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Oat Cover Crop Integration in Alfalfa-Tall Fescue Mixed Grasslands: Optimizing Sowing Ratios and Spatial Arrangements for Enhanced Productivity and Weed Suppression

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Keywords: cover crops | forage yield | mixed grasslands | nutritional quality | weed suppression

ABSTRACT

The integration of cover crops during forage establishment represents a widely adopted agronomic strategy to suppress weed emergence, enhance stand establishment, and improve grassland community stability. In this study, a two-year field experiment (2023–2024) was conducted in Jiaozhou, Shandong Province, China, to evaluate the effects of varying sowing proportions of oat (*Avena sativa*), employed as a protective cover crop, on forage productivity and weed dynamics in alfalfa (*Medicago sativa*) and tall fescue (*Festuca arundinacea*) mixed grasslands. The oat sowing ratios were set at 0%, 15%, 30%, 45%, and 60% in 2023, and subsequently refined to 0%, 10%, 20%, 30%, and 40% in 2024, based on first-year performance. Two spatial configurations (same-row and inter-row sowing) were examined to assess resource partitioning effects. Results demonstrated that inter-row sowing combined with moderate oat inclusion (15%–20%) significantly improved system performance. In 2023, inter-row sowing with 15% oat yielded 16.57 t/ha, while in 2024, inter-row sowing with 20% oat achieved the maximum dry matter yield of 18.4 t/ha. Crude protein concentration also improved by 25.6%, reaching 20.13%. Meanwhile, grass and broadleaf weed biomass decreased by 87.2% and 83.4%, respectively, with total weed biomass and coverage reduced by 64.5% and 60.8%. Additionally, the land equivalent ratio (LER) peaked at 1.48, reflecting a 48% increase in land-use efficiency compared to monoculture systems. Collectively, these findings indicate that incorporating 15%–20% oat as a cover crop, particularly under inter-row sowing patterns, offers a practical and ecologically sound strategy for optimizing forage yield, improving nutritional quality, and achieving robust weed suppression. This approach contributes to sustainable intensification and reduced dependence on chemical herbicides in temperate forage systems.

Xiaoyu Zhao and Yuchen Sun contributed equally to this work and share first authorship.

1 | Introduction

Mixed grasslands that combine forage legumes such as alfalfa (*Medicago sativa*) with perennial grasses like tall fescue (*Festuca arundinacea*) are vital for sustainable livestock grazing and forage production in temperate regions (Bi et al. 2019; Clemensen et al. 2017). These systems not only provide high-quality forage but also contribute to ecological sustainability by improving soil health, promoting biodiversity, and supporting carbon sequestration (Büchi et al. 2020). However, maintaining the productivity and ecological balance of these systems poses significant challenges, particularly due to the persistent invasion of weeds. Weed competition for essential resources such as light, water, and nutrients diminishes forage yield and quality, while also threatening the long-term stability of grassland ecosystems (Mahato et al. 2017; Osipitan et al. 2018).

Traditional weed control methods, including herbicide applications and mechanical interventions, though effective in the short term, incur high economic costs and present environmental risks, including soil degradation, water contamination, and loss of biodiversity (Liebman and Davis 2000; Mirsky et al. 2012). These challenges underscore the critical need for sustainable and integrated weed management strategies. In this context, cover crops, particularly oats (*Avena sativa*), have emerged as a promising approach due to their agronomic, environmental, and economic benefits (Mirsky et al. 2012). Oats, as a fast-growing cereal crop, possess traits that make them suitable for integration into mixed grassland systems. Their rapid canopy formation effectively intercepts light, thereby reducing weed germination, which is an important biochemical mechanism that suppresses seedling establishment and plant growth of weeds (Fan et al. 2021; Liebman and Davis 2000). Additionally, oats compete with weeds for resources such as water and nutrients, leading to weed suppression by up to 50% or more in some systems (Boetzl et al. 2023). Such weed suppression mechanisms not only enhance forage productivity but also contribute to the broader goal of reducing herbicide dependence in sustainable agriculture (Baraibar et al. 2017; Elsalahy et al. 2019).

During the early establishment stages (spring and autumn) of perennial mixed grasslands, the incorporation of fast-growing annual grasses such as oat and Italian ryegrass (*Lolium multiflorum*) as protective cover crops can not only effectively suppress weed emergence but also support forage production for the slow-establishing legume-grass mixtures (Poudel et al. 2022). Moreover, tall cereal species like oat can provide windbreak and insulation functions for seedlings, while minimizing nutrient loss from soil erosion during rainy seasons (Bergtold et al. 2020). The legume-grass mixed system itself exhibits strong ecological complementarity, wherein legumes enhance soil nitrogen availability through biological nitrogen fixation (Luo et al. 2024).

Previous studies have demonstrated that reasonable mixing ratios between alfalfa and cereal grasses such as oat can significantly improve total forage yield and competitive advantage, thereby suppressing weed proliferation (Zhang et al. 2011). The integration of oat as a companion crop in mixed forage systems can enhance overall productivity while concurrently reducing the incidence of noxious weeds (Lanini et al. 1992). However, the effects of crop density and spatial arrangement on weed suppression remain less thoroughly investigated in mixed forage systems (Çağlar et al. 2025). For instance, mixtures of common vetch (*Vicia sativa*) and oat at a 3:1 ratio exhibited superior forage productivity, while mixtures of hairy vetch (*Vicia villosa*) and oat at a 1:1 ratio also performed favorably (Sen and Orak 2007). In California-based trials, intercropping oat with alfalfa during establishment increased first-cut yields by 2.45–8.62 kg/ha while concurrently reducing weed densities compared to alfalfa monocultures (Lanini et al. 1992).

