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NOTES AND INSIGHTS

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Effects of organic amendments on productivity, nitrogen uptake, and protein content in pea–barley intercrops

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Abstract

Cereal-legume intercropping combined with organic amendments is considered to be a promising technique to improve crop productivity and efficiency in land use. The intercropping performance is influenced by pedoclimatic conditions, crop combinations, and crop management. Intercropping of pea (*Pisum sativum* L.) and barley (*Hordeum vulgare* L.) is commonly practiced in Denmark to produce both seeds and fodder. This study aimed to evaluate the effects of organic amendments on productivity, nitrogen uptake, and grain protein content in pea–barley intercrops (PB IC). A 1-year field study was carried out in a strip-plot design with three cropping systems, PB IC, pea sole (PS), and barley sole (BS), with six organic amendment treatments: unamended control, biochar, compost, insect frass, vermicompost, and pelletized frass. Averaged across amendments, PB IC increased grain yield by 12%–135%, aboveground dry biomass by 18%–57%, and grain nitrogen uptake by 66%–94% more than solecrops, while weed biomass was 83% lower relative to PS. Averaged across cropping systems pelletized frass increased grain yield by 105% and straw and grain nitrogen uptake by 49% and 101%, respectively, compared to the control. Among the treatments, the land equivalent ratio varied from 1.15 to 2.47, indicating improved land use efficiency in intercrops. Barley protein content in PB IC was consistently higher than BS across all treatments. The sygergistic effects of organic amendments in PB IC, particularly with pelletized frass, improved crop yield, N-uptake, grain protein content, and land use efficiency. The present study provided robust evidence that combining pea–barley intercropping with organic amendments is beneficial in multiple ways to promote sustainable intensification.

Abbreviations: AGDB, aboveground dry biomass; APD, achieved plant density; BIC, barley intercrop; BS, barley sole; CS, cropping systems; DAS, days after sowing; LEC, land equivalent coefficient; LER, land equivalent ratio; OA, organic amendments; PB IC, pea–barley intercrop; PFP, partial factor productivity; PS, pea sole; SPI, system productivity index; TPD, target plant density.

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Plain Language Summary

Sustainable farming practices that use resources well with changing climatic conditions, is necessary to enhance crop productivity while restoring soil health. This study evaluated the effects of organic amendments in pea–barley intercropping systems (growing two or more crops together) compared to sole crops in Taastrup, Denmark. On average, pea–barley intercropping enhanced aboveground biomass by 18%–57%, grain yield by 12%–135%, and grain nitrogen uptake by 66%–94% more than sole cropping systems. Organic amendments, particularly pelletized frass (insect-based fertilizer pellets), improved grain yield by 105% and nitrogen uptake in straw and grain by 49% and 101%, compared to control. These results demonstrate that pelletized frass combined with intercropping synergistically improves yield and nitrogen uptake in resource-efficient agricultural systems.

1 | INTRODUCTION

Ensuring food security while reducing adverse effects on the environment is one of the biggest challenges in the context of climate change, environmental degradation, and increasing population pressure. These factors pose a significant threat to sustainability, making it necessary to transition toward farming systems that are both productive and sustainable (Wani et al., 2024). Intercropping, which is the practice of growing two or more crops together in the same piece of land, has increasingly gained attention as a potential strategy to achieve sustainable intensification (Gałęzewski et al., 2022; Mbanyele et al., 2024).

Cereal-legume intercropping has demonstrated agronomic and ecological benefits, such as improved nitrogen (N) cycling, greater biodiversity, suppression of pests and weeds, and more efficient use of light, water, and nutrients (Bedoussac et al., 2015; Haug et al., 2023; Raza et al., 2023). These benefits are largely attributed to the complementary traits of the intercropped plant functional types. Cereal-legume intercropping, particularly pea (*Pisum sativum* L.)-barley (*Hordeum vulgare* L.), improves aboveground and belowground temporal and spatial complementarity, reducing the need for external N inputs while enhancing yields and protein concentration in barley grains (Hauggaard-Nielsen et al., 2001; Tavoletti et al., 2023).

Organic amendments (OA), namely, compost, vermicompost, biochar, and insect frass, are increasingly proposed as sustainable alternatives to synthetic fertilizers. These amendments enhance soil health and fertility while reducing nutrient leaching, greenhouse gas emissions, and environmental pollution (Garbowski et al., 2023; Owusu et al., 2024). Often derived from waste streams (residual biomass) and by-products such as organic waste, crop residues, and manures, these amendments contribute to circular bioeconomy objectives (Kaszycki et al., 2021). OA have the potential to increase the soil organic matter content, water-holding capacity, root growth, and microbial activity (Naseri-Minabi et al., 2024; Noor et al., 2024).

Each organic amendment has distinct properties. Compost is known to provide nutrients and humus, which can help to improve the soil structure (Bremaghani, 2024). Vermicompost contains high levels of phytohormones and other bioactive substances shows biostimulant properties that affect the physiology of plants (Aremu et al., 2015; Benazzouk et al., 2020). Biochar, which is known to have high porosity and stability, can help to improve the water-holding capacity, soil aeration, and long-term carbon sequestration (Kabir et al., 2023). Insect frass is a relatively new organic amendment derived from insect-rearing byproducts; it provides essential nutrients and chitin, which can stimulate the soil microorganisms and activate the plants defense mechanisms (Houben et al., 2020; Szopa et al., 2023).

Despite OA have the ability to provide agronomic benefits, their benefits can be variable due to the type of soil, microbial activity, and climate conditions (Rastogi et al., 2023; Urra et al., 2019). However, by combining the OA with intercropping, these effects can potentially be minimized due to complementarity in resource use under intercropping, which allows nutrient availability from OA (Mirzaei et al., 2025).

While the intercropping adoption is limited, its multiple benefits are well documented. Combining OA with intercropping can potentially improve and provide consistent yields by offsetting the limitations of both organic and conventional farming practices. Therefore, the objective of this study was to evaluate the effects of OA on crop yield, land productivity, N-uptake, and barley grain protein content in pea–barley intercrop (PB IC) compared to sole crops under field conditions in Denmark.

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TABLE 1 Mean ± SE ($n = 3$) of soil properties before sowing.

Parameter	Unit	Value
pH	–	6.86 ± 0.03
Bulk density	(g cm^{-3})	1.53 ± 0.13
Total N	(%)	0.13 ± 0.003
Total C	(%)	1.45 ± 0.06
Available P	(mg/kg)	100 ± 2.25
Exchangeable K	(mmol+/kg)	6.3 ± 0.45
CEC	(mmol+/kg)	91 ± 6.56
Potentially mineralizable N	(mg N/kg)	44.8 ± 2.25

Abbreviation: CEC, cation exchange capacity.

