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Barley–field bean intercropping improves grain quality with reduced nitrogen inputs

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Abstract

The practice of growing two or more crops on the same land at the same time is called intercropping, a diversification strategy that enhances the sustainability of cropping systems. Its alignment with high-input, mechanized feed production has not been thoroughly evaluated, and its impact on grain quality attributes beyond protein remains inadequately addressed. On a loam Xerofluvent soil in Italy, this 2-year field study compared barley (*Hordeum vulgare* L.) and field bean (*Vicia faba* L. var. *minor*) sole crops and their intercropping under five nitrogen (N) rates (0–200 kg N ha^{-1}) to assess grain quality and nutrient yield. Intercropped barley exhibited higher crude protein concentrations than sole-cropped across N rates, whereas sole-cropped barley required high nitrogen inputs to achieve similar protein content. Intercropping increased ether extract and fiber fractions but reduced nonfibrous carbohydrates and total digestible nutrients in barley grain. In field bean, intercropping increased fat and cellulose but reduced protein and digestible nutrient yields. The grain of barley–field bean intercropping resulted in higher protein and fiber concentration, but lower starch and digestibility compared with sole crops. Notably, increasing N fertilization had limited effects on grain quality and nutrient yield in intercropping, suggesting that farmers could use less nitrogen inputs while maintaining grain quality. These findings demonstrate that barley–field bean intercropping can improve grain nutritional balance for animal feeding while reducing dependence on N fertilizers, thereby supporting intercropping as a viable diversification strategy for improving nitrogen-use efficiency in mechanized feed production systems that use mixed grains.

Plain Language Summary

Growing barley and field bean together helps crops use resources more efficiently but factors affecting grain quality are not fully understood. In a 2-year field study, we

Abbreviations: ADF, acid-detergent fiber; ADL, acid-detergent lignin; AS, ash; CP, crude protein; CS, cropping system; EE, ether extract; IC, intercropping; NDF, neutral-detergent fiber; NFC, nonfibrous carbohydrate; NR, nitrogen rate; SC, sole cropping; TDN, total digestible nutrients.

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compared intercropping with sole cropping under different nitrogen fertilizer rates. We found that intercropping, regardless of nitrogen fertilizer level, increased grain protein, fat, and fiber content while only slightly reduced digestibility compared to monocultures. Barley grown with field bean always had more protein than when grown alone. Importantly, grain quality in intercrops did not improve with higher nitrogen fertilizer rates, indicating that farmers can reduce fertilizer use without sacrificing feed quality. Overall, intercropping barley and field beans is a good way to produce high-quality animal feed while using less synthetic fertilizer and reducing environmental harm.

1 | INTRODUCTION

Sustainable intensification seeks to enhance agricultural productivity while preserving soil, ecosystem, human, and environmental health (Pretty & Bharucha, 2014); it particularly emphasizes avoiding historically documented ecological failures (Clay et al., 2024), such as those arising from the industrialization of agriculture (i.e., simplified cropping systems (CSs) and high external inputs), which raised concerns about long-term sustainability and resilience of intensive CSs (Cochrane, 1993). To prevent repeating the mistake of oversimplifying agroecosystems, strategies like crop rotation, cover cropping, and intercropping (IC) are increasingly recommended (Altieri et al., 2015; Tilman et al., 2002; Wezel et al., 2014). Intercropping (i.e., the practice of cultivating two or more crops together at the same time in the same field) has been shown to enhance resource use efficiency, promote soil fertility, and support biodiversity compared to monocultures (Vandermeer, 1992). IC contributes to multiple ecosystem functions central to sustainable CSs (e.g., enhanced nutrient cycling, reliance on synthetic inputs, and increased system stability) that align with sustainable intensification goals (e.g., improved land-equivalent ratios and soil health outcomes).

However, while crop rotation and cover cropping are widely adopted in large-scale CSs (Obour et al., 2021, 2022; Tyler et al., 2025), IC remains relatively underutilized, particularly in mechanized and high-input systems (Mbanyele et al., 2024). Despite the several documented benefits of IC, its integration into industrialized agriculture is constrained by uncertainties about system design, crop compatibility, nitrogen (N) management, and suitability for mechanized grain production (Pampana et al., 2022). Furthermore, a recent review indicates that diversified CSs can improve crop quality through multiple agronomic and ecological mechanisms, while also noting that agronomic effects on feed grain quality—particularly beyond crude protein (CP)—remain insufficiently explored in CSs research (Fan et al., 2025). Nevertheless, in recent interviews with farmers, they quoted the difficulty in agronomic management as a major problem, while fodder quality was cited as one of the most important reasons for intercropping (Stone & Thorsøe, 2023). Addressing these knowledge gaps is therefore critical for assessing the potential of intercropping as a scalable diversification strategy in contemporary, mechanized CSs (Bedoussac et al., 2015; Mbanyele et al., 2024) and requires a robust evaluation of whether intercropping can reliably maintain or improve grain quality.

In cereal–legume intercropping systems, the balance between competition and facilitation plays a key role in determining crop performance and resource-use efficiency (Agegnehu et al., 2008; Bedoussac et al., 2015; Hauggaard-Nielsen & Jensen, 2001; Tosti et al., 2010). Facilitative interactions are mainly associated with the legume's ability to fix atmospheric nitrogen, which can enhance nitrogen availability for the companion cereal, particularly under low soil N conditions (Bedoussac et al., 2015; Hauggaard-Nielsen & Jensen, 2001; Jensen, 1996; Rodriguez et al., 2020; Tosti et al., 2010). At the same time, competitive interactions may arise for other resources such as light, water, and soil nutrients, and their intensity depends on species traits, plant density, and spatial arrangement (Connolly et al., 2001; Martin & Snaydon, 1982; Tosti et al., 2010; Vandermeer, 1992). The outcome of these interactions often results in asymmetric competition, where cereals tend to dominate for soil mineral nitrogen while legumes rely more on biological N_2 fixation (Li et al., 2020; Rodriguez et al., 2020). Moreover, the magnitude and direction of competition and facilitation processes are strongly influenced by environmental conditions, including soil characteristics (Bedoussac et al., 2015) and seasonal weather patterns (Lithourgidis & Dordas, 2010; Mariotti et al., 2018). Therefore, understanding how these biotic and abiotic factors interact is essential for optimizing intercropping design and management under different agroecological conditions.

However, most existing studies focused on forage or low-input systems (Bacchi et al., 2021; Tsialtas et al., 2018; Zhu et al., 2022), and there is a knowledge gap regarding grain quality responses and nitrogen requirements in mechanized, high-input environments. Nitrogen availability plays a

crucial role in determining grain quality in cereals (Garrido-Lestache et al., 2004), which is why high levels of synthetic fertilizer or manure are frequently applied to meet their nitrogen requirements. However, in systems with low N input, it becomes challenging to achieve sufficient grain yield and protein content. To address these challenges, cereal–legume intercropping is often implemented, as legumes can increase N availability for companion non-fixing crops. Consequently, determining the optimal nitrogen fertilizer rate is essential to ensure that soil N availability meets the cereal's needs and to obtain high-quality grain.

