

INFLUENCE OF INTERCROPPING AND NUTRIENT MANAGEMENT PRACTICES ON THE FODDER YIELD, PROXIMATE COMPOSITION AND FEED QUALITY OF OATS (*Avena sativa*) AND BERSEEM (*Trifolium alexandrinum*)

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ABSTRACT. A major limitation to livestock productivity is the insufficient and poor supply quality supply of green fodder, especially during the off season. To address this gap, the present study evaluated the influence of intercropping systems and nutrient management practices on the yield and nutritional quality of oats (*Avena sativa*) and berseem (*Trifolium alexandrinum*). The underlying hypothesis was that intercropping and enriched nutrient strategies would enhance the total fodder availability and improve the feed value through better resource utilisation. The experiment followed

a factorial randomised block design with four cropping patterns (oats, berseem, and oats: berseem in 2:1 and 1:2 row ratios) and four nutrient management treatments, replicated three times. Oats and berseem alone produced the highest green fodder yields, but the 2:1 intercropping pattern resulted in a total green fodder (37.6 t ha⁻¹) and dry matter yield (6.7 t ha⁻¹) comparable to that of oats alone, with superior forage quality. Among nutrient treatments, using 100% of the recommended fertiliser dose with plant growth-promoting rhizobacteria and two foliar sprays of seaweed extract (NM₄) resulted in the highest



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green (38.35 t ha⁻¹) and dry fodder yields (6.41 t ha⁻¹) and improved the proximate composition. The interaction of the 2:1 intercropping system and NM₄ resulted in the best performance, indicating a sustainable approach for enhancing the fodder supply and supporting resilient livestock production.

Keywords: feed quality; fodder yield; intercropping; nutrient management; proximate composition.

INTRODUCTION

Livestock production is a vital component of the agricultural economy, particularly in developing countries where it contributes significantly to household nutrition, rural employment and national gross domestic product (Asresie *et al.*, 2015; Said, 2022). However, a persistent challenge limiting livestock productivity is the insufficient and inconsistent availability of high-quality green fodder, especially during dry or lean periods. In many regions, fodder shortages lead to nutritional deficits, reduced milk and meat output, and poor reproductive performance, affecting farmer incomes and food security (Balehegn *et al.*, 2020; Hailesilassie, 2016). Thus, it is imperative to devise sustainable and efficient fodder production strategies that ensure the availability of nutritious forage for livestock.

Grass-legume intercropping has been widely recognised as a practical and resource-efficient method for producing balanced animal feed. Grasses generally supply the energy component of the diet, as they are rich in carbohydrates and fibre, whereas legumes are high in protein and essential amino acids (Kaithwas *et al.*, 2020; Kubkomawa *et al.*, 2015).

However, feeding legumes, such as berseem, in isolation can result in metabolic disorders, such as bloating in ruminants (Dewhurst *et al.*, 2009). A balanced combination of grass and legume species meets the nutritional needs of animals, enhances land-use efficiency and maintains soil fertility. The success of such intercropping systems depends largely on the compatibility of crop species and the optimisation of row arrangements to reduce interspecific competition and promote synergistic growth (Pankou *et al.*, 2022; Singh *et al.*, 2010).

Oats and berseem are considered highly compatible for rabi season fodder production. Oats are known for their high biomass, palatability and adaptability to a wide range of soil and climatic conditions. They serve as a good source of fibre, essential minerals and digestible energy. However, berseem is a Pho (N)-fixing legume that enriches the soil and provides a protein-rich, highly digestible forage (Choudhary, 2019; Hazra, 2014; Roy *et al.*, 2019). Intercropping these crops in appropriate row ratios may result in a fodder mixture that is both high-yielding and nutritionally superior. Despite these advantages, limited research has been conducted to assess the agronomic performance and feed quality outcomes of oat-berseem intercropping under varied management practices, particularly with respect to nutrient input strategies.

Another crucial factor influencing the fodder yield and quality is nutrient management. Although conventional chemical fertilisation practices are effective, they often pose environmental risks and are economically unsustainable for smallholder farmers. Nutrient

management, which combines inorganic fertilisers with organic or biological inputs, offers a sustainable alternative that enhances nutrient availability, improves soil health and boosts crop productivity (Kemal and Abera, 2015; Selim, 2020). Among biological inputs, plant growth-promoting rhizobacteria (PGPR) and seaweed extract are increasingly gaining attention. PGPR improves plant nutrient uptake by mechanisms such as phosphate solubilisation, N fixation and hormone production (Das *et al.*, 2022; He *et al.*, 2024). As a rich source of micronutrients, vitamins and natural growth stimulants, seaweed extract enhances photosynthetic efficiency and plant vigour, resulting in higher biomass and quality (Zafar *et al.*, 2022). Despite their known individual benefits, the effects of the combined application of PGPR and seaweed extract with recommended doses of chemical fertilisers on fodder-based intercropping systems remains unknown. Moreover, the interactive effects of these nutrient strategies with different oat–berseem intercropping patterns have not been adequately studied. This represents a significant research gap in developing holistic and sustainable fodder production systems. Therefore, the present study was undertaken to investigate the effects of oat–berseem intercropping row ratios and nutrient management practices involving PGPR and seaweed extract on fodder yield, proximate composition and feed quality. We hypothesised that the combination of optimal intercropping and enriched nutrient inputs would synergistically improve the biomass yield and nutritional quality, supporting more efficient and

sustainable livestock production systems. The findings provide practical recommendations for farmers to grow fodder with a high yield and nutritive value.

MATERIALS AND METHODS

Experimental details

The experiment was conducted in the winter season of 2020–2021 at the Agronomy Research Block, ICAR-National Dairy Research Institute, Karnal, Haryana, India, which has a subtropical climate. During the crop season (October 2020–February 2021), the maximum and minimum temperatures ranged from 13.9 to 34.5°C and from 3.5 to 18.1°C, respectively, with mean values of 25.0 and 10.7°C, respectively. The relative humidity varied from 92.0 to 100.0% (maximum) and from 41.4 to 92.8% (minimum), with seasonal means of 96.3 and 62.8%. Rainfall was low (0.0–5.6 mm day⁻¹), and the evaporation and sunshine hours ranged from 0.7 to 4.1 mm day⁻¹ and from 1.8 to 8.2 h day⁻¹, respectively. The soil at the experimental site was characterised as clay loam, exhibiting a pH ranging from neutral to alkaline, with a moderate organic carbon content of 0.68%. Soil analysis indicated low available N (188.9 kg ha⁻¹), moderate potassium (K) levels (192.4 kg ha⁻¹) and high available phosphorus (P, 30.5 kg ha⁻¹). The N content was assessed using standard methods, and the P content was measured using the standard alkaline permanganate method (Subbiah and Asija, 1956) for available N, 0.5 M sodium bicarbonate method (Olsen *et al.*, 1954) for available K and ammonium

Influence of intercropping and nutrient management practices

acetate extraction (Jackson, 1973) for available P were utilised. Before sowing, the field was irrigated to ensure adequate soil moisture for seed germination. The land was then tilled by cross-ploughing with a tractor-mounted disc harrow, followed by rotavator operation and planking to create a well-prepared seedbed with fine tilth. The experimental design employed a factorial randomised block design, incorporating four intercropping systems and four nutrient management strategies, each replicated three times. The details of the treatments are given in *Table 1*. The intercropping system was based on a replacement series, in which the total plant population remained constant but the proportion of oats and berseem varied based on the row ratios. The distance between rows was 30 cm with a gross plot size for each treatment of 30 m².

