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Sustainable feed innovation for mountain livestock: reducing the need for imported feed with local resources first

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Introduction: Livestock farming in Nepal's mid-hills, high hills, and mountain regions faces challenges including feed scarcity, high imported feed costs, and declining pastures. Developing locally sourced feed formulations offers potential to improve productivity, sustainability, and economic outcomes.
Methods: A mixed-method approach was employed involving feed surveys, laboratory analyses, 120-day feeding trials, participatory workshops, and economic and environmental assessments. The study engaged 150 farmers, five cooperatives, and three institutions across diverse agro-climatic zones. Locally formulated high-, medium-, and low-cost feeds were compared with conventional feed.
Results: High- and medium-cost local feeds significantly improved average daily gain, milk yield, body condition, and reproductive performance compared with conventional feed ($p < 0.05$). Post-hoc analyses indicated high-cost feeds outperformed control and low-cost groups, while medium-cost feeds generally exceeded low-cost feeds (Tukey test, $p < 0.05$). Feed costs decreased by 25–50%, greenhouse gas emissions by 20–30%, and energy use by 15–25%. Participatory workshops indicated high palatability and strong farmer willingness to adopt the feeds. Regional differences in feed availability highlighted the importance of context-specific strategies.
Discussion/conclusion: Locally formulated feeds enhance livestock productivity, reduce environmental impact, and provide economic benefits. These findings suggest that scalable, sustainable feed strategies tailored to regional resources can support Nepal's livestock sector across diverse agro-climatic zones.

KEYWORDS

economic efficiency, environmental impact, locally sourced feed, Nepal, smallholder farmers, sustainable livestock

Introduction

According to the Ministry of Agriculture and Livestock Development (MoALD, 2023), livestock farming in Nepal serves as one of the most important livelihood sources for rural households, particularly in the hilly and mountain regions. Livestock provides milk, meat, manure, draft power, and income for millions of smallholder farmers who rely on mixed crop-livestock systems (FAO, 2013). However, feed scarcity, high prices of imported concentrates, and declining pasture productivity caused by land degradation and climate change have created serious challenges for livestock keepers (Singh and Singh, 2019). These problems have led to lower milk and meat production, poor animal health, and increasing economic vulnerability among smallholders. Studies show that livestock feed constitutes 60%–70% of total production costs, and any increase in feed prices directly affects farm profitability and sustainability (de Montenegro Wit and Canfield, 2024).

In the mountain and hill regions of Nepal, farmers traditionally feed their animals with seasonal grasses, crop residues, tree fodder, and forest leaves (Kafle et al., 2024). These resources form the foundation of traditional livestock systems that depend on natural cycles and locally available materials (Brown et al., 2021; Pinca et al., 2024). However, over the years, the quality and quantity of local feed resources have declined because of overgrazing, land fragmentation, and changing rainfall patterns (Chhetri et al., 2013). As a result, farmers increasingly depend on imported feed ingredients such as maize bran, soybean meal, and commercial concentrates purchased from the lowlands or neighboring countries. This dependency creates financial strain for small-scale farmers and increases Nepal's reliance on feed imports (Paudel et al., 2016; Shively and Sununtnasuk, 2015). Similar challenges have been documented in other mountain regions. For example, Rai et al. (2025) in Bhutan reported that rising feed import costs negatively affected smallholders, while Pretty et al. (2008) found that promoting native fodder species in India's Himalayan region improved livestock nutrition and reduced feed dependency.

Sustainable livestock production in Nepal requires a shift from dependence on imported feed to locally sourced and renewable feed resources. The "Local Resources First" principle emphasizes the use of available materials such as agricultural by-products, native forages, and community feed systems to meet animal nutritional needs while minimizing environmental and economic costs (Pinca et al., 2024). Locally sourced feeds contribute to resource efficiency, reduce transport-related emissions, and strengthen community self-reliance. For example, Adhikari and Timsina (2022) demonstrated that maize husks, rice bran, and leguminous forages could be processed into balanced and affordable feed mixtures that maintained animal health and productivity. Likewise, studies in Nepal and elsewhere show that crop residues, tree leaves, and local grasses contain valuable nutrients that, when properly managed, can sustain livestock year-round (Osti, 2020).

Even though many studies talk about livestock feed problems in Nepal, there are still important gaps. Most research describes the shortage of feed, the high price of imported feed or the decline of natural fodder. But there is very little work that clearly identifies which local feed resources are available in different mountain areas and what their exact nutrient values are. There is also limited research on how these local materials can be combined to make balanced, low-cost feeds that can replace imported concentrates. Few studies have tested these mixtures in real farm conditions to see if they support animal health, growth and production. Because of these gaps, farmers still depend on expensive imported feeds, and there is no practical model that shows how local resources can fully support livestock throughout the year.

To make the research objective clearer, this study focuses on three specific tasks: (1) identifying the local feed resources that farmers use in different mountain regions, (2) analyzing the nutrient content of these resources to understand their actual feeding value, and (3) developing and testing low-cost feed mixtures that can replace imported concentrates without reducing animal performance. These points build directly on the problems and gaps described earlier in the Introduction and show how the study will provide practical, local solutions for smallholder livestock keepers.

This study develops and evaluates sustainable, locally sourced feed solutions for mountain livestock in Nepal, based on the concept of "Local Resources First." The research identifies and analyzes locally available feed resources across different agro-climatic zones to determine their nutritional profiles. The study formulates and tests cost-effective feed mixtures that maintain animal growth, reproduction, and health without relying on imported feed supplements. These locally based innovations aim to address nutritional deficiencies that reduce livestock performance and contribute to feed insecurity in rural areas.

Reducing dependency on imported feed carries environmental and economic benefits. Locally produced feeds generally have lower carbon footprints because they require less energy for transportation and processing (Sen et al., 2020). They also allow for more efficient recycling of agricultural by-products, supporting circular farming systems where waste materials from crops become inputs for livestock production. Gauchan et al. (2022) found that community-based feed initiatives in rural Nepal created local employment, encouraged cooperative action, and strengthened rural economies. By developing feed at the community level, farmers enhance their control over production resources, share knowledge, and ensure more stable feed supplies even during the dry season.

Therefore, the research on sustainable feed innovation underscores the importance of using local resources first in addressing the feed challenges of mountain livestock systems in Nepal. Dependence on imported feeds weakens rural economies, while local feed production enhances self-sufficiency and environmental sustainability. By documenting and testing locally appropriate feed mixtures and production systems, this study contributes to creating more resilient and sustainable livestock farming models for Nepal's diverse mountain environments.

Literature review

Sustainable feed innovation and local resources first

The concept of sustainable feed innovation in livestock production has gained growing importance as developing countries face challenges of feed scarcity, high input costs, and climate-related pressures. In Nepal, livestock farming remains a vital part of rural livelihoods, particularly in mountain and hill regions where mixed crop livestock systems are common (MoALD, 2023). However, the sustainability of these systems is increasingly threatened by the rising dependence on imported feed ingredients such as maize bran, soybean meal, and commercial concentrates (Nepal et al., 2021). The idea of "Local Resources First" focuses on reducing this dependency by promoting the use of locally available feed resources, such as crop residues, tree fodder, native grasses, and agricultural by-products (Neopane et al., 2022; Singh and Singh, 2019). This approach aims to build resilient and self-sufficient livestock systems that align with local ecological and economic conditions.