Barley (*Hordeum vulgare* L.) is extensively cultivated in Italy, covering around 239 kha (ISTAT, 2024), and primarily serves as grain and forage for animal feed (Royo et al., 1997). The grains represent an important energy source due to high starch concentration; also, compared with corn, they offer more protein, methionine, lysine, cysteine, and tryptophan (Acosta et al., 1991; Nikkhah, 2012). Field bean (*Vicia faba* L. var. *minor*) is widely used in the Mediterranean environment for grain, green manure, and forage. Well suited to temperate growing conditions, it might serve as a promising alternative to pea and common vetch for forage production, providing higher protein concentration and stem strength (Strydhorst et al., 2008) and to soybean for feed grain (Volpelli et al., 2010).

Barley–field bean intercropping has been investigated for several agronomic and environmental aspects and previous studies have explored its effects on nitrogen leaching (Mariotti et al., 2015), forage production and quality (Agegnehu et al., 2006; Angeletti et al., 2024; Lithourgidis & Dordas, 2010; Pampana et al., 2022; Strydhorst et al., 2008), and N_2 fixation (Knudsen et al., 2004).

However, compared with forage-related quality traits (Angeletti et al., 2024; Billman & Myers, 2024; Sadeghpour et al., 2013), grain quality for animal feed has received much less attention (Carr et al., 2025) despite its importance for livestock production systems.

To address these knowledge gaps, our study evaluated the effects of barley–field bean intercropping and nitrogen fertilization on grain quality and nutrient yields under Mediterranean conditions. In addition to CP, key grain components relevant to animal nutrition were assessed, including ether extract (EE) (which indicates fat content), neutral and acid-detergent fiber (NDF and ADF) (representing parts of plant cell walls), nonfibrous carbohydrates (NFCs) (easily digestible energy sources), and total digestible nutrients (TDN) (a standard measure of energy for both feed composition and animals' needs).

The specific objectives were (1) to determine whether barley–field bean intercropping improves grain nutritional value compared with sole cropping, and (2) to identify N-fertilization rates that optimize grain quality in intercropping systems.

Core Ideas

- Intercropping increased barley grain protein by ~30% at low N compared with sole cropping.
- Barley grain quality in intercrops varied <6% across 0–200 kg N ha^{-1} versus 26% in sole crops.
- Intercropping raised grain fiber fractions by 7%–10% while reducing digestibility by only ~1%.
- High N rates increased sole-crop nutrient yields but had limited effects in intercrops.
- Stable feed grain quality was achieved with null and low N rates in intercropping.

2 | MATERIALS AND METHODS

Data for this study were obtained from a larger experiment conducted over two consecutive cropping seasons—from November 2014 to June 2015 and from November 2015 to June 2016—at the Research Centre of the Department of Agriculture, Food, and Environment of the University of Pisa, Italy (43°40′ N, 10°19′ E) evaluating five nitrogen rates (NRs) for barley and field bean in both sole cropping and intercropping systems. The soil is classified as loamy Xerofluvent (Soil Survey Staff, 1999), containing approximately 2.1% organic matter as determined by the Walkley and Black method. Total nitrogen content was measured at around 1 g kg^{-1} using the Kjeldahl method (Angeletti et al., 2023). The climate is classified as typical Mediterranean (Csa), with hot summers and cool winters that warm up quickly in spring. According to long-term averages (Angeletti et al., 2023), rainfall mainly occurs in autumn and spring, with the site receiving an average annual rainfall of 971 mm. The long-term mean annual maximum and minimum daily air temperatures are 20.2°C and 9.5°C, respectively.

Earlier work addressed biomass production (Pampana et al., 2022) and forage quality and nutrient yield (Angeletti et al., 2024), while here we present grain quality and nutrient yield data of this cereal–legume intercrop, providing practical insights for the development of mechanized intercropping systems. We measured key bromatological parameters (in % of dry weight [DW]) and nutrient yield (in kg ha^{-1}) in barley and field bean grains across three CSs: barley sole crop, field bean sole cropping (F-SC), and intercropping of barley and field bean in a 1:1 additive design and under five NRs: 0, 50, 100, 150, and 200 kg N ha^{-1}. The highest NR (i.e., 200 kg N ha^{-1}) was included as the upper bound of the experimental gradient to represent input-intensive barley management and to test whether barley–field bean intercropping could maintain or even improve grain quality under a wide range of N availability. Nitrogen fertilization was split into a small starter

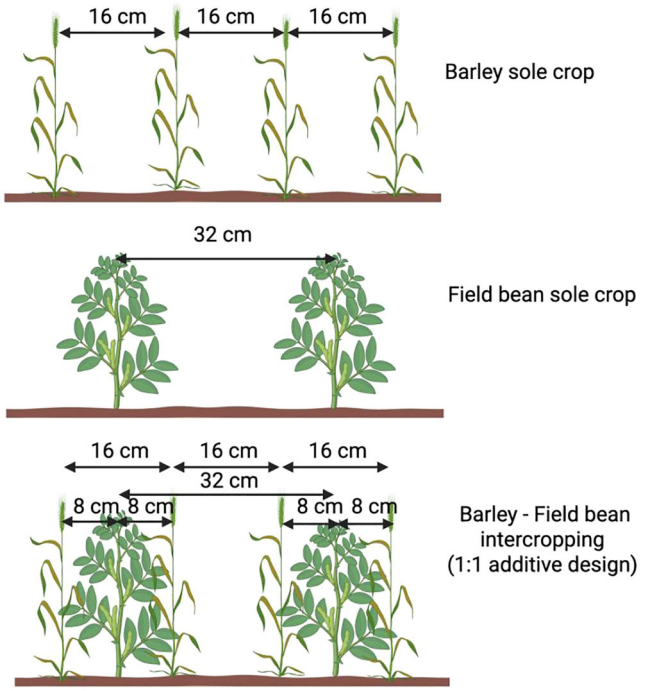

FIGURE 1 Design of the three cropping systems studied in Pisa, Italy. Crop distribution and row spacing (cm) in barley sole crop, field bean sole crop, and barley–field bean intercropping 1:1 additive design. Created in BioRender (https://BioRender.com/qder5ze; Pampana 2025).

dose at sowing (25 kg N ha^{-1}) and a main topdressing at barley stem elongation (BBCH 30), following the fertilization scheme adopted in the larger experiment and maintaining the same timing across the three CSs (i.e., sole crops and intercrops) to ensure a balanced experimental setup and enable robust comparative analysis.

Each year, the experimental design consisted in a randomized complete block design, replicated three times, including 15 treatments (3 CS × 5 NR) for a total of 45 plots (15 × 3 replicates) of about 21 m^2. The barley used in this study was the Ketos cultivar, derived from (Gotic × Orblonde) × (12,813 × 91H595), and the field bean was the Chiaro di Torrelama cultivar, both largely cultivated in Italy.

