Range Management and Agroforestry 47 (1) : 265-275, 2026
ISSN 0971-2070 (Print); 2249-5231 (Online)
https://doi.org/10.59515/rma.2026.v47.i1.15

Research article

Seasonal dynamics of feed carbon footprint in sheep field flocks under semi-intensive system in Karnataka, Southern India

Mech A[1*], Letha Devi G[1], M. Sivaram[2], A.P Kolte[1], P.K. Malik[1], N.M Soren[1], S.B.N. Rao[1], A. Dhali[2] and Maya G[1]

[1]ICAR-National Institute of Animal Nutrition and Physiology, Bangalore-560030, India
[2]ICAR-National Dairy Research Institute, Southern Regional Station, Bangalore-560030, India
[*]Corresponding author email: anjumoni_0071@yahoo.co.in

Received: 21st October, 2025 Accepted: 28th January, 2026

Abstract

Feed management plays a crucial role in mitigating greenhouse gas (GHG) emissions from livestock production systems. Despite India possessing one of the largest sheep populations globally, information on the environmental impacts of sheep production remains limited. The present study was conducted in Karnataka, South India, where over 400 sheep from 18 semi-intensive flocks were monitored over a two-year period. A cradle-to-farm-gate life cycle assessment (LCA) approach was employed in accordance with ISO 14040/44 standards, using IPCC Tier 2 methodologies to quantify GHG emissions. Feed carbon footprint (CF) varied significantly across seasons, with the highest CF during winter (0.89 kg CO_2-eq day^{-1} sheep^{-1}) and declining during the monsoon and post-monsoon (0.30–0.38 kg CO_2-eq day^{-1} sheep^{-1}). Common grazing lands contributed 15 to 56% of total nutrient intake, depending on season, substantially reducing reliance on purchased feeds. Strategic incorporation of seasonal green fodder and crop byproducts lowered feed-related emissions by up to 55 to 65% and reduced per day per sheep feed costs up to 12.2%. The findings highlight the critical role of seasonal forage availability in reducing both emissions and production costs, particularly in dryland regions.

Keywords: Carbon footprint, Feeding management, Life cycle assessment, Seasonal variation, Semi-intensive, Sheep farming

Introduction

The sheep population occupying one-quarter of the world's surface area contributes 254.4 million tonnes CO_2-eq greenhouse gas (GHG) to global GHG emissions. The key contributors of GHG emissions from sheep farming were identified as methane (CH_4) from enteric fermentation (46-56%) and manure, nitrous oxide (N_2O) emissions from manure (3–6%) and fertilizer use and carbon dioxide (CO_2) emissions from purchased feed (24–42%) that consists of transportation, feed production, and land-use changes (Sarkar *et al*., 2024). It was estimated that sheep and goats emit 0.96 Tg (teragrams) CH_4, representing about 10% of the total CH_4 emissions from livestock in the country, with the majority of these coming from enteric fermentation (Sharma, 2020). There are several factors that may affect the carbon footprint (CF) of sheep farms, including climate, vegetation, topography, and grazing intensity, etc. Most importantly, seasonal variation and weather conditions can also impact the CF of sheep farms. Hence, feed management decisions are an important element of managing GHG and nitrogen (N) emissions in livestock farming systems (Ouatahar *et al*., 2021).

According to the 20th Indian livestock census (Livestock Census, GOI, 2022) Karnataka state is third in sheep population, constituting 11.1 million sheep of which the majority (51.2%) are nondescript (Kumar *et al*., 2022). The sheep are usually managed under three farming systems, namely intensive (zero grazing), extensive (grazing on large areas/migratory flock) and semi-intensive farming system incorporating elements of both extensive and intensive farming practices (Kumar *et al*., 2022). Sheep grazing occupies around 1.4 billion hectares of land, which is roughly one-quarter of the world's ice-free land area (FAO, 2013). In India, about 58.7% of the land is under cultivation, 23.5% under forest, and 3.34% under permanent pasture and grazing land (Ministry of Agriculture and Farmers Welfare, GOI, 2024). Reducing GHG emissions from sheep farming requires sustainable practices, namely, improved grazing management, efficient feed production and use, manure management and utilization, breeding and selecting low-emission sheep breeds. Further, according to a study that highlighted the importance of considering the environmental impact of sheep farming practices in semi-arid regions of India while exploring strategies to reduce emissions among three different sheep farming systems, the semi-intensive system was found to be the most carbon-efficient (Sarkar *et al.,* 2024).

In semi-intensive farming, the availability of seasonal greens has an impact on the feeding schedule and GHG emissions from feed production, processing and transportation. Nevertheless, there is not a single national report from farmers' fields evaluating the effect of season on the feed carbon footprint of semi-intensive sheep farms. Thus, a two-year study of approximately 400 sheep from 18 different flocks, all managed under semi-intensive systems in the rural districts of Bangalore, Karnataka, was conducted to estimate seasonal fluctuations in the feed-related carbon footprint.

