38±0.40^a$
T5	$46±0.50^a$	$46±0.46^a$	$38±0.36^b$	$36±0.45^b$
T6	$41±0.55^b$	$37±0.43^d$	$32±0.46^c$	$29±0.39^e$

Note: Different letters within each column indicate significant differences between treatments according to Tukey's HSD test at $P < 0.05$.

According to the pattern of co-dependence, the analysed parameters could be divided into four main clusters, while the thousand kernel weight formed a relatively isolated variable. The first cluster (I) included dry and fresh biomass at 30 and 60 days after emergence, which were strongly positively correlated with each other due to their common biological nature (r > 0.81). The second cluster (II) comprised dry biomass at 90 days after emergence, grain yield, straw yield, and stand density. Within this cluster, the correlations ranged from strong (r > 0.63) to very strong, particularly in relation to dry biomass at 90 days after emergence. At the same time, among the variables of the first cluster, the second cluster showed a significant positive relationship, mainly with fresh biomass at 60 days after emergence.

The third cluster (III) grouped mineral nitrogen indicators measured before sowing and after harvesting in both soil layers. These variables were very strongly positively correlated with each other (r > 0.84). Mineral nitrogen before sowing was strongly correlated between the 0–20 and 20–40 cm soil layers, indicating a consistent vertical distribution of mineral N within the analysed soil profile. Strong positive correlations were also observed between mineral nitrogen before sowing and after harvest in both soil layers. This suggests that the treatments which increased mineral N availability before sowing generally maintained a higher residual mineral N level after crop harvest. At the same time, the relationship between this cluster and biomass indicators from cluster I was weak to moderately positive (r = 0.36–0.59), whereas its

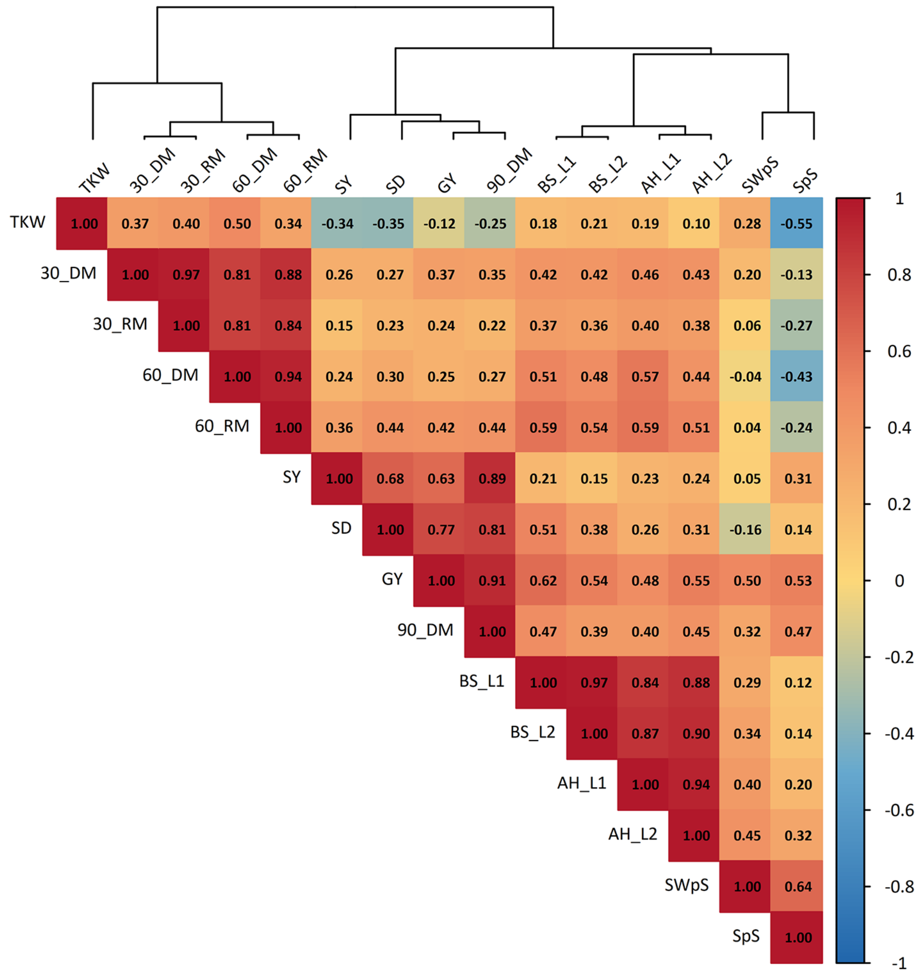

Figure 4. Correlation matrix of plant productivity indicators and soil parameters (Pearson method)