Sowing was conducted with a Wintersteiger Øyjord plot drill (model 1983) on November 18, 2014, and November 12, 2015. Barley was sown at 400 seeds m^{-2}, with 16-cm row spacing, and field bean at 70 seeds m^{-2} with 32-cm spacing. In the IC plots, the two species were sown sequentially: barley was first sown with the same apparatus of the sole crop, and field bean was subsequently sown in a second pass between the barley rows to achieve the planned 1:1 additive row arrangement, that is, the density of each component was the same as the density of the sole crop (Snaydon, 1991) (Figure 1). The additive design was chosen because it allows interspecific competition to be studied without being confounded by the effects of intraspecific competition, as occurs in replacement designs (Snaydon, 1991), and to maintain the compatibility with standard mechanized practices used in commercial cereal-based CSs.

Phosphorus and potassium fertilizers (as triple superphosphate and potassium sulphate) were applied at 150 kg ha^{-1} of P_2O_5 and K_2O before sowing in all plots. Nitrogen was applied as urea, except in unfertilized control plots, with 25 kg ha^{-1} at sowing and again during pseudo-stem elongation (BBCH 30) on February 14, 2015, and February 22, 2016. As the presence of the weeds and pathogens was negligible in both years, no application of herbicide and pesticide was performed.

Grain harvests took place on June 18, 2015, and June 14, 2016, when barley was at full ripening (BBCH 92) (Meier, 2001) and field bean at 40% ripening (BBCH 84). Plants from contiguous 100-cm-long rows were manually cut at the ground level. The number of rows varied by CSs: six for barley sole cropping (B-SC), three for F-SC, and six of barley plus three of field bean for the intercropping (IC). In IC samples, cereal and legume components were separated. Grain from both IC and SC samples was harvested, weighed and oven-dried at 65°C to constant weight for dry matter measurement.

Grain samples were then milled to pass a 1-mm sieve, and analyzed to determine CP, ash (AS), EE, NDF, ADF, and acid-detergent lignin (ADL), according to Martillotti et al. (1987). NFC and total digestible nutrients (TDN) were estimated using the equations from NRC (2001) as follows:

$$\text{NFC } (\%) = 100 - (\text{NDF}\% + \text{CP}\% + \text{EE}\% + \text{AS}\%) \quad (1)$$

$$\text{TDN } (\%) = (-1.291 \times \text{ADF}) + 101.35 \quad (2)$$

Nutrient yields (of CP, EE, NDF, ADF, NFC, and TDN) per unit area were calculated by multiplying the grain DM yield by the corresponding concentrations.

Hereafter, we refer to "combined grain" as the total grain produced by barley and field bean, whether grown as sole crops or intercropped, measured over an equivalent area (specifically, 1 ha of intercropping or the combined area of 0.5 ha each of barley and field bean sole crops), as already described for the "combined forage" by Angeletti et al. (2023). Accordingly, data for sole-cropped barley and field bean were averaged to enable a direct comparison with the area-equivalent scale of intercropping, which utilized half the land area. Conversely, for IC values were summed since both crops were cultivated together on the same plot. This approach allows a theoretical comparison of grain yields between mixed SC and IC systems.

For the combined grain, nutrient concentrations were derived by dividing the nutritive yield of each bromatological trait (from either combined SC or IC) by the corresponding grain DW, thus expressing values on a concentration basis.

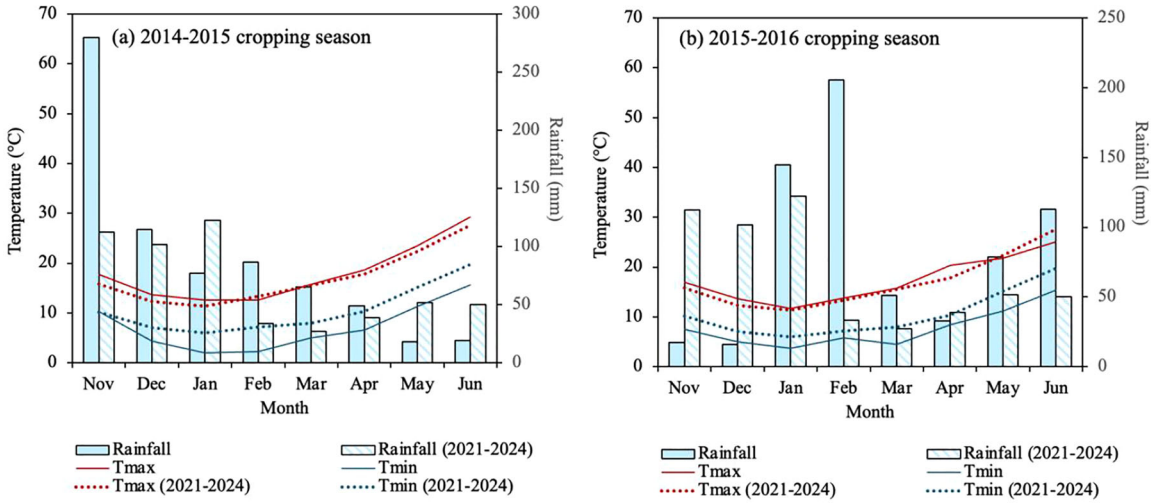

FIGURE 2 Rainfall and maximum and minimum temperatures across the cropping season (November–June) at Pisa, Italy, for (a) 2014–2015 and (b) 2015–2016, compared with the last 5-year (2021–2024) reference period. Solid bars and lines indicate monthly mean rainfall (mm) (secondary *y*-axis) and monthly minimum and maximum air temperatures (˚C) (primary *y*-axis), while hatched bars (secondary *y*-axis) and dashed lines (primary *y*-axis) denote rainfall and temperatures for 2021–2024 period.

The cropping season and its interaction with the CS and NR treatments were not found significant by the analysis of variance (ANOVA) for any of the studied parameters, and the Barlett's test revealed the homogeneity of variance over the 2 years. Therefore, a combined ANOVA over the two seasons was performed arranging data in a split–plot design with NR as the main plots and CS as the subplots and all data were shown as the average over the two cropping seasons. For significant main effects or interactions between NR and CS treatments, the values were separated at the 0.05 probability level following Tukey's Honestly Significant Difference (HSD) Test.

3 | RESULTS

Rainfall distribution differed markedly between years: In 2014–2015, rainfall was about 50 mm higher than in 2015–2016 (710 mm vs. 659 mm), concentrated in November–December, and in January–February in 2015–2016 (Figure 2). To better interpret the potential implications for fertilizer N availability and recovery, 10-day rainfall totals are reported in Figure S1.