Some studies, however, reported contrasting results, indicating that oat inclusion as a protective crop may negatively affect forage nutritional quality compared to pure alfalfa stands, potentially due to inappropriate sowing densities during protective seeding (Matloob et al. 2020). Although many studies have discussed the advantages of both same-row and inter-row legume-grass mixtures, research specifically examining the spatial configuration effects of companion crops remains limited. In *Bromus inermis* and *Onobrychis viciifolia* mixtures, inter-row sowing was shown to improve canopy photosynthetic efficiency and interspecific competitiveness of legumes, resulting in a more stable community structure and higher production performance (Seeno et al. 2022; Weih et al. 2022). Conversely, same-row sowing has been reported to enhance stand stability and improve both forage yield and nutritional quality (Hao et al. 2025).

Beyond weed suppression, oats play a crucial role in improving forage quality and ecological functioning. When sown into mixed grasslands, oats facilitate the establishment of forage species like alfalfa and tall fescue, reducing competitive pressure from early-growing weeds and creating a microenvironment conducive to improved growth (Restovich et al. 2022). Studies have shown that oats can increase the dry matter yield of mixed grasslands by 10%–30%, primarily through reduced competition and enhanced soil fertility (Florence et al. 2019; Samson 1991; Teasdale 1996). The decomposition of oat residues contributes to increased soil organic matter and nutrient availability, promoting forage quality characteristics such as crude protein content, digestibility, and relative feed value (RFV) (Boselli et al. 2021; Kremen and Miles 2012). These improvements enhance livestock productivity while promoting the long-term sustainability of pasture systems (Badreldin et al. 2021; Loucougaray et al. 2015).

While oats offer distinct advantages, maximizing their potential in mixed grassland systems requires further research. Key management considerations, such as planting density, spatial configuration (e.g., inter-row vs. intra-row planting), and timing of oat termination, significantly influence the balance between competitive and facilitative interactions in these systems (Mirsky et al. 2012). Excessive amounts of oats may lead to increased competition with forage species for light and nutrients (Tlahig et al. 2024) negating their benefits and reducing total forage yields (Assefa and Ledin 2001). Although moderate levels of oats improve forage quality, higher levels can negatively impact forage parameters such as Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF) (Tlahig et al. 2024), which are critical for livestock feeding (Figure 4).

In this study, we focused on legume-grass mixed grasslands with protective cover crops, evaluating forage yield, nutritional quality, and weed occurrence to elucidate the effects of protective sowing ratios and spatial configurations on the productivity and weed suppression efficiency of mixed grasslands, thereby providing a scientific basis for optimizing establishment strategies of cover crop-based mixed forage systems. Therefore, the objectives of this study were: (1) to evaluate the effects of oat sowing ratio and spatial arrangement on forage yield, nutritional quality, and weed suppression; and (2) to develop management recommendations for sustainable forage production and integrated weed control in mixed alfalfa-tall fescue systems.

2 | Materials and Methods

2.1 | Study Site Characteristics and Experimental Design

The research was carried out in the Modern Agricultural Science and Technology Demonstration Park of Qingdao Agricultural University (36°26′ N, 120°04′ E; elevation: 10 m above sea level) at Qingdao, Shandong Province, China. The site is characterized by a warm temperate humid monsoon climate with an annual mean precipitation of 698.1 mm (60% occurring during April–October) and a mean annual temperature of 12°C (Figure 1). Meteorological data were recorded at 60-min intervals using an automated weather station equipped with a precision rain gauge (0.5 mm resolution). The experimental soil was classified as brown soil with the following physicochemical properties: organic matter content 0.99%, pH 6.18, total nitrogen 51.2 mg/kg, available phosphorus 2.74 mg/kg, and available potassium 127.16 mg/kg.

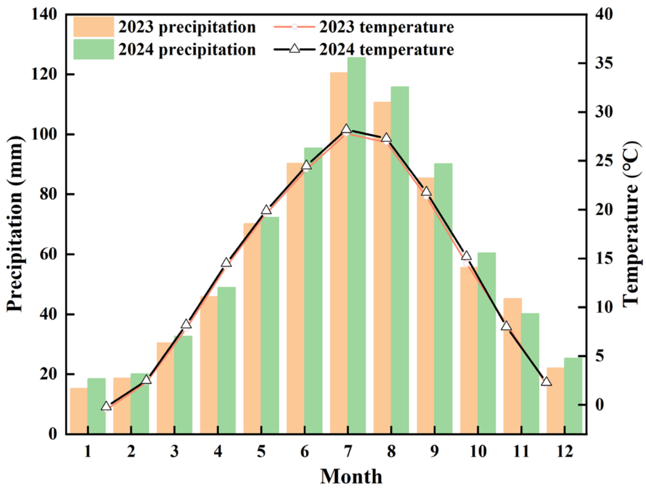

FIGURE 1 | Precipitation and temperature dynamics during the 2023 and 2024 growing seasons at the experimental site in Qingdao, China.

The experiment employed a randomized complete block design (RCBD) with three replications, conducted over two consecutive growing seasons (November 2022–November 2024). Individual plots measured 3 × 4 m and were separated by 1-m buffer zones to minimize treatment interference. The study utilized three plant species: alfalfa (*Medicago sativa* L., cv. WL363HQ), tall fescue (*Festuca arundinacea* cv. K31), and oat (*Avena sativa* L., "The Sun God") as a cover crop, with all seeds sourced from Beijing Best Grassland Co. Ltd., Beijing, China.

2.2 | Treatment Structure and Implementation

The experiment was designed based on two primary factors: the proportion of oat in the seeding mixture and the spatial configuration of sowing (Figure 2). In 2023, five oat seeding proportion treatments were established at 0%, 15%, 30%, 45%, and 60% of the standard oat monoculture rate (225 kg/ha). Based on comprehensive evaluations conducted in the first year—including total forage yield, weed suppression efficiency, and forage nutritive value—it was observed that oat proportions exceeding 30% led to a marked decline in total yield. Consequently, the oat seeding ratios for the 2024 growing season were refined to 0%, 10%, 20%, 30%, and 40%, focusing on the optimal inclusion range (15%–30%) to balance forage productivity with effective weed control, while excluding the higher, less efficient ratios identified in the previous year.