Materials and Methods

Study area: The study was conducted in Doddaballapura Taluk, Bangalore Rural District, Karnataka. The area lies at an elevation of 896 m above mean sea level and with geographic coordinates of 13.3° N latitude and 77.5° E longitude. The region falls within the Eastern Dry Zone, characterized by semi-arid conditions. Eighteen semi-intensive sheep flocks, managing over 400 sheep, were monitored for a two-year period in two villages of Doddaballapura, namely Lakshmidevipura and S Nagenahalli. In Lakshmidevipura, the total agricultural area is 239.61 ha, of which about 229.01 ha is unirrigated area and only about 10.6 ha is irrigated by wells or tube wells. The gross cropped area in S Nagenahalli is 107.8 ha. The climate of the region is semi-arid tropical with a mean annual rainfall of 826.1 mm and a temperature of 23.8°C, and falls under the eastern dry zone of Karnataka. In general, Karnataka has four seasons in the year: the winter season extends from December to February, the summer season from March to May, the monsoon season from June to September and the post-monsoon season from October to November (Anonymous, 2020).

Data collection: The study involved more than 400 nondescript sheep from 18 sheep flocks for a period of two years, from 2020 to 2022. Baseline information, which was collected at the commencement of the study, included particulars on ownership, experience in sheep farming, land holding and livestock holdings, machinery/mechanization, etc. Thus, the subsequent information collected encompasses all impacts associated with farm operation, production, processing and transport of feed in alliance with ISO 14040:2006 and 14044:2006, using a cradle to farm gate strategy. The average agricultural land ownership recorded was 1.8 acres. Subsequently, data were collected on a seasonal basis for two consecutive years for monitoring flock dynamics, feeding pattern, production and reproduction performance and assessing the effect of seasons on different parameters and GHG emissions of the sheep flocks. Data recorded with respect to animal numbers, lambing, feeding, grazing, general management practices, etc. and the information regarding animal, flock and farm characteristics are shown in table1. Simultaneously, sheep representing different age groups were randomly selected and body weight was recorded using a platform balance available at the village co-operative society office.

Management of sheep: The sheep were reared under a semi-intensive management system, wherein they were taken out for grazing to village common land in Lakshmidevipura and in the forest area of S. Nagenahalli during the morning and afternoon hours by shepherds. The community grazing ground in Lakshmidevipura was approximately 50 acres, whereas the forest grazing area in S. Nagenahalli was around 300 acres in size. Grazing usually occurred from 6:00 a.m. to 11:00 a.m. and again from 3:00 p.m. to 5:00 or 6:00 p.m., providing the sheep with a daily grazing duration of approximately 7 to 8 hours. In the evenings, the sheep were brought back to their respective shelters and were provided with supplementary feed, including concentrates, green fodder, and dry roughage.

Feed nutrient content and intake estimation: Feed samples were collected at regular intervals from individual flocks and grazing areas for nutritional analysis in the laboratory (AOAC, 2019). The energy concentration of feeds and forages was determined by total digestible nutrients (TDN). Dry matter intake (DMI) from pasture was estimated using pasture neutral detergent fiber (NDF) content based on the rumen fill-based intake regulation model of Mertens (1987, 1994), which limits voluntary NDF intake to approximately 1.1–1.2% of body weight and is applicable to grazing sheep. To evaluate the environmental impact, the carbon footprint of each feed component was computed separately and expressed as kilograms of CO_2 equivalent (kg CO_2-eq) per kilogram of feed DM and was aggregated to derive the overall feed-related emissions.

Sheep farmers obtained cattle feed pellets manufactured by the Karnataka Co-operative Milk Producers' Federation Limited (KMF) from local markets for feeding their sheep. Data on off-farm feed inputs, such as purchased concentrates, crop byproducts, and oilseed meals, were collected from farmers and local suppliers. This included information on supplier identity, mode of transportation, and average annual pricing. The amount of feed utilized on each farm was approximated using data provided by the farmers. The study encompassed both on-farm and off-farm feed sources. GHG emissions (CO_2, CH_4 and N_2O) associated with feed production and transportation were calculated following the Tier 2 approach as per the IPCC guidelines. For transportation-related emissions, emission factors for Indian vehicles were applied, as specified by Ramachandra and Shwetmala (2009).

Feed consumption of the flock was documented by observation and structured interviews with farmers. The body weight of representative sheep, categorized by age and physiological status, and was recorded at intervals of 2.5 months using a platform balance.

Grazing DMI was estimated using the neutral detergent fiber (NDF) content of pasture, based on the rumen fill–based intake regulation model proposed by Mertens (1987, 1994), which constrains voluntary NDF intake to approximately 1.1 to 1.2% of body weight (BW). Consequently, maximum pasture was calculated as a function of animal BW and forage NDF concentration, and total daily DMI (1.2% of NDF) was obtained by adding intake from supplemental feeds. Although originally developed largely from cattle data, the NDF intake ceiling of 1.1 to 1.2% of body weight has been shown to be applicable to small ruminants, including sheep, under grazing conditions (Minson, 1990; Mertens, 1994; Patra, 2012), particularly in systems characterized by seasonal variation in forage quality and limited availability of individual animal intake records.