Mean maximum and minimum temperatures were similar across both seasons, at roughly 18˚C and 7˚C, respectively (Figure 2); moreover, in both experimental seasons, minimum temperatures during winter were lower than those of the reference period, whereas maximum temperatures were close to the reference values.

Overall, the average values and patterns of variability observed between the two cropping seasons were consistent with those documented in the recent 5-year period 2021–2024, indicating that these data are representative of current climate conditions in the experimental area (Figure 2).

3.1 | Barley grain

3.1.1 | Bromatological traits

The CS significantly affected barley grain bromatological characteristics (i.e., composition): IC increased EE, NDF, and ADF by 11%, 10%, and 7%, while reducing NFC and TDN by 8% and 1%, compared to SC (Table 1).

NR significantly varied the nutritive value of barley grain (Table 2): from N0 to N200, the concentrations of AS, ADF, and ADL decreased almost progressively up to 18%, 22%, and 23%, respectively, while the TDN concentration slightly increased (+2%).

Nitrogen fertilization affected the CP concentration, differently depending on the CSs, that is, the CS × NR interaction was significant (Figure 3). Thus, in intercropped barley, increasing N from N0 to N200, had little effect on grain CP concentration, which measured near 10%, while in sole-cropped barley grain, CP concentration increased by about 26% in relative value from N0 to N200, but remained lower than in IC barley at all NRs.

3.1.2 | Nutrient yield

To improve readability, only CP yield, as the most informative species-specific quality trait, is presented in the main text for

TABLE 1 Mean concentration of ether extracts (EE), neutral-detergent fiber (NDF), acid-detergent fiber (ADF), nonfibrous carbohydrate (NFC), and total digestible nutrients (TDN) in barley grain, as affected by cropping system (CS) main effect. Values are means of 2 years, five N rates, and three replicates.

Cropping system	EE (%)	NDF (%)	ADF (%)	NFC (%)	TDN (%)
Barley sole crop	1.52b	23.2b	6.8b	65.3a	92.5a
Intercropped barley	1.68a	25.5a	7.3a	60.0b	91.9b

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 2 Mean concentration of ash (AS), acid-detergent fiber (ADF), acid detergent lignin (ADL), and total digestible nutrients (TDN) in barley grain, as affected by nitrogen rate (NR) main effect. Values are means of 2 years, two cropping systems, and three replicates.

Nitrogen rate (kg ha^{-1})	AS (%)	ADF (%)	ADL (%)	TDN (%)
0	2.95a	7.85a	0.52a	91.2c
50	2.77b	7.54a	0.56a	91.6c
100	2.63bc	7.18b	0.51a	92.1b
150	2.41d	6.50c	0.41b	93.0a
200	2.49cd	6.22c	0.40b	93.3a

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

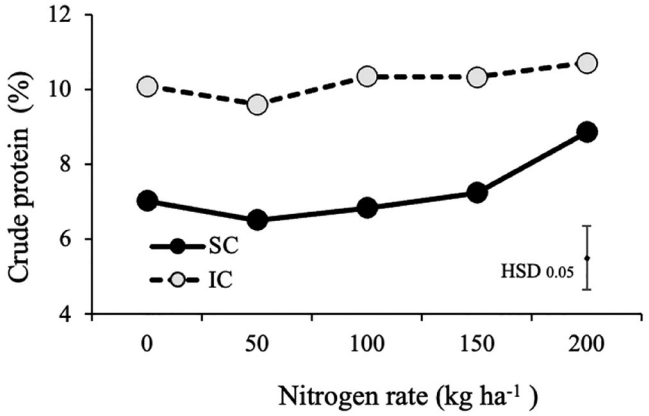

FIGURE 3 Mean concentration of crude protein in barley grain, as affected by nitrogen rate (NR) × cropping system (CS) interaction. Values are means of 2 years and three replicates. The vertical line represents HSD at $p \leq 0.05$. IC, intercropping; SC, sole cropping.

barley and field bean (Figure 4a,b), whereas the remaining nutrient-yield responses are provided in the Figures S2 and S3.

Barley grain nutrient yield per unit area was influenced by the NR × CS interaction (Figure 4a; Figure S2). Overall, in intercropping, values varied only slightly, mainly at the highest N dose, whereas in sole cropping, the responses to N fertilizer were larger and more consistent, with increases from N0 to N200 ranging from 263% (CP) to 111% (ADF). Barley grain nutrient contents of EE, NDF, ADF, NFC, and TDN are shown in Figure S2.

3.2 | Field bean grain

3.2.1 | Bromatological traits

The CS influenced the field bean grain composition: EE and NDF concentrations were by 52% and 5% higher in IC than in SC (Table 3), whereas AS, ADL, and NFC concentrations were lower by −7%, −6%, and −5%, respectively (Table 3).

NR (Table 4) caused significant variations in field bean grain quality, but only the highest NR changed ADF and TDN concentrations: the former increased by 6%, the latter slightly decreased. ADL concentration, indeed, was the lowest and NFC the highest at N50 and N100 rates, respectively.

3.2.2 | Nutrient yield

EE nutrient yield (kg ha^{-1}) of field bean grain was affected by both the CS and the NR. Switching from SC to IC, increased EE yield by 8% (Table 5), while raising N from N0 to N200, resulted in a 42% increase (Table 6).

The CS also influenced the NDF yield, and field bean grain in SC produced 32% more NDF than in IC (Table 5).

Field bean grain yields were influenced by the interaction NR × CS (Figure 4b; Figure S3). Across all NRs, CP yield was consistently higher in sole cropping than in intercropping, and the response to increasing N was generally more evident in sole cropping (Figure 4b). Overall, as fertilizer rate increased, the values for SC increased up to approximately 30%, while those for IC remained unchanged (CP, ADF, and NFC) or decreased, especially with the highest NR N200 (Figure S3).

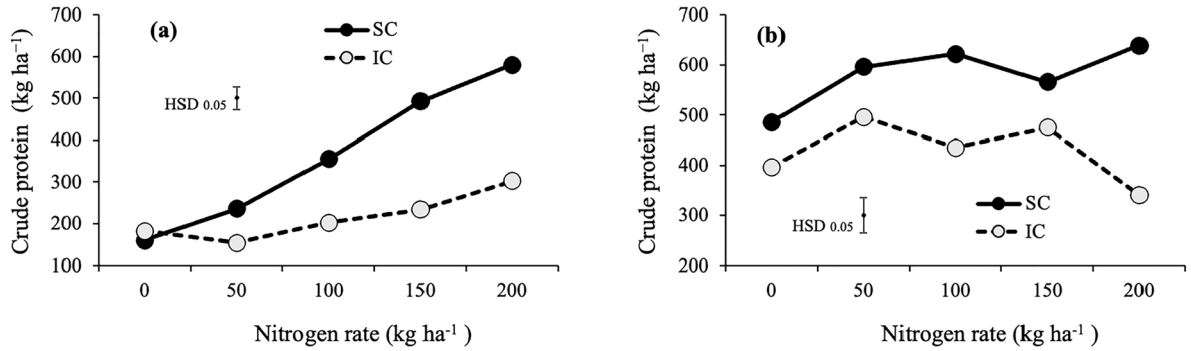

FIGURE 4 Mean nutrient crude protein yields of in (a) barley grain and (b) field bean grain, as affected by nitrogen rate (NR) × cropping system (CS) interaction. Values are means of 2 years, and three replicates. The vertical lines indicate HSD at $p \leq 0.05$. IC, intercropping; SC, sole cropping.