Seed rates of 100 and 25 kg ha⁻¹ were used for oats and berseem, respectively. The recommended dose of fertilizers (RDF) for oats (120:40:40 kg ha⁻¹ N, P₂O₅, and K₂O) and berseem

(20:60:40 kg ha⁻¹ N, P₂O₅, and K₂O) were applied using urea, diammonium phosphate and muriate of potash. In the case of oats, N was applied in three split doses, and the first dose of 60 kg ha⁻¹ was given as basal fertiliser with the remaining doses of 30 kg ha⁻¹ applied at 30 days after sowing (DAS) and at first cut. In berseem, the whole dose of N was applied with the basal application. The P and K fertilisers were applied as basal doses only.

Seed treatment was performed with 150 mL PGPR per hectare. A bio-stimulant seaweed extract (28% w/w) was sprayed after 15 and 30 DAS and 15 and 30 days after the first cut of the crop at a rate of 2 mL litre⁻¹ of water. Hand weeding was performed at 30 DAS to prevent early weed crop competition. After sowing, the crop was irrigated at 25 and 45 DAS in all the treatments. The crop was irrigated after the first cut and again at 15 days after the first cut. The first cut was performed at 65 DAS, and the second cut was performed at 35 days after the first cut.

Table 1 – Details of intercropping and nutrient management treatments applied to oats and berseem

No.	Treatment details	Symbol
Intercropping		
1.	Oats (alone)	IC ₁
2.	Berseem (alone)	IC ₂
3.	Oats + berseem (2:1 row ratio)	IC ₃
4.	Oats + berseem (1:2 row ratio)	IC ₄
Nutrient Management		
1.	100% RDF (control)	NM ₁
2.	50% RDF + PGPR + 2 sprays of seaweed extract	NM ₂
3.	75% RDF + PGPR + 2 sprays of seaweed extract	NM ₃
4.	100% RDF + PGPR + 2 sprays of seaweed extract	NM ₄

Note: Intercropping systems (IC): IC₁: oats (sole crop), IC₂: berseem (sole crop), IC₃: oats + berseem (2:1 row ratio), IC₄: oats + berseem (1:2 row ratio). Nutrient management practices (NM): NM₁: 100% recommended dose of fertilizers (RDF) – control, NM₂: 50% RDF + PGPR + two foliar sprays of seaweed extract, NM₃: 75% RDF + PGPR + two foliar sprays of seaweed extract, NM₄: 100% RDF + PGPR + two foliar sprays of seaweed extract.

Yield and quality estimation

Oats and berseem were manually harvested from a 20 m² area, excluding a 0.5-m border on each side. The fresh weights were recorded and subsequently converted from kilograms per plot to tonnes per hectare to determine the green fodder yield (GFY). Representative samples (0.5 kg) collected from each plot were oven-dried at 60°C and weighed at regular intervals until no further change in weight was observed (constant weight), which generally required approximately 48 h.

The resulting dry weight was then used to calculate the dry fodder yield (DFY), expressed in tonnes per hectare. In these samples, the ether extract (EE), total ash (TA) and organic matter (OM) contents were determined following the standard methods outlined by AOAC (2005). The crude protein (CP) content was estimated by multiplying the N concentration, which was determined using the Kjeldahl method, by a conversion factor of 6.25.

Subsequently, the yields of CP, EE and TA were derived by multiplying their respective concentrations by DFY. Additionally, the neutral detergent fibre (NDF), cell, acid detergent fibre (ADF), acid detergent lignin (ADL), cellulose and hemicellulose contents were measured using the procedure described by Van Soest *et al.* (1991).

The feed quality parameters, namely dry matter intake (DMI), dry matter digestibility (DMD), total digestible nutrient (TDN), relative feed values (RFV) and relative feed quality (RFQ), were estimated using the procedures described by Horrocks and Valentine

(1999) and Undersander and Moore (2002).

Statistical evaluation

The experiment was laid out in a factorial randomised block design. The main effects of intercropping systems and nutrient management practices are presented in the *Figure 1* and *Figure 2*, main manuscript *Table 2*, *Table 3*, *Table 4*, *Table 5*, *Table 6*, and interaction effects (IC × NM) are provided in *Supplementary Tables 1-25*. Analysis of variance (ANOVA) was performed following the procedure outlined by Gomez and Gomez (1984).

When significant treatment effects were observed ($p < 0.05$), post-hoc comparisons among means were conducted using the least significant difference (LSD) test to control for type I error in multiple comparisons. Correlation analyses among yield components, proximate composition and fibre fractions were conducted using Pearson's correlation coefficient in JASP software version 0.18.3.0.

RESULTS

Crop yield

The GFY and DFY of oats and berseem were significantly influenced by intercropping and nutrient management practices. The preeminent GFY for oats during the first (24.7 t ha⁻¹) and second cuts (12.8 t ha⁻¹) as well as the highest GFY for berseem during the first (13.3 t ha⁻¹) and second cuts (13.8 t ha⁻¹) were observed in IC₁ (oats alone) and S₂ (berseem alone), respectively.

These yields were higher than those observed under IC₃ and IC₄, in which oats and berseem were sown in 2:1 and 1:2

row ratios, respectively (*Figure 1a*). The highest total GFY (37.6 t ha^{-1}) was observed under S_1 , which was comparable to that under IC_3 (36.6 t ha^{-1}). Among the integrated management practices, NM_4 resulted in a superior GFY in the first and second cuts of oats (21.8 and 9.8 t ha^{-1}) and berseem (8.1 and 11.5 t ha^{-1}). The total GFY (38.3 t ha^{-1}) was also higher under NM_4 compared to NM_2 . NM_1 and NM_3 were statistically comparable to each other.

The DFY of oats during the first (4.5 t ha^{-1}) and second cuts (2.2 t ha^{-1}) and the highest DFY of berseem during the first (1.8 t ha^{-1}) and second cuts (1.9 t ha^{-1}) were observed under IC_1 and IC_2 , respectively.

These yields were significantly superior to those obtained under IC_3 and IC_4 (*Figure 1b*). IC_1 demonstrated the highest total DFY (6.7 t ha^{-1}), which was statistically comparable to that obtained under IC_3 (6.5 t ha^{-1}). In terms of nutrient management practices, NM_4 resulted in the maximum DFY for both cuts of oats (3.9 and 1.6 t ha^{-1}) and berseem (1.2 and 1.7 t ha^{-1}). Similarly, the total DFY (6.4 t ha^{-1}) was highest under NM_4 .

Intercropping and nutrient management practices had a significant impact on GFY and DFY in both oats and berseem, except for GFY in oats. Detailed interaction effects are presented in *Supplementary Tables 1–3*. In berseem, the maximum GFY was recorded under IC_2NM_4 during the first and second harvests.

For oats, the highest DFY (4.92 t ha^{-1}) during the first cut was achieved under IC_1NM_4 . In berseem, the highest DFY was observed under IC_1NM_4 at the first cut and IC_4NM_4 at the second cut.