Core Ideas

- Pea–barley intercropping enhanced land use efficiency more than sole cropping system.
- Pea–barley intercropping increased aboveground dry biomass by 18%–57% and grain yield by 12%–135% compared to sole crops.
- Grain yield under pelletized frass was 105% higher compared to unamended control.
- Intercropping suppressed weed biomass by 83% compared to pea sole crop.
- Insect frass under intercropping increased barley grain protein content by 28%.

2 | MATERIALS AND METHODS

2.1 | Experimental site and climatic conditions

The field experiment was conducted in 2023 at the Experimental Farms of the University of Copenhagen in Taastrup, Denmark (55.67° N, 12.29° E). The soil of the experimental plot is characterized as sandy loam (luvisols). In the previous year, the site had been cultivated with beetroot and maize under conventional crop management practices.

Before sowing, a composite soil sample from 0- to 30-cm depth, consisting of 5-6 sub-samples was collected and divided into three replicates for baseline soil analysis. Soil parameters including pH, bulk density, total N, total carbon (C), available phosphorus (P), exchangeable potassium (K), cation exchange capacity, and potentially mineralizable N were measured using the AgroCares soil nutrient scanner (AgroCares is a trademark of Care4Agro B.V., 6709 PA), and the results are presented in Table 1.

Climate data for growing season (April to August 2023) were collected from the weather station at the experimental site and compared with previous 5-year average (2018–2022), as shown in Figure 1. The mean temperature in 2023 was similar with the previous 5-year average. However, rainfall patterns varied: May and June 2023 experienced drought, followed by above-average rainfall in July and August (Figure 1). The field was irrigated twice during the drought—20 mm in May and 30 mm in June—to reduce the drought stress on the crops.

2.2 | Field preparation and experimental design

The field was ploughed and harrowed, and prepared for sowing. A strip-plot design field experiment was established with three replicates. The vertical strips consisted of three cropping systems (CS), including pea sole (PS), barley sole (BS), and PB IC, while the horizontal strips represented the six organic amendment treatments. The soil amendment treatments were control (no amendment), biochar, compost, insect frass (yellow mealworm frass), vermicompost, and pelletized frass (pelletized yellow mealworm frass).

Seed sowing was carried out on April 20, 2023. The pea variety ORCHESTRA and the barley variety WISH were sown in sole crops and intercrops. The target plant density (TPD) and achieved plant density (APD) for sole and intercrops, applied with different OA are provided in Table 2. TPD is the actual planned density sown after the land preparation, and the APD is the plant density counted after the emergence of seedlings. In PB IC plots, pea:barley seeding ratio equivalent to 80:40 of sole crop density was followed to reduce competition and enhance complementarity between the intercropped species. Each plot was 15 m^2, with dimension of 10 m × 1.5 m. Along the 10 m plot length, 12 rows were sown spaced at 12.5 cm apart, and the same spacing was followed for the sole crops and intercrops.

2.3 | Applications of OA

Before sowing, the OA consisting of biochar, compost, insect frass, vermicompost, and pelletized frass was applied to each treatment plot on April 19, 2023, at the same rate of 2.5 t/ha (3.75 kg per 15 m^2 plot). The field was then harrowed. Biochar (T1) was produced from sludge, a by-product of anaerobic digestion (Aquagreen), whereas compost (T2) was locally prepared from hay (40%), woodchips (35%), grass silage (10%), forest floor litter (5%), and aged compost (5%). Insect frass (T3, Frodas) was supplied by Tebrito (Mora) and was based on a diet of wheat bran, potato peels, and nutritional yeast. Vermicompost (T4) was supplied by Bio-humus and produced from cow manure using earthworms (Eisenia fetida). Pelletized frass (T5, Ynfrass) was provided by Ÿnsect from Tenebrio molitor reared on wheat bran, wheat grains, oilseed

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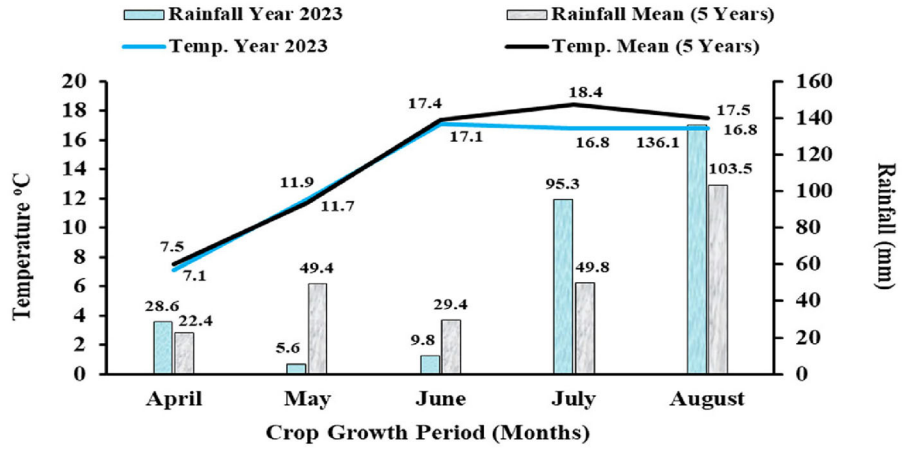


FIGURE 1 Average monthly rainfall and temperature during the growing season (April–August 2023) compared to the 5-year mean (2018–2022).

TABLE 2 Average target plant density (TPD) and achieved plant density (APD) of barley sole, barley intercrop, pea sole, and pea intercrop in organic amendment treatments.

	BS		BIC		PS		PIC	
Treatments	**TPD**	**APD**	**TPD**	**APD**	**TPD**	**APD**	**TPD**	**APD**
T0	300	308	120	140	70	92	56	44
T1	300	300	120	176	70	84	56	44
T2	300	324	120	120	70	84	56	68
T3	300	288	120	132	70	88	56	72
T4	300	328	120	204	70	80	56	68
T5	300	340	120	132	70	72	56	68

Abbreviations: BIC, barley intercrop; BS, barley sole; PIC, pea intercrop; PS, pea sole.

TABLE 3 Nutrient composition of the organic amendments.