Estimating carbon footprint of feed: The CF of various feeds (kg CO_2-eq. kg^{-1}feed) including finger millet/ragi, ragi ball, wheat bran, Bengal gram, maize grain, maize stem, groundnut cake (GNC), mustard leaves, and lablab pods, was estimated using mass allocation based on secondary data related to greenhouse gas (GHG) emissions from the production of crops and their byproducts (bran, stem, stover), and their respective production rates per hectare (Gowda *et al.*, 1999; Sah and Devakumar, 2018). The CF of fodder was computed by incorporating the average fodder yield in Karnataka and accounting for emissions from key agricultural inputs like fertilizers, farmyard manure (FYM), pesticides, irrigation, diesel, and other contributing factors (Manoj *et al.*, 2022).

The CF of processed feeds, including cattle feed pellets produced by the Karnataka Milk Federation (KMF) and concentrate mixtures formulated by the National Institute of Animal Nutrition and Physiology (NIANP), was derived by summing the emission factors for each feed ingredient, in addition to the emissions from processing and transportation. The energy emission factors used were 100.6 kJ/kg for pellet feed and 30.8 kJ/kg for crushed feed, respectively (Dabbour *et al.*, 2014). Emission factors for freight transport considered were as follows: trucks (3.23 kg CO_2/km), tempos (1.09 kg CO_2/km), and two-wheelers (0.12 kg CO_2/km) (Ramachandra and Shwetmala, 2009). In the case of compound cattle feed, ingredient intake contributed the majority (73–82%) of the total CF, while energy use and transportation accounted for approximately 8–12% (Adom *et al.*, 2013). All GHG emissions were expressed in terms of carbon dioxide equivalents (CO_2-eq) and calculated using global warming potentials (GWPs) from the IPCC Sixth Assessment Report: CO_2 = 1, CH_4 = 27.9, and N_2O = 273 (IPCC, 2021). Finally, the feed-related CF for each farm was determined by dividing the total daily GHG emissions from feed consumption by the number of adult sheep in the farm. This value was expressed as kilograms of CO_2-eq per day per farm or sheep (kg CO_2-eq. d^{-1} $farm^{-1}$ or $sheep^{-1}$).

Statistical analysis: Data were analyzed using analysis of variance (ANOVA) in DATAtab to assess the significance of parameter variation across seasons (winter, summer, monsoon, and post-monsoon) at a significance level of $p < 0.05$. When ANOVA indicated a significant overall effect, Tukey's post hoc test was employed to identify pairwise differences between group means. Further, Pearson's correlation analysis was conducted using the DATAtab package to evaluate the linear relationship between feed carbon footprint (CF, kg CO_2-eq. day^{-1} $sheep^{-1}$) and the total digestible nutrient (TDN) contribution (%) from various dietary sources, including concentrate, offered green fodder, pasture, and roughage.

Results and Discussion

Characteristics and management of sheep flocks: The perusal of Table 1 reveals the flock characteristics in sheep populations across different seasons. The mean flock size and body weight (kg, $sheep^{-1}$) of adult sheep varied between 25.4 to 28.1 and 24.5 to 27.5 during the winter, summer, monsoon, and post-monsoon seasons, respectively. The current study found that the mean body weight difference between the rams and ewes was only about 1 kg, despite the fact that mating rams are typically 4 to 5 kg larger than ewes. This was primarily due to the age structure of breeding males in the flock. The younger age group (12–18 months) included about 50 to 70% of breeding rams, with body weights between 24 and 26 kg. On the other hand, the majority of fully grown and heavier rams were either sold or slaughtered every year in May (Bakri Eid), which resulted in their under-representation during the data collection period. Males aged 18 to 38 months weighed 27 to 35 kg, while rams aged ≥48 months weighed 46–49 kg, according to age-wise analysis. However, the low proportion of older, heavier rams was insufficient to substantially influence the overall mean body weight of males. In Munjal sheep flock raised predominantly on grazing in

Punjab, Haryana, and Rajasthan states, the ewe to ram ratio of 18:1 was reported, with an average flock size of 53, including 36 ewes, 2 rams, and 15 lambs (Yadav *et al.*, 2010). Whereas in the current study, the average flock size was comparatively smaller (26.4), consisting of 13.7 ewes, 6.2 breeding rams, and 3.7 lambs. Furthermore, the ewe-to-breeding ram ratio remained between 6:1 and 7.6:1 across the four seasons, indicating that more rams were maintained in sheep flocks than the optimum requirement. According to previous reports, the recommended ideal ewe-to-ram ratio in Indian conditions is typically 21 to 30 females for each breeding ram (Rajanna *et al.*, 2014). In the current study, high ram-to-ewe ratio reflects typical smallholder management rather than a deliberate breeding strategy, as sheep sales were driven by body weight and urgent cash needs rather than breeding relevance. Opportunistic sale of bigger males, lack of planned culling or ram replacement resulted in retention of more rams than the optimal requirement for the flock.