Note: Correlation coefficients with a value of 0.33 or higher (or −0.33 or lower) are statistically significant. Labels: TKW – thousand kernel weight; 30_, 60_, 60_ are days after emergence; DM – dry mass, g/m^2; RM – raw (fresh) mass, g/m^2, SY – straw yield, t/ha; SD – stand density, spikes/m^2; GY – grain yield, t/ha; BS– Nmin before sowing; AH – Nmin after harvesting; L1 – layer 0–20 cm; L2 – layer 20–40 cm; SWpS – seed weight per spike, g; SpS – seeds per spike, pcs.

relationship with productivity traits from cluster II was moderate (r = 0.48–0.55). A stronger relationship was observed between grain yield and Nmin content in the upper soil layer before sowing. Because pre-sowing Nmin partly reflects the initial and pre-crop soil status, these correlations were interpreted as relationships between soil N availability and crop performance, rather than as proof of direct causality of the fertilisation treatments.

The fourth cluster (IV) included grain weight per spike and number of grains per spike, which were strongly correlated. However, their relationships with most other parameters were generally weak or non-significant, with several exceptions. The number of grains per spike showed a moderate negative correlation with thousand kernel weight and dry biomass at 60 days after emergence, but a moderate positive correlation with grain yield and dry biomass at 90 DAE. Most other relationships involving grain number per spike were not significant. Grain weight per spike also showed a moderate positive correlation with grain yield and with Nmin content after harvesting in both soil layers.

The negative correlation between thousand kernel weight and grains per spike indicates a compensatory relationship between grain number and grain filling. Thus, the productivity response to fertilisation was realised primarily through improved spike density, greater grain number per spike, and higher final biomass accumulation, whereas thousand kernel weight played a secondary role.

Yield-scaled CO_2-equivalent emissions

The fertilisation treatments differed not only in grain yield response but also in CO_2-equivalent emissions associated with fertiliser inputs and total barley production (Table 7). In the unfertilised control, total emissions amounted to 4633.20 kg CO_2-eq/ha, corresponding to 810.0 kg CO_2-eq/t of grain. All fertilised treatments increased total CO_2-eq emissions per hectare compared with the control, mainly due to emissions associated with fertiliser production and nutrient input.

The largest increase in total CO_2-eq emissions was recorded for the compost-based treatments. Full-rate compost application increased total emissions by 687.50 kg CO_2-eq/ha compared with the control, whereas the combined compost and mineral nitrogen treatment increased emissions by 484.25 kg CO_2-eq/ha. In contrast, the mineral nitrogen treatment, full-rate vermicompost, and the combined vermicompost–mineral nitrogen treatment showed lower additional emissions (270– 281 kg CO_2-eq/ha).

It should be noted that, when recalculated per 1 t of grain, all alternative treatments reduced CO_2 emissions compared with the control. However, the compost-based treatments had higher emission values than the purely mineral fertiliser treatment (T2). The full rate of vermicompost produced a similar result to mineral fertilisation, whereas its combination with mineral fertilisers reduced emissions to 692.6 kg CO_2-eq/t, which was 78.3 kg CO_2-eq/t lower than in the mineral fertiliser treatment. In terms of CO_2 emissions per additional tonne of grain, the combined application of vermicompost and mineral fertilisers also showed the lowest value, at 213.6 kg CO_2-eq per additional tonne, which was 151.3 kg CO_2-eq/t lower than under mineral fertilisation alone. In contrast, the full compost rate and its combination with mineral fertilisers resulted in substantially higher CO_2 emissions per additional tonne of grain yield.