Amendment	**pH**	**Electrical conductivity (mS/cm)**	**N (%)**	**C (%)**	**P (%)**	**K (%)**	**C/N**
Compost	–	–	1.55	21.05	–	–	13.6
Insect frass (Frodas)	6.6	18	2.12	39.64	1.3	2.1	18.7
Pelletized frass (Ynfrass)	6.6	18	3.48	39.88	3.4	2.4	11.5
Vermicompost	7.6	16	1.18	12.52	0.41	4.2	10.6
Biochar	7.7	1	2.82	24.42	–	–	8.66

meal, and starchy flour. The frass products were heat-treated in accordance with EU regulations. The difference between the two frass types was feedstock type, rearing conditions, and the pelletized form of T5. The nutrient analysis of insect frass (T3) was performed by ALS Global (chemical analysis company in Sweden, https://www.alsglobal.se/en) and for pelletized frass and vermicompost by LMI (chemical analysis company in Sweden, https://www.lmiab.com/da/). Compost and biochar nutrient analysis were performed in the university lab using a CHNS/O elemental analyzer (flash combustion method). The nutrient contents of the applied OA are shown in Table 3.

2.4 | Field samplings during growing period

After crop emergence, plant population was counted on May 15, 2023, using a 0.5 m × 0.5 m (0.25 m^2) iron frame, which was placed in each experimental plot, and number of plants was counted for each treatment. Based on this, the APD for

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each treatment was recorded as shown in Table 2. Biomass was harvested at three growth stages: 60 days after sowing (DAS) at early vegetative stage; 89 DAS at 50% barley anthesis and pea flat-pod stage; and 112 DAS at physiological maturity.

At 60, 89 and 112 DAS, for each intercrop treatment, the pea and barley components were separated, and fresh biomass was then measured using a gravimetric scale and subsequently oven-dried at 65°C for 48 h (Cowden et al., 2020) for dry weight measurements. Similarly, weed fresh biomass was measured at these three-sampling times within the same-sized quadrant. At 112 DAS, crops were first threshed and separated into grains and straw and weighed. Then, grain and straw samples of pea and barley were ground into powder using a fine mill machine.

2.5 | Productivity indices

To evaluate the biological efficiency of the intercropping system, three indices were calculated: land equivalent ratio (LER), land equivalent coefficient (LEC), and system productivity index (SPI) (Cowden et al., 2020; Araújo Júnior et al., 2023).

The LER quantifies the total productivity of the intercrop relative to that of the sole crops. It was calculated as follows:

$$\mathrm{LER}_{\mathrm{barley}} = \frac{Y_{\mathrm{BIC}}}{Y_{\mathrm{BS}}} \tag{1}$$

$$\mathrm{LER}_{\mathrm{pea}} = \frac{Y_{\mathrm{PIC}}}{Y_{\mathrm{PS}}} \tag{2}$$

$$\mathrm{LER}_{\mathrm{intercrop}} = \mathrm{LER}_{\mathrm{barley}} + \mathrm{LER}_{\mathrm{pea}} \tag{3}$$

where Y_{BIC} and Y_{PIC} are the component yields of intercropped barley and intercropped pea, respectively, in the PB IC (kg/ha); Y_{BS} and Y_{PS} are the sole crop yields (kg/ha) of barley and pea, respectively. $\mathrm{LER}_{\mathrm{barley}}$ and $\mathrm{LER}_{\mathrm{pea}}$ are the partial LERs of barley and pea, respectively. An LER value >1 indicates a yield and land use advantage of intercropping over sole cropping. Intercropping has no advantage over sole cropping if LER = 1 or less.

The LEC, which reflects the interaction between component crops, was calculated as follows:

$$\mathrm{LEC}_{\mathrm{intercrop}} = \mathrm{LER}_{\mathrm{barley}} \times \mathrm{LER}_{\mathrm{pea}} \tag{4}$$

LEC not only measures the productivity efficiency of the intercropping mixture but also reflects the interaction between the component crops. It is the product of the partial LER components of pea and barley. A value >0.25 suggests a biologically efficient intercropping system with positive species interactions. The SPI, which quantifies the relative contribution of the secondary crop (pea) in relation to the main crop (barley), was calculated as follows:

$$\mathrm{SPI} = \left(\frac{Y_{\mathrm{BS}}}{Y_{\mathrm{PS}}}\right) \times Y_{\mathrm{PIC}} + Y_{\mathrm{BIC}} \tag{5}$$

2.6 | Nitrogen uptake and grain protein determination

N concentration in ground grain and straw samples was determined using a FlashSmart CHNS/O elemental analyzer (Model: Flash 2000; Thermo Fisher Scientific) at the laboratory of Crop Science Section, University of Copenhagen (Taastrup). N-uptake (kg N/ha) was calculated as follows:

$$\mathrm{Plant}\ N_{\mathrm{uptake}} = N\mathrm{content} \times \mathrm{DM} \tag{6}$$

where N_{Content} is the nitrogen concentration (%) in straw or grain, and DM is the dry matter yield (kg/ha). Partial factor productivity (PFP) is an indicator of input (organic amendment) use efficiency, defined as the yield of harvested crop grain yield per unit of N applied through organic amendments (Kiwia et al., 2019; Sheoran et al., 2017). It is expressed in kg of grain per kg of N applied. PFP was calculated as follows:

$$\mathrm{PFP} = \frac{Y}{N} \tag{7}$$

where Y is the grain yield (kg/ha), and N is the amount of applied nitrogen (kg/ha).

Grain N concentration was estimated using the Dumas combustion method according to ISO 16634-2 (2016). Subsequently, protein content was calculated by using Equation (8), as commonly applied in agronomic studies (Reuter et al., 2022).

$$\mathrm{Protein\ content}\ (\%) = N_{\mathrm{Content}} \times 6.25 \tag{8}$$

2.7 | Statistical analysis

Field data collected during the entire growth period were analyzed using R software (version 4.4.2) in RStudio (version 2024.09.1+394). To ensure the normality of variance, Shapiro-Wilk tests were conducted, and data was transformed if necessary to meet the assumptions of an ANOVA. Strip-plot ANOVA analysis was performed for aboveground dry biomass, weed biomass, grain yield, plant N-uptake, and PFP. The effects of PB IC and organic amendments on all the

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TABLE 4 Analysis of variance (ANOVA) table (p-values) for grain yield (GY) at harvest, aboveground dry biomass (AGDB), and weed biomass at three sampling times as affected by organic amendments (OA) and cropping systems (CS).

			AGDB			Weed biomass		
Source of variation	***df***	**Grain yield**	**60 DAS**	**89 DAS**	**112 DAS**	**60 DAS**	**89 DAS**	**112 DAS**
Organic amendment (OA)	5	<0.001***	0.043*	0.183ns	0.028*	0.002**	0.012*	0.056ns
Cropping systems (CS)	2	0.002**	0.002**	0.328ns	0.003**	0.051ns	0.037*	0.017*
OA × CS	10	0.003**	0.395ns	0.034*	0.156ns	0.040*	0.001**	0.003**

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.
Abbreviations: DAS, days after sowing; ns, non-significant.

above-mentioned parameters were evaluated at significance level of $\alpha = 0.05$. When statistical differences were detected (p-value < 0.05), Fischer's least significant difference (LSD) test was used for pairwise comparisons. Pearson correlation matrix among the studied parameters was generated using the same RStudio software.