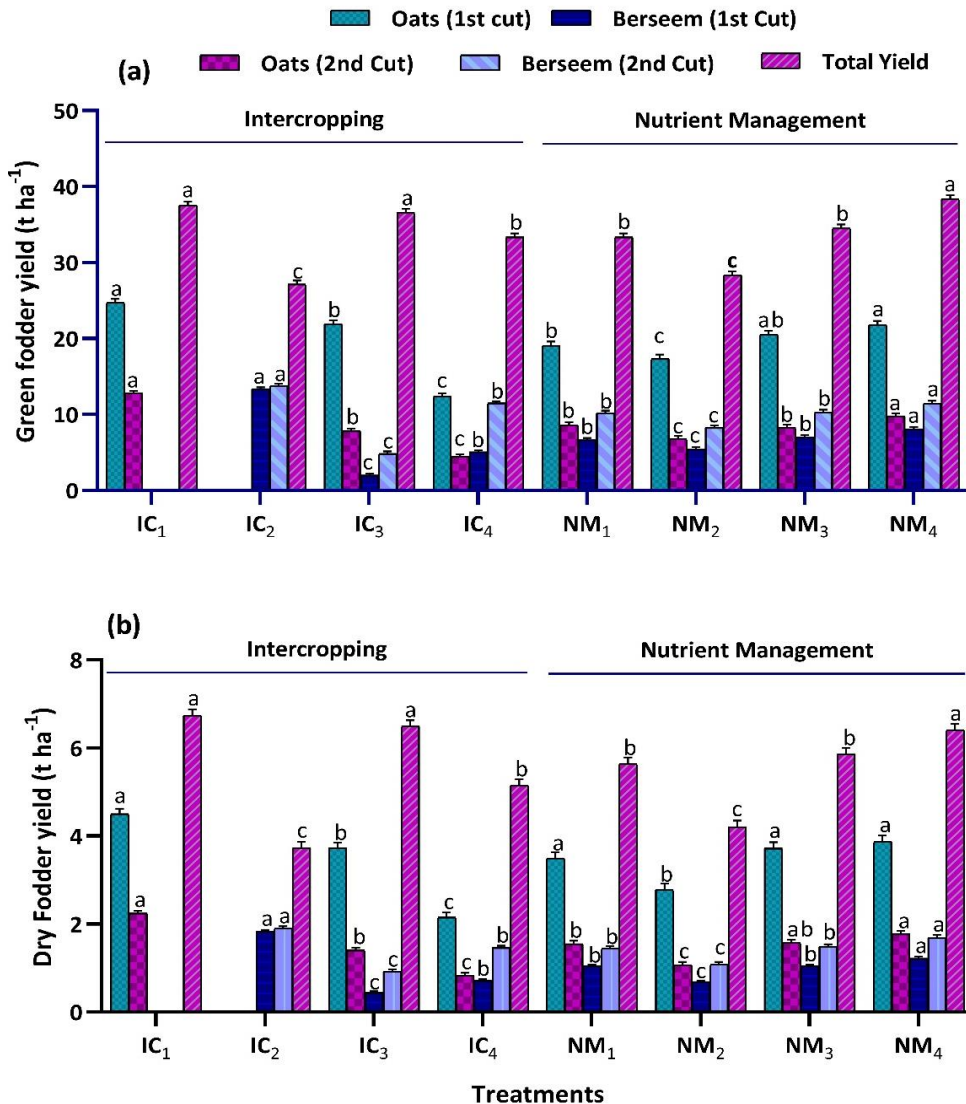
Proximate composition

In both crops, significant variation in the proximate composition was observed at both cuts, influenced by intercropping and nutrient management practices (*Figure 2a–c*). IC_3 in oats resulted in the highest CP (11.15 and 10.49%), EE (2.64% and 2.53%) and TA contents (8.72 and 8.63%) during the first and second cuts, respectively. Conversely, for berseem, IC_2 demonstrated the highest CP (19.17 and 19.50%), EE (3.44 and 3.25%) and TA contents (15.14 and 14.91%) during the first and second cuts, respectively. The CP, EE and TA contents were similar under IC_3 and IC_1 in oats. However, IC_3 was significantly superior to IC_4 in both cuts of oats. The CP, EE and TA contents under IC_2 and IC_4 were significantly superior to those under IC_3 for both cuts of berseem. The highest OM content was recorded in oats under IC_4 and in berseem under IC_3 . Among the nutrient management practices, NM_4 resulted in the highest CP, EE and TA contents in both crops.

Significant interactions between intercropping and nutrient management practices influenced the CP, EE and TA contents in oats and berseem. IC_1NM_4 and IC_1NM_3 resulted in the highest CP contents of 11.50 and 10.90% , respectively, during the first and second cut in oats (*Supplementary Table 4*). In berseem, IC_2NM_4 and IC_4NM_1 resulted in the highest CP contents of 19.40 and 20.35% , respectively, at the first and second cuts. Detailed interaction effects are presented in *Supplementary Table 5*. The highest EE contents of 3.08 and 2.87% were observed in IC_3NM_4 and IC_3NM_3 at the first and second cuts, respectively, in oats (*Supplementary*

Table 6). In berseem, IC₄NM₃ resulted in the highest EE content (4.07 and 3.80%) at the first and second cuts, respectively (Supplementary Table 7). In oats, the highest TA content was observed under IC₃NM₄ (8.98%) at the first cut