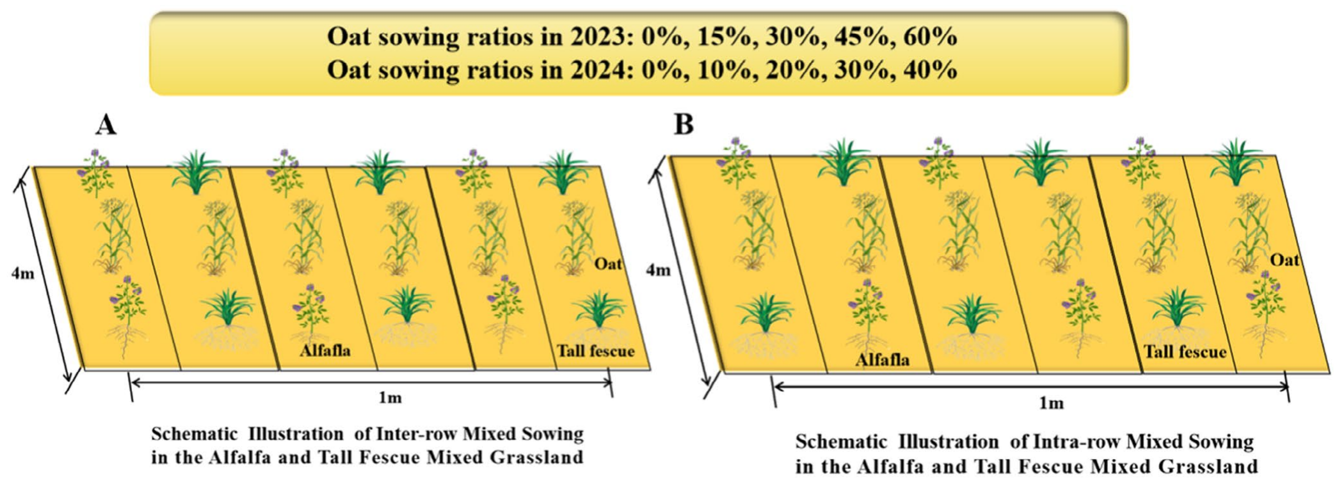

FIGURE 2 | Schematic diagram of planting structure under different sowing modes (uniform-row and alternate-row intercropping) for protective sowing of *Medicago sativa* × *Festuca arundinacea* mixed grassland with varying proportions of oat. (A) represents inter-row mixed sowing grassland; oat sowing proportions were set at 0%, 15%, 30%, 45%, and 60%. (B) represents intra-row mixed sowing grassland. The oat sowing ratios were adjusted to 0%, 10%, 20%, 30%, and 40%, reducing the higher proportions used in the previous year.

Two spatial sowing configurations were evaluated (Figure 2): (1) *Same-row intercropping*, where alfalfa and tall fescue were co-seeded within the same row, with oats evenly mixed into each row according to the treatment ratios; (2) *Alternate-row intercropping*, where alfalfa and tall fescue were sown in alternating rows, and oat was planted in separate rows but at the same specified proportions.

The sowing operations were carried out on March 15, 2023, and March 15, 2024. Except for the adjustment of the sowing ratio for oats, the sowing amounts of other crops remained unchanged. During the sowing process, we strictly followed conventional field management practices, ensuring effective control of pests and other factors. We used manual narrow-row strip seeding with an inter-row spacing of 20 cm. Each experimental plot consisted of 15 crop rows. The control treatment included no oat addition. In both years, oat seeding proportions were applied relative to the standard monoculture rate (225 kg/ha). Alfalfa and tall fescue were increased at 50% of their respective monoculture seeding rates, specifically 3.75 kg/ha for alfalfa and 7.50 kg/ha for tall fescue.

A compound NPK fertilizer (15% N, 15% P_2O_5, 15% K_2O) was applied at a rate of 570 kg/ha using a broadcast method. The fertilizer was incorporated into the soil at a depth of 15–20 cm using a rotary tiller. Routine irrigation and field management were conducted according to local climate and soil conditions.

Additionally, three monoculture treatments (alfalfa, tall fescue, and oat) were established to facilitate subsequent calculations of forage yield and quality components. In total, 13 treatments were implemented in both 2023 and 2024, with three replicates per treatment, resulting in 39 plots per year. Each plot measured 3 × 4 m.

2.3 | Determination of Forage Performance and Quality Indices and Weed Occurrence

2.3.1 | Forage Sampling and Yield Assessment

Forage sampling was conducted during the growing seasons of 2023 and 2024 to evaluate the effects of different sowing treatments on forage production. In 2023, alfalfa samples were collected three times: on June 7, July 18, and August 23, all during the early flowering stage, to ensure optimal nutritional value and accurate yield assessments. The samples were collected from randomly selected 1 m^2 areas within each experimental plot to measure dry matter yield.

Similarly, in 2024, three harvests were performed on June 5, July 14, and August 22, again at the early flowering stage. The harvested forage samples were immediately weighed to determine their fresh weight, then placed in an oven at 105°C for 40 min to inactivate metabolic processes. Subsequently, the samples were dried at 65°C until a constant weight was achieved. The dry weight of forage from each plot was recorded, and the total annual dry matter yield for each treatment was calculated to facilitate direct comparison of the performance of different sowing ratios and methods.