3 | RESULTS

3.1 | Grain yield, AGDB, and weed incidence

Table 4 shows the effects of CS and OA on grain yield, AGDB, and weed biomass at 60, 89, and 112 DAS.

Averaged across CS, the highest grain yield was recorded in PB IC (2.67 t/ha), followed by BS (2.39 t/ha), and PS (1.14 t/ha) (Figure 2A). The maximum grain yield was observed in plots receiving pelletized yellow mealworm frass (T5; 3.23 t/ha) (Figure 2B).

In BS, the highest grain yield was observed with pelletized frass treatment (3.73 t/ha). In PB IC, the most notable grain yield increase was also recorded with pelletized frass (4.48 t/ha), producing 2.7 times more grain yield than control (Figure 2C). In compost treatment, the highest grain yield was achieved in PB IC (2.74 t/ha). Notably, under pelletized frass, PB IC recorded the maximum grain yield of 4.48 t/ha in PB IC (Figure 2D). Hence, integrating pelletized insect frass with PB IC proved to be an efficient strategy to increase grain yields.

At 60 DAS, PS produced the highest aboveground biomass (3.75 t/ha), followed by PB IC (3.49 t/ha) and BS (1.84 t/ha), indicating more vigorous early growth in pea. At later stages (89 and 112 DAS), PB IC measured the highest biomass (5.45 and 4.90 t/ha, respectively), while BS and PS showed lower values (Figure 3A). Among the treatments, pelletized frass consistently resulted in the greatest increase in aboveground dry biomass compared to control by 35%, 50%, and 34% at 60, 89, and 112 DAS, respectively. Vermicompost also improved aboveground dry biomass, with increases of 15% and 25% at 89 and 112 DAS, respectively compared to control treatment (Figure 3B).

At 60 DAS, weed biomass in BS and PS was 16% and 170% higher than in PB IC, respectively. At 89 and 112 DAS, BS measured 1% and 22% less weed fresh biomass than PB IC, while PS had 18% and 83% more (Figure 3C). At 60 DAS, weed fresh biomass was reduced by 43% and 38% under compost and pelletized frass treatments, respectively, compared to control. At 89 DAS, the reductions were 26% and 24%, respectively compared to control. At 112 DAS, vermicompost and biochar treatments recorded the highest reductions of weed fresh biomass (37% and 33%, respectively) than control (Figure 3D). Overall, PB IC demonstrated increased aboveground dry biomass, which effectively shaded out weeds, resulting in a reduction in weed fresh biomass.

3.2 | Productivity in intercrops compared to monocrops

At three samplings, LER (AGDB) ranged from 1.40 to 1.54, indicating a 40-54% advantage of PB IC over the sole crops. At 60 DAS, the contribution of the barley component (0.71) was 3% higher than that of pea (0.69), whereas at 89 and 112 DAS, the pea component contributed 33 and 96% more than barley, respectively (Figure 4A). LER values (grain yield) ranged from 1.15 to 2.47, indicating a 15-147% more productivity advantage of intercropping over monoculture. Pelletized frass measured the highest LER value (2.47), with the pea component (1.95) contributing 3.75 times more than the barley component (0.52) at harvest (Figure 4B). LEC values ranged from 0.33 to 1.12, with the highest value recorded in compost, suggesting strong complementarity between the intercropped species (Figure 4C). SPI ranged from 2.65 to 8.75, with pelletized frass showing the highest value, indicating a high relative contribution of the pea component to intercrop productivity (Figure 4C). Hence, these indices demonstrate that PB IC with pelletized frass provided highest yield advantage over monocrops compared to other organic amendment treatments.

3.3 | Nitrogen uptake and grain protein content

Among the CS (BS, PS, and PB IC), intercropping proved to be the most efficient practice, resulting in the highest

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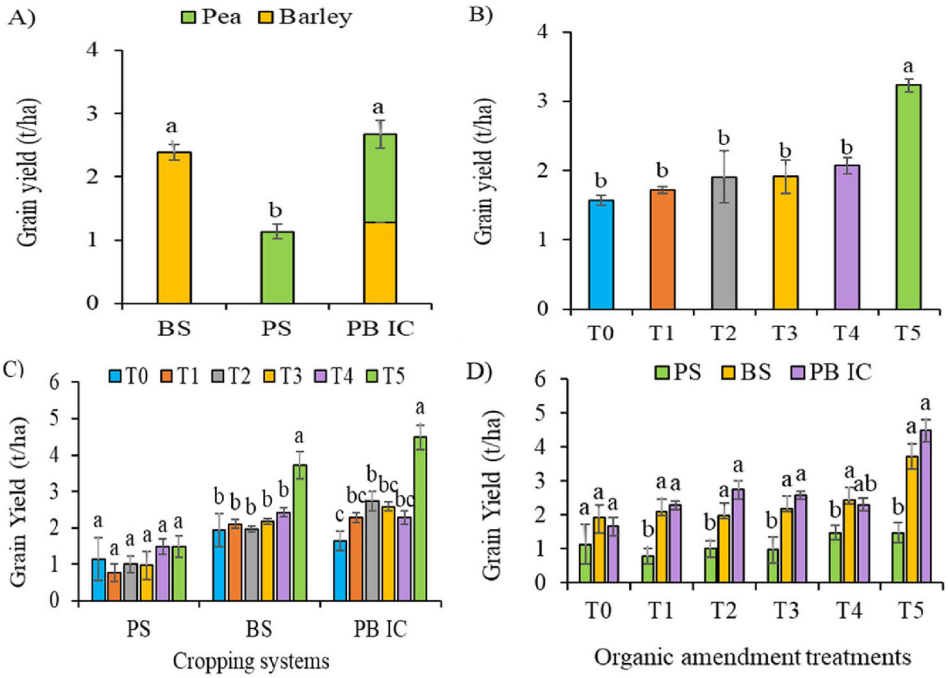


FIGURE 2 Mean grain yields (t/ha) in barley sole (BS), pea sole (PS), and pea–barley intercrops (PB IC): (A) averaged across organic amendments; (B) averaged across three cropping systems; (C) organic amendment treatment effects on mean grainyields (t/ha); and (D) cropping system effects on grain yields. The organic amendment treatments are T0 (control), T1 (biochar), T2 (compost), T3 (insect frass), T4 (vermicompost), and T5 (pelletized frass). Error bars represent the standard error of the means ($n = 3$). Means with different small letters are significantly different from one another ($p < 0.05$).