TABLE 3 Mean concentration of ether extracts (EE), ash (AS), neutral-detergent fiber (NDF), acid-detergent lignin (ADL), and nonfibrous carbohydrate (NFC) in field bean grain, as affected by cropping system (CS) main effect. Values are means of 2 years, five N rates, and three replicates.

Cropping system	EE (%)	AS (%)	NDF (%)	ADL (%)	NFC (%)
Field bean sole crop	0.79b	4.32a	31.3b	0.85a	42.2a
Intercropped field bean	1.20a	4.00b	32.9a	0.80b	40.1b

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 4 Mean concentration of acid-detergent fiber (ADF), acid detergent lignin (ADL), nonfibrous carbohydrate (NFC), and total digestible nutrients (TDN) in field bean grain, as affected by nitrogen rate (NR) main effect. Values are means of 2 years, two cropping systems, and three replicates.

Nitrogen rate (kg ha^{-1})	ADF (%)	ADL (%)	NFC (%)	TDN (%)
0	15.0b	0.86b	38.3b	82.0a
50	14.9b	0.66c	45.5a	82.2a
100	14.9b	0.63c	43.6a	82.1a
150	15.2b	0.92b	39.4b	81.8a
200	15.9a	1.06a	39.1b	80.8b

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 5 Mean nutrient yields of ether extracts (EE) and neutral-detergent fiber (NDF) in field bean grain, as affected by cropping system (CS) main effect. Values are means of 2 years, five N rates, and three replicates.

Cropping system	EE (kg ha^{-1})	NDF (kg ha^{-1})
Field bean sole crop	21.5b	842.1a
Intercropped field bean	23.3a	638.5b

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 6 Mean nutrient yields of ether extracts (EE) in field bean grain, as affected by nitrogen rate (NR) main effect. Values are means of 2 years, two cropping systems, and three replicates.

Nitrogen rate (kg ha^{-1})	EE (kg ha^{-1})
0	17.5c
50	21.6b
100	23.2ab
150	24.9a
200	24.9a

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 7 Mean concentration of ether extracts (EE), neutral-detergent fiber (NDF), acid detergent fiber (ADF), nonfibrous carbohydrate (NFC), and total digestible nutrients (TDN) in combined grain, as affected by cropping system (CS) main effect. Values are means of 2 years, five N rates, and three replicates.

Cropping system	EE (%)	NDF (%)	ADF (%)	NFC (%)	TDN (%)
Combined sole crops	1.23b	26.3b	10.0b	56.6a	83.8a
Combined intercropped crops	1.47a	28.7a	10.9a	50.7b	82.8b

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 8 Mean concentration of ether extracts (EE), neutral-detergent fiber (NDF), acid detergent fiber (ADF), nonfibrous carbohydrate (NFC), and total digestible nutrients (TDN) in combined grain, as affected by nitrogen rate (NR) main effect. Values are means of 2 years, two cropping systems, and three replicates.

Nitrogen rate (kg ha^{-1})	EE (%)	NDF (%)	ADF (%)	NFC (%)	TDN (%)
0	1.24c	29.9a	11.4a	50.3b	81.8b
50	1.30bc	25.4c	11.2ab	55.1a	83.8a
100	1.37ab	26.3c	10.4b	55.1a	83.7a
150	1.44a	28.0b	9.8c	53.8a	83.4a
200	1.41a	27.9b	9.5c	53.9a	83.7a

Note: Within a column, means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

3.3 | Combined grain (system-level response)

3.3.1 | Bromatological traits

Considering the grain of combined crops (i.e., the two crops grown on the same unit area), the concentrations of EE, NDF, ADF, NFC, and TDN were influenced by the CS (Table 7), and intercropping raised EE by 20%, and NDF and ADF by 9%, while decreasing NFC by 10% and TDN by 1% compared to the two sole crops.

EEs concentration increased progressively with NR up to N150 and then plateaued, whereas NDF and ADF decreased with a similar trend (Table 8). Conversely, NFC and TDN concentrations were higher at all NRs than in unfertilized control.

Nitrogen had different effects on CP, AS, and ADL concentrations in the two CSs (Figure 5); in intercropping it had little or no effect, whereas in sole crops, the values decreased by 26%, 24%, and 61% particularly between 0 and 150N.

3.3.2 | Nutrient yield

The nutrient yield of NDF in the combined grain was influenced by both CS and NR. NDF yield was about 18% higher in IC compared to SC (Table 9), while increasing by about 45% from N0 to N200 (Table 10).

Nitrogen rate influenced several traits differently in the two CSs, as shown by a significant interaction between CS and NR. In IC, NR had minimal effects across rates for most traits (Figure 6), while in SC, increases from N0 to N150 significantly raised 64%, 151%, 56%, 133%, and 115%, respectively, CP, EE, ADF, NFCs, and total digestible nutrients. Further increasing the fertilizer rate to N200 benefited only CP values (+15%). As a result of these different trends in response to NR, nutrient yields were similar in IC and SC at high NR but favored the crops in IC at low NRs.

TABLE 9 Mean nutrient yield of neutral-detergent fiber (NDF) in combined grain, as affected by cropping system (CS) mean effect. Values are means of 2 years, five N rates, and three replicates.

Cropping system	NDF (kg ha^{-1})
Combined sole crops	992.1b
Combined intercropped crops	1169.1a

Note: Means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

TABLE 10 Mean nutrient yield of neutral-detergent fiber (NDF) in combined crops grain, as affected by nitrogen rate (NR) mean effect. Values are means of 2 years, two cropping systems, and three replicates.

Nitrogen rate (kg ha^{-1})	NDF (kg ha^{-1})
0	887.6c
50	896.0c
100	1060.5b
150	1282.7a
200	1276.3a

Note: Means with a letter in common are not significantly different at the 5% level according to Tukey's HSD test.