Land equivalent ration: To quantify the land use advantage of intercropping, the Land Equivalent Ratio (LER) was calculated for each treatment based on the biomass yield of oat, tall fescue, and alfalfa. The LER is defined as the sum of the relative yields of each component crop in the intercropping system compared to their respective monocultures:

$$\mathrm{LER}_{\mathrm{oat}} = \frac{Y_{\mathrm{oat,inter}}}{Y_{\mathrm{oat,mono}}}$$

$$\mathrm{LER}_{\mathrm{tall\ fescue}} = \frac{Y_{\mathrm{tall\ fescue,inter}}}{Y_{\mathrm{tall\ fescue,mono}}}$$

$$\mathrm{LER}_{\mathrm{alfalfa}} = \frac{Y_{\mathrm{alfalfa,inter}}}{Y_{\mathrm{alfalfa,mono}}}$$

$$\mathrm{LER}_{\mathrm{Group\ crops}} = \mathrm{LER}_{\mathrm{oat}} + \mathrm{LER}_{\mathrm{tall\ fescue}} + \mathrm{LER}_{\mathrm{alfalfa}}$$

Here, $Y_{\mathrm{crop,inter}}$ refers to the yield of each crop in the intercropping system, and $Y_{\mathrm{crop,mono}}$ refers to the yield of the same crop in monoculture. An LER value greater than 1 indicates a land use advantage of intercropping over sole cropping, suggesting that the intercropping system is more efficient in utilizing available land resources.

2.3.2 | Determination of Nutritional Quality Indicators in Forage Species

Crude Protein (CP) Content: CP content was determined by passing samples through an elemental analyzer to determine the total content of nitrogen, with the CP content therefore obtained by multiplying the total nitrogen value (mg/g sample) by 6.25.

Contents of Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF): The contents of NDF and ADF were determined by ANKOM2000i automatic fiber analyzer. Such indicators offer information on the fiber content of the forage, which in turn relates to its digestibility.

Forage samples were dried for 24 h at 65°C to a constant weight and ground to a fine powder for analysis. Different measurements used to determine the nutritional quality of forages focused specifically on CP, NDF, and ADF, which are important findings for livestock feeding.

The RFV of the forage was computed to assess overall forage nutritional quality and digestibility. RFV incorporates the influences of the fiber fractions content (NDF and ADF) with dry matter intake (DMI) to create a single index to evaluate different forage types. The following formulas were used to calculate the RFV (Fekadu et al. 2017):

$$\mathrm{DMI} = 120 / \mathrm{NDF} \tag{1}$$

$$\mathrm{DDM} = 88.9 - 0.779 \times \mathrm{ADF} \tag{2}$$

$$\mathrm{RFV} = \mathrm{DMI} \times \mathrm{DDM} / 1.29 \tag{3}$$

2.3.3 | Weed Occurrence Measurement and Analysis in Mixed Sown Grasslands

The experiment was repeated in the subsequent year, with weed incidence measured during the growing seasons in terms of

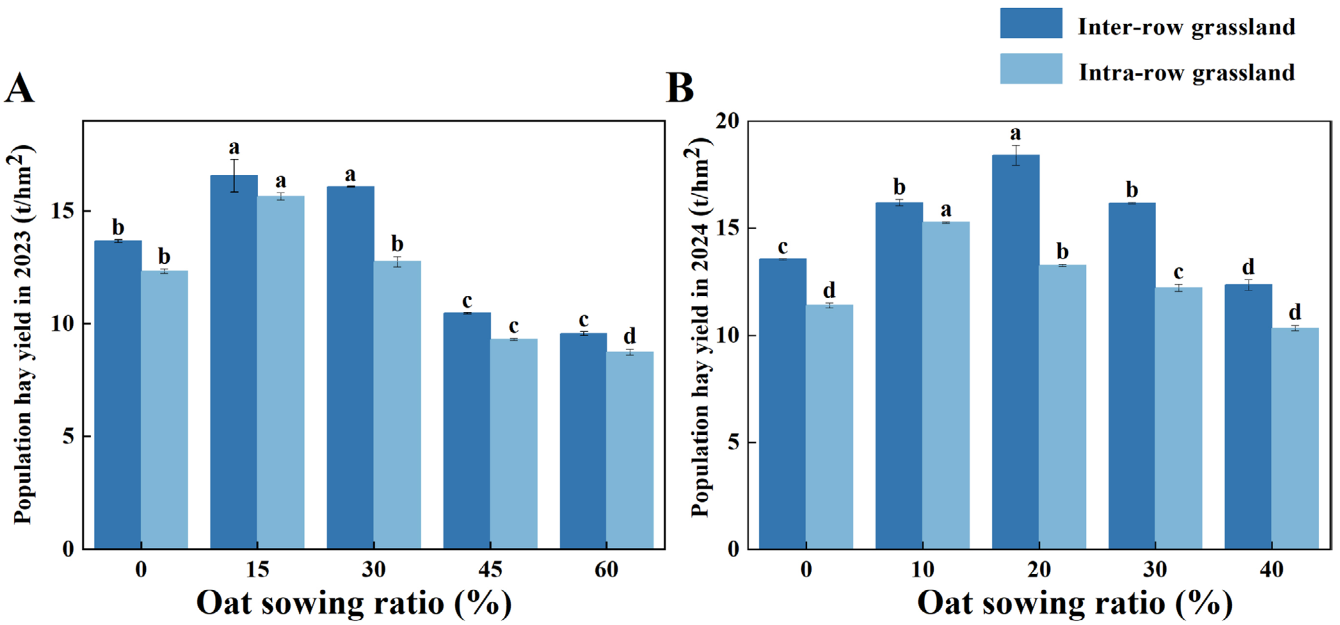

FIGURE 3 | The influence of oat cover crop seeding ratios on the dry matter yield of the intercropped grassland community in 2023–2024. (Panel A) represents the 2023 dry matter yield of the intercropped grassland community; (Panel B) represents the 2024 dry matter yield of the intercropped grassland community. Value columns with different small letters indicate significant differences ($p < 0.05$).