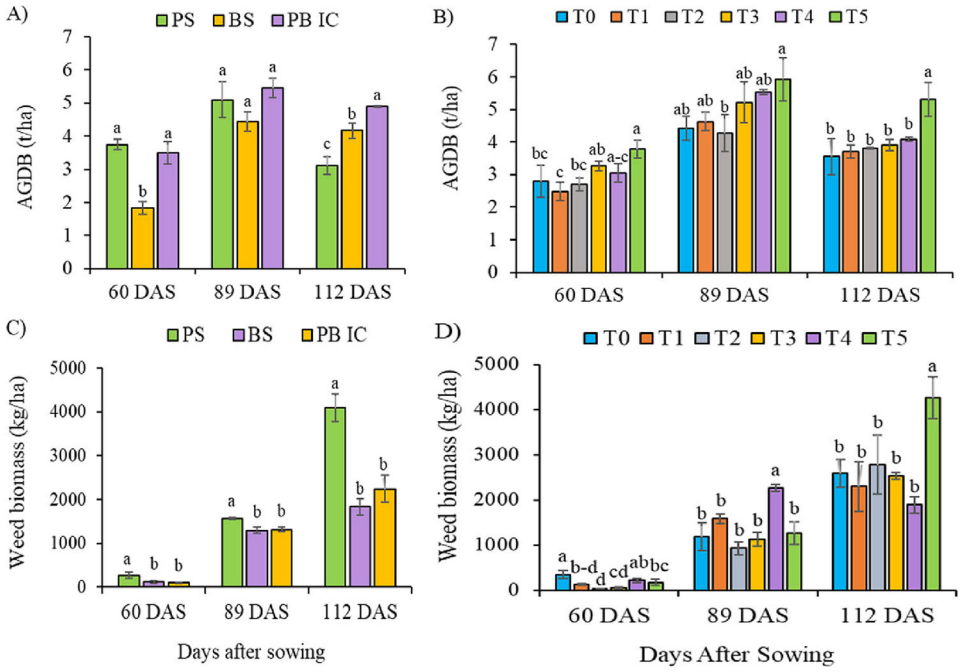


FIGURE 3 Aboveground dry biomass (AGDB; t/ha) and weed fresh biomass (kg/ha) across cropping systems (A and C) and organic amendment treatments (B and D) measured at 60, 89, and 112 days after sowing (DAS). Treatments: T0 (control), T1 (biochar), T2 (compost), T3 (insect frass), T4 (vermicompost), T5 (pelletized frass). Error bars represent the standard error of the means ($n = 3$). Different letters denote significant differences at $p < 0.05$.

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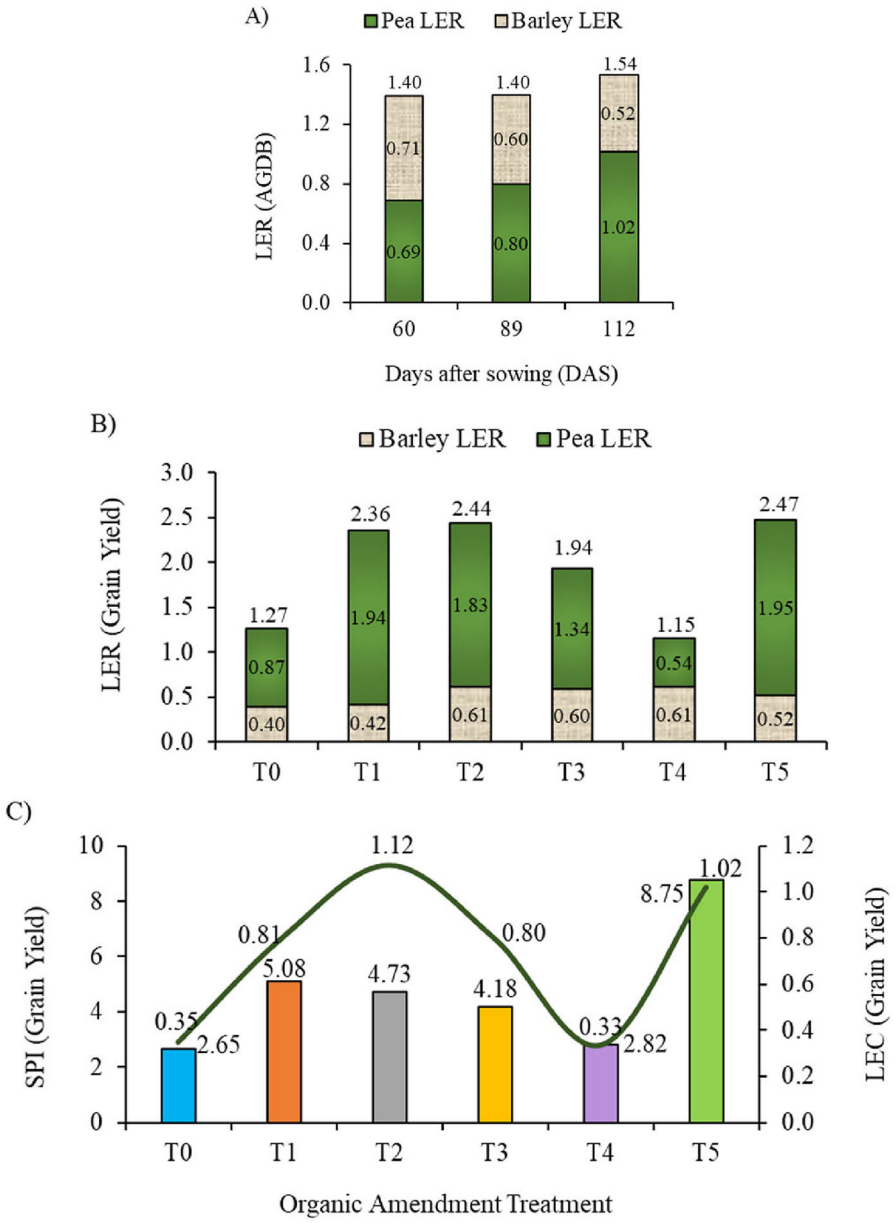


FIGURE 4 Intercropping indices including (A) land equivalent ratio (LER) based on aboveground dry biomass (AGDB) at three sampling times (60, 89, and 112 days after sowing [DAS]), (B) LER based on grain yield, and (C) land equivalent coefficient (LEC) and system productivity index (SPI) based on grain yield in the PB IC across organic amendment treatments (T0: control; T1: biochar; T2: compost; T3: insect frass; T4: vermicompost; and T5: pelletized frass).

grain N-uptake (62.95 kg/ha), followed by PS (37.88 kg/ha), while the lowest was found in BS (32.50 kg/ha). When comparing intercrop components to their sole crop counterparts, BS had 13% and 58% higher straw and grain N-uptake, respectively, than barley intercrop (BIC) (Figure 5A). Among the treatments, pelletized frass resulted in 101% higher grain N-uptake than control. Thus, PB IC with pelletized frass significantly increased grain N-uptake compared to the control.