Several studies have shown that livestock feed constitutes a major share of production costs often up to 70% in smallholder systems (Paudel et al., 2019). Any fluctuation in feed prices directly affects farm profitability and household income. In mountain areas of Nepal, the limited availability of commercial feeds further adds to this challenge. Farmers often rely on seasonal grasses and forest fodder, which are affected by land degradation and erratic rainfall patterns (MoALD, 2023). Campbell (2018) reported that degraded pastures and deforestation in mid-hill areas have significantly reduced the supply of high-quality forage, leading to nutritional deficiencies in cattle and goats. As a result, farmers are forced to purchase expensive imported concentrates, creating financial stress and reducing their

profit margins. Similar findings were reported by Rai et al. (2025) in Bhutan, where rising feed import costs lowered productivity and increased vulnerability among mountain farmers.

Research from different mountain contexts supports the idea that local feed resources can effectively replace imported feed when properly managed. Bisht et al. (2018) in India's Himalayan region found that the integration of native fodder species such as *Setaria*, *Stylosanthes*, and *Desmodium* improved livestock nutrition while reducing reliance on external inputs. In Nepal, Fleming-Muñoz et al. (2023) demonstrated that mixing maize husks, rice bran, and leguminous forages produced balanced, cost-effective feed mixtures that maintained animal growth and milk yield. These findings highlight the potential of locally sourced feed ingredients to meet nutritional needs in sustainable ways. Tiwari et al. (2008) further observed that the use of underutilized resources, like crop residues and tree leaves can provide consistent feed availability throughout the year when combined with proper preservation methods such as silage or haymaking.

Nutritional and environmental benefits of local feeds

The use of local feed resources not only enhances feed security but also supports environmental sustainability. According to FAO (2013), locally produced feed generally has a lower carbon footprint due to reduced transportation and processing requirements. Utilizing agricultural by-products, such as rice bran and wheat straw, promotes circular farming systems in which waste materials from crops are recycled back into livestock production (Meinzen-Dick et al., 2009). This reduces waste, increases resource efficiency, and lowers greenhouse gas emissions associated with long-distance feed transport. Studies from the Philippines (Walker et al., 2009) and Kenya (Waaswa et al., 2022) similarly found that incorporating local crop residues and leguminous forages into animal diets reduced methane emissions per unit of production and improved soil fertility through better manure recycling.

Environmental benefits are closely linked with economic advantages. Local feed production reduces farmers' dependence on volatile global markets and imported feed prices. Eben Saleh (1997) noted that community-based feed production in rural Nepal not only improved local feed availability but also generated rural employment and cooperative income. Moreover, farmers engaged in local feed processing were able to sell surplus feed mixtures within their communities, fostering small-scale agribusiness opportunities. Comparable outcomes were observed in Ethiopia by Mulatu and Kassa (2001), where local feed cooperatives reduced feed costs by 25% and strengthened local economies. These studies collectively indicate that promoting local feed innovations can simultaneously support ecological balance, economic stability, and rural development.

Community-based feed systems and farmer participation

Developing sustainable feed systems requires active participation from farmers, cooperatives, and local institutions. Participatory innovation models have proven effective in ensuring that new practices align with local knowledge and resource availability. Sen et al. (2020) emphasized that involving farmers in feed formulation trials helps identify practical and culturally acceptable solutions. In their study across Nepal's mid-hills, farmers were more likely to adopt feed technologies that they helped design and test. Similarly, Xu et al. (2025) found that community-led forage development projects improved adoption rates, as local farmers gained ownership and trust in the process. These participatory approaches also strengthen social networks and collective problem-solving capacities, leading to long-term sustainability.

Cooperatives play a critical role in scaling up such initiatives. By organizing feed production and storage collectively, cooperatives reduce individual risks and ensure a consistent feed supply during lean seasons (Swagemakers et al., 2019). They also help with quality control and bulk purchasing of feed ingredients, lowering production costs for members. In Nepal, several dairy cooperatives have started producing local feed mixtures using maize bran, mustard cake, and dried grasses to reduce dependence on imported feeds (Kahiluoto et al., 2012). These efforts not only enhance feed security but also improve animal health and milk productivity. Studies from Kenya (Zenebe et al., 2022) and Uganda (Kansiime, 2012) confirm similar benefits from cooperative-based feed systems, where farmer groups successfully developed low-cost, locally adapted feed formulations.

Challenges and opportunities

Despite clear benefits, several challenges remain in implementing local feed innovations. Many rural areas lack technical knowledge about feed formulation, nutrient balancing, and preservation techniques. Kannan et al. (2017) observed that smallholders often underutilize available crop residues because they lack the means to process them into digestible forms. Similarly, Afifi et al. (2016) noted that native forage species are frequently neglected in agricultural planning and need better documentation and nutritional analysis. Limited access to laboratories and feed testing facilities also constrains accurate formulation. Addressing these challenges requires institutional support, farmer training, and the integration of feed innovation into local agricultural extension systems (Babajani et al., 2023).

However, opportunities for innovation are expanding. Advances in low-cost feed processing technologies, such as mobile feed mixers and community-level pellet machines, are making local feed production more feasible (Goswami et al., 2021). The rise of digital advisory platforms and farmer field schools has further improved knowledge-sharing in remote areas (Osti, 2020). Moreover, the growing focus on climate-smart agriculture in Nepal provides policy support for sustainable livestock feeding practices (FAO, 2013). Government programs promoting leguminous forages and fodder trees like *Leucaena*, *Flemingia*, and *Mulberry* align well with the "Local Resources First" principle and can be expanded to more mountain communities.

Toward climate-resilient livestock systems

The shift toward local feed resources contributes to broader goals of climate resilience and rural self-reliance. Sustainable feed

innovation enables farmers to adapt to unpredictable weather and pasture shortages by diversifying their feed base. Studies in Nepal's western hills (Behnassi et al., 2024) and eastern mountains (Raj et al., 2025) showed that farmers using mixed feed systems combining agricultural by-products, tree fodder, and grasses maintained livestock productivity even during drought periods. Such systems reduce the risk of feed shortages and stabilize milk and meat output, which are vital for local nutrition and incomes.

Overall, the literature suggests that "Local Resources First" is not just a feed strategy but a framework for sustainable rural development. It links environmental management, economic efficiency, and community empowerment. The reviewed studies demonstrate that locally based feed solutions can replace imported feeds without compromising productivity, while also fostering cooperation, reducing emissions, and strengthening local economies. Future research should focus on testing specific feed combinations across different agro-climatic zones of Nepal and quantifying their long-term environmental and economic impacts.

By integrating local feed resources, participatory innovation, and community-based production systems, Nepal's mountain livestock sector can transition toward greater sustainability and resilience. These insights provide a foundation for developing practical feed innovations that enhance livestock productivity, support farmer livelihoods, and align with national goals for climate-smart agriculture.

Methods

Study design

This study was conducted in the hilly and mountain regions of Nepal to develop and evaluate sustainable feed innovations for livestock using locally available resources. The research was guided by the principle of "Local Resources First," aiming to reduce dependence on imported feed while improving animal health and productivity. A mixed-method design (Chatzipetrou and Nakas, 2020) was adopted to capture both quantitative data on feed nutritional composition and livestock performance, and qualitative insights from farmers, cooperatives, and local institutions regarding feasibility and adoption of locally produced feed. The study was conducted over 2 years and covered multiple agro-climatic zones of Nepal, including the mid-hills, high hills, and mountain regions. The design integrated field surveys, laboratory nutritional analyses, feeding trials, and participatory workshops, allowing comprehensive evaluation of feed resources, formulation, and community adoption. The mixed-method approach facilitated triangulation of results, ensuring robust and contextually relevant findings, consistent with methods previously used in livestock nutrition and sustainable feed studies (Bai et al., 2020; Bay-Larsen et al., 2018; Mulatu and Kassa, 2001).