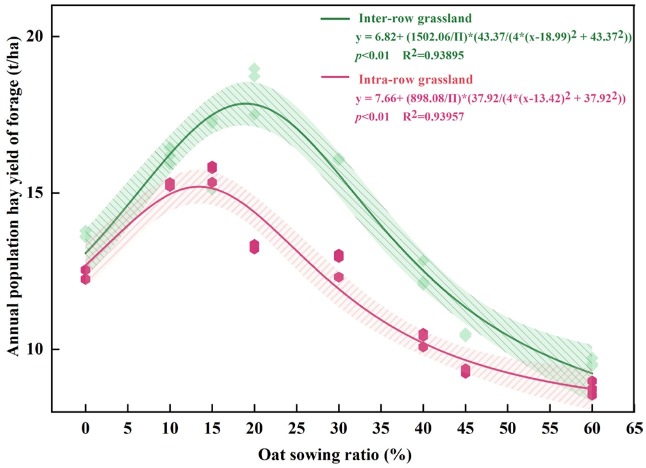

FIGURE 4 | The fitting situation of the annual dry matter yield of mixed-grass meadow communities under different sowing proportions of cover crop oats ($p < 0.01$).

both coverage and biomass. A fixed quadrat of 1 m^2 was randomly placed within each treatment plot before and after each harvest to evaluate weed occurrence. Weed species were identified and classified into broadleaf and grass categories for detailed analysis.

Weed Coverage Measurement: Weed coverage refers to the proportion of the sample area covered by plant leaves and branches. This was measured using digital images captured with a camera. The images were processed in Photoshop 2024, converting them into grayscale images. The "Color Range" tool was used to select green plant areas, which were then filled with white, while non-plant areas were filled with black. The pixel count of plant areas and total sample areas was used to calculate coverage percentages using the formula: Plant Coverage = Total sample pixels/Number of plant pixels × 100% (Lukina et al. 1999).

Weed Biomass Measurement: After each harvest, weed biomass was determined by cutting the weeds at ground level, drying them at 65°C, and weighing them to determine the fresh weight. The biomass was recorded separately for broadleaf and grass weeds, allowing for a direct comparison of weed suppression across different oat sowing ratios and sowing methods (Neeser et al. 2000).

2.4 | Data Analysis

The data was initially processed using Excel 2010. One-way analysis of variance (ANOVA) and least significant difference (LSD) analysis were conducted using SPSS26.0 software to compare and test the significance of differences among different treatments. Bar charts were created using Origin 2021 software ($p < 0.05$).

3 | Results

3.1 | Forage Yield Performance Across Growing Seasons and Sowing Methods

In 2023, under the alternate-row intercropping pattern, total hay yield was significantly higher when the seeding proportions of oat were 15% and 30%, compared to other treatments ($p < 0.05$). Under the same-row intercropping pattern, the highest total hay yield (15.66 t/ha) was observed at a 15% oat seeding proportion, which was significantly greater than that of other treatments. Moreover, the total dry matter yield significantly decreased with increasing oat seeding proportion ($p < 0.05$, Figure 3A). In 2024, the highest annual total dry matter yield (18.4 t/ha) was recorded at a 20% oat seeding proportion under the alternate-row intercropping pattern, significantly exceeding other treatments ($p<0.05$). In the same-row intercropping pattern, a 20% oat seeding proportion also resulted in the highest hay yield (13.26 t/ha), significantly higher than that of other treatments ($p<0.05$, Figure 3B). Overall, regardless of intercropping pattern, oat seeding proportions of 15%–20% resulted in the highest total hay yields.

The annual total hay yield under the alternate-row intercropping pattern followed the green fitted curve shown in Figure 4 ($R^2=0.93$), while the yield under the same-row intercropping pattern followed the red fitted curve ($R^2=0.93$). As the seeding proportion of oat increased, the annual hay yield of the forage community first increased and then decreased. Under the alternate-row intercropping pattern, the optimal oat seeding proportion ranged from 15% to 25%, while under the same-row intercropping pattern, it ranged from 10% to 20% ($p<0.01$, Figure 4).

As shown, the LER of all intercropping treatments with oat inclusion (10%–30%) was significantly higher than the 0% control, indicating a clear land use advantage. The highest LER (1.48) was observed under inter-row intercropping with 20% oat, which was markedly superior to the control, suggesting enhanced resource complementarity. In contrast, treatments with higher oat proportions (≥40%) showed a significant decline in LER, in some cases approaching or even falling below the control level. Furthermore, inter-row intercropping consistently outperformed intra-row configurations at the same oat ratios (except at 0%), highlighting the effectiveness of spatial separation in mitigating interspecific competition. Overall, moderate oat inclusion (15%–30%) under inter-row sowing significantly improved land use efficiency compared to the control, whereas excessive oat proportion negatively affected system productivity (Figure 5).

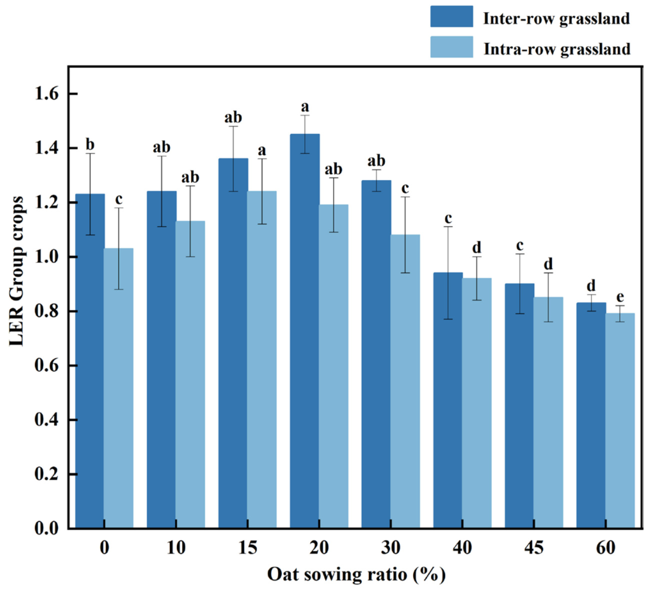

FIGURE 5 | The influence of different proportions of oats on the land equivalent ratio of the mixed-grassland ecosystem (2023–2024). Value columns with different small letters mean significant difference ($p<0.05$).