The annual requirements for concentrate, fuel, and electricity were estimated as 965 kg farm^{-1} yr^{-1}, 13.8 liters farm^{-1} yr^{-1}, and 32.1 kW farm^{-1} yr^{-1}, respectively (Table 1). In a previous study by Lal *et al.*, (2022), that assessed carbon footprints and production outputs of crops and sheep in Rajasthan, India, the resource requirements for rearing popular Indian sheep breeds (Malpura, Avishaan, Patanwadi, and Kheri) under dominant forage production systems (Napier, perennial grasses, forage legumes, and bajra) were reported to be comparatively higher. Specifically, the reported requirements were 6–13 liters of fuel per ha^{-1}, 328.4 to 419.7 kg of feed per livestock unit^{-1} yr^{-1}, and 0.5 to 2.8 kWh of electricity. Another study from Rajasthan, India, reported annual emissions from fuel and electricity in semi-intensive sheep flocks as 0.39 and 0.70 kg CO_2-eq per kg of mutton produced (Sarkar *et al.*, 2024). These reports were mostly from organized studies conducted in research facilities, as opposed to the current study situation, in which information was acquired from farmers' fields. Concentrate feed was typically purchased once every one to two months from shops in the Doddaballapura town market, located 7.5 to 15 km from the respective sheep farms. Transportation was usually by auto-rickshaw or two-wheeler. The quantity of concentrate feeds transported at one time varied from 100 to 350 kg, depending upon the requirements of individual sheep flocks. In addition, annually, once or twice, fertilizers and other farm inputs were also acquired from the same place and were transported along with feeds. Once a year, each sheep farmer received 60 kg of a concentrate mixture formulated by NIANP. The mixture consisted of 44 parts maize, 25 parts groundnut cake, 29 parts wheat bran, 1 part salt, and 1 part mineral mixture, and it contained 18% crude protein (CP) and 72% TDN.

The total GHG emission for feed was calculated based on the emissions from feed production, processing and transportation, and energy usage for processing as mentioned in the methodology. The sheep were allowed to graze for 7 to 8 hours and were supplemented with concentrate, roughage and greens once they were back to the shed. The sheep were fed KMF cattle pellets combined with NIANP formulated sheep concentrate. A few farmers additionally fed home-grown Bengal gram (crushed) and ragi balls. Most farmers combined wheat bran with a concentrate mixture; some also added rava bhusa and groundnut cake (GNC) for feeding their sheep (2–4 kg flock^{-1}). Extra greens were provided based

Table 1. Flock structure of semi intensive sheep flocks across four seasons

Parameters	Seasons			
	Winter	**Summer**	**Monsoon**	**Post-monsoon**
Average body wt., kg, ewe^{-1}	25.2 ± 0.47	26.4 ± 0.54	24.5 ± 0.69	27.5 ± 0.66
Average body wt.,kg, ram^{-1}	26.1 ± 0.58	26.6 ± 0.68	25.4 ± 0.75	27.4 ±0.79
	Flock characteristics			
Flock size, number of sheep flock^{-1}	25.4 ±1.31	27.3 ± 1.43	26.2 ± 1.45	28.1 ± 1.48
Number of adult sheep flock^{-1}	22.9 ± 1.10	23.7 ± 1.18	22.4 ± 1.31	22.9 ± 1.43
Number of ewe flock^{-1}	13.7 ± 0.89	14.1 ± 0.83	13.6 ± 1.14	13.4 ±1.10
Pregnant ewe no flock^{-1}	3.24 ± 0.25	2.93 ± 0.28	3.17± 0.31	3.11± 0.33
Number of ram above 1 yr flock^{-1}	5.93 ± 0.38	6.63 ± 0.40	5.67 ± 0.44	6.44 ± 0.56
Number of lambs below 1yr flock^{-1}	3.87 ± 0.40	4.09 ± 0.37	3.06 ± 0.44	3.64 ± 0.47
Grazing time, h, day^{-1}	7	8	8	7
	Annual Inputs in the farm			
Concentrate purchased, kg, flock^{-1} yr^{-1}	965 ± 40.1			
Fuel (diesel) used, liters flock^{-1} yr^{-1}	13.8 ±1.62			
Electricity used, kW, farm^{-1} yr^{-1}	32.1± 6.24			

on seasonal availability, and there were a few farmers (N=8) who grew sorghum fodder (COFS-29 or COFS-31) for feeding their animals (Table 2). The findings of Table 2 demonstrated that feeds like mustard leaves (2.75 kg CO_2-eq/kg) and maize stem (2.44 kg CO_2-eq/kg), though rich in nutrients, contributed disproportionately to the farm's total emissions. Conversely, wheat bran, local grasses, and NIANP formulations provided cost-effective and climate-friendly alternatives. This showed that seasonal and feed-type variations significantly impact the carbon footprint of semi-intensive sheep farms. Winter months, characterized by reduced natural fodder availability, led to shifting towards higher-CF concentrates and crop byproducts. In contrast, post-monsoon and monsoon seasons supported increased use of green forages with low or zero CF, such as local grasses, resulting in a reduced environmental impact.

The findings of the current study underscore the significant influence of feed type and seasonal availability on the CF in semi-intensive sheep farming systems. In line with previous research (Gerber *et al*., 2013; Opio *et al*., 2013), our results confirm that the choice of feed inputs, particularly those requiring external sourcing and processing, substantially impacts GHG emissions. Feeds such as mustard leaves and maize stems, though nutritionally beneficial, were associated with high CF values (2.75 and 2.44 kg CO_2-eq/kg, respectively). These values are reflective of high energy inputs in cultivation, water use, and transport, consistent with findings from cradle-to-farm-gate LCA studies in other ruminant systems (Thoma *et al*., 2013). In contrast, mixed local grasses and tree leaves require minimal external inputs and thus involve negligible production-related carbon emissions (Conant *et al*., 2001; Lal, 2004), highlighting the

Table 2. List of feeds fed (√ = feeds fed) to the sheep in the semi-intensive sheep farms (N=18) across different months during four Seasons.