Participants

The study engaged smallholder livestock farmers, local cooperatives, and agricultural institutions across three agro-climatic zones in Nepal. Maximum variation sampling was applied to ensure representation of diverse livestock systems, herd sizes, and resource availability. A total of 150 farmers participated, with approximately 50 farmers from each region. Selection criteria included willingness to participate, ownership of livestock (cattle, goats or buffalo), and access to locally available feed resources such as crop residues, grasses, and tree fodders. In addition, five cooperatives and three local agricultural extension offices were included to facilitate feed processing, quality monitoring, and participatory workshops. Participants provided informed consent and engagement was voluntary. The diversity of participants allowed identification of practical feed strategies applicable across various ecological and socio-economic contexts. Participant demographics and regional distribution are summarised in Table 1.

Feed resource survey and sampling

A structured survey was carried out to identify and map locally available feed resources, including crop residues (maize stalks, rice straw, wheat straw), tree fodders (Flemingia, Leucaena, Morus), grasses, and agricultural by-products (rice bran, maize husk, oilseed cakes). Participatory rural appraisal techniques were used to involve farmers and gather information on seasonal availability and feeding practices. For each type of feed (crop residue, tree fodder, grass, by-product), samples were collected in triplicate from 3–5 farms in each region. These sub-samples were combined into one composite sample per farm, labelled, and transported to the laboratory in cool conditions. Samples were air-dried if needed before analysis. Laboratory tests were done in three technical replicates for each composite. Proximate and fiber analyses followed AOAC (2016) methods. Dry matter (DM) was measured by drying samples at 60 °C until they reached a constant weight. Crude protein (CP) was determined using the Kjeldahl method, which measures total nitrogen and multiplies it by 6.25. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed using the Van Soest method to estimate cell wall content. Ash content was measured by burning samples in a muffle furnace at 550 °C, and minerals such as calcium and phosphorus were measured using atomic absorption spectrophotometry. Instruments and reagent details were recorded in the laboratory logbook.

TABLE 1 Demographic characteristics of study participants.

Group	Frequency	Percentage%
Gender	Male	92
	Female	58
Region	Mid-hills	50
	High hills	50
	Mountains	50
Livestock type	Cattle	70
	Buffalo	45
	Goats	35
Cooperative involvement	Yes	5
Agricultural institution	Yes	3

Feed formulation

Locally available feed ingredients were combined to create balanced feed mixtures for cattle, buffalo, and goats. The mixtures were formulated according to the nutritional requirements of each species, as recommended by the National Research Council (2001) and other standard references for small ruminants and bovines. Protein, energy, and fiber levels in each mixture were calculated to meet species-specific needs for maintenance and production. The formulation process used laboratory analysis results, livestock nutritional requirements, seasonal feed availability, and cost considerations. Linear programming and least-cost ration methods were applied to optimize the mixtures for protein, energy, and fiber while keeping costs low. Assumptions and constraints, such as nutrient targets, ingredient limits, costs, and seasonal availability, were carefully documented. The calculations were implemented in R using the lpSolve package. Three types of feed mixtures were developed for each livestock species: high, medium, and low-cost formulations using locally available ingredients. Each mixture was tested in small pilot trials on selected farms to evaluate palatability and acceptability before the main feeding trials. Table 2 shows examples of the feed mixtures developed for cattle.

Feeding trials

Feeding trials were conducted over 120 days in each agro-climatic zone to evaluate the performance of the formulated feed mixtures. Each zone included 80 animals (30 cattle, 30 buffalo, and 20 goats), with 40 assigned to the control group receiving the usual farmer feed and 40 to the treatment group receiving the formulated local feed. Animals were randomly selected from participating farms, ensuring they were healthy, of similar age (2–4 years for cattle and buffalo, 1–2 years for goats), and had comparable body condition, while animals with illness, injury, or pregnancy complications were excluded. A 14-day adaptation period preceded the trials, during which baseline data including age, sex, breed, initial weight, and body condition score (BCS) were recorded. Housing, water access, and deworming/vaccination schedules were standardized across groups. Feed intake was measured by recording refusals, and key performance indicators included body weight (measured every 14 days), average daily gain (ADG), BCS (1–5 scale), daily milk yield, health parameters such as digestive disorders and general morbidity, and reproductive performance. Reproductive assessments included estrus observation, conception rates, pregnancy confirmation, calving/kidding intervals, and reproductive disorders in females. For males, reproductive parameters included scrotal circumference, semen volume, sperm concentration, motility, viability, and morphology, to evaluate the effect of feed on fertility. Housing, water access, and deworming/vaccination schedules were standardized across groups. Laboratory analyses were performed in triplicate, and data from 80 animals per group per zone were analyzed using ANOVA or linear mixed models, with animal or farm included as random effects when appropriate. Post-hoc comparisons were conducted using Tukey or emmeans contrasts, with significance set at $p < 0.05$. Model diagnostics, data cleaning scripts, randomization seeds, and full analysis code are archived for reproducibility. All procedures followed established animal welfare guidelines and received ethical approval.

Data were analyzed using ANOVA and linear mixed models in R, with animal or farm as random effects. Post-hoc comparisons used Tukey or emmeans contrasts. Significance was set at $p < 0.05$. All procedures followed animal welfare guidelines and were approved by the institutional ethics committee.

TABLE 2 Example feed mixtures for cattle.

Feed ingredient	High-cost mixture (%)	Medium-cost mixture (%)	Low-cost mixture (%)
Maize husk	30	40	50
Rice bran	25	20	15
Mustard cake	20	15	10
Leguminous tree fodder	15	15	15
Grass	10	10	10

Environmental and economic assessment

Life cycle assessment (LCA) was used to evaluate the environmental impact of producing locally sourced feed compared with imported concentrates. A "cradle-to-farm-gate" approach was followed, covering all stages from feed production (cultivation, collection, processing) to delivery at the farm (Neupane et al., 2018; Usva et al., 2025). Key environmental indicators included greenhouse gas emissions (CO_2, CH_4, N_2O), energy use, and resource efficiency (water and land use). Primary data were collected from farms, cooperatives, and feed processing units, including fuel and electricity use, input materials, and transport distances. Secondary data, such as emission factors, energy conversion, and standard agricultural practices, were obtained from FAO databases, Nepalese government reports, and published literature. Economic analysis calculated feed cost per kilogram of live-weight gain, total feed cost per lactating animal, and potential savings from reducing imported feed use (Ricci et al., 2013). Cost–benefit analysis also considered additional income from community-based feed production and sales of surplus feed in local markets. Assumptions for labor and market prices were recorded in a cost–benefit worksheet.

The combined LCA and economic framework allowed a comprehensive evaluation of the sustainability, cost-effectiveness, and environmental benefits of using locally produced feed. Functional units were 1 kg of feed produced and 1 kg of live-weight gain. Figure 1 illustrates how environmental and economic factors were studied from production to the farm, including the main data collected, key measures like greenhouse gas emissions, energy use, and feed costs, and how these were integrated to assess overall sustainability.