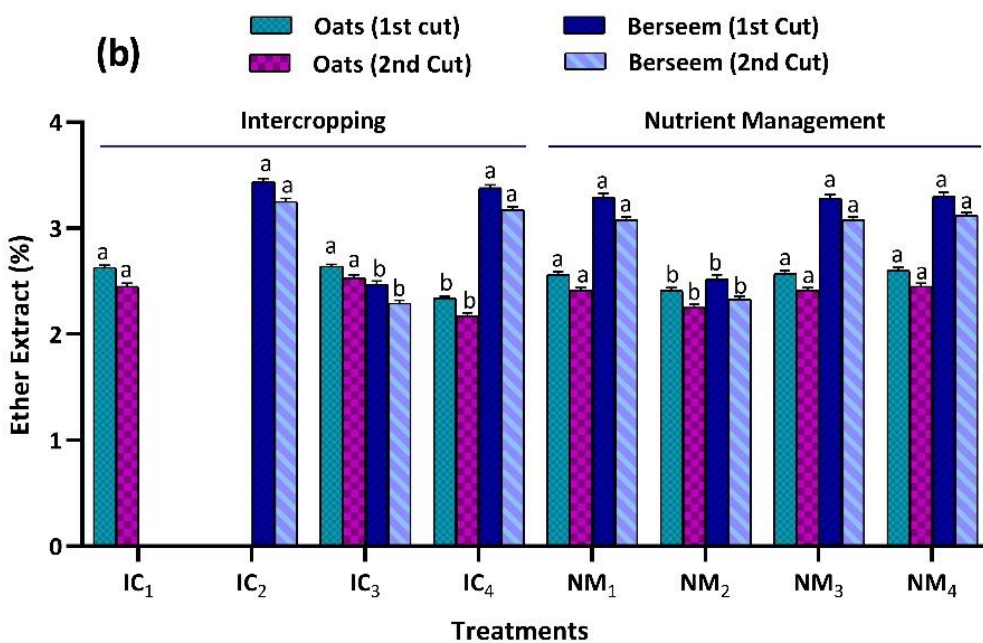
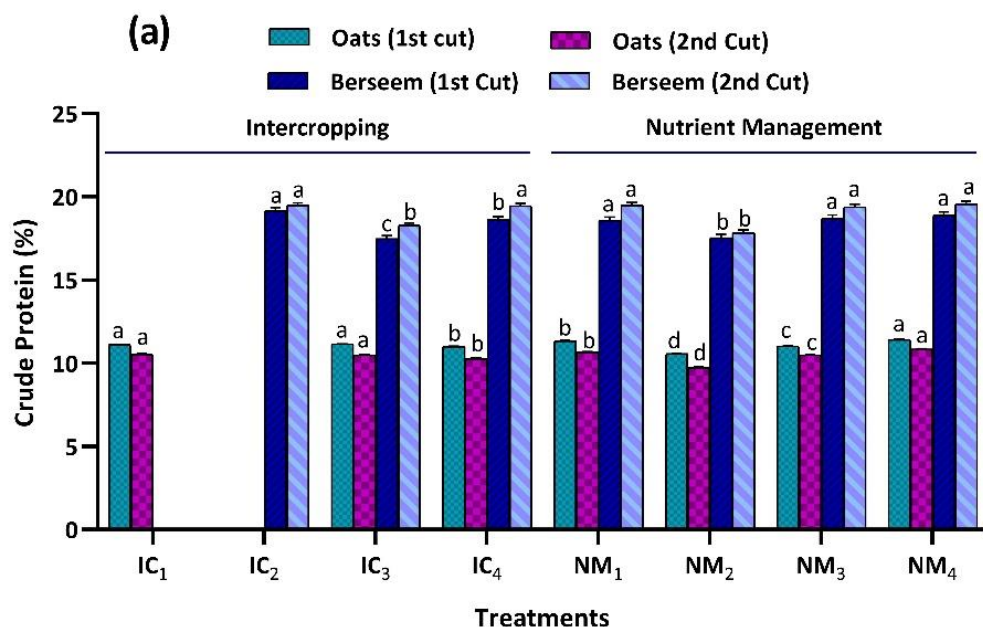
(Supplementary Table 8). In berseem, the highest TA content was observed under IC₂NM₂ (16.41 and 16.14%) at the first and second cuts, respectively (Supplementary Table 9).

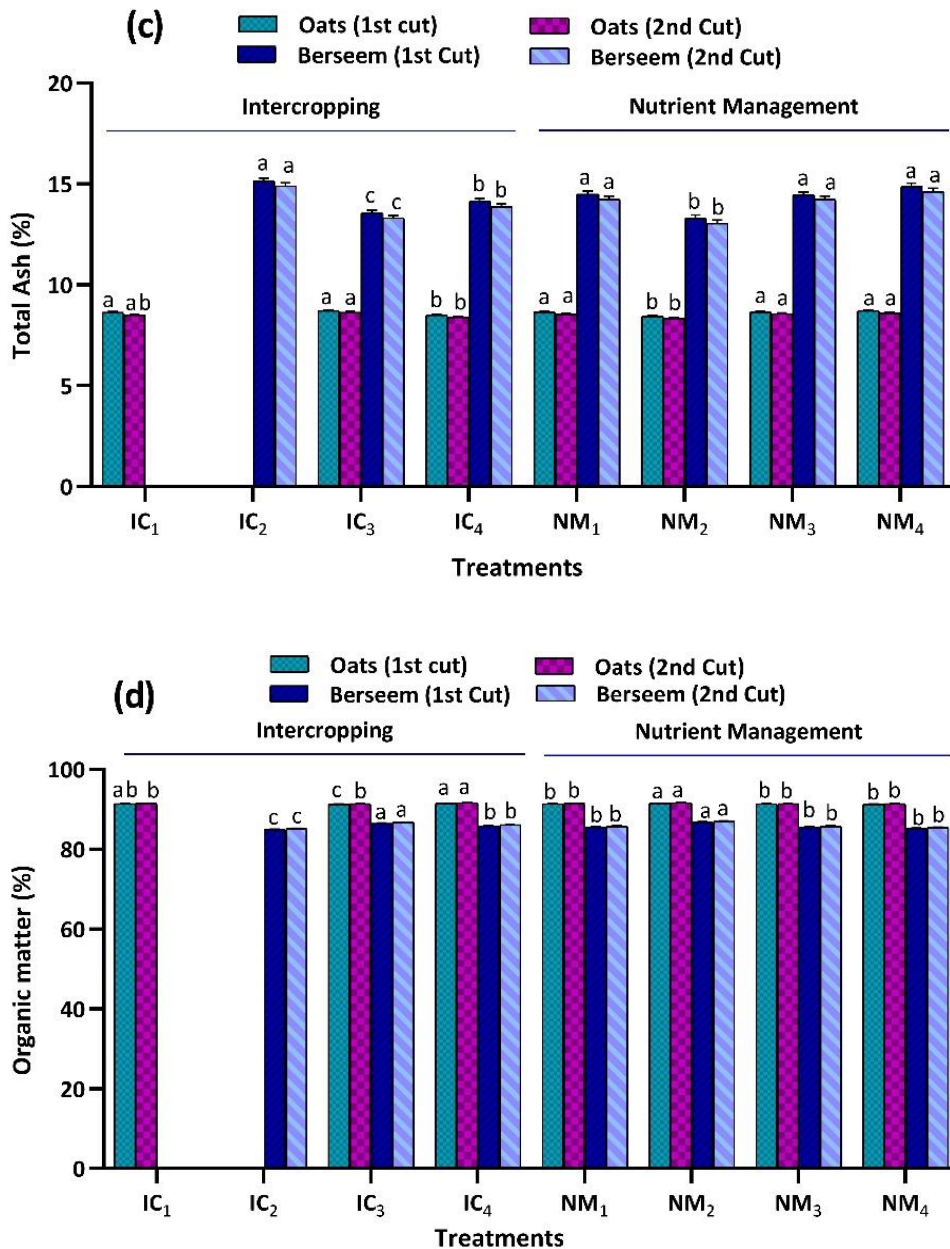


The data represent the mean values across treatments with error bars indicating mean standard error. Different lowercase letters indicate significant differences among treatments based on the LSD test

Figure 1 – Influence of intercropping and integrated nutrient practices on the yield of oats and berseem. (a) Green fodder yield and (b) dry fodder yield

Influence of intercropping and nutrient management practices





The data represent the mean values across treatments with error bars indicating the mean standard error. Different lowercase letters indicate significant differences among treatments based on the LSD test

Figure 2 – Impact of intercropping and integrated nutrient practices on the proximate composition of oats and berseem: (a) crude protein, (b) ether extract, (c) total ash and (d) organic matter contents

Oats under IC₁ exhibited the highest CP (5.0 and 2.37 q ha⁻¹), EE (1.18 and 0.55 q ha⁻¹) and TA contents (3.88 and 1.90 q ha⁻¹) at the first and second cuts, respectively. Conversely, for berseem, IC₂ resulted in the highest CP (3.51 and 3.70 q ha⁻¹), EE (0.62 and 0.62 q ha⁻¹) and TA contents (2.74 and 2.82 q ha⁻¹) at the first and second cuts, respectively. Oats under IC₃ had significantly higher CP, EE and TA contents than those under IC₄. IC₄ resulted in significantly superior CP, EE and TA contents compared to IC₃ in berseem at both the cuts. Among the nutrient management practices, NM₄ exhibited higher CP, EE and TA contents in both oats and berseem (Table 2).