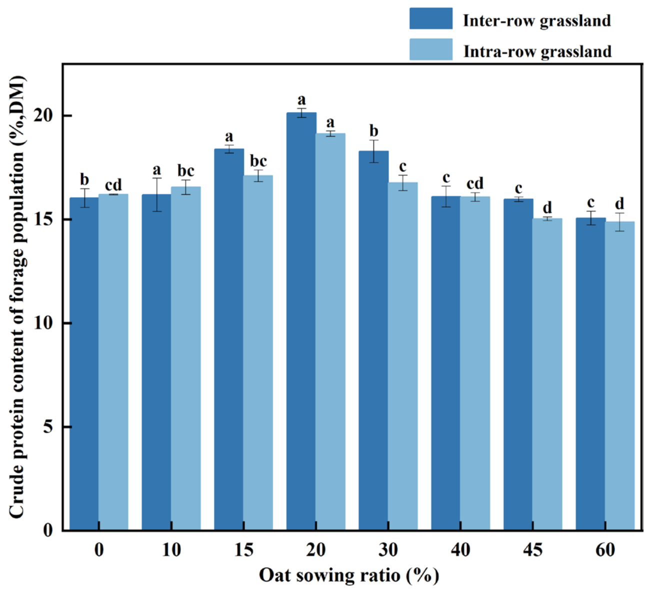

FIGURE 6 | The effect of different sowing ratios of the cover crop oat on the crude protein content of forage populations in mixed grasslands. Value columns with different small letters mean significant differences ($p<0.05$).

3.2 | Forage Nutritional Quality

Under the alternate-row intercropping pattern, the forage community exhibited the highest CP content of 20.13% at a 20% oat seeding proportion, representing a significant increase of 25.6% compared to the control ($p<0.05$). At a 60% oat seeding proportion, the CP content was significantly lower than that of other treatments ($p<0.05$). Under the same-row intercropping pattern, the maximum CP content of 19.13% was also observed at a 20% oat seeding proportion, which was 18.1% higher than the control ($p<0.05$). Similarly, at a 60% oat seeding proportion, the CP content was significantly reduced compared with other treatments ($p<0.05$). In both intercropping patterns, the CP content of the forage community showed a consistent trend of initially increasing and then decreasing with increasing oat seeding proportion (Figure 6).

The RFV of the forage community under the alternate-row intercropping pattern followed the green fitted curve ($p<0.01$, $R^2=0.79$), while that under the same-row intercropping pattern followed the red fitted curve ($p<0.01$, $R^2=0.88$, Figure 7). Under the alternate-row intercropping pattern, RFV peaked when the oat seeding proportion ranged from 20% to 30%; under the same-row intercropping pattern, the peak occurred at a 20%–25% oat seeding proportion. In both intercropping patterns, the RFV of the forage community showed a trend of initially increasing and then decreasing with increasing oat seeding proportion. Inter-row sowing demonstrated slight advantages in maintaining higher forage quality compared to intra-row sowing, emphasizing the importance of spatial arrangements in mitigating competition.

3.3 | Weed Suppression Effectiveness

In this experiment, weed occurrence was primarily observed during the first harvest cycle of alfalfa growth, whereas in the second and third harvest cycles, weed occurrence significantly decreased or was no longer present. Therefore, a comparative analysis was conducted on weed occurrence and related indicators before and after the sowing of the cover crop oat. Additionally, weeds were classified into broadleaf weeds and grass weeds to facilitate subsequent calculations (Table 1).

Across all weed types and metrics, a consistent U-shaped response was observed with increasing oat sowing ratio, indicating that moderate seeding levels are most effective for weed control. For grass weeds, coverage was significantly reduced at moderate oat densities. Compared to the control, where inter-row and intra-row grass weed coverage reached 16.00% and 21.67%, the lowest values occurred at 30% and 20% oat sowing, with reductions to 3.33% and 2.67%, respectively (Figure 8A). A similar trend was observed for grass weed biomass, which decreased from 927.67 g/m^2 (inter-row) and 776.00 g/m^2 (intra-row)in the control to 118.67 g/m^2 and 173.67 g/m^2 at 20% sowing, respectively. However, at the highest sowing level (60%), both weed coverage and biomass rebounded sharply, surpassing or returning to control levels (Figure 8C). For broadleaf weeds, the most effective suppression also occurred at 20%–30% sowing. Inter-row biomass decreased to 104.00 g/m^2 and intra-row to 114.67 g/m^2 (Figure 8B). Coverage reductions were also evident, intra-row planting maintained values below 2% from 15% to 45% sowing, with a minimum of 0.10%, whereas inter-row coverage dropped to 3.67% at 20% before rising steeply to 23.67% at 60% (Figuure 8B,D, $p < 0.05$).

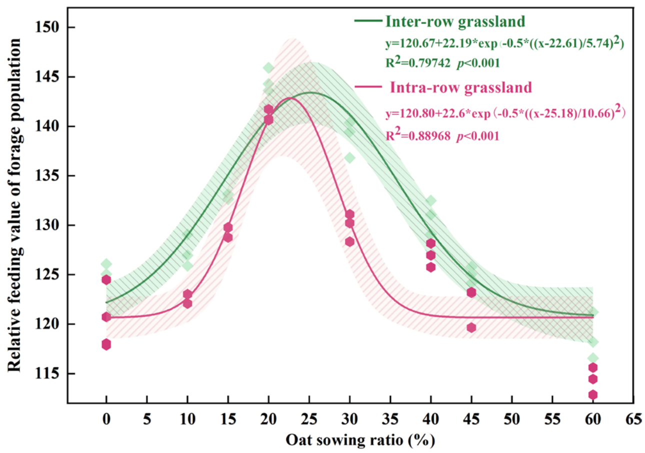

FIGURE 7 | The fitting of forage population relative feeding value (RFV) of mixed cover crop oat grassland with different seeding ratios.

4 | Discussion

4.1 | Yield Improvement Through Moderate Oat Inclusion

This study confirmed that moderate oat inclusion (15%–20%), particularly under inter-row sowing, significantly improved forage yield in mixed alfalfa-tall fescue grasslands. The maximum dry matter yield (18.4 t/ha) was observed at 20% oat inclusion, representing a 26.4% increase over the control, while CP content reached 20.13%, an increase of 25.6%. These results align with previous findings suggesting that moderate cereal cover crop proportions improve resource allocation while reducing interspecific competition (Moreno-Cadena et al. 2024).