Participatory workshops and farmer feedback

Participatory workshops were held in each region to involve farmers, cooperatives, and agricultural officers in evaluating feed formulations and implementation feasibility. Workshops included practical demonstrations of feed preparation, silage and hay

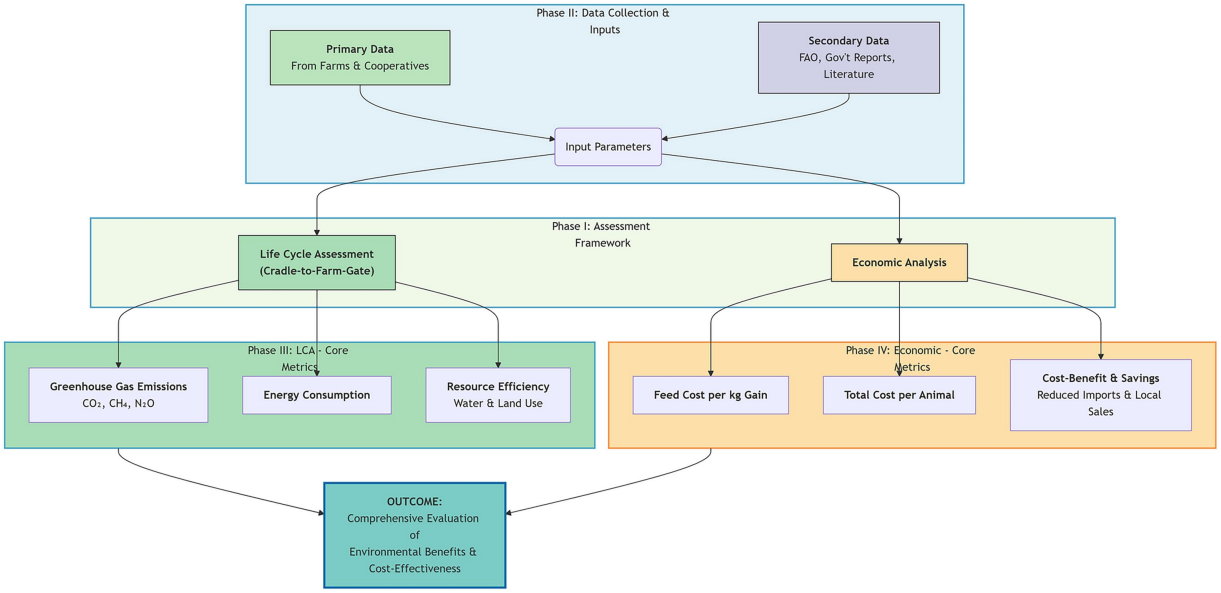

FIGURE 1
Integrated framework for sustainability assessment of locally sourced feed.

making, and feed mixing techniques. Participants provided feedback on palatability, ease of preparation, and cost-effectiveness. Workshops facilitated knowledge sharing, encouraged adoption, and strengthened collaboration between farmers and local institutions. Feedback was recorded, transcribed, and analyzed thematically to identify barriers and enablers for sustainable feed adoption.

Data collection and analysis

Quantitative data from laboratory analyses and feeding trials were entered into Microsoft Excel (Version 2,507 Build 16.0.19029.20136) and R statistical software for descriptive and inferential analyses. Growth performance, milk yield, and reproductive indicators were compared between experimental and control groups using ANOVA, and *post hoc* Tukey tests were used to identify significant differences ($p < 0.05$). Economic and environmental data were analyzed descriptively to provide context and support the qualitative findings. Data for this study were collected in February and July, 2024. Informed consent was taken from all participating farmers and households before data collection. Consent was obtained both in written and verbal form, depending on the participants' preference. Participation was voluntary, and participants could withdraw at any time.

Qualitative data from surveys, participatory workshops, and farmer interviews were analyzed using thematic analysis (Madududu et al., 2024). Data familiarization involved repeated reading of transcripts and field notes. Initial codes were generated from textual data, focusing on feasibility, acceptability, and perceived benefits of local feed mixtures. Codes were refined collaboratively among the research team to ensure consistency. Sub-themes were identified through grouping related codes, including feed availability, preparation ease, cost-effectiveness, animal health outcomes, and community engagement. Themes were reviewed for coherence, and a thematic map was developed to visualize relationships among sub-themes.

The themes presented in Table 3 were derived using a systematic thematic analysis approach. First, all qualitative data from surveys, participatory workshops, and farmer interviews were transcribed and reviewed thoroughly by the research team. Initial coding was performed independently by two trained coders to capture key ideas related to feed availability, preparation, economic feasibility, environmental impact, and community engagement. The coders then met to compare codes, resolve discrepancies, and refine the coding framework. Sub-themes were generated by grouping related codes, and overarching themes were identified based on patterns emerging across data sources. Validation was achieved through peer review within the research team and by cross-checking representative quotes with original transcripts to ensure consistency and accuracy. This process ensured that the thematic analysis was reliable, transparent, and reflective of participants' perspectives.

Results

A total of 150 smallholder livestock farmers participated in this study across three agro-climatic zones in Nepal, including the mid-hills ($n = 50$), high hills ($n = 50$), and mountain regions ($n = 50$). Of the participants, 92 were male and 58 were female. Participants owned a variety of livestock, including cattle ($n = 70$), buffalo ($n = 45$), and goats ($n = 35$). Additionally, five local cooperatives and three agricultural institutions were actively involved in the study to support feed processing, quality monitoring, and participatory workshops. Participants were selected to ensure diversity in herd size, resource availability, and feeding practices.

Baseline characteristics of experimental animals are summarized in Table 4. Animals were randomly allocated to control and experimental groups within each livestock species and agro-ecological

TABLE 3 Themes, sub-themes, sample codes, and representative quotes from qualitative data on feed resource use, preparation, and adoption, derived through a structured coding process with multiple coders and validation steps.

Step	Description	Details
Data familiarization	Repeated reading of transcripts and field notes	Ensured thorough understanding of content
Initial coding	Two coders independently assigned codes	Codes captured key points related to feed, cost, environment, and community
Code comparison and refinement	Coders discussed differences and refined codes	Consensus achieved on all codes
Sub-theme Development	Grouped related codes into sub-themes	Examples: seasonal feed diversity, palatability, cost savings
Theme identification	Aggregated sub-themes into main themes	Five main themes: Feed availability, feed preparation, economic feasibility, environmental impact, community engagement
Validation	Peer review and cross-checking with original data	Ensured accuracy and consistency

region. No statistically significant differences were observed between groups for age, body weight, body condition score (BCS), or initial milk yield, indicating successful randomization and comparable baseline conditions.

At baseline, livestock in the control and experimental groups showed comparable characteristics across all agro-ecological regions. In the mid-hills, cattle in the control group had a mean age of 3.1 ± 0.4 years, body weight of 320 ± 25 kg, body condition score (BCS) of 2.8 ± 0.3, and milk yield of 6.2 ± 0.5 L/day. Corresponding values for the experimental group were 3.0 ± 0.5 years, 322 ± 23 kg, BCS 2.9 ± 0.4, and milk yield 6.3 ± 0.6 L/day.

Similar patterns were observed for buffalo and goats in the mid-hills, as well as for all species in the high hills and mountain regions. Across regions, age, body weight, BCS, and milk yield were closely aligned between the two groups within each species. These descriptive statistics indicate that the control and experimental groups were well matched at the start of the study, providing a sound basis for assessing the effects of the feed intervention without baseline bias.

The study involved surveys, feed sampling, laboratory nutritional analysis, formulation of locally sourced feed mixtures, feeding trials, participatory workshops, and economic and environmental assessments. Data were analyzed both quantitatively and qualitatively to understand feed resource availability, animal performance, economic feasibility, environmental impact, and community engagement. Analysis of results identified four main themes: (1) Feed Resource Availability, (2) Feed Formulation and Acceptability, (3) Economic and Environmental Benefits, and (4) Community Participation and Knowledge Sharing. Each theme contained several sub-themes as described below.

Feed resource availability

Participants reported that livestock feeding in their regions primarily relied on locally available resources such as crop residues, tree fodders, grasses, and agricultural by-products. Seasonal availability of feed was a major concern for farmers. In the mid-hills, maize stalks and rice straw were abundant during winter, whereas fresh grasses were scarce in dry seasons. Farmers in the high hills and mountains depended heavily on tree fodders such as Flemingia, Leucaena, and Morus, along with natural grasses. The survey and participatory mapping revealed that most farmers (approximately 78%) used crop residues extensively, while only 45% regularly used tree fodders.