The OM content (Figure 2d) of oats was lower under IC₃ (91.28 and 91.37%), IC₄ (91.50 and 91.60%) and IC₁ (91.37 and 91.50%) at both cuts. In contrast, the OM content (Figure 2d) of berseem was lower under IC₂ (84.86 and 85.09%) than under IC₃ (86.44 and 86.69%) and IC₄ (85.86 and 86.12%) at both cuts.

Among nutrient management practices, a lower OM content was recorded in oats and berseem under NM₄ at both cuts, while an increasing trend was found under NM₁ and NM₃.

Fibre fractions

The fibre fractions of both crops were influenced by intercropping and nutrient management practices (Table 3). In oats, IC₃ resulted in the lowest NDF (57.16 and 57.65%), ADF (34.21 and 34.72%) and ADL contents (3.87 and 4.14%), which were significantly lower compared to those under IC₄ at both cuts (Table 3). Conversely, in berseem, the NDF (41.77 and 42.08%) and ADF contents (24.00 and 24.30%) under IC₃

were comparable to those under IC₄ at both cuts, while the ADL content (3.48 and 3.89%) was substantially higher under IC₃ than under IC₄ at both cuts.

The application of nutrient management practices reduced the fibre fractions in oats and berseem. In both crops and at both cuts, NM₄ resulted in lower NDF, ADF and ADL contents, while NM₃ and NM₁ exhibited comparable values. Conversely, NM₂ resulted in the highest NDF, ADF and ADL contents.

Intercropping and nutrient management practices had a significant impact on the NDF, ADF and ADL contents in oats and berseem. IC₃NM₄ resulted in the lowest NDF content (49.65 and 51.02%) at the first and second cuts in oats.

Detailed interaction effects are presented in Supplementary Table 10. Berseem under IC₂NM₄ had the lowest NDF content (38.17 and 38.45%) at the first and second cuts, respectively (Supplementary Table 11).

The lowest ADF content (30.79 and 31.01%) was observed in oat under IC₃NM₄ at the first and second cuts, respectively (Supplementary Table 12). Berseem under IC₂NM₄ recorded the lowest ADF content (21.70 and 21.97%) at the first and second cuts, respectively (Supplementary Table 13).

In oats, IC₃NM₂ resulted in the lowest ADL content (3.57 and 3.90%) at the first and second cuts, respectively (Supplementary Table 14). Berseem under IC₂NM₂ had the lowest ADL content (2.63 and 3.04%) at the first and second cuts, respectively (Supplementary Table 15).

Table 2 – Effects of intercropping and integrated nutrient practices on the crude protein, ether extract and total ash contents (quintal/ha) in oats and berseem

Treatment	Crude protein content				Ether extract content				Total ash content			
	Oats		Berseem		Oats		Berseem		Oats		Berseem	
	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)
Intercropping												
IC ₁	5.00 ^a	2.37 ^a	3.51 ^a	3.70 ^a	1.18 ^a	0.55 ^a	0.62 ^a	0.62 ^a	3.88 ^a	1.90 ^a	2.74 ^a	2.82 ^a
IC ₂	4.19 ^b	1.48 ^b	0.77 ^c	1.70 ^c	0.99 ^b	0.35 ^b	0.11 ^c	0.23 ^c	3.27 ^b	1.21 ^b	0.60 ^c	1.25 ^c
IC ₃	2.37 ^c	0.86 ^c	1.33 ^b	3.03 ^b	0.51 ^c	0.18 ^c	0.25 ^b	0.48 ^b	1.83 ^c	0.70 ^c	1.02 ^b	2.08 ^b
IC ₄	0.39	0.21	0.21	0.32	0.09	0.05	0.04	0.05	0.32	0.16	0.15	0.23
LSD ($p \leq 0.05$)	0.39	0.21	0.21	0.32	0.09	0.05	0.04	0.05	0.32	0.16	0.15	0.23
Nutrient management												
NM ₁	3.95 ^b	1.65 ^b	1.94 ^b	2.99 ^a	0.90 ^b	0.39 ^a	0.36 ^a	0.45 ^b	3.01 ^b	1.33 ^b	1.50 ^b	2.04 ^b
NM ₂	2.94 ^c	1.05 ^c	1.22 ^c	1.96 ^b	0.69 ^c	0.25 ^b	0.19 ^b	0.30 ^c	2.35 ^c	0.90 ^c	0.95 ^c	1.52 ^c
NM ₃	4.11 ^{ab}	1.66 ^b	1.98 ^b	2.95 ^a	0.96 ^{ab}	0.38 ^a	0.36 ^a	0.47 ^b	3.22 ^{ab}	1.34 ^{ab}	1.54 ^b	2.14 ^b
NM ₄	4.43 ^a	1.92 ^a	2.35 ^a	3.32 ^a	1.02 ^a	0.44 ^a	0.40 ^a	0.54 ^a	3.39 ^a	1.52 ^a	1.83 ^a	2.46 ^a
LSD ($p \leq 0.05$)	0.45	0.24	0.24	0.38	0.10	0.06	0.04	0.06	0.37	0.18	0.18	0.26

Note: Different lowercase letters indicate significant differences among treatments based on the LSD test.

Intercropping systems (IC): IC₁: oats (sole crop), IC₂: berseem (sole crop), IC₃: oats + berseem (2:1 row ratio), IC₄: oats + berseem (1:2 row ratio).

Nutrient management practices (NM): NM₁: 100% recommended dose of fertilizers (RDF) – control, NM₂: 50% RDF + PGPR + two foliar sprays of seaweed extract, NM₃: 75% RDF + PGPR + two foliar sprays of seaweed extract, NM₄: 100% RDF + PGPR + two foliar sprays of seaweed extract. Days after sowing (DAS).

Table 3 – Effects of intercropping and integrated nutrient practices on fibre fractions (%) in oats and berseem

Treatment	Neutral Detergent Fiber (%)				Acid Detergent Fiber (%)				Acid Detergent Lignin (%)			
	Oats		Berseem		Oats		Berseem		Oats		Berseem	
	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)	1 st cut (60 DAS)	2 nd cut (95 DAS)
Intercropping												
IC ₁	58.43 ^b	58.83 ^b	-	-	34.27 ^b	35.12 ^b	-	-	3.96 ^b	4.22 ^b	-	-
IC ₂	-	-	40.48 ^b	40.74 ^b	-	-	22.96 ^b	23.25 ^b	-	-	3.13 ^c	3.52 ^c
IC ₃	57.16 ^b	57.65 ^b	41.77 ^a	42.08 ^a	34.21 ^b	34.72 ^b	24.00 ^a	24.30 ^a	3.87 ^b	4.14 ^b	3.48 ^a	3.89 ^a
IC ₄	62.18 ^a	62.51 ^a	41.56 ^a	41.86 ^a	35.82 ^a	36.54 ^a	23.66 ^{ab}	23.98 ^{ab}	4.16 ^a	4.41 ^a	3.25 ^b	3.66 ^b
LSD ($p \leq 0.05$)	1.32	1.27	1.04	1.03	1.00	0.99	0.77	0.77	0.13	0.14	0.10	0.12
Nutrient Management												
NM ₁	58.73 ^b	59.39 ^b	41.61 ^a	41.92 ^a	34.63 ^b	35.40 ^b	23.61 ^a	23.91 ^a	3.98 ^b	4.22 ^b	3.30 ^b	3.70 ^b
NM ₂	61.03 ^a	61.20 ^a	42.48 ^a	42.75 ^a	36.14 ^a	36.35 ^a	24.28 ^a	24.58 ^a	4.15 ^a	4.44 ^a	3.51 ^a	3.92 ^a
NM ₃	59.01 ^b	59.68 ^b	41.64 ^a	41.93 ^a	34.70 ^b	35.56 ^b	23.57 ^a	23.87 ^a	3.98 ^b	4.22 ^b	3.33 ^b	3.77 ^b
NM ₄	58.26 ^b	58.37 ^b	39.35 ^b	39.64 ^b	33.61 ^b	34.54 ^b	22.70 ^b	23.00 ^b	3.88 ^b	4.15 ^b	2.99 ^c	3.38 ^c
LSD ($p \leq 0.05$)	1.53	1.46	1.20	1.19	1.16	1.14	0.89	0.89	0.15	0.16	0.12	0.14