Grain PFP between CS was highest in PB IC (56.24 kg/kg), followed by BS (49.43 kg/kg) (Figure 5C). Among organic amendment treatments, the highest grain PFP was recorded in vermicompost (70.15 kg/kg), followed by compost (49.16 kg/kg).

The maximum grain protein content in BIC was measured in control treatment (11.09%), while the highest in BS was observed in pelletized frass (9.37%). Intercropping increased barley grain protein content by 28% compared to BS in insect

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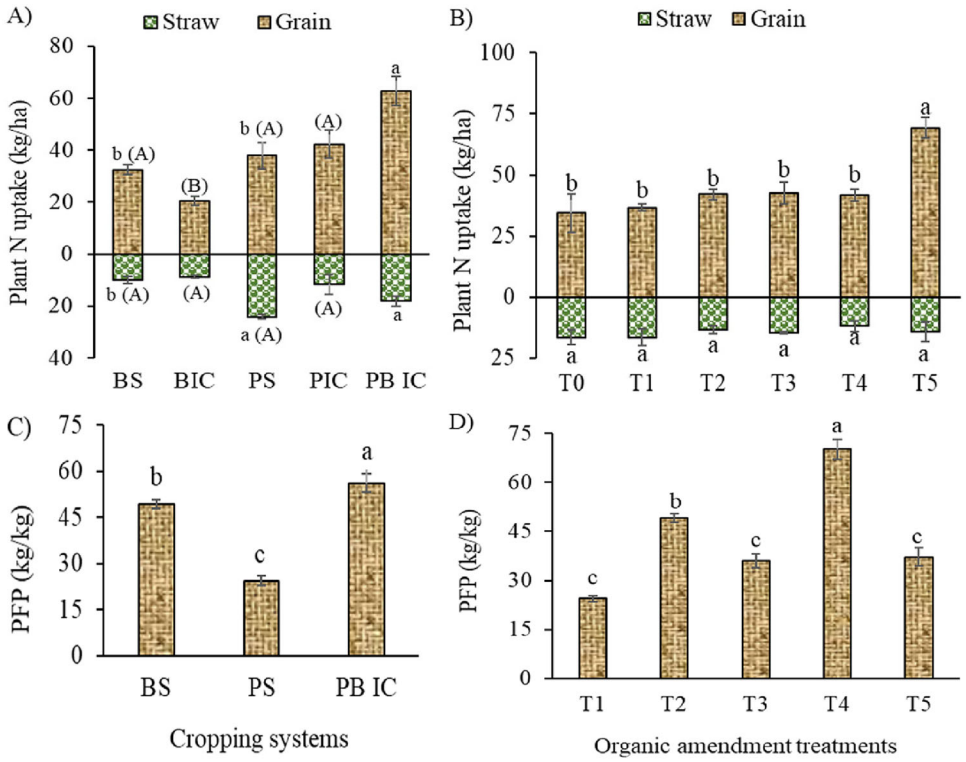


FIGURE 5 Plant N-uptake (kg/ha) in straw and grains: (A) under cropping systems (BS: barley sole, BIC: barley intercrop, PS: pea sole, PIC: pea intercrop, and PB IC: pea–barley intercrop, and (B) under organic amendment treatments (T0: control; T1: biochar; T2: compost; T3: insect frass; T4: vermicompost; and T5; pelletized frass); grain partial factor productivity (PFP, kg/kg): (C) under cropping systems, and (D) under organic amendment treatments. Error bars represent the standard error of the means ($n = 3$). Lowercase letters indicate differences among the means of cropping systems (BS, PS, and PB IC) or organic amendment treatments, whereas uppercase letters indicate differences between the means of cropping systems (BS vs. BIC and PS vs. PIC). Means with different lowercase letters are significantly different from one another ($p < 0.05$).

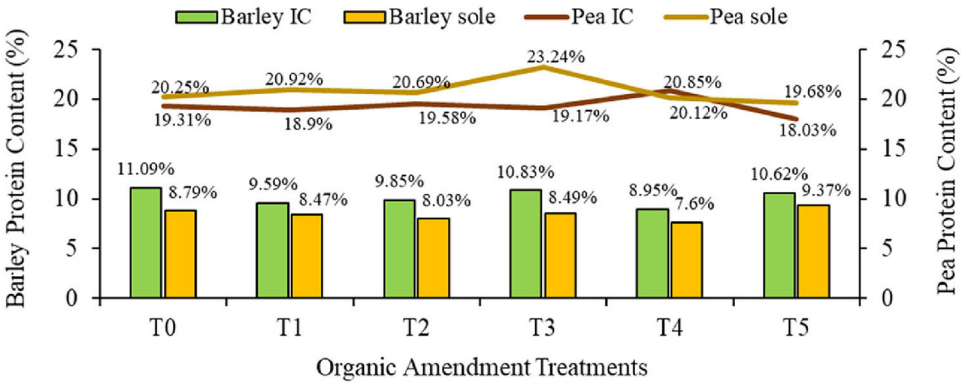


FIGURE 6 Grain protein content (%) in sole and intercrop barley (bars) and pea (lines) across organic amendment treatments (T0: control, T1: biochar, T2: compost, T3: insect frass, T4: vermicompost, and T5: pelletized frass).

frass treatment, followed by a 26% increase in unamended control treatment. In pea, the highest grain protein content in pea intercrop was found in vermicompost treatment (20.85%), whereas in PS, the maximum value of grain protein content was recorded in insect frass (23.24%) (Figure 6). Therefore, intercropping was more effective in increasing barley grain protein content than in pea, relative to their respective monocrops.