Type of Feed (N= no. of farms)	Winter (December to February)	Summer (March to May)	Monsoon (June to September)	Post-monsoon (October to November)	Amount, kg, day^{-1} $farm^{-1}$	Calculated CF, kg CO_2 kg^{-1} feed
Concentrate (kg day^{-1} $farm^{-1}$)						
KMF cattle pellet feed (N=18)	√	√	√	√	1.0–2.0	0.40
NIANP concentrate formulation (N=18)		√	√		1.0–2.0	0.38
Maize (N=2)	√			√	1.0–2.0	0.38
Bengal gram (N=8)				√	1.0–2.0	2.36
Ragi ball (N=2)	√				0.2	1.29
Crop byproducts (kg day^{-1} $farm^{-1}$)						
Wheat bran (N=14)	√	√		√	1.0–2.0	0.17
Ground nut cake (N=2)	√	√	√	√	0.5	0.92
Rava Bhoosa (N=6)		√	√	√	0.5–1.0	0.99
Roughage (kg day^{-1} $farm^{-1}$)						
Finger millet Straw (N=18)	√	√	√	√	2.0–10.0	0.92
Bengal gram dry fodder with pods (N=14)	√	√	√	√	1.0–5.0	1.24
Salt (g, kg $^{-1}$ feed) (N=18)	√	√	√	√	0.05	0.06
Offered green (kg day^{-1} $farm^{-1}$)						
COFS-29 (N=3)	√	√			3.0–5.0	2.08
COFS-31 (N=5)	√	√			3.0–5.0	2.08
Maize stem (N=4)	√				3.0–5.0	2.44
Mustard leaves (N=4)			√		3.0–5.0	2.75
Lablab pods (N=1)				√	2.0–3.0	1.35
Mixed local grass and tree leaves (N=18)	√	√	√	√	3.0–5.0	0.0

√ = indicating feed availability during different months potential of indigenous, naturally available feed resources to reduce reliance on high-emission feed ingredients. The estimated carbon sequestration potential of grasslands ranges from 0.01 to 0.30 Gt C yr^{-1} within the global soil potential of 0.4 to 1.2 Gt C yr^{-1}, with improved grazing management enhancing soil carbon storage, while overgrazing and poor management accelerate grassland degradation and carbon loss (Ghosh and Mahanta, 2014). Trees act as effective natural carbon sinks, enhancing carbon storage in both biomass and soil and thereby supporting progress toward net-zero targets (Wang *et al*., 2024a). As natural carbon sinks, trees absorb atmospheric CO_2 via photosynthesis and store it in their wood, leaves, roots and surrounding soils, significantly contributing to emission mitigation. Silvipasture systems combining *Ficus infectoria* or *Acacia nilotica* with *Megathyrsus maximus* or *Chrysopogon fulvus* produced high fodder yields (26–37 Mg ha^{-1}) and substantial biomass carbon stocks (13.6–20.8 Mg C ha^{-1}), while delivering significant environmental benefits, including sequestration of up to 76.3 Mg CO_2e ha^{-1} and oxygen release of 36–56 Mg ha^{-1}, indicating strong potential for restoring degraded semi-arid lands (Kumar *et al*., 2024). Availability of ample green fodder during the post-monsoon season reduces reliance on carbon-intensive concentrate feeds, supporting the statement that optimizing forage availability during specific seasons significantly lowers overall feed-related greenhouse gas emissions (Misra, 2019). Furthermore, 6.0 to 12.2% lower feed expenditure in the post-monsoon compared to winter highlighted the economic and environmental co-benefits of feed planning. This study also aligns with the conclusions of Singh *et al.* (2019), who emphasized that sustainable feed strategies must be reinforced by pasture improvement and carbon sequestration efforts.

Overall, findings advocate for an integrated policy approach that supports farmer training, development of common grazing lands, and incentives for using low-CF feed sources. Such interventions would reinforce India's goals under climate-smart agriculture and sustainable livestock development (FAO, 2013). Henceforth, farmers must adapt their feeding schedules to account for the fluctuating availability of seasonal greens. This could include supplementing with external feed sources during periods of scarcity or lowering feed intake during times of excess.