Intercropping affected the hemicellulose content (%) of oats at both cuts, while it had no statistically significant effects on the hemicellulose content (%) of berseem at either cut (*Table 4*). In oats, the lowest hemicellulose content at each cut was recorded under IC₃ (22.95 and 22.92%), followed by IC₁ (24.16 and 23.71%). IC₄ resulted in the highest hemicellulose content. The lowest hemicellulose content in berseem was observed under IC₂ (17.52 and 17.49%), followed by IC₃ (*Table 4*). The nutrient management practices did not have a significant effect on the hemicellulose content in either crop at either cut. For oats, the lowest hemicellulose content (24.10%) was recorded under NM₁ at the first cut, while at the subsequent cut, NM₄ resulted in the lowest hemicellulose content (23.84%). In berseem, NM₁ resulted in the lowest hemicellulose content (18.01 and 18.01%), which was statistically similar to that under NM₃ at both cuts.

Intercropping and nutrient management practices influenced the cellulose content in oats at both cuts, as shown in *Table 4*. Conversely, no notable impact of intercropping and nutrient management practices was observed on the cellulose content (%) in berseem at either cut. In oats, the lowest cellulose content (31.66 and 32.14%) at both cuts was recorded under IC₃, which was comparable to that under IC₁. Berseem under IC₂ had the lowest cellulose content (19.83 and 19.72%) at both cuts. Regarding nutrient management practices, NM₄ resulted in the lowest cellulose content in oats (29.73 and 30.48%) and berseem (19.71 and 19.62%) at both cuts. The cellulose

content was highest in both crops under NM₂ at both stages.

Feed quality

The intercropping system and nutrient management practices had significant impacts on the feed quality of both crops (*Table 5*). Oats under IC₃ exhibited the highest DMI (2.11 and 2.09%), DMD (62.25 and 61.85%) and TDN contents (57.21 and 56.56%) at both cuts, followed by IC₁. Conversely, the lowest DMI, DMD and TDN contents were observed under IC₄. For berseem, IC₂ resulted in the highest DMI (2.97 and 2.96%), DMD (71.02 and 71.79%) and TDN contents (71.74 and 71.36%) at both cuts, followed by IC₄. Berseem under IC₃ had the lowest DMI, DMD and TDN contents. In terms of nutrient management practices, NM₄ resulted in superior DMI, DMD and TDN contents for both oats and berseem at both cuts, while NM₂ resulted in the lowest DMI content for both crops (*Table 5*).

Intercropping and nutrient management practices influenced the DMI, DMD and TDN contents in oats and berseem. IC₃NM₄ resulted in the highest DMI content (7.25 and 7.06%) in oats at the first and second cuts, respectively (*Supplementary Table 16*). Berseem under IC₂NM₄ recorded the highest DMI content (9.44 and 9.37%) at the first and second cuts, respectively (*Supplementary Table 17*). The highest DMD content (194.7 and 194.2%) was observed in oats under IC₃NM₄ at both the first and second cuts, respectively (*Supplementary Table 18*). Berseem under IC₂NM₄ had the highest DMD content (216.0 and 215.3%) at the first and second cuts, respectively (*Supplementary Table 19*).

Table 4 – Effects of intercropping and integrated nutrient practices on fibre fractions in oats and berseem

Treatment	Hemicellulose (%)					
	Oats		Berseem		Cellulose (%)	
	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)
Intercropping						
IC ₁	24.16 ^b	23.71 ^b	-	30.31 ^b	-	-
IC ₂	-	-	17.52	17.49	-	19.83
IC ₃	22.95 ^b	22.92 ^b	17.77	17.79	30.58 ^b	20.41
IC ₄	26.36 ^a	25.96 ^a	17.90	17.89	31.66 ^a	20.41
LSD ($p \leq 0.05$)	1.75	1.76	NS	NS	1.00	NS
Nutrient Management						
NM ₁	24.10	23.99	18.01	18.01	30.65 ^b	20.31
NM ₂	24.90	24.85	18.20	18.18	31.99 ^a	20.77
NM ₃	24.30	24.12	18.07	18.06	30.73 ^b	20.24
NM ₄	24.65	23.84	16.65	16.64	29.73 ^b	19.71
LSD ($p \leq 0.05$)	NS	NS	NS	NS	1.16	NS

Table 5 – Effects of intercropping and integrated nutrient practices on feed quality of oats and berseem fodder crops

Treatment	DMI (%)				DMD (%)				TDN (%)			
	Oats		Berseem		Oats		Berseem		Oats		Berseem	
	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)	1 st cut (60 DAS)	II nd cut (95 DAS)
Intercropping												
IC ₁	2.07 ^a	2.05 ^a	-	-	62.20 ^a	61.54 ^a	-	-	57.14 ^a	56.05 ^a	-	-
IC ₂	-	2.97 ^a	2.96 ^a	-	-	-	71.02 ^a	70.79 ^a	-	-	71.74 ^a	71.36 ^a
IC ₃	2.11 ^a	2.09 ^a	2.88 ^b	2.86 ^b	62.25 ^a	61.85 ^a	70.20 ^b	69.97 ^b	57.21 ^a	56.56 ^a	70.39 ^b	70.01 ^b
IC ₄	1.94 ^b	1.93 ^b	2.89 ^b	2.87 ^b	61.00 ^b	60.43 ^b	70.47 ^b	70.22 ^{ab}	55.14 ^b	54.21 ^b	70.83 ^{ab}	70.42 ^b
LSD ($p \leq 0.05$)	0.04	0.04	0.07	0.07	0.78	0.77	0.60	0.60	1.30	1.28	1.00	0.99
Nutrient Management												
NM ₁	2.04 ^{ab}	2.02 ^{ab}	2.89 ^b	2.87 ^b	61.93 ^a	61.32 ^{ab}	70.51 ^b	70.27 ^b	56.68 ^a	55.68 ^{ab}	70.90 ^b	70.50 ^b
NM ₂	1.99 ^b	1.99 ^b	2.83 ^b	2.81 ^b	60.75 ^b	60.59 ^b	69.99 ^b	69.75 ^b	54.73 ^b	54.46 ^b	70.03 ^b	69.64 ^b
NM ₃	2.04 ^{ab}	2.01 ^b	2.89 ^b	2.87 ^b	61.87 ^a	61.20 ^{ab}	70.54 ^{bb}	70.31 ^{ab}	56.59 ^a	55.47 ^{ab}	70.94 ^{ab}	70.56 ^{ab}
NM ₄	2.08 ^a	2.07 ^a	3.05 ^a	3.03 ^a	62.72 ^a	62.00 ^a	71.22 ^a	70.98 ^a	58.00 ^a	56.80 ^a	72.07 ^a	71.68 ^a
LSD ($p \leq 0.05$)	0.05	0.05	0.08	0.08	0.90	0.89	0.70	0.69	1.50	1.48	1.15	1.15

Influence of intercropping and nutrient management practices

In oats, IC₃NM₄ resulted in the highest TDN content (184.9 and 184.1%) at the first and second cuts, respectively (*Supplementary Table 20*). The highest TDN content in berseem was reordered under IC₂NM₄ (220.1 and 219.0%) at the first and second cuts, respectively (*Supplementary Table 21*).