Laboratory analysis showed clear variation in the nutritional composition of locally available feed resources (Table 5). Tree fodder, particularly *Flemingia* leaves, exhibited the highest crude protein content (18.0 ± 0.8%) and comparatively low fiber fractions (NDF and ADF), indicating a higher nutritive value relative to other feeds.

Crop residues such as maize stalks and rice straw contained low crude protein (6.2 ± 0.3% and 5.1 ± 0.2%, respectively) and high levels of structural carbohydrates, reflected by elevated NDF and ADF values. These characteristics suggest that crop residues primarily serve as maintenance roughage rather than nutrient-dense feeds.

Grasses provided moderate crude protein levels (8.0 ± 0.4%) but remained relatively high in fiber, which may limit digestibility when fed alone. Rice bran, an agro-industrial by-product, showed relatively high crude protein (14.5 ± 0.6%) and the highest metabolizable energy content (11.0 ± 0.5 MJ/kg DM), highlighting its potential as an important energy- and protein-rich supplement in balanced feeding strategies.

Overall, the results demonstrate substantial differences in nutritional quality among locally available feed resources, underscoring the importance of combining crop residues with protein- and energy-rich supplements to improve livestock diets.

Farmers highlighted seasonal challenges, noting, "We have plenty of maize stalks in the winter, but little fresh grass during dry months." Similarly, rice bran and other by-products were described as "abundant and affordable, so we often mix it with fodder leaves." Thus, feed availability varied by agro-climatic zone, season, and household resources, emphasizing the need for structured feed formulation and preservation techniques to maintain year-round supply.

Feed formulation and acceptability

Locally sourced feed ingredients were combined to develop balanced feed mixtures for cattle, buffalo, and goats. Three formulations were developed per species, categorized as high, medium, and low-cost mixtures. Formulations were based on laboratory nutritional analysis, livestock requirements, seasonal feed availability, and cost considerations.

Feeding trials over 120 days compared the performance of livestock fed locally formulated feed mixtures against control animals receiving conventional feed. Average daily gain (ADG) was the primary indicator of growth performance. Across all regions, cattle, buffalo, and goats receiving high- and medium-cost local feed mixtures showed higher ADG compared to control animals, while low-cost mixtures still maintained growth within acceptable limits.

TABLE 4 Baseline characteristics of livestock in control and experimental groups across agro-ecological regions.

Region	Species	Group	*N*	Age (years) Mean ± SD	Body weight (kg) Mean ± SD	BCS Mean ± SD	Milk yield (L/day) Mean ± SD
Mid-hills	Cattle	Control	15	3.1 ± 0.4	320 ± 25	2.8 ± 0.3	6.2 ± 0.5
		Experimental	15	3.0 ± 0.5	322 ± 23	2.9 ± 0.4	6.3 ± 0.6
	Buffalo	Control	15	3.2 ± 0.6	270 ± 20	2.7 ± 0.3	4.5 ± 0.4
		Experimental	15	3.1 ± 0.5	272 ± 22	2.8 ± 0.3	4.6 ± 0.5
	Goats	Control	10	1.5 ± 0.2	35 ± 4	2.5 ± 0.3	NA
		Experimental	10	1.6 ± 0.3	36 ± 5	2.6 ± 0.2	NA
High hills	Cattle	Control	15	3.2 ± 0.4	315 ± 20	2.7 ± 0.3	5.9 ± 0.4
		Experimental	15	3.3 ± 0.5	318 ± 21	2.8 ± 0.3	6.0 ± 0.5
	Buffalo	Control	15	3.1 ± 0.5	268 ± 18	2.6 ± 0.3	4.3 ± 0.4
		Experimental	15	3.2 ± 0.6	270 ± 19	2.7 ± 0.3	4.4 ± 0.4
	Goats	Control	10	1.5 ± 0.2	34 ± 3	2.4 ± 0.2	NA
		Experimental	10	1.6 ± 0.3	35 ± 4	2.5 ± 0.3	NA
Mountains	Cattle	Control	15	3.1 ± 0.5	310 ± 22	2.7 ± 0.4	5.7 ± 0.5
		Experimental	15	3.2 ± 0.4	312 ± 21	2.8 ± 0.3	5.8 ± 0.6
	Buffalo	Control	15	3.0 ± 0.5	265 ± 20	2.6 ± 0.3	4.2 ± 0.4
		Experimental	15	3.1 ± 0.5	267 ± 19	2.7 ± 0.3	4.3 ± 0.4
	Goats	Control	10	1.5 ± 0.2	33 ± 3	2.4 ± 0.2	NA
		Experimental	10	1.6 ± 0.3	34 ± 4	2.5 ± 0.3	NA

Values are presented as mean ± standard deviation. BCS, Body Condition Score; NA., not applicable (non-lactating goats).

TABLE 5 Nutritional composition of locally available feed resources (mean ± SD, *n* = 3).

Feed resource	DM (%)	CP (%)	NDF (%)	ADF (%)	Ash (%)	Energy (MJ/kg DM)
Maize stalks	89.2 ± 0.6	6.2 ± 0.3	72.1 ± 1.5	45.6 ± 1.2	5.3 ± 0.2	7.8 ± 0.4
Rice straw	91.0 ± 0.5	5.1 ± 0.2	75.0 ± 1.6	49.2 ± 1.4	6.0 ± 0.3	7.2 ± 0.3
Grass	87.5 ± 0.7	8.0 ± 0.4	65.3 ± 1.2	42.1 ± 1.1	7.1 ± 0.2	8.5 ± 0.5
Flemingia leaves	85.0 ± 0.6	18.0 ± 0.8	40.5 ± 1.0	23.0 ± 0.8	9.2 ± 0.3	10.5 ± 0.4
Rice bran	88.5 ± 0.5	14.5 ± 0.6	35.0 ± 1.1	18.0 ± 0.7	10.5 ± 0.4	11.0 ± 0.5

Values are presented as mean ± standard deviation (SD). DM, dry matter; CP, crude protein; NDF, neutral detergent fiber; ADF, acid detergent fiber.

Differences were statistically significant ($p < 0.05$), indicating the effectiveness of locally sourced feed formulations (Table 6).

Average daily gain (ADG) of livestock varied by species, region, and feed type (Table 6). Across all regions, high-cost local feed resulted in the highest growth, followed by medium-cost formulations. In the mid-hills, cattle fed high-cost local feed gained 0.85 ± 0.04 kg/day compared with 0.82 ± 0.05 kg/day for controls ($p = 0.03$). Buffalo ADG was 0.63 ± 0.03 kg/day for high-cost local feed versus 0.60 ± 0.04 kg/day in controls ($p = 0.02$). Goats gained 0.20 ± 0.01 kg/day compared with 0.18 ± 0.02 kg/day for controls ($p = 0.04$). Similar trends were observed in high hills and mountain regions.

ANOVA results indicated that feed type had a statistically significant effect on growth. Post-hoc tests using Tukey or emmeans contrasts identified specific feed groups that differed significantly, as indicated by superscript letters in the table.

In mid-hills, cattle receiving high-cost local mixtures gained 0.85 kg/day compared to 0.82 kg/day for controls. Buffalo and goats displayed similar trends, demonstrating that feed formulated from local resources could match or exceed conventional feed in promoting growth. In high hills and mountains, tree fodders formed a larger proportion of feed mixtures, with corresponding increases in ADG for cattle and buffalo. These results suggest that locally available feed can support robust growth when appropriately formulated.

Milk yield increased in all experimental feed groups compared to controls, particularly with high-cost local feeds (Table 7). In the mid-hills, cattle fed high-cost local feed produced 6.6 ± 0.4 L/day, significantly higher than controls at 6.2 ± 0.5 L/day (ANOVA, p = 0.02). Buffalo showed a similar pattern, with high-cost local feed yielding 4.8 ± 0.3 L/day versus 4.5 ± 0.4 L/day in controls (p = 0.03). In the high hills and mountain regions, high- and medium-cost local feeds consistently increased milk yield by 4%–8% compared with controls, with all differences confirmed as statistically significant by Tukey post-hoc tests. These results demonstrate that locally formulated feeds can effectively improve milk production across regions and livestock types.