Table 7. Net-carbon emission of cultivation technology of spring barley by different treatments

Treatment	Grain yield, t/ha	Additional grain yield, + to control, t/ha	Total CO_2, kg/ha e	Fertilisers*, kg CO_2-eq/ha	Additional CO_2 emission compared to control, kg/ha	Emission CO_2 per 1 t of grain, kg	Emission CO_2 per 1 additional t of grain
T1 (c)	5.72	–	4633.20	149.22	–	810.0	–
T2	6.49	0.77	5003.29	430.22	281.00	770.9	364.9
T3	6.80	1.08	5277.01	836.72	687.50	776.0	636.6
T4	6.56	0.84	5215.32	633.47	484.25	795.2	576.5
T5	6.49	0.77	4989.01	419.22	270.00	767.7	350.6
T6	7.01	1.29	4855.41	424.72	275.50	692.6	213.6

Note: * Based on ecological assessment of production: compost – 125 kg CO_2 e/t, vermicompost – 75 kg CO_2 e/t, N-fertiliser – 5.62 kg CO_2-eq/kg of N, P_2O_5 – 1.47 CO_2-eq/kg, K_2O – 1.36 CO_2-eq/kg.

DISCUSSION

The productivity of spring barley under compost, vermicompost, and their combination with mineral nitrogen was determined not only by the total amount of nitrogen applied but also by the source of nitrogen supply and the weather conditions during the growing season. This is particularly important because all fertilised treatments were balanced according to the planned total nitrogen input of 50 kg N/ha, whereas biomass accumulation, yield-component formation, residual soil mineral nitrogen and carbon efficiency differed substantially among treatments. Compost and vermicompost should be considered not only as alternative nitrogen sources, but also as biologically active organic amendments capable of influencing nutrient release, soil biological activity, and plant tolerance to stress conditions (du Jardin, 2015; Rouphael and Colla, 2020).

A key limitation of the experimental design is that only nitrogen input was balanced among the fertilised treatments. Compost and vermicompost additionally supplied different amounts of P_2O_5 and K2O, while the basal P and K rate was identical in all variants. Consequently, the observed differences in biomass, yield structure, and grain yield cannot be attributed exclusively to the nitrogen source. They should be interpreted as the combined agronomic response to each complete fertilisation system, including nitrogen form, organic matter input, amendment biological activity as well as the accompanying P and K supply. This is particularly important for the compost treatments, which supplied more additional P_2O_5 and K_2O than the vermicompost-based treatments.

The most pronounced differences among fertilisation treatments in terms of biomass accumulation became evident from 60 days after emergence, during the period of active vegetative growth and transition to generative development. This indicates that the effect of organic amendments was not limited to early nutrient supply but was expressed mainly when crop nutrient demand increased. The difference between compost- and vermicompost-based treatments in different years may be explained by year-specific moisture and temperature conditions, since the mineralisation of organically bound nitrogen and the mobilisation of phosphorus and potassium from organic amendments depend strongly on soil moisture, temperature, and amendment composition (Lazicki et al., 2020). Similar patterns were reported by Khalifa et al. (2022) in barley under water stress, where organic fertilisers improved soil properties and increased crop water productivity. In the present study, the interaction between fertilisation strategy and hydrothermal conditions suggests that organic amendments may play a stabilising role, but their effectiveness depends on the timing of nutrient release relative to critical stages of barley development.

The effect of compost was most clearly manifested through the formation of a more productive stem density. On average, over two years, the full-rate compost application provided one of the highest yield levels, mainly due to an increase in spike density rather than enhanced grain filling. This indicates that compost supported the initiation and survival of productive tillers, probably owing to the gradual release of nutrients and improved soil capacity to retain nutrients. Studies on barley have also shown that compost can increase crop growth and yield while improving soil chemical fertility, primarily through the accumulation of organic matter and nutrients (Salis et al., 2024). However, in the present study, the full compost treatment did not provide the best grain weight per spike or thousand kernel weight, indicating that compost mainly influenced the structural basis of yield formation rather than the final grain-filling process.

The combined application of compost and mineral nitrogen did not always provide an additional yield advantage compared with full-rate compost (Hijbeek et al., 2017). This may indicate that the synchronisation between mineral nitrogen availability and crop demand was not optimal in this treatment under the specific weather conditions of the experiment. Although mineral nitrogen can rapidly supply available N during early growth, the simultaneous presence of mineral and organically bound nitrogen does not automatically guarantee higher yield if water availability, temperature, or crop phenological stage limit nutrient uptake (Fan et al., 2023). This finding is consistent with the general concept of integrated nutrient management, where the effectiveness of combined organic and mineral fertilisation depends on the balance between readily available nutrients and slower nutrient release from organic sources (Padbhushan et al., 2021; Asaye et al., 2022).