Nutritional content of feeds and forages: The forage nutritional composition (Table 3) exhibited seasonal variation in dry matter (DM) and crude protein (CP), reflecting changes in availability and species of pasture (Table 4). Winter and summer grazing was dominated by low-quality, dry or sparsely green grasses, predominantly *Heteropogon contortus*, *Themeda triandra*, *Chrysopogon fulvus*, *Dactyloctenium aegyptium*, and *Cynodon dactylon*, whereas the monsoon period was characterized by abundant green forage and greater species diversity, including *Eragrostis* spp. and *Paspalum canarae*, with moderate green biomass persisting until post-monsoon. The increase DM content observed during summer corresponded with the predominance of mature, dry grasses, indicating accelerated plant maturity and increased structural carbohydrate accumulation, a pattern consistent with reports from semi-arid and tropical regions where high temperatures and radiation enhance moisture loss and cell wall lignification, thereby reducing forage nutritive value (Lee *et al*., 2017; Tlahig *et al*., 2024). In contrast, CP content increased significantly during the monsoon (9.51%) and post-monsoon (12.3%) seasons, coinciding with abundant growth of green grasses such as *Eragrostis* spp. and *Paspalum canarae*. Improved soil moisture, higher leaf-to-stem ratio, and active vegetative growth during these seasons likely contributed to enhanced protein concentration and overall forage quality. Similar seasonal patterns in pasture CP content have been reported from Indian grazing systems, where monsoon vegetation supports superior nutrient supply compared to dry periods (Sankhyan *et al*., 1999; Singh *et al*., 2021).

Fibre fractions (CF, NDF, and ADF), ash, and total digestible nutrients (TDN) did not vary substantially across seasons, suggesting relatively stable fibre dynamics under the moderate climatic conditions prevailing in the study area. This contrasts with reports from more climatically extreme regions, where sharper seasonal fluctuations in fibre content have been observed (Biazzi *et al*., 2017). Overall, the combined evidence from Tables 3 and 4 demonstrates that monsoon and post-monsoon grazing periods provide nutritionally superior forage, underscoring the importance of season-specific grazing and supplementation strategies to sustain sheep productivity under semi-intensive systems in South Karnataka.

Sheep under a semi-intensive system showed significant seasonal variations in their nutrient intake (Table 5), with total DM intake highest during the monsoon, followed by winter, and decreasing during summer and post-monsoon ($p < 0.05$). A characteristic of tropical grazing systems, voluntary grazing, was enhanced by an increase in monsoon intake due to an abundance of palatable pasture (Kearl, 1982; Devendra and Leng, 2011). Due to limited pasture availability and poor fodder quality, summer had the lowest DM, CP, and TDN intake, while monsoon and winter demonstrated the highest TDN intake.

Assessment of seasonal effects on nutrient intake from different sources revealed that DM and TDN consumed from grazing were significantly higher ($p < 0.001$) during the monsoon and post-monsoon (53.0, 54.9% DM; 20.9, 21.6% TDN) compared to winter and summer (47.5, 48.6% DM; 18.3%, 21.1% TDN). Similarly, CP intake from grazing was significantly higher ($p < 0.001$) in monsoon and post-monsoon (65.5, 56.6%) compared to winter and summer (49.0, 58.2%), with the highest CP intake recorded in the

Table 3. The nutritional content (%) of forage during different seasons

Nutrient	Seasons			
	Winter	**Summer**	**Monsoon**	**Post-monsoon**
DM %	37.5 ± 0.90[a]	64.4 ± 9.01[b]	54.0 ± 5.74[c]	43.8 ± 5.10 [ac]
CP%	6.83 ± 0.00[abc]	5.81 ± 1.34[b]	9.51 ± 1.54[ac]	12.3 ± 1.73[c]
CF%	46.3 ± 0.00	40.8 ± 2.76	51.8 ± 2.53	44.3 ± 2.86
NDF%	55.2 ± 3.03	65.9 ± 4.93	50.7± 5.59	50.7± 2.10
ADF%	36.0 ± 0.00	33.3 ± 3.76	43.3 ± 4.01	35.9 ± 4.42
ADL%	9.28 ± 0.00	6.34 ± 0.86	6.58 ± 1.08	6.24 ± 0.89
Ash	12.7 ± 2.10	9.20 ± 1.56	10.4 ± 1.25	11.4 ± 2.33
TDN	60.3 ± 0.10	65.4 ± 1.31	59.6 ± 1.11	61.5 ± 1.73

Figures within a row having different superscripts differ significantly (p <0.05); DM: Dry matter, CP: Crude protein, EE: Ether extract, CF: Crude fibre, NDF: Neutral detergent fibre, ADF: Acid detergent fibre, ADL: Acid detergent lignin, TDN: Total digestible nutrient

Table 4. Seasonal abundance of common grass species in sheep grazing lands and forest areas of S. Nagenahalli and Lakshmidevipura, South Karnataka

Dry/Winter (Dec–Feb)	Summer (Mar–May)	Monsoon (Jun–Sep)	PostMonsoon (Oct–Nov)
Low, dry/ fibrous, limited green like, *Heteropogon contortus, Chrysopogon fulvus, Themeda triandra, Dactyloctenium aegyptium, Cynodon dactylon*	Sparse green forages like *Heteropogon contortus, Themeda triandra, Chrysopogon fulvus, Dactyloctenium aegyptium, Cynodon dactylon, Imperata cylindrica*	Abundant green forage like *Heteropogon contortus, Themeda triandra, Chrysopogon fulvus, Eragrostis, and Paspalum canarae, Dactyloctenium aegyptium, Cynodon dactylon, etc.*	Sparse green forages, like *Heteropogon contortus, Themeda triandra.* Moderate green forage like *Chrysopogon fulvus, Paspalum canarae, Eragrostis, Dactyloctenium aegyptium, Cynodon dactylon etc.*