3.4 | Pearson correlation matrix within the measured and calculated crop parameters

Among the parameters studied, there was a strong positive correlation between grain yield and AGDB ($r = 1.00$), as well as with grain N-uptake ($r = 0.99$, $p < 0.001$) (Figure 7A). Similarly, as illustrated in Figure 7A for the organic amendment treatments, a strong positive correlation was observed

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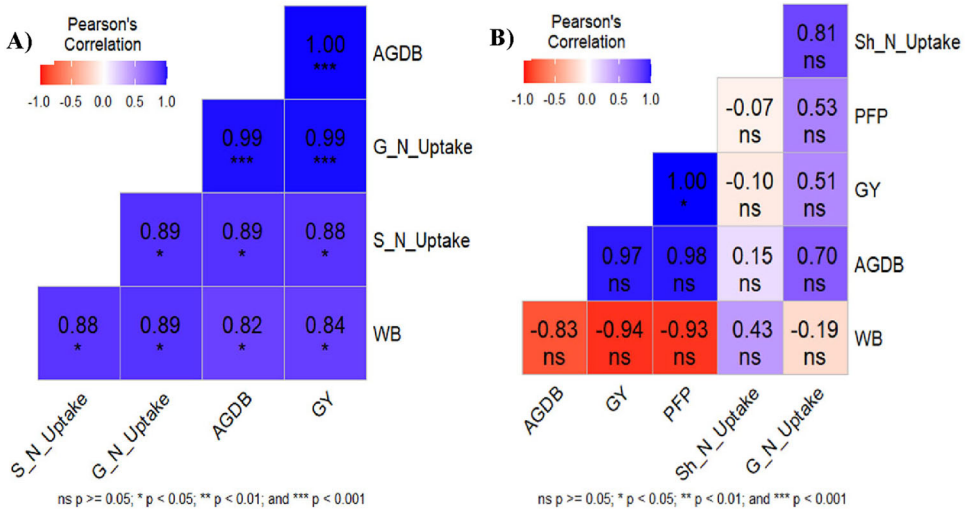


FIGURE 7 Pearson correlation matrix between aboveground dry biomass (AGDB), weed fresh biomass (WB), grain yield (GY), partial factor productivity (PFP), straw N-uptake (S_N_Uptake), and grain N-uptake (G_N_Uptake) in organic amendments (A) and in cropping systems (B) study.

between AGDB, and grain N-uptake ($r = 0.99$, $p < 0.001$). Additionally, positive correlations were found among straw N-uptake, grain N-uptake, AGDB and grain yield. As illustrated in Figure 7B, when analyzing the correlations among the three CS (BS, PS, and PB IC), a strong and significant positive correlation was found between grain yield and PFP ($r = 1.00$, $p < 0.001$).

4 | DISCUSSION

4.1 | AGDB production and crop yield performance in pea–barley intercropping

In cereal-legume intercropping, cereals are generally more competitive than legumes (Annicchiarico et al., 2019, 2021). The increase in AGDB and grain yield by pea–barley intercropping compared to monocrops aligns with previous studies showing enhanced productivity through complementary growth dynamics and improved resource use (Bahia et al., 2024; Cowden et al., 2020). Pea, as a nitrogen-fixing legume, likely boosted soil nitrogen, supporting better barley growth and overall system productivity (Mbanyele et al., 2024). The yield increase in pea-barley intercrop was due to niche complementarity and facilitation because of differences in their rooting systems and nutrient acquisition strategies, hence reducing competition (Corre-Hellou et al., 2011).

OA such as compost, biochar, frass, and vermicompost increase aboveground dry biomass and yield of crops by improving nutrient availability and soil structure. Moderate rates of OA promote the growth of barley through gradual release of nutrients, while peas provide atmospheric N through the process of biological N fixation (Bedoussac et al., 2018). Especially, pelletized frass was observed to be effective in promoting nutrient uptake. Houben et al. (2020) reported in his study that pelletized frass is composed of bioactive compounds that stimulate microbial activity to enhance mineralization (Abd Manan et al., 2024). This explains the significant effects of pelletized frass on nutrient uptake, photosynthetic efficiency, and stress resistance (Gebremikael et al., 2022; Poveda, 2021).

4.2 | Weed suppression in pea–barley intercropping

Pea–barley intercropping suppressed weed biomass by 83% than PS, which aligns with previous studies showing that cereal-legume intercrops reduce weeds through greater ground cover and improved resource use efficiency (Sarunaite et al., 2012; Tavoletti et al., 2023). The fast-growing and extensive root system in the PB IC system (Hauggaard-Nielsen et al., 2006; Andrew et al., 2015) contributes to reduced weed biomass. Barley's rapid growth and dense canopy exploit soil mineral N, while pea occupies a distinct niche, creating asymmetric competition that limits weed growth and biomass. Conversely, in PS, slower growth and open canopy allow more light and mineral-N for weeds (Corre-Hellou et al., 2011). Legumes are generally more vulnerable to weed competition; hence, intercropping with a competitive cereal like barley creates a shading canopy and root competition, which reduces the incidence of weeds (Deveikytė et al., 2009).

4.3 | Intercropping indices and land productivity

LER values for aboveground biomass (1.40–1.54) and grain yield (1.15–2.47) demonstrated yield and land use advantage

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of PB IC over sole cropping, shifts in LER contributions across growth stages, with pea becoming more dominant at later stages, illustrate temporal complementarity. This aligns with earlier studies that intercrops are better at efficient use of moisture, light, and nutrients (Chen et al., 2004; Cowden et al., 2020). Similar or higher LERs have been widely reported in cereal-legume systems (Table 5) for biomass, yield, N-uptake, and protein content across diverse CS (Mbah et al., 2020; Adam et al., 2025). Hauggaard-Nielsen et al. (2009) also found 25-30% higher grain yield due to efficient resource use. In line with Reuter et al. (2022), who found that intercropping reduced land requirements by up to 17%, our findings suggest that PB IC combined with organic inputs is a highly resource-efficient practice for enhanced productivity.

LEC and SPI values exceeded the 0.25 threshold across treatments, particularly under compost and pelletized frass, which indicates the synergistic effects of OA and pea–barley intercropping in systems productivity (Agegnehu et al., 2006). Araújo Júnior et al. (2023) and Lithourgidis et al. (2011) report similar trend: combining legumes with cereals under OA enhances intercrop productivity and resilience.

4.4 | Nitrogen uptake and PFP

N uptake and PFP of applied N are key measures of nutrient use efficiency (Amanullah, 2016), which was significantly improved by PB IC compared to monocrops. This increase reflects strong complementarity, where pea enhances N availability and boosts barley performance (Hartwig et al., 2002). Intercropping improves the nodulation and total N fixation by biological N fixation (Ghaley et al., 2005; Chapagain and Riseman, 2014), as reported by Hauggard-Nielsen et al. (2009), 10% higher N fixation and 35-74% (Monti et al., 2016; Pötzsch et al., 2019) greater N uptake than monocrops (Pappa et al., 2012; Jannoura et al., 2014). Similarly, Zhang et al. (2024) found similar results where intercropping increased PFP by 55% in maize. In a long-term study, legume-maize intercropping significantly improved the plant N-uptake by 16%–35% and PFP by 20%–80% (Gungaabayar et al., 2023; Wang et al., 2022).

Pelletized frass further improved N uptake due to their high N content in labile carbon fraction (Table 2) that simulates microbial activity and rapid mineralization (Houben et al., 2020). Thus, microbial activity further enhances the breakdown of complex organic molecules to available forms that increase the nutrient uptake (Liu et al., 2017). This explains the increased N-uptake observed in our study.