TABLE 6 Average daily gain (ADG, kg/day) of livestock by feed group.

Livestock	Region	Control	High-cost local	Medium-cost local	Low-cost local	*p*-value	*Post-hoc* Results
Cattle	Mid-hills	0.82 ± 0.05^{a}	0.80 ± 0.05^{b}	0.84 ± 0.05^{ab}	0.85 ± 0.04^{b}	0.03	HC > C, MC > LC
Buffalo	Mid-hills	0.60 ± 0.04^{a}	0.58 ± 0.04^{b}	0.62 ± 0.04^{ab}	0.63 ± 0.03^{b}	0.02	HC > C, MC > LC
Goats	Mid-hills	0.18 ± 0.02^{a}	0.17 ± 0.02^{b}	0.19 ± 0.02^{ab}	0.20 ± 0.01^{b}	0.04	HC > C
Cattle	High hills	0.80 ± 0.05^{a}	0.79 ± 0.05^{b}	0.82 ± 0.05^{ab}	0.83 ± 0.04^{b}	0.03	HC > C
Buffalo	High hills	0.58 ± 0.03^{a}	0.57 ± 0.04^{b}	0.60 ± 0.03^{ab}	0.61 ± 0.03^{b}	0.02	HC > C
Goats	High hills	0.17 ± 0.02^{a}	0.16 ± 0.02^{b}	0.18 ± 0.02^{ab}	0.19 ± 0.01^{b}	0.04	HC > C
Cattle	Mountains	0.78 ± 0.05^{a}	0.77 ± 0.05^{b}	0.80 ± 0.05^{ab}	0.81 ± 0.04^{b}	0.03	HC > C
Buffalo	Mountains	0.57 ± 0.03^{a}	0.56 ± 0.04^{b}	0.59 ± 0.03^{ab}	0.60 ± 0.03^{b}	0.02	HC > C
Goats	Mountains	0.16 ± 0.02^{a}	0.15 ± 0.02^{b}	0.17 ± 0.02^{ab}	0.18 ± 0.01^{b}	0.04	HC > C

HC, High-Cost; MC, Medium-Cost; LC, Low-Cost; C, Control. *Post-hoc* results show which feed groups were significantly different based on Tukey or emmeans contrasts.
Values are mean ± standard deviation. Different superscript letters (a, b) within a row indicate statistically significant differences between feed groups ($p < 0.05$).

TABLE 7 Milk yield (L/day) of cattle and buffalo by feed group.

Livestock	Region	Control (Mean ± SD)	High-cost local	Medium-cost local	Low-cost local	ANOVA *p*-value	*Post-hoc* test (Tukey)
Cattle	Mid-hills	6.20 ± 0.50^{a}	6.60 ± 0.40^{b}	6.50 ± 0.50^{b}	6.10 ± 0.50^{a}	0.02	HC > Control; MC > LC
Buffalo	Mid-hills	4.50 ± 0.40^{a}	4.80 ± 0.30^{b}	4.70 ± 0.40^{b}	4.40 ± 0.40^{a}	0.03	HC > Control; MC > LC
Cattle	High hills	5.90 ± 0.40^{a}	6.30 ± 0.40^{b}	6.20 ± 0.50^{b}	5.80 ± 0.40^{a}	0.02	HC > Control; MC > LC
Buffalo	High hills	4.30 ± 0.40^{a}	4.60 ± 0.30^{b}	4.50 ± 0.40^{b}	4.20 ± 0.30^{a}	0.03	HC > Control; MC > LC
Cattle	Mountains	5.70 ± 0.50^{a}	6.10 ± 0.40^{b}	6.00 ± 0.50^{b}	5.60 ± 0.50^{a}	0.02	HC > Control; MC > LC
Buffalo	Mountains	4.20 ± 0.40^{a}	4.50 ± 0.30^{b}	4.40 ± 0.40^{b}	4.10 ± 0.40^{a}	0.03	HC > Control; MC > LC

Different superscript letters (^{a}, ^{b}) indicate statistically significant differences between feed groups based on Tukey *post-hoc* tests ($p < 0.05$).
HC, High-Cost Local feed; MC, Medium-Cost Local feed, LC, Low-Cost Local feed.
ANOVA *p*-values indicate overall differences among feed groups within each livestock × region combination.

BCS improved in all experimental groups over the 120-day feeding period, with the largest gains seen in animals receiving high-cost local feed (Table 8). In the mid-hills, cattle fed high-cost local feed improved from 2.9 ± 0.4 to 3.1 ± 0.3. Buffalo and goats showed similar improvements. Superscript letters indicate significant differences between groups ($p < 0.05$). These results suggest that the locally formulated feeds provided sufficient energy and protein to maintain and improve body condition.

The feed cost analysis showed that locally formulated feeds consistently reduced both total feed costs and cost per kilogram of weight gain across all livestock types. Low-cost local feed reduced 120-day feed expenses to 75.0 ± 3.0 USD per cattle, 70.0 ± 3.0 USD per buffalo, and 30.0 ± 1.0 USD per goat, with corresponding reductions in cost per kg gain (0.94 ± 0.04, 1.08 ± 0.03, and 1.67 ± 0.05 USD, respectively) compared to control feeds. Medium- and high-cost local feeds also decreased costs while supporting good growth performance. Cattle were emphasized due to their dominant contribution to milk and meat production, making the economic comparison particularly relevant (see Table 9).

Palatability was reported to be high across all livestock species. Farmers observed, "The cows eat the mixture well and drink more water," suggesting good acceptance. Preparation and feeding were considered manageable with minimal additional effort. Silage and hay-making techniques were successfully demonstrated in participatory workshops, and participants found them feasible when provided with proper guidance and storage materials. Farmers highlighted the importance of proper mixing and storage: "Making the silage is easy if we have proper bags and guidance."

These findings suggest that locally formulated feed mixtures using crop residues, tree fodders, grasses, and agricultural by-products can provide balanced nutrition and support livestock growth and productivity without reliance on imported concentrates.

TABLE 8 Change in BCS (mean ± SD) over 120 days with post-hoc comparisons.

Livestock	Region	Control	High-cost local	Medium-cost local	Low-cost local	*Post-hoc* test result
Cattle	Mid-hills	$2.8 \pm 0.3^{a} \rightarrow 2.9 \pm 0.3^{a}$	$2.9 \pm 0.4^{b} \rightarrow 3.1 \pm 0.3^{b}$	$2.9 \pm 0.3^{b} \rightarrow 3.0 \pm 0.3^{b}$	$2.8 \pm 0.3^{a} \rightarrow 2.9 \pm 0.3^{a}$	High- and Medium > Control ($p < 0.05$)
Buffalo	Mid-hills	$2.7 \pm 0.3^{a} \rightarrow 2.8 \pm 0.3^{a}$	$2.8 \pm 0.3^{b} \rightarrow 3.0 \pm 0.3^{b}$	$2.7 \pm 0.3^{b} \rightarrow 2.9 \pm 0.3^{b}$	$2.7 \pm 0.3^{a} \rightarrow 2.8 \pm 0.3^{a}$	High- and Medium > Control ($p < 0.05$)
Goats	Mid-hills	$2.5 \pm 0.3^{a} \rightarrow 2.6 \pm 0.2^{a}$	$2.6 \pm 0.2^{b} \rightarrow 2.7 \pm 0.2^{b}$	$2.5 \pm 0.2^{a} \rightarrow 2.6 \pm 0.2^{a}$	$2.5 \pm 0.3^{a} \rightarrow 2.5 \pm 0.2^{a}$	High > Control ($p < 0.05$)

Values are expressed as mean ± standard deviation.
Superscript letters (a, b) indicate statistically significant differences between groups at the end of 120 days (Tukey *post-hoc* test, $p < 0.05$). Groups sharing the same letter are not significantly different.