Table 5. Variation in nutrient intake (g, day^{-1} sheep$^{-1)}$ from different sources during four seasons in the semi-intensive sheep flocks

Parameters	Winter	Summer	Monsoon	Post monsoon
	DM consumption from different feeds g, day^{-1} head^{-1}			
Offered green	114 ± 9.21[a]	100 ± 11.0 [ab]	90. ± 6.65 [ab]	75.4 ± 8.99[b]
Concentrate	133 ± 11.8[a]	82.7 ± 8.52[b]	106 ± 14.2[ab]	103 ± 10.6[ab]
Roughage	347 ± 27.7	290 ± 35.9	355 ± 35.3	232 ± 14.7
Grazing	537 ± 14.7[a]	447 ± 20.6[b]	623 ± 14.1[c]	500 ± 14.4[a]
Total DM consumed	1131 ± 45.2[a]	920 ± 67.3[b]	1176 ± 61.4[a]	910 ± 37.8[b]
% DM intake on live wt. basis	4.31 ± 0.14[a]	3.51 ± 0.13[b]	3.80 ± 0.14[ab]	3.51 ± 0.11[b]
	CP consumption from different feeds, g, day^{-1} head^{-1}			
Offered green	11.1 ± 1.11[a]	6.56 ± 1.18[b]	5.12 ± 0.75[b]	10.1 ± 1.09[a]
Concentrate	25.5 ± 2.38[a]	14.1 ± 1.53[b]	19.5 ± 2.91[a]	19.9 ± 2.45[a]
Roughage	24.9 ± 1.99[a]	10.94 ± 1.29[b]	12.9 ± 1.28[b]	11.4 ± 0.92[b]
Grazing	59.26 ± 2.45[a]	43.9 ± 2.65[b]	72.0 ± 3.62[a]	53.9 ± 1.62[b]
Total CP	121 ± 5.62[a]	75.4 ± 5.12[b]	110 ± 6.45[ac]	95.3 ± 4.11[c]
	TDN consumption from different feeds, g, day^{-1} head^{-1}			
Offered green	67.1 ± 5.49[a]	62.6 ± 6.92[a]	60.8 ± 4.42[a]	44.7 ± 5.41[b]
Concentrate	102 ± 9.03[a]	67.1 ± 6.58[b]	86.0 ± 11.4[ab]	79.0 ± 8.03[b]
Roughage	526 ± 25.5[a]	450 ± 36.1[ab]	528 ± 35.7[a]	412 ± 21.7 [b]
Grazing	156 ± 4.28[a]	155 ± 7.23[a]	178 ± 4.20[b]	148 ± 3.96 [a]
TDN consumed	851 ± 37.2[a]	735 ± 53.5[ab]	853 ± 52.7[a]	684 ± 35.1[b]

Figures within a row having different superscripts differ significantly (p <0.05); DM: Dry matter, CP: Crude protein, TDN: Total digestible nutrient, DMI: Dry matter intake monsoon season. Overall, grazing lands contributed 47 to 55% of total DM, 49 to 66% of CP, and 18 to 22% of TDN required by semi-intensive sheep, highlighting the critical role of grazing, particularly during monsoon and post-monsoon periods, in meeting the nutrient requirements of sheep. From an environmental perspective, higher reliance on grazing during monsoon and post-monsoon reduces dependence on carbon-intensive concentrate feeds, thereby lowering feed-related GHG emissions per unit of intake. Conversely, reduced intake efficiency and higher supplementation during summer may increase emission intensity. These findings highlight that optimizing seasonal feed and grazing management is critical for improving nutrient utilization while simultaneously reducing the CF of semi-intensive sheep production systems in South Karnataka and similar tropical regions (FAO, 2018). A study on 180 farmers from western Tamil Nadu using the Minimization of Total Absolute Deviation (MOTAD) model revealed that reallocating land toward silvipasture (≈60%) and profitable pulses like black gram under high climatic risk not only enhanced farm net returns and resilience but also strengthened livestock rearing by ensuring year-round fodder availability through *Cenchrus ciliaris* grass and *Acacia* spp., thereby improving feed security and sustainability of crop–livestock systems (Mohanasundari *et al.*, 2025).

Seasonal trend in feed expenditure and carbon footprints (CF) of feed: Perusal of Table 5 revealed distinct seasonal trends in feed expenditure (₹ $sheep^{-1}$ day^{-1}). The cost of concentrate feeding was highest during winter (₹2.30 ± 0.24 $sheep^{-1}$ day^{-1}) and lowest during the monsoon (₹2.02 ± 0.20). Feed costs during the monsoon were 6.0% and 12.2% lower compared to winter and summer, respectively, with only marginal differences observed between summer and post-monsoon seasons. Seasonal fluctuations in forage availability and quality strongly influenced feed costs by altering the requirement for supplemental feeding. Although strategic, stage-specific nutritional management has been recommended to improve ewe and lamb performance (Carvalho *et al*., 2022), such practices were not adopted in the surveyed flocks.