4.5 | Grain protein content

Pea–barley intercrop have been well known for improving grain protein content, especially in improving the protein concentration of cereal grains (Oram et al., 2014; Niazi et al., 2017). This has also been known to improve the baking quality of bread wheat (Jensen et al., 2015). Intercropping has consistently improved the protein content of barley compared to monoculture. This is likely due to the improved N availability, which is an important building block of proteins (amino acids) (Shanmugam et al., 2022). Pea intercropped with OA improved nutrient availability resulted in increased protein accumulation in barley grains, as reported by Chapagain and Riseman (2014) and Lauk and Lauk (2008). The 28% increase in the protein content of barley grains amended with insect frass was likely due to increased biological nitrogen fixation and greater C:N ratio (Güereña et al., 2015). In addition, OA improves soil moisture retention and increases microbial population. This creates a favorable environment for nutrient assimilation and protein synthesis (Yuan et al., 2023). The reduction in the protein content of peas under intercropping might be due to increased N translocation to barley (Vlachostergios et al., 2015; Gungaabayar et al., 2023). Thus, organic farming systems have the potential to enhance the protein content of crops, which is particularly important while considering solutions to food security and nutritional quality concerns (Epule, 2018).

The combination of pea–barley intercropping and the use of OA was found to be an effective method for increasing crop yield, nutrient efficiency, and grain quality while reducing environmental impact. The strong synergistic effect between pea–barley intercropping and pelletized frass shows the promise for the development of low-input systems with high efficiency and potential for sustainable intensification. However, some challenges remain, including the determination of optimal crop component ratio, matching the release of nutrients with the crop nutrient demand, and the adaptation to the environmental conditions of the location. The difference in the various OA highlights the importance of the amendment quality and the interaction of the amendments with the soil and the local climate. Intercropping design, long-term effects of the intercropping system on the soil health and microbial activity, and the role of the intercropping system in improving the resilience of crops to drought, heat, and nutrient stress are areas that must be addressed in the future as a way of building a climate-smart agroecosystem.

5 | CONCLUSIONS

Pea–barley intercropping combined with OA enhanced multiple agronomic outcomes, including AGDB, grain yield, land productivity, N-uptake, and barley protein content. Across all OA, PB IC increased AGDB by 18%–57% and grain yield by 12%–134% and improved grain N-uptake compared to monocrops. These gains reflect improved resource-use efficiency through complementarity in above and belowground interactions, particularly in the capture and utilization of

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TABLE 5 Selected studies on cereal-legume intercropping combinations, ratios, treatments, land equivalent ratio (LER) values, and effects on productivity, nitrogen uptake, and grain quality.

Studies	Cereal	Legume	IC ratio	Treatment	LER	Yield effect	N/Protein effect	References
1	Barley	Pea	P50:B50 –	Control 100 kg N/ha	1.14 1.1	↑ Biomass by 10%–32% –	↑ Barley grain N by 23% –	Cowden et al. (2020)
2	Wheat	Pea	P50:W50 –	Control 40 kg N/ha	1.34 0.96	↑ Grain yield (2%) ↓ Yield under added N	↑ Grain N uptake (53%) –	Ghaley et al. (2005)
3	Barley	Pea	P50:B50 –	Control 50 kg N/ha	1.11 1.02	↑ Grain yield by 17%–74% –	↑ Grain N uptake (59%); ↓ weeds (280%) (vs. PS) –	Hauggaard-Nielsen et al. (2001)
4	Oats	Pea	P100:O20 –	Control Manure Compost	1.1 1.14 1.20	–	↑ N in oat by 16%, in pea by 5% ↑ N fixation by 60% ↑ N fixation by 33%	Jannoura et al. (2014)
5	Maize	Soybean/peanut	M75:S60/P60 –	Biochar (20–40 t/ha)	1.14–1.19	↑ Yield by 9%–17% (IC vs. SC)	↑ N uptake by 12%–30%	Liu et al. (2017)
6	Barley	Red pea	P60:B40 P80:B20	–	1.04 0.94	–	↓ Protein in IC vs. SC	Vlachostergios et al. (2015)
7	Barley	Pea	P75:B75 P90:B50	–	1.16 1.11	–	↑ Barley protein by 9% ↑ Barley protein by 6%	Reuter et al. (2022)
8	Barley	Pea	P1:B1 P1:B2 Mixed	–	1.15 1.32 1.12	↑ Grain yield in IC	↑ BNF by 23%, ↑ nodulation by 36%, ↑ barley protein by 13%–28%	Chapagain and Riseman (2014)
9	Maize	Groundnut	–	Swine manure Sheep–goat manure	1.59 1.67	↑ Yield by 27%–52% (IC vs. SC) –	–	Mbah et al. (2020)
10	Maize	Mungbean	M50:Mu50 M75:Mu25 M25:Mu75	Control Vermicompost (2.5 t/ha) Vermicompost (5 t/ha)	1.15 1.17 1.19	–	↑ Maize protein by 43%–57% – –	Niazi et al. (2017)
11	Wheat/rye/triticale	Pea	P60:C40 P80:C20	–	0.98–1.10 1.08–1.19	– ↑ N uptake in all three cereals	↑ Protein by 14%–19% –	Lithourgidis et al. (2011)
12	Barley	Fababean	B100:F12.5 B100:F25 B100:F37.5 B100:F50 B100:F62.5	–	1.05 1.08 1.23 1.17 1.21	– – ↑ Yield and SPI – –	–	Agegnehu et al. (2006)

Abbreviations: BNF, biological nitrogen fixation; PS, pea sole; SPI, system productivity index.

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nutrients, water, and light. Pelletized frass amplified the intercropping effects by increasing grain yield and N-uptake by 105% and 101%, respectively, relative to the control. Pea–barley intercropping and OA have the potential to improve the protein content of barley grains, and insect frass from yellow mealworm increased the protein content in BIC by 28% compared to BS, indicating that the use of OA can optimize resource use efficiency, enhance crop quality, and reduce environmental impacts, thus contributing to sustainable agricultural intensification. Thus, the combination of intercropping and OA is an effective strategy for the sustainable intensification by minimizing the use of inorganic inputs, improving soil fertility, and promoting the productivity of agroecosystems. Moreover, long-term experiments and optimization of different agro-ecological environments will be required to maximize the benefits of the environmentally friendly CS.

AUTHOR CONTRIBUTIONS

Saad Mir: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Vaibhav Pradip Chaudhary**: Data curation; formal analysis. **Nicolò Maria Villa**: Resources; writing—review and editing. **Bhim Bahadur Ghaley**: Conceptualization; funding acquisition; methodology; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts interest.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

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