Vermicompost modified barley productivity partly through a different pathway. The highest grain yield over the two years was obtained with the combination of vermicompost and mineral nitrogen, indicating the advantage of a treatment in which a biologically active organic fertiliser was supplemented with a readily available source of mineral nitrogen. Vermicompost can also supply humic substances, enzymes, and microbial metabolites that stimulate root system development, nutrient uptake, and rhizosphere microbial activity (Oyege and Balaji Bhaskar, 2023). Recent studies on barley also showed that vermicompost can increase grain yield, soil organic carbon, microbial respiration and enzymatic activity (Shilev et al., 2024). For malting barley, it has also been shown that combining vermicompost with mineral nitrogen improved soil fertility, yield, and economic efficiency, confirming the potential of partial rather than complete substitution of mineral nitrogen (Terefe et al., 2024). At the same time, the effect of vermicompost depends on its origin, chemical composition, and application rate, since at high rates of organic materials, it is necessary to control their quality and the possible accumulation of undesirable elements (Shen et al., 2022).

The analysis of yield structure components showed that yield formation occurred through different compensatory mechanisms. In 2025, a higher number of grains per spike was accompanied by a lower thousand-grain weight, indicating a typical trade-off between grain number and grain size. Overall, the yield advantage of fertilised treatments was more closely associated with spike density, grain number, and final dry biomass than with thousand-grain weight (Preiti et al., 2021). Nitrogen fertilisation affected yield through the number of spikes and the number of grains per spike, whereas grain weight showed a weaker or compensatory response. This pattern is relevant not only for two-row barley but also for six-row barley and triticale (Mirosavljević et al., 2025). Similar studies also confirm that plant density, nitrogen nutrition, and varietal characteristics determine yield primarily through tillering, the number of spikes per unit area, and total biomass accumulation (Mazurenko et al., 2020; Balducci et al., 2024). It is important to note that the effect of biologically active substances may vary substantially depending on growing conditions, as well as on the presence of competition for growth factors, including competition with weeds or a companion crop (Mazurenko et al., 2025).

Changes in soil mineral nitrogen further explain the differences in crop response. All fertilised treatments increased mineral nitrogen availability before sowing, confirming that both autumn-applied organic amendments and spring-applied mineral nitrogen contributed to the formation of a higher available N pool. After harvesting, mineral nitrogen content decreased in all treatments, reflecting crop uptake and seasonal nitrogen transformation. However, the fertilised treatments maintained higher residual mineral nitrogen levels than the control, especially in the compost + mineral nitrogen and full-rate vermicompost treatments. From an agronomic perspective, this indicates a prolonged nitrogen supply and a possible residual effect for subsequent crops. From an ecological perspective, however, a high post-harvest mineral N pool should be interpreted carefully, because it may represent both a nutrient reserve and a potential source of nitrogen losses if not synchronised with subsequent crop uptake. Therefore, future studies should combine Nmin monitoring with indicators of nitrate leaching risk, nitrous oxide emissions, and post-harvest cover crop use.

The pre-sowing Nmin results require special caution. In the first experimental year, they may partly reflect spatial variability in the experimental field and the residual nutrient status before the treatments had a full annual cycle of influence. Therefore, the direct effect of fertilisation systems on pre-sowing Nmin should be discussed mainly for the second year, whereas the pooled pre-sowing values are more appropriate as indicators of soil mineral N status at crop establishment.

Correlation analysis also showed that soil mineral nitrogen was associated with biomass formation, particularly during the period of active growth, whereas final yield depended more strongly on the ability of plants to maintain dry biomass accumulation until harvest. This suggests that the effect of organic fertilisers was not limited to increasing early nitrogen availability but was realised through a more prolonged synchronisation between nutrient supply, vegetative growth, and the formation of yield components. Such synchronisation is one of the key principles of integrated nutrient management, especially under variable climatic conditions (Waqas et al., 2020; Lazicki et al., 2020).

The carbon emission assessment provides an additional perspective for interpreting fertilisation efficiency. Although all fertilised treatments increased total CO_2-equivalent emissions per hectare compared with the unfertilised control, all of them reduced yield-scaled emissions due to higher grain yield. This confirms that the environmental performance of fertilisation cannot be evaluated only by total emissions per hectare; it should also be assessed per unit of agricultural output (Gao and Serrenho, 2023). The compost-based treatments caused the largest increase in total CO_2-equivalent emissions, mainly because of the higher carbon cost associated with the amount of organic amendment applied and its nutrient content (Walling and Vaneeckhaute, 2020). Nevertheless, full-rate compost still reduced emissions per tonne of grain compared with the control, because the yield increase partly compensated for the additional carbon cost.