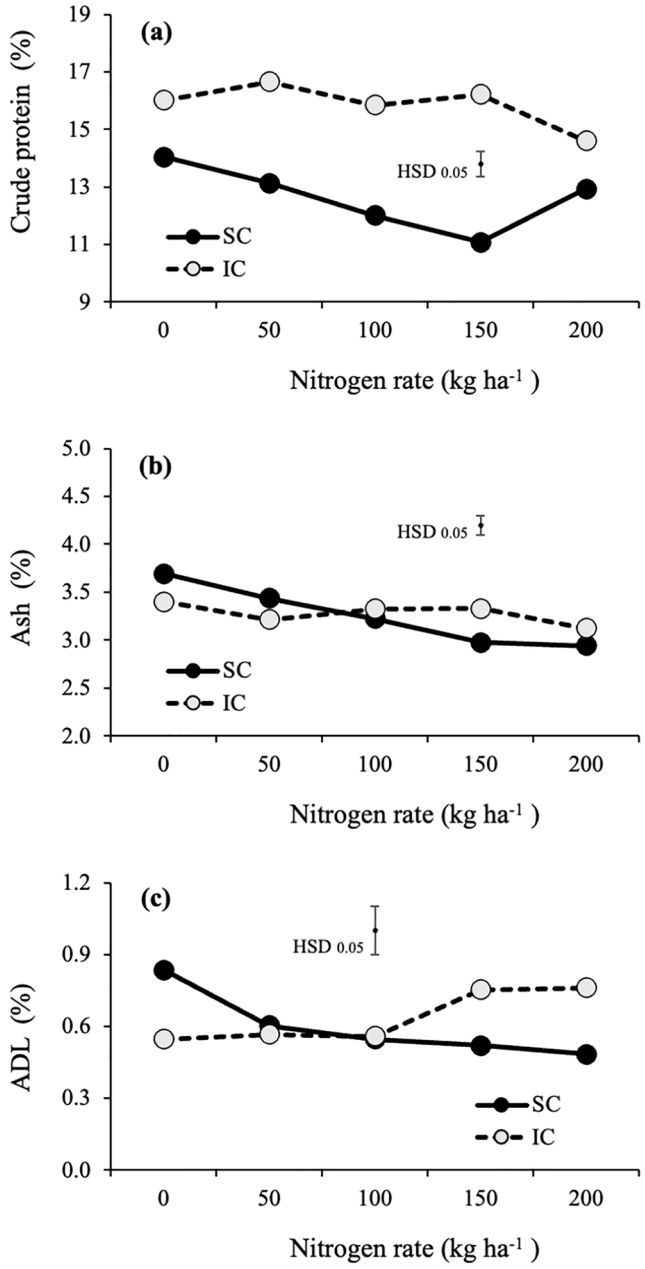

FIGURE 5 Mean concentration of (a) crude protein, (b) ash, and (c) acid-detergent lignin (ADL) in combined grain, as affected by nitrogen rate (NR) × cropping system (CS) interaction. Values are means of 2 years and three replicates. The vertical lines indicate HSD at $p \leq 0.05$. IC, intercropping; SC, sole cropping.

4 | DISCUSSION

4.1 | Effects of intercropping

Our hypothesis that intercropping barley and field bean boosts grain nutrient yields via complementary resource use, and is affected by nitrogen availability, was supported by the present findings. Crop-specific responses confirmed that the interaction between CS and nitrogen fertilization significantly influenced both grain quality and nutrient yields.

Examining grain composition offers further insight into these mechanisms. In barley, intercropping consistently increased CP concentration compared with sole cropping, irrespective of NR. Sole-cropped barley required more nitrogen inputs to match the protein levels of intercropped barley (CP concentration increasing by about 30% from N0 to N200), confirming that the cultivation with field bean enhanced the nitrogen acquired by the cereal (Guiducci et al., 2018; Rodriguez et al., 2020). This effect is most likely attributable to complementary nitrogen use and indirect benefits of biological nitrogen fixation by the legume, as previously documented in cereal–legume intercrops under Mediterranean conditions (Guiducci et al., 2018; Li et al., 2020; Mariotti et al., 2015; Martin-Guay et al., 2020; Rodriguez et al., 2020).

For feed applications, barley with about 10%–13% CP is generally optimal (Eroshenko et al., 2019; Jaeger et al., 2021), but in our research, barley sole crops never reached this level, while unfertilized barley intercropped with field bean achieved nearly 10%, indicating intercropping improves grain quality. The higher CP in IC likely stems from greater or longer nitrogen uptake through interaction with field bean.

Beyond protein, intercropping increased the concentrations of EE, NDF, and ADF in barley grain, while reducing those of NFC and TDN. This aligns with previous findings from forage-based research (Angeletti et al., 2024; Liu et al., 2023) and extends this evidence to grain production, highlighting the nuanced impact of intercropping on nutritional profiles. In fact, these parameters have rarely been addressed in grain production. In runner bean (*Phaseolus coccineus* L.) and maize (*Zea mays* L.), intercropping had no appreciable effects on the fiber concentration of EE and CP in the grain (Hamburdă et al., 2016). The discrepancies between our findings and those of previous research may be attributable to the specific species selected for intercropping, as well as the use of a non-additive design, which resulted in reduced interactions among species (Snaydon, 1991). For fiber fractions (NDF and ADF), barley grain showed similar but lesser pronounced results than those we obtained in forage (Angeletti et al., 2024), probably because of the differences in tissue structure and cell wall composition (Angeletti et al., 2024; Burton & Fincher, 2014).

In contrast, intercropping had varying effects on field bean grain quality. While EE and cellulose concentrations increased, CP concentration and digestible nutrient yields were reduced compared with sole cropping. These results suggest that competitive interactions with barley limited the legume's access to soil resources, in particular N, thus constraining its grain quality and yield (Pampana et al., 2022; Rodriguez et al., 2020). Similar patterns have been observed in other studies conducted under Mediterranean rainfed conditions, where the legume component was often penalized by intercropping with cereals (Mariotti et al., 2018). Moreover,