TABLE 9 Feed cost and cost per kg weight gain for livestock (Mean ± SD).

Livestock	Feed group	Feed cost (USD/animal/120 d)	Cost per kg gain (USD/kg)	AVG (Mean ± SD)
Cattle	Control	150.0 ± 5.0^{a}	1.83 ± 0.06^{a}	$150.0 \pm 5.0/1.83 \pm 0.06^{a}$
	High-cost local	112.0 ± 4.0^{b}	1.32 ± 0.05^{b}	$112.0 \pm 4.0/1.32 \pm 0.05^{b}$
	Medium-cost local	98.0 ± 3.0^{c}	1.16 ± 0.04^{c}	$98.0 \pm 3.0/1.16 \pm 0.04^{c}$
	Low-cost local	75.0 ± 3.0^{d}	0.94 ± 0.04^{d}	$75.0 \pm 3.0/0.94 \pm 0.04^{d}$
Buffalo	Control	140.0 ± 5.0^{a}	2.10 ± 0.07^{a}	$140.0 \pm 5.0/2.10 \pm 0.07^{a}$
	High-cost local	105.0 ± 4.0^{b}	1.65 ± 0.05^{b}	$105.0 \pm 4.0/1.65 \pm 0.05^{b}$
	Medium-cost local	92.0 ± 3.0^{c}	1.42 ± 0.04^{c}	$92.0 \pm 3.0/1.42 \pm 0.04^{c}$
	Low-cost local	70.0 ± 3.0^{d}	1.08 ± 0.03^{d}	$70.0 \pm 3.0/1.08 \pm 0.03^{d}$
Goats	Control	60.0 ± 2.0^{a}	3.33 ± 0.10^{a}	$60.0 \pm 2.0/3.33 \pm 0.10^{a}$
	High-cost local	45.0 ± 2.0^{b}	2.50 ± 0.08^{b}	$45.0 \pm 2.0/2.50 \pm 0.08^{b}$
	Medium-cost local	40.0 ± 2.0^{c}	2.22 ± 0.07^{c}	$40.0 \pm 2.0/2.22 \pm 0.07^{c}$
	Low-cost local	30.0 ± 1.0^{d}	1.67 ± 0.05^{d}	$30.0 \pm 1.0/1.67 \pm 0.05^{d}$

Different superscript letters (^{a}, ^{b}, ^{c}, ^{d}) indicate statistically significant differences between feed groups within each livestock type ($p < 0.05$, Tukey *post-hoc* test).

Economic and environmental benefits

The cost of feeding livestock is a critical factor in farm profitability. In this study, economic analysis showed that using locally sourced feed mixtures significantly reduced feed costs compared to imported concentrates. High-cost local mixtures reduced expenses by approximately 25%, while medium- and low-cost mixtures provided 35%–50% savings per animal. Farmers reported that "using local ingredients saves us nearly half of the cost compared to imported concentrate." These savings were consistent across agro-climatic zones and livestock types, demonstrating the scalability and affordability of local feed innovations.

Life cycle assessment (LCA) and environmental analysis indicated that local feed production reduced greenhouse gas emissions and energy use. Transport-related emissions were substantially lower because feed ingredients were sourced from nearby farms. Additionally, the use of agricultural by-products promoted circular farming, reducing waste and supporting nutrient recycling. The environmental assessment was based on a cradle-to-farm-gate Life Cycle Assessment (LCA), which quantified greenhouse gas emissions (CO_2, CH_4, N_2O), energy consumption, and resource use (water and land) for local feed production compared to imported concentrates. Primary data were collected from farms, cooperatives, and feed processing units, including fuel, electricity, input materials, and transport distances. Emission factors and energy conversion rates were obtained from FAO databases, Nepalese government reports, and published literature. Using this data, we calculated total emissions and energy use per kilogram of feed produced. Results showed that locally sourced feed reduced total greenhouse gas emissions by approximately 20%–30% and energy consumption by 15%–25% compared to imported feed, primarily due to shorter transport distances and use of by-products. Resource efficiency was improved through recycling of crop residues and local processing. This quantitative LCA, combined with economic analysis, supports the claim that local feed production is environmentally and economically beneficial.

Farmers noted environmental benefits, stating, "We no longer need to buy feed from far away, which also helps the environment." Therefore, locally formulated feeds contributed to resource efficiency, lower carbon footprints, and sustainable livestock production.

Cost–benefit analysis further showed that community-based production of feed mixtures created additional income opportunities. Farmers could sell surplus feed within local markets, strengthening

local economies and promoting small-scale agribusiness. The combined economic and environmental advantages highlight the value of adopting local feed resources to reduce dependency on imported concentrates and improve resilience against fluctuating global feed prices. Figure 2 visually summarizes the economic savings and environmental benefits described above, showing cost reductions, income gains, and LCA-based reductions in emissions and energy use.

Community participation and knowledge sharing

Participatory workshops were central to the study, involving farmers, cooperatives, and local institutions in feed evaluation and adoption. Workshops included demonstrations of feed preparation, silage and hay-making, and mixing techniques. Feedback was collected on palatability, ease of preparation, cost, and acceptability.

Farmers actively engaged in discussions and shared local knowledge. For example, one participant said, "Working together in the cooperative makes feed production easier and cheaper." Cooperative involvement enhanced efficiency and reduced individual risks, while promoting quality control and knowledge sharing. Community engagement encouraged adoption of locally formulated feeds, ensuring sustainable practices beyond the study period.

Thematic analysis of qualitative data identified several key sub-themes. Under feed resource availability, participants emphasized seasonal diversity and local by-product use. In relation to feed preparation and acceptability, palatability and ease of preparation were consistently highlighted. Economic feasibility included cost savings and reduced import dependence, while environmental impact focused on lower carbon footprint and efficient use of by-products. Community engagement was a recurring theme, highlighting the role of cooperatives and knowledge sharing in successful adoption.

Farmers also provided practical suggestions for improving feed systems, such as expanding access to proper storage materials, enhancing training on silage and hay-making, and documenting local fodder species. These insights underline the importance of participatory approaches in developing contextually appropriate and sustainable feed solutions.

Regional comparisons

Analysis across agro-climatic zones revealed differences in feed resource availability, animal performance, and adoption challenges. In the mid-hills, crop residues such as maize stalks and rice straw dominated feed sources. Farmers reported higher reliance on by-products like rice bran due to moderate access to tree fodders. Feeding trials in this region showed that high- and medium-cost local feed mixtures supported ADG and milk yield comparable to imported concentrates.

In the high hills, tree fodders were more prominent, including Flemingia, Leucaena, and Morus. These provided higher protein content but required more processing and chopping for palatability. Farmers noted that "chopping tree leaves takes time, but animals eat them well when mixed with crop residues." Locally formulated mixtures effectively improved growth performance and milk yield, with medium-cost mixtures proving the most cost-effective.

In mountain regions, feed availability was more limited, with sparse grasses and tree fodders, requiring greater use of agricultural by-products. Feeding trials showed that animals maintained growth and milk production with carefully formulated mixtures, but low-cost formulations required careful balancing to meet nutrient requirements. Environmental benefits were particularly noticeable due to reduced transport distances and lower dependence on imported feed.