RFV and RFQ were significantly influenced by the adoption of intercropping and nutrient management practices (*Table 6*). Oats under IC₃ exhibited the highest RFV (102.2 and 100.5%) and RFQ (98.74 and 96.61%) at both cuts. Conversely, IC₄ resulted in the lowest RFV and RFQ values. Berseem under IC₂ had the highest RFV (163.9 and 162.3%) and RFQ (173.8 and 171.7%) at both cuts, followed by IC₄. The lowest RFV and RFQ were observed under IC₃ (*Table 6*). Among nutrient management practices, NM₄ resulted in a superior RFV and RFQ for both oats and berseem at both cuts, whereas NM₂ resulted in the lowest. Intercropping and nutrient management practices influenced RFV and RFQ in oats and berseem. Oats under

IC₃NM₄ had the highest RFV (364.8 and 354.5%) at the first and second cuts, respectively (*Supplementary Table 22*). Berseem under IC₂NM₄ had the highest RFQ (526.8 and 521.4%) at the first and second cuts, respectively (*Supplementary Table 23*).

The highest RFQ (363.2 and 352.2%) was observed under IC₃NM₄ at the first and second cuts, respectively, in oats (*Supplementary Table 24*). In berseem, IC₂NM₄ resulted in the highest RFQ (562.90 and 556.1%) at the first and second cuts, respectively (*Supplementary Table 25*).

Correlation matrix

The correlation plot matrices (*Supplementary Figures 1–2*) showed positive correlations ($r > 0.908$ and > 0.925) between crop yield and proximate composition (ether extract, total ash and organic matter) and negative correlations ($r > 0.262$ and > 0.871) between the proximate composition (EE, TA and OM) and fibre fractions (NDF, ADF and ADL) at the first and second cuts, respectively.

Table 6 – Effects of intercropping and integrated nutrient practices on the feed quality of oats and berseem

Treatment	RFV (%)				RFQ (%)			
	Oats		Berseem		Oats		Berseem	
	I st cut (60 DAS)	II nd cut (95 DAS)	I st cut (60 DAS)	II nd cut (95 DAS)	I st cut (60 DAS)	II nd cut (95 DAS)	I st cut (60 DAS)	II nd cut (95 DAS)
Intercropping								
IC ₁	99.47 ^b	97.71 ^b	-	-	95.71 ^b	93.25 ^b	-	-
IC ₂	-	-	163.9 ^a	162.3 ^a	-	-	173.8 ^a	171.7 ^a
IC ₃	102.2 ^a	100.5 ^a	156.7 ^b	155.0 ^b	98.74 ^a	96.61 ^a	164.8 ^b	162.7 ^b
IC ₄	91.7 ^c	90.36 ^c	157.9 ^b	156.2 ^b	87.04 ^c	85.06 ^c	166.4 ^b	164.2 ^b
LSD ($p \leq 0.05$)	2.15	2.08	4.49	4.39	2.57	2.47	5.25	5.14
Nutrient management								
NM ₁	98.16 ^b	96.13 ^b	157.9 ^b	156.2 ^b	94.23 ^b	91.56 ^b	166.6 ^b	164.5 ^b
NM ₂	93.90 ^c	93.38 ^c	153.6 ^b	152.1 ^b	88.76 ^c	88.06 ^c	161.2 ^b	159.2 ^b
NM ₃	97.62 ^b	95.41 ^{bc}	157.9 ^b	156.3 ^b	93.63 ^b	90.69 ^{bc}	166.6 ^b	164.5 ^b
NM ₄	101.6 ^a	99.96 ^a	168.5 ^a	166.7 ^a	98.71 ^a	96.25 ^a	178.9 ^a	176.6 ^a
LSD ($p \leq 0.05$)	2.49	2.40	5.18	5.07	2.97	2.85	6.06	5.94

Positive correlations ($r > 0.837$ and $r > 0.918$) were observed between crop yield and the proximate composition (EE, TA and OM), and negative correlations ($r > 0.446$ and $r > 0.465$) were observed between the proximate composition (EE, TA and OM) and fibre fractions (NDF, ADF and ADL) at the first and second cuts, respectively (Supplementary Figures 3–4).

DISCUSSION

The maximum GFY and DFY of oats and the highest GFY of berseem during the initial and subsequent cuts were attained in IC₁ and IC₂, respectively. This was due to the lack of component crop competition for nutrients and moisture, increasing growth, which contributes to a higher photosynthetic rate and increased yield (Kaur *et al.*, 2018; Kushwah *et al.*, 2024; Liliane and Charles, 2020). Feng *et al.* (2021) reported that intercropping with a bandwidth of 2.0 m showed the highest N accumulation, N use efficiency and N competition ratio but lower yields in maize–soybean intercropping compared to monocropping due to high resource competition. Huang *et al.* (2019) reported that the yield of maize intercropped with watermelon was reduced to one-third compared to maize monocropping in the North China Plain. Among nutrient management practices, NM₄ resulted in the highest increase in green, dry and total fodder yield. This increase in crop yield might be due to the integrated application of PGPR and foliar seaweed extract and the RDF, as PGPR and seaweed extract support plant growth and yield through direct and indirect modes of action, such as root exudate secretion,

plant growth hormones, nutrient availability and reducing plant pathogen populations. Hammad *et al.* (2020) reported that RDF increased nutrient availability, increasing photosynthesis, which wheat yield. Yasmin *et al.* (2020) showed that inoculation with PGPR and RDF application affect the yield of sweet potatoes. Mohammed *et al.* (2022) found that the integrated application of biofertilisers, RDF and foliar spray of seaweed extract increased the accessibility of nutrients for plant growth and development and enhanced the yield of lettuce.

In our study, intercropping and nutrient management significantly increased GFY and DFY in oats and berseem, except for GFY in oats, indicating its limited sensitivity to these factors. Berseem's highest GFY was observed under IC₂NM₄ at both cuts, suggesting improved nutrient uptake and interspecies synergy. Oats had the highest DFY (4.92 t ha⁻¹) under IC₁NM₄, indicating nutrient-driven biomass accumulation. DFY peaked in berseem under IC₁NM₄ and IC₄NM₄ at the first and second cuts, reflecting stage-specific nutrient requirements and the cumulative benefits of intercropping over time.