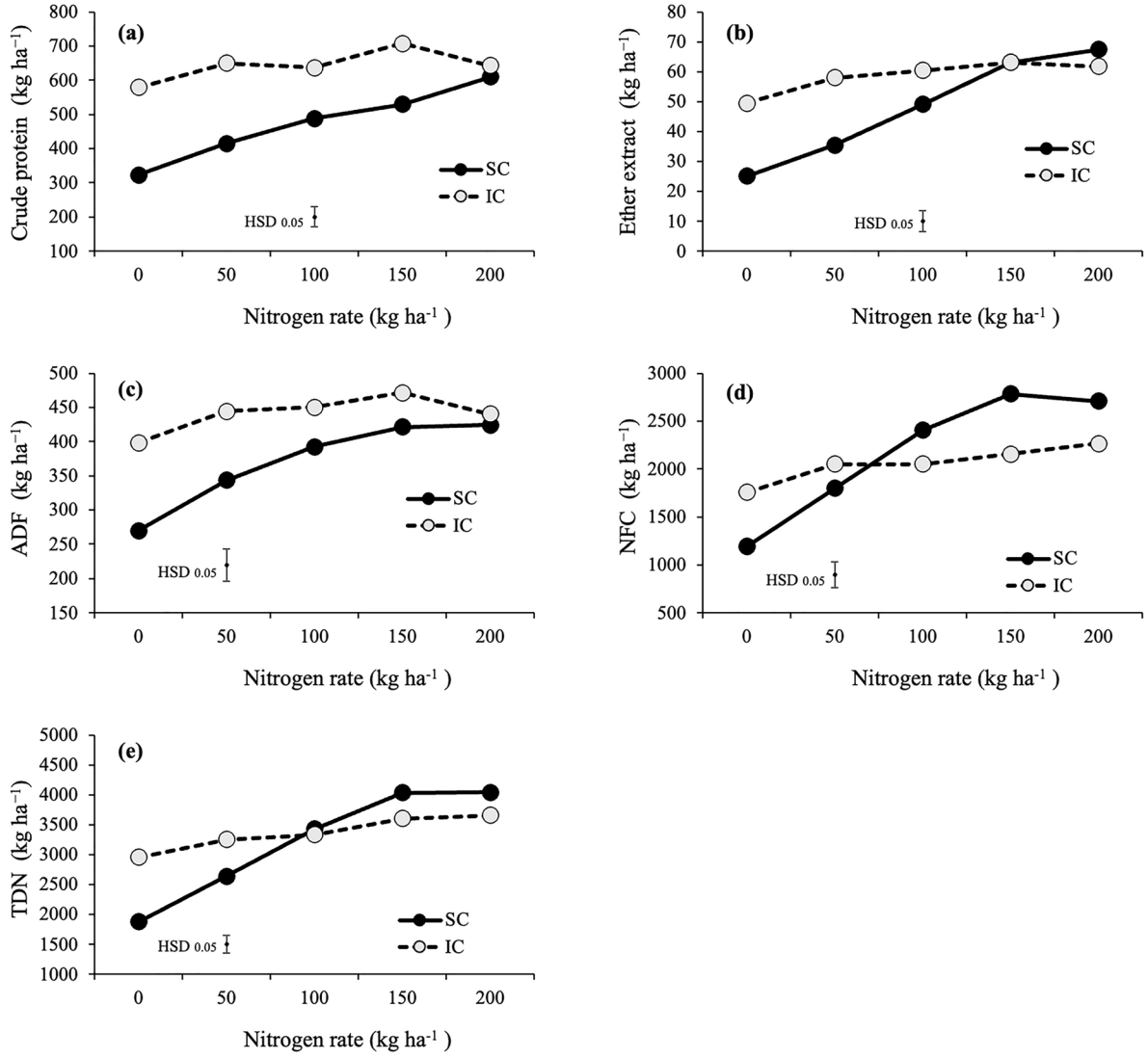

FIGURE 6 Mean nutrient yields of (a) crude protein, (b) ether extracts (EE), (c) acid-detergent fiber (ADF), (d) nonfibrous carbohydrates (NFC), and (e) total digestible nutrients (TDN) in combined crops grain, as affected by nitrogen rate (NR) × cropping system (CS) interaction. Values are means of 2 years and three replicates. The vertical lines indicate HSD at $p \leq 0.05$. IC, intercropping; SC, sole cropping.

the limited responsiveness of intercropped field bean to nitrogen fertilization further suggests a predominant reliance on biological fixation, which is less effective under competitive conditions (Bedoussac et al., 2015; Jensen, 1996),

4.2 | Effects of NR

Nitrogen availability strongly influenced grain quality and nutrient yields in sole crops, while its effects were markedly attenuated in intercropping. As expected, the positive response of barley grain quality and nutrient yield to increasing N fertilization in sole cropping is consistent with well-established evidence from Mediterranean environments (Anderson, 1985; Pampana et al., 2022); however, the weaker response observed in intercropping highlights the role of cereal–legume interactions in improving nitrogen-use efficiency.

Increasing NRs in sole-cropped barley increased CP concentration and nutrient yields as previously demonstrated by Eroshenko et al. (2019), but still resulted in lower values than those observed in intercropped barley, even at the highest NRs. Under Mediterranean rainfed conditions, however, the efficiency of fertilizer N may be reduced when substantial rainfall occurs after application, particularly for fall-applied N and for large single topdressings (Anderson, 1985; García del Moral et al., 1995; Pampana & Mariotti, 2021). Therefore, the weak response observed at the highest NRs may partly reflect lower fertilizer recovery under rainy conditions rather than a lack of crop response. This interpretation is especially relevant for the wetter season, although in the present study the season × treatment interaction was not significant for the final

grain-quality traits. Furthermore, recent research conducted in Italy on barley demonstrates that under conditions of elevated nitrogen availability, the timing of nitrogen application plays a crucial role in managing plant height and reducing the likelihood of lodging (Balducci et al., 2024).

In contrast, intercropped barley had steady CP concentrations across fertilization levels, indicating that intercropping buffered barley against nitrogen limitation and reduced dependence on external fertilizer inputs.

For field bean, nitrogen fertilization influenced only a subset of quality traits, with the highest NR negatively affecting digestibility-related parameters.

Thus, applying 200 kg N ha^{-1} may be excessive for barley–field bean intercropping, but including this rate in our study revealed that such high levels of nitrogen did not benefit the grain quality of the intercrop. Therefore, the inclusion of N200 was useful from an experimental perspective, but the results do not support it as an agronomic recommendation for the intercrop and confirm that high nitrogen applications appear unnecessary in barley–field bean intercrops because moderate fertilization is sufficient to achieve stable nutrient yields and acceptable grain quality for animal feeding. These results have important implications for sustainable agriculture in Mediterranean regions, where reducing synthetic fertilizer use is a priority for environmental protection (Garrido-Lestache et al., 2004; Rodriguez et al., 2020). Although the experiment was conducted at a single location over two growing seasons, similar one-site/two- to three-season designs have been widely used in cereal–legume intercropping research (Agegnehu et al., 2006, 2008; Lithourgidis & Dordas, 2010; Mariotti et al., 2015), and in our study, the absence of significant season × treatment interactions supports the consistency of treatment responses across years.

4.3 | System-level implications of barley–field bean intercropping

Even if agronomic research has found that intercropping cereals with legumes can increase the concentration of nitrogen and protein in the cereal grains, other quality parameters have rarely been studied (Carr et al., 2025) and to the best of our knowledge direct assessments of combined grain composition for animal consumption are not available, with most comprehensive studies concentrating on forage rather than grain (Angeletti et al., 2024; Billman & Myers, 2024; Strydhorst et al., 2008).

In our research, when evaluated at the system level, considering the combined grain harvested from cereal–legume intercrop, the nutritional composition was significantly altered compared with sole cropping systems; intercropping increased CP and structural fiber fractions (i.e., neutral and ADF), whereas reduced NFCs and total digestible nutrients.

The increase in CP in intercropped barley may reflect enhanced N acquisition via cereal–legume complementarity and biological N_2 fixation (Bedoussac et al., 2015; Guiducci et al., 2018; Rodriguez et al., 2020; Tosti et al., 2010). The simultaneous increase in structural fiber and decrease in NFC and TDN indicate a shift in grain composition driven by C–N allocation, whereby improved N availability promotes N-rich and structural compounds at the expense of starch, leading to a trade-off between protein and carbohydrate fractions (Garrido-Lestache et al., 2004).