The most favourable carbon efficiency was obtained with the combined application of vermicompost and mineral nitrogen. This treatment produced the highest grain yield and the lowest yield-scaled emissions, reducing emission intensity to 692.6 kg CO_2-eq/t of grain. It also had the lowest CO_2-equivalent emissions per additional tonne of grain, indicating that the additional carbon cost of fertilisation was most efficiently converted into additional yield. In contrast, compost-based treatments, especially full-rate compost, showed relatively high emissions per additional tonne of grain. This does not necessarily mean that compost is environmentally ineffective, because the present assessment focused mainly on production-related CO_2-equivalent emissions and did not fully account for possible long-term soil carbon sequestration, improved soil structure, or residual effects (Oldfield et al., 2019). However, it shows that short-term carbon efficiency may differ substantially between organic amendments even when they are applied at equivalent nitrogen rates.

These findings are relevant in the broader context of reducing the environmental footprint of cereal production. Synthetic nitrogen fertilisers are associated with substantial greenhouse gas emissions during manufacture, transport, and field use (Menegat et al., 2022), while agri-food systems as a whole contribute significantly to global anthropogenic greenhouse gas emissions (Crippa et al., 2021). Therefore, the fertilisation strategies for cereals should aim to reduce emission intensity and improve nutrient-use efficiency while increasing the yield. The present study showed that partial substitution of mineral nitrogen with vermicompost can improve the balance between productivity, soil nitrogen availability and carbon efficiency. At the same time, full substitution with organic amendments may be less predictable, because nutrient release depends on amendment properties and weather conditions.

Thus, the results indicate that the most promising strategy for spring barley was the integration of organic fertilisers with mineral nitrogen. Compost and vermicompost increased productivity through different mechanisms: compost mainly supported the formation of a denser productive stem stand, whereas vermicompost, especially in combination with mineral nitrogen, contributed more strongly to biomass accumulation and grain yield formation. From a practical perspective, the combination of vermicompost with mineral nitrogen is the most balanced option, while the full compost rate may be useful when the priority is to improve stem density and soil fertility. However, the obtained results have certain limitations, as the study was conducted over only two growing seasons at a single experimental site, and the organic amendments supplied unequal accompanying amounts of P and K. Therefore, the observed treatment responses should be interpreted primarily within the specific soil-climatic and management conditions of this experiment. Confirmation of these findings under multi-year and multi-site conditions is needed before drawing broader conclusions about long-term effects. Future studies should also include additional indicators, such as soil biological activity, nitrogen use efficiency, grain quality, direct greenhouse gas emissions, nitrate-leaching risk, and residual effects within crop rotation.

CONCLUSIONS

The two-year field experiment showed that compost, vermicompost, and their combinations with mineral nitrogen improved spring barley productivity, soil mineral nitrogen availability, and yield-scaled CO_2-equivalent emissions under the conditions of a typical chernozem in the right-bank forest-steppe of Ukraine. All fertilised treatments increased grain yield compared with the unfertilised control. The highest two-year average yield was obtained with vermicompost N_{25} + mineral N_{25} (7.01 t/ha), followed by full-rate compost with 6.80 t/ha, compared with 5.72 t/ha in the control. Compost mainly improved yield through increased spike density, whereas the vermicompost–mineral nitrogen combination promoted biomass accumulation, grain filling, and final yield formation.

Higher post-harvest Nmin indicates a possible residual nutrient reserve for the following crop, but it may also increase the risk of nitrogen losses if not synchronised with subsequent uptake. The carbon assessment showed that all fertilised treatments reduced estimated yield-scaled CO_2-equivalent emissions compared with the control. The most favourable result was obtained with vermicompost N_{25} + mineral N_{25}, which reduced emission intensity to 692.6 kg CO_2-eq/t of grain and had the lowest estimated emissions per additional tonne of yield.

Overall, partial substitution of mineral nitrogen with vermicompost may be considered the most balanced fertilisation strategy within the tested conditions, combining high productivity, improved soil nitrogen availability, and lower estimated emission intensity. These findings should be treated as short-term comparative results because the study covered only two growing seasons, the P and K inputs differed among organic treatments, and greenhouse gas emissions and soil carbon changes were not directly measured.

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