The proximate composition indicates the quality of fodder crops. The highest CP, EE and TA contents were observed under IC₁ and IC₂. This increase was attributed to reduced inter-specific competition for space, light, water and nutrients, as there was no competition from component crops. Similar findings were reported by Bhakar *et al.* (2020) in sorghum–guar intercropping. In the present study, among the nutrient management practices, NM₄ resulted in

higher CP, EE and TA contents in oats and berseem at both cuts. This can be ascribed to the improved obtainability of nutrients resulting from elevated nutrient doses. These doses were applied either in the form of recommended fertilisers or through a combination with organic sources, such as PGPR and seaweed extract. This combined approach ensures sufficient nutrient availability for crops, promoting enhanced nutrient uptake. Consequently, it contributes to high-quality fodder production. Kumar *et al.* (2021) reported that combining PGPR with recommended fertilisers improved nutrient availability, enhancing nutrient uptake and plant growth, which increased the proximate composition in maize crops. Ibrahim *et al.* (2009) demonstrated that inoculation with biofertilisers and the application of mineral fertilisers enhanced the EE and TA contents in teosinte. Furthermore, Craigie (2011) showed that seaweed extract modifies the responses of plants and animals at a fundamental level. The foliar application of seaweed extract along with organic and mineral fertilisers improves nutrient availability, increasing the proximate composition in sorghum–guar intercropping (Bhakar *et al.*, 2020). These results agree with those of Dutta *et al.* (2021) in cowpea crop and Ote *et al.* (2025). Oats under IC₃ and IC₁ had a lower OM content than those under IC₄. Similarly, NM₄ resulted in the lowest OM content in both crops. The lower values may be attributed to the higher TA content, which resulted from the increased availability of space, water, light and nutrients. The OM content is directly contingent upon the TA content, which dictates the mineral composition in the fodder crop. Increasing the TA

content decreases the OM content (Baljeet *et al.*, 2020; Choudhary *et al.*, 2024; O Di Nasso *et al.*, 2010). Combining intercropping and nutrient management practices affected the CP, EE and TA contents in oats and berseem, indicating the importance of integrated agronomic strategies for optimising the forage quality.

The increase in CP, EE, and TA content may be due to enhanced nitrogen assimilation, lipid metabolism and synthesis and optimized availability and absorption of essential minerals.

In the present study, oats recorded the lowest fiber fractions, viz., NDF, ADF, ADL, hemicellulose, and cellulose in treatment IC₃, while treatment IC₄ recorded significantly higher values of fiber fractions at both cuts (Table 3 and 4). Armstrong *et al.* (2008) reported that high interspecific competition among intercrops for resources leads to a decrease in succulence and an increase in fiber fractions in crop plants under maize-based intercropping. Strydom *et al.* (2008) reported that increasing the planting density of legumes such as faba bean, lupin, and pea in intercropping with barley increases the ADF and ADL fractions in fodder.

In the present study, application of nutrient management practices led to substantial reductions in fiber fractions observed in both oats and berseem crops. Treatment NM₄ exhibited the lowest fiber fractions across both cuts of oats and berseem. Conversely, treatments NM₁ and NM₃ demonstrated an increase in fiber fractions, with both treatments exhibiting comparable levels. The elevation in fiber fractions, NDF, ADF, and ADL, may be ascribed to low nutrient availability resulting from the application

of low nutrient levels in both crops. Inoculation of PGPR in Hungarian vetch leads to a reduction in NDF, ADF, and ADL content (Yolcu *et al.*, 2012). Bhakar *et al.* (2020) observed that the application of mineral fertilizers coupled with foliar application of seaweed extract yielded notable improvements in nutrient availability within the sorghum-guar intercropping system. Furthermore, this combined approach demonstrated efficacy in reducing the fiber fraction in the cultivated crops.

The combined effect of intercropping and nutrient management practices highlights their effect on the fiber composition of oats and berseem, as reflected in the variations in NDF, ADF, and ADL contents. The reduction in NDF and ADF contents suggests improved forage digestibility and quality, which can be attributed to optimized nutrient availability and the complementary effects of intercropping systems. The combinations that resulted in the lowest fiber fractions indicate that strategic pairing of intercropping with nutrient management can effectively modulate the structural carbohydrate profile in both crops. Moreover, the observed decrease in ADL content, a key component limiting digestibility due to its association with lignin, further supports the potential of these integrated practices in enhancing forage quality. This interplay between intercropping and nutrient management likely promotes better nutrient uptake and utilization, leading to softer, more digestible plant tissues that are beneficial for livestock feeding.

Intercropping and nutrient management practices significantly

affected feed quality in both crops. In our study, oats, treatments IC₃ and IC₁ exhibited higher DMI, DMD, and TDN, while IC₄ recorded the lowest values. In berseem, IC₂ showed the highest content, followed by IC₄, and IC₃ with the lowest. RFV and RFQ followed similar patterns. In oats, IC₃ and IC₁ had higher RFV and RFQ, while IC₄ has the lowest. In berseem, IC₂ recorded maximum values, followed by IC₄, and IC₃ recorded the lowest values. Among nutrient management practices, NM₄ recorded the highest values, and NM₂ showed the lowest DMI, DMD, TDN, RFV, and RFQ values for both oats and berseem crops. The fiber fractions (NDF, ADF, ADL) play a crucial role in determining the nutritional value and digestibility of fodder, which, in turn, affect DMI, DMD, TDN, RFV, and RFQ. Lower fiber content generally corresponds to improved forage quality and nutrient utilization by animals. Javanmard *et al.* (2009, 2015) recorded a decrease in NDF and ADF fractions, achieved through intercropping maize and legumes, leading to an increase in DMI and TDN content. Kaur and Goyal (2017) reported a negative association between DMD and NDF, ADF, and crude fiber under the recommended dose of fertilization. Application of balanced fertilization results in better DMI, TDN, RFV, and RFQ content in berseem (Arif *et al.*, 2022). Further, Yadav *et al.* (2022) reported that the application of balanced fertilization increases the proximate composition and decreases the fiber content in the fodder crops, resulting in an increase in the feed quality of the crop.

The correlation results, as depicted in the matrices (*Supplementary Figures*.

1-2 and Figures 3-4), indicate significant positive associations ($r > 0.908$ and 0.925) between oats crop yield and proximate composition. Simultaneously, negative correlations ($r > 0.262$ and 0.871) were observed between proximate composition and fiber fractions at both cuts. These findings suggest intricate relationships between crop yield, proximate composition, and fiber fractions, providing valuable insights into the interdependencies within the system.

CONCLUSIONS

Strategic intercropping and nutrient management practices significantly enhanced the yield and quality of oats and berseem fodder. Although monocropping yielded the highest fodder quantities, intercropping, particularly with a 2:1 row ratio (IC₃), produced competitive yields when paired with advanced nutrient management practices, such as NM₄. IC₃NM₄ increased GFY and DFY and improved the nutritional quality by increasing the CP, EE and TA contents, while reducing fibre fractions, thus enhancing feed digestibility. Feed quality parameters, such as DMI, DMD and TDN, were higher under these combined treatments. The positive correlations between yield and proximate composition and negative correlations with fibre content highlight the potential of optimising intercropping and nutrient strategies to improve productivity and fodder quality. These findings support the need for sustainable agricultural practices that enhance livestock nutrition and promote efficient resource use.

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