The increased presence of field bean, which has higher CP and ADF but lower starch than barley, results in IC grains having higher CP and more structural components, but slightly lower NFC (starch) content and reduced digestibility. However, in the context of livestock nutrition, moderate increases in fiber fractions may support rumen function, promote optimal gut motility, and contribute to higher milk fat yields, suggesting functional benefits despite slightly reduced digestibility (Grant, 2023).

A key system-level finding of this study is the limited responsiveness of intercropping systems to increasing NRs, particularly above 100–150 kg N ha^{-1}. Although sole cropping systems exhibited substantial gains with higher nitrogen inputs, intercropping systems maintained relatively stable nutrient yields and quality. Therefore, the reduction in cereal nutrient yields in IC, we observed in this research, confirms a strategic trade-off in which gains in grain quality, nutrient-use efficiency, and stability are prioritized at the system level over maximizing SC output (Zhu et al., 2022).

This conclusion, consistent with other references, supports intercropping as a means of reducing dependence on nitrogen fertilizers and lowering the environmental impact of cereal production (Bedoussac et al., 2015; Glaze-Corcoran et al., 2020; Zhu et al., 2022).

The rainfall variability across the two experimental cropping seasons is characteristic of Mediterranean regions and aligns with current climate trends. Nevertheless, our research demonstrates that IC can improve both grain quality and nutrient yield, and that the impact of nitrogen fertilization surpassed interannual variations. These results provide important information for producers growing feed grains for beef cow/calf pairs, dairy heifers, and non-lactating cows who must deal with year-to-year weather changes (Pandey et al., 2025).

4.4 | Implications for intercropping in mechanized CSs

Barley serves as an important feed grain in Europe and North America—including Canada and the United States—particularly in dairy cows and beef cattle and is often combined with other grains during the beef finishing phase due to its higher fermentability in the rumen (Boyles et al.,

2001; Hunt, 1996). Because the energy and protein content of barley can vary more than that of other grains (Hunt, 1996), grain quality must be carefully evaluated before inclusion in beef and dairy cattle rations. Our results show that barley–field bean intercropping stabilizes grain composition across a wide range of nitrogen fertilizer rates, enhancing system reliability under variable management conditions. While single crops had significant changes in response to higher nitrogen levels, intercrops maintained more stable grain quality and nutrient yields across different fertilization rates. For example, CP in sole barley varied by 26% as NRs increased from 0 to 200 kg N ha^{-1}, while CP in intercropped barley changed by only 6%.

This stability is an indication of improved nitrogen-use efficiency—meaning the plants produce more grain or protein per unit of fertilizer applied—and functional complementarity, where each crop uses resources differently, resulting in better overall system performance. In contrast to sole crops, which require precise fertilization strategies to optimize both yield and quality, intercropping systems appear more buffered against suboptimal nitrogen management, suggesting a simplification of management decisions, a key consideration for adoption in mechanized systems (Mbanyele et al., 2024). Nevertheless, intercropping is likely to be attractive to farmers primarily when it offers greater financial returns than growing single crops. One important benefit of IC can be the enhancement of barley's protein content, which will translate into increased livestock production. Also, our results suggest that adopting intercropping can simplify fertilization decisions, reduce the need for high nitrogen inputs, and decrease production costs while maintaining acceptable grain quality. Additionally, reduced fertilizer use decreases the risk of nitrogen loss, supporting policy goals for environmental protection.

However, by maintaining stable yields and quality, barley–field bean intercropping offers a practical, economically viable, and environmentally friendly approach for mechanized farming systems. Such stability may simplify farm-level decision-making by reducing the need for precise nitrogen input optimization, thereby increasing the robustness of intercropping systems under mechanized management.

While these aspects highlight the potential of intercropping to simplify N management and improve system robustness, practical implementation in mechanized systems also presents some operational challenges (Mbanyele et al., 2024). In particular, the coexistence of species with different phenology and seed characteristics may require adjustments along the production chain. At sowing, achieving the desired spatial arrangement may require modifications to seeding equipment to ensure correct seed placement and species-specific sowing rates, especially in additive designs, and may involve compromises in sowing dates between the two species. A potential limitation for mechanized harvesting arises from the different maturity stages of the component crops (Bedoussac et al., 2015; Mbanyele et al., 2024). In our study, field bean was harvested at approximately 40% ripening (BBCH 84), a stage at which seed moisture is still relatively high (35%–55%), whereas barley had reached full maturity. Such differences may complicate direct mechanical harvesting and could require delayed harvest, swathing, or postharvest drying. Therefore, while combine harvester settings (e.g., threshing intensity and airflow) may need to be adapted to minimize grain losses and damage, particularly when handling grains with contrasting size and texture, synchronizing crop phenology through cultivar choice or management practices represents an important area for future research.

Overall, the buffering capacity observed in intercropping systems may contribute to greater resilience under current variable climatic conditions and fluctuating input prices. In this context, cereal–legume intercropping can be viewed not only as a diversification practice but as a risk-mitigation strategy that enhances system robustness while reducing dependence on external inputs.

5 | CONCLUSIONS

Our study aimed to determine the optimal N-fertilizer rate for achieving high grain quality and to evaluate whether barley–field bean intercropping enhances grain nutritional value compared to sole cropping in Central Italy. Specifically, under Mediterranean rainfed conditions, our findings reveal that applying no N or low rates (N50 and N100) is better for grain yield and quality based on CP concentration and yields and demonstrate that barley–field bean intercropping can improve the grain nutritional balance in grain feed production systems and reduce reliance on synthetic nitrogen fertilizers. This contributes to lower environmental impacts and promotes resilient agricultural systems capable of maintaining productivity under variable climatic conditions. Moreover, the minimal responsiveness of intercropping to increasing NRs highlights its potential as a durable and management-resilient strategy within mechanized grain production systems.

However, the observed reduction in cereal nutrient yield within the intercrop points to the need for further optimization. Future research should investigate optimal sowing ratios and cultivar combinations to maximize nutrient yield in intercrops by enhancing the performance of both species. Additionally, long-term field trials assessing soil health and environmental impacts would further validate the sustainability of these systems. Such studies could provide critical insights for agronomy researchers and policy makers, informing best practices for crop diversification and resource management in Mediterranean and other dryland agroecosystems.

AUTHOR CONTRIBUTIONS

Marco Mariotti: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; validation; visualization; writing—original draft; writing—review and editing. **Iduna Arduini**: Formal analysis; investigation; supervision; writing—review and editing. **Francesco Giovanni Salvo Angeletti**: Investigation; methodology; resources; validation; writing—original draft; writing—review and editing. **Silvia Pampana**: Conceptualization; data curation; formal analysis; investigation; methodology; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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