TABLE 1 | The primary classification of weeds observed at the experimental site.

Latin name	Common name	Family name	Generic name	Lifestyle type	Broadleaf weeds	Grass weeds
Chenopodium glaucum	Pigweed	Amaranthaceae	Chenopodium	Annual	☐	—
Descurainia sophia	Flannelwort	Brassicaceae	Descurainia	Annual/biennial	☐	—
Capsella bursa-pastoris	Shepherd's purse	Brassicaceae	Capsella	Biennial	☐	—
Calystegia hederacea	Calydalis	Convolvulaceae	Calystegia	Perennial	☐	—
Humulus scandens	Scandent hop	Cannabaceae	Humulus	Perennial	☐	—
Amaranthus retroflexus	Redroot pigweed	Amaranthaceae	Amaranthus	Annual	☐	—
Abutilon theophrasti	Chingma abutilon	Malvaceae	Abutilon	Annual	☐	—
Convolvulus arvensis	Field bindweed	Convolvulaceae	Convolvulus	Perennial	☐	—
Portulaca oleracea	Common purslane	Portulacaceae	Portulaca	Annual	☐	—
Eleusine indica (L.) *Gaertn.*	Goosegrass	Poaceae	Eleusine	Annual	—	√
Digitaria sanguinalis	Crabgrass	Poaceae	Digitaria	Annual	—	√
Echinochloa crus-galli	Barnyard grass	Poaceae	Echinochloa	Annual	—	√
Setaria viridis	Green bristlegrass	Poaceae	Setaria	Annual	—	√
Sorghum halepense	Johnson grass	Poaceae	Sorghum	Perennial	—	√

Note: "☐" indicating broadleaf weeds; "√" indicating grass family weeds.

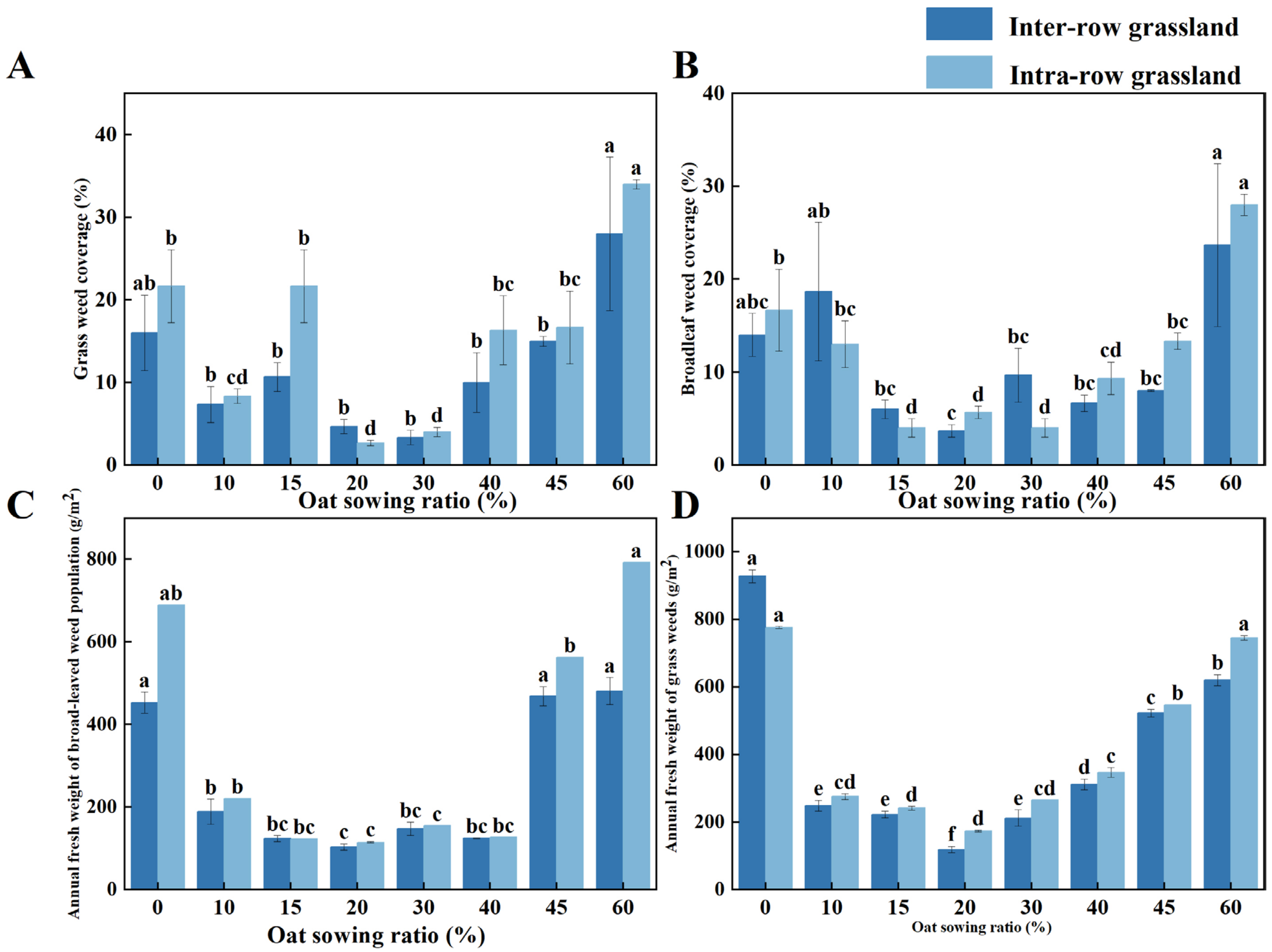

FIGURE 8 | Effects of different oat cover crop sowing ratios on weed suppression in mixed grassland systems (A) grass weed coverage (%), (B) broadleaf weed coverage (%), (C) annual fresh weight of grass weeds (g/m^2), and (D) annual fresh weight of broadleaf weeds (g/m^2) under different oat sowing ratios in inter-row and intra-row grassland planting patterns. Value columns with different small letters mean significant difference ($p < 0.05$).