This enhanced utilization of seasonal grazing resources during the monsoon and post-monsoon significantly reduces feed CF in semi-intensive sheep systems by relocating concentrate and roughage-based nutrient supply. The CF of feed (kg CO_2-eq.$day^{-1}$$sheep^{-1}$) was significantly higher during winter (0.86) in consequent to higher nutrient intake from sources other than grazing during winter (Table 5) In comparison significantly lesser CF of feed (kg CO_2-eq.day^{-1} $sheep^{-1}$) during summer, monsoon (0.36, 0.38) and least in post-monsoon (0.30) coincided with higher nutrient intake from grazing. However, in this study low feed carbon footprint (kg CO_2-eq/day/sheep) observed during summer is primarily due to the low-input feeding practices employed in field flocks, despite the reduced availability of grazing forage. Although summer heat stress was not pronounced in South Karnataka, a moderate reduction in voluntary feed intake resulted in lower daily feed consumption. Nevertheless, sheep predominantly depended on natural grazing and dry roughages or crop residues, which were associated with relatively low emission burdens. As a result, the combined impact of decreased daily feed consumption and limited utilization has occurred. The study thus indicates that seasonal effects could lead to a 55 to 65% reduction in the CF of feed in sheep farms. This pattern aligns with Indian and global evidence that optimizing local forage resources

Table 6. Seasonal trend in feed expenditure and feed carbon footprint in semi intensive sheep flock

Parameter	Winter	Summer	Monsoon	Post-monsoon
Cost of concentrate (Rs), $sheep^{-1}$ day^{-}	2.30 ± 0.24	2.15 ± 0.27	2.02 ± 0.20	2.13 ± 0.22
feed carbon footprint (kg CO_2 eq. day^{-1} $sheep^{-1}$)	0.86 ± 0.05^a	0.36 ± 0.03^b	0.38 ± 0.03^b	0.30 ± 0.03^b

Figures within a row having different superscripts differs significantly (P< 0.001)

Table 7. Pearson Correlation among TDN contribution (%) from different feed component and carbon footprint (CF) of feed (kg CO_2-eq. day^{-1} $sheep^{-1}$)

	Offered green TDN%	Forage TDN%	Concentrate TDN%	Roughage TDN%	CF of feed kg CO_2-eq. day^{-1} $sheep^{-1}$
Offered green TDN%	1.00				
Forage TDN%	0.07	1.00			
Concentrate TDN%	-0.12	-0.26*	1.00		
Roughage TDN%	-0.21*	-0.64**	-0.46**	1.00	
CF of feed kg CO_2-eq. day^{-1} $sheep^{-1}$	-0.48**	-0.68**	0.27*	0.35*	1.00

*(p <0.05); **(p <0.01)

is a key mitigation pathway in smallholder livestock systems (Patra, 2017; FAO, 2019). This interpretation was confirmed by Pearson's correlation analysis between TDN intake (%) from different feed sources and the carbon footprint (CF) of feed, which revealed a significant (*p* <0.01) positive correlation between CF of feed (kg CO_2-eq day^{-1} $sheep^{-1}$) and TDN contribution from concentrates and roughages. In contrast, a significant (*p* <0.01) negative relationship was observed between CF of feed and nutrient contribution from forage and offered green fodder, indicating a clear substitution effect among feed resources (Table 6). A study on sheep farming systems in semi-arid regions of India reported that the total carbon footprint from purchased feed was 1.04, 0.69 and 0.00 kg CO_2-eq per kilogram of mutton produced in intensive, semi-intensive, and extensive systems, respectively (Sarkar *et al*., 2024). Consequently, it can be inferred that by incorporating seasonal greens into the feeding plan, farmers can lessen their dependence on external feed sources, lowering GHG emissions and reducing their feed expenses. During times of abundance, sheep can graze on the green grasses, reducing their reliance on external feed sources. It was also recommended that supplementing crop byproducts in livestock feeds can reduce GHG emissions by up to 25.6% (Wang et al., 2024b).

Conclusion

In conclusion, the carbon footprint of semi-intensive sheep production systems in India is significantly influenced by seasonal feed management. Seasonal green fodder and agricultural byproducts can be strategically included to reduce feed-related emissions by up to 65% and feed expenditures per sheep per day by 6.0 to 12.2%. Across all seasons, common grazing areas accounted for 15 to 56% of the overall nutrient intake, highlighting their vital role in maintaining low-input systems. Particularly in dry land areas, a greater reliance on locally accessible, low-CF feed alternatives can significantly reduce dependency on purchased feeds, cutting production costs and greenhouse gas emissions. The present study reflects prevailing low-input management practices; adoption of improved breeding and targeted feeding strategies could further enhance productivity and reduce emission intensity. However, stocking rate, pasture–soil carbon sequestration potential, and seasonal green fodder availability remain key determinants of feed efficiency and overall environmental impact, highlighting the need for further research on grazing land development and management to support sustainable sheep production.

Acknowledgment

We sincerely acknowledge the support of Dr. Chaithra G.J. Senior Research Fellow and Mr. Manoj and Mr. Punith, field assistants of the Farmers FIRST Project, for their valuable assistance in conducting surveys and data collection. We are also grateful to the participating farmers for their unrelenting cooperation in repeated long-term surveys and for providing essential primary data for this study.

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