The yield enhancement likely results from complementary mechanisms: (i) early-stage oat canopy effectively suppresses weed competition (Sardana et al. 2017), (ii) oat residue decomposition enhances soil fertility, and (iii) spatial segregation under inter-row sowing reduces intra-row competition, facilitating niche differentiation and more efficient use of light, water, and nutrients (Reyes-Puig et al. 2024; Robakowski et al. 2018).

The strong quadratic relationship between oat proportion and yield ($R^2 > 0.92$) underscores that excessive oat inclusion (> 30%) impairs productivity, consistent with prior reports of detrimental competition in cereal-dominant systems (Evans et al. 1991). Our results confirm that maintaining oat sowing ratios within 15%–20% provides an optimal balance between facilitative and competitive interactions.

4.2 | Weed Suppression Mechanisms

Moderate oat inclusion also significantly suppressed weed occurrence. At 20% sowing, grass weed biomass decreased by 87.2%, and broadleaf weed biomass declined by 83.4%. Coverage followed a similar pattern, with intra-row broadleaf weed cover decreasing from 21.67% to 2.67%. This strong suppression aligns with earlier work attributing weed control to shading, competition for nutrients, and allelopathy (Gfeller et al. 2018; Little and van Staden 2003).

The particularly high suppression of broadleaf weeds corroborates previous studies suggesting that broadleaf species are more sensitive to shading and nutrient depletion than grasses (Tang et al. 2024). Light-demanding species such as *Amaranthus retroflexus* and *Setaria viridis* were notably reduced, supporting the role of early canopy closure as a key mechanism (Wu et al. 2019).

Interestingly, at oat proportions ≥ 45%, weed biomass and coverage rebounded—sometimes exceeding control levels, suggesting that excessive oat competition weakens the forage canopy, reducing suppression efficacy. This is consistent with findings in cereal-based systems where overdominance of cover crops compromised overall weed control (Colbach et al. 2025).

4.3 | Effects on Forage Quality

Nutritional analysis revealed that 15%–20% oat inclusion improved forage quality, as reflected by higher CP and RFV values. The increased CP content likely results from improved light and nutrient conditions favoring legume performance, and reduced weed pressure that allows alfalfa to allocate more energy to protein synthesis (Feng et al. 2022).

However, oat inclusion above 30% significantly increased NDF and ADF, reducing forage digestibility—likely due to higher oat biomass proportion and reduced legume dominance. Similar findings have been observed in other studies showing that excessive cereal biomass reduces the feed value of mixed forage (Liu et al. 2023). Therefore, our findings emphasize that 15%–20% oat sowing strikes a nutritional balance, enhancing feed quality while avoiding the trade-offs associated with high oat density (Otto et al. 2024).

4.4 | Role of Spatial Configuration in System Efficiency

Inter-row sowing significantly outperformed intra-row sowing in all key metrics, Rinke et al. (2022) yield, weed suppression, and feed quality, highlighting the importance of spatial arrangement (Geddes and Gulden 2021). The inter-row configuration promotes complementary resource use, reduces competition between forage species and oats, and optimizes light capture and canopy structure (Otto et al. 2024).

This configuration also achieved the highest land equivalent ratio (LER = 1.48), indicating better land-use efficiency. While intra-row sowing is easier to implement operationally, it showed stronger yield penalties and less stable suppression at higher oat densities due to intensified competition (Rinke et al. 2022).

These results support the theory of niche differentiation in agroecosystems and reinforce the utility of spatial diversification in enhancing both productivity and resilience (Hoy 2015).

4.5 | Practical Implications and Recommendations

Based on these findings, the following recommendations are proposed for oat cover crop integration in mixed grassland systems: Sowing ratio: Use 15%–20% oat relative to monoculture rates (1.85–2.5 kg/ha) to balance yield, quality, and weed suppression. Spatial arrangement: Prioritize inter-row sowing, which offers greater land-use efficiency and suppressive capacity. Timing: Although not directly tested, previous research suggests terminating oats before flowering may reduce long-term competition risks (Korczak et al. 2019). System dynamics: The increase in optimal oat ratio from 15% (2023) to 20% (2024) underscores the need for adaptive management based on yearly climate and soil variation (Schwamback et al. 2024).

A key limitation is the two-year scope of the study; longer-term trials are necessary to validate these strategies under diverse environmental and management conditions. Moreover, further research is needed to explore oat termination timing, economic returns, and oat-induced soil legacy effects.

5 | Conclusion

This two-year study demonstrated that moderate oat inclusion (15%–20%) under inter-row sowing significantly enhanced mixed alfalfa-tall fescue grassland performance. In 2024, 20% oat sowing achieved the highest dry matter yield (18.4 t/ha), a 26.4% increase over the control, and improved crude protein by 25.6% (20.13%). Oat inclusion effectively suppressed weeds, reducing grass and broadleaf weed biomass by 87.2% and 83.4%, respectively. Total weed biomass and coverage were reduced by 64.5% and 60.8%. The Land Equivalent Ratio reached 1.48, reflecting a 48% increase in land-use efficiency. These results indicate that 15%–20% oat sowing with inter-row spacing optimizes yield, quality, and weed suppression, offering a sustainable approach to forage production with reduced herbicide dependence.

Author Contributions

F.M., J.S., C.Y., and G.Y. designed the study. X.Z., Y.L., F.M., and Y.S. wrote and revised the manuscript. X.Z., Y.S., Y.J., M.X., and Y.J. carried out the data analysis. X.Z., Y.S., Y.L., Y.J., M.X., Y.J., G.Y., J.S., C.Y., W.T., Y.X., and F.M. performed the experiments. All authors contributed to the article and approved the submitted version.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

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