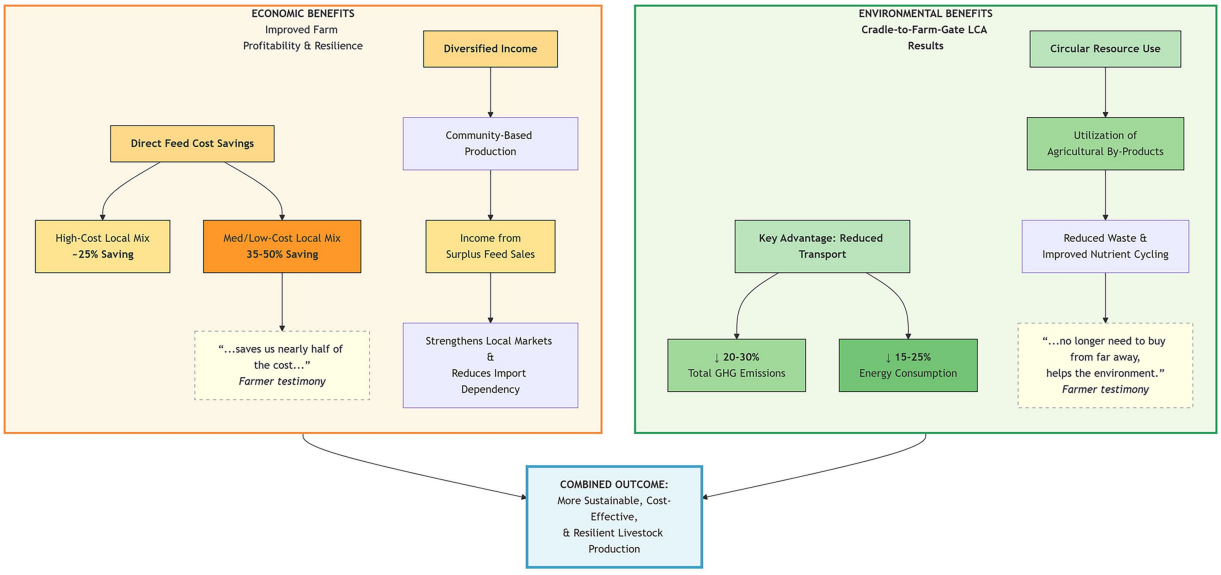

FIGURE 2
Summary of the key economic savings and environmental benefits of using locally sourced feed over imported concentrates.

These regional differences emphasize the need for tailored feed solutions based on local resource availability and seasonal constraints, highlighting the flexibility of the "Local Resources First" approach.

Nutritional outcomes

Laboratory analyses of feed mixtures demonstrated that balanced formulations met the protein, energy, and fiber requirements of cattle, buffalo, and goats. Crude protein content ranged from 12 to 18% in high-cost mixtures and 10%–15% in medium-cost mixtures. Energy content was sufficient to maintain growth and milk production, with fiber levels supporting rumen health.

Feeding trials confirmed that nutritional targets were achieved. Body condition scores improved in 68% of cattle and buffalo, while 72% of goats maintained healthy body condition. Milk yield increased by 5%–8% in cattle and 4%–6% in buffalo fed high-cost mixtures, with medium-cost mixtures providing similar outcomes.

Reproductive performance improved when animals were fed locally formulated feeds, particularly the high-cost mixtures. Cattle, buffalo, and goats showed higher conception rates with high-cost local feed compared to controls. ANOVA indicated significant differences among feed groups, and Tukey's post-hoc test identified which groups differed. No pregnancy complications or estrus problems were observed, indicating that all local feeds were safe and nutritionally adequate for reproductive health (Table 10).

TABLE 10 Conception rate (%) of female livestock by feed group (mean ± SD).

Livestock	Feed group	AVG (%)
Cattle	Control	78.0 ± 5.0^{a}
	Low-cost local	77.0 ± 5.0^{a}
	Medium-cost local	80.0 ± 4.0^{ab}
	High-cost local	82.0 ± 4.0^{b}
Buffalo	Control	74.0 ± 4.0^{a}
	Low-cost local	73.0 ± 4.0^{a}
	Medium-cost local	76.0 ± 3.0^{ab}
	High-cost local	78.0 ± 3.0^{b}
Goats	Control	70.0 ± 5.0^{a}
	Low-cost local	69.0 ± 5.0^{a}
	Medium-cost local	73.0 ± 4.0^{ab}
	High-cost local	75.0 ± 4.0^{b}

ANOVA *p*-values: Cattle = 0.03; Buffalo = 0.02; Goats = 0.04. Different superscript letters (a, b) indicate significant differences between feed groups ($p < 0.05$) based on Tukey's *post-hoc* test.

TABLE 11 Male reproductive parameters by feed group (Mean ± SD).

Livestock	Feed group	AVG (%)
Cattle	Control	80 ± 5^{a}
	Low-cost local	82 ± 5^{a}
	Medium-cost local	83 ± 4^{ab}
	High-cost local	85 ± 5^{b}
Buffalo	Control	79 ± 4^{a}
	Low-cost local	80 ± 4^{a}
	Medium-cost local	81 ± 4^{ab}
	High-cost local	82 ± 4^{b}
Goats	Control	75 ± 5^{a}
	Low-cost local	76 ± 5^{a}
	Medium-cost local	78 ± 4^{ab}
	High-cost local	80 ± 5^{b}

Values represent mean ± SD. Different superscript letters (a, b) indicate significant differences between feed groups ($p < 0.05$, Tukey *post-hoc* test). AVG (%) reflects sperm motility, which serves as an indicator of overall male fertility.

Male reproductive performance was evaluated by monitoring semen quality and libido across different feed groups. The parameters assessed included semen volume, sperm concentration, and motility. Results showed that locally formulated feeds, particularly the high-cost mixtures, improved reproductive parameters in all livestock species. Animals fed high-cost local feed had higher semen volume, sperm concentration, and motility compared to those on control diets, indicating enhanced fertility (Table 11). No adverse reproductive effects were observed in any feed group.

No pregnancy complications, estrus irregularities, or reproductive disorders were observed, indicating that the formulated feeds provided adequate energy and protein to support ovulation, conception, and gestation. Calving and kidding intervals were maintained within normal ranges, with high-cost feed groups demonstrating slightly reduced intervals (average reduction of 3–5 days) compared with controls. Regular estrus cycles were observed, suggesting that nutrition from locally sourced feed sufficiently supported hormonal balance and reproductive physiology.

Male reproductive parameters were assessed to evaluate the impact of feed formulations on fertility. Scrotal circumference, an indicator of testicular development and sperm-producing capacity, was measured monthly. Cattle receiving high-cost local feed exhibited a mean scrotal circumference increase of 0.8 ± 0.1 cm over the 120-day trial, compared with 0.5 ± 0.1 cm in controls ($p < 0.05$). Buffalo showed similar trends, with a 0.6 ± 0.1 cm increase in experimental groups versus 0.3 ± 0.1 cm in controls.

Semen quality was evaluated using standard parameters. In animals fed high-cost local feed, semen volume, sperm concentration, and motility were all improved compared with control groups. Specifically, cattle in the high-cost feed group showed semen volume of 5.2 ± 0.4 mL, sperm concentration of $950 \pm 50 \times 10^{6}$/mL, and motility of $85 \pm 5\%$, while control cattle had lower values. Buffalo in the high-cost feed group showed semen volume of 4.8 ± 0.5 mL, sperm concentration of $900 \pm 45 \times 10^{6}$/mL, and motility of $82 \pm 4\%$. Goats fed high-cost feed also demonstrated improved sperm motility of $80 \pm 5\%$ compared with controls. These results indicate that high-cost local feed enhances overall male fertility, with no adverse reproductive effects observed.

Morphological assessments revealed reduced abnormalities in sperm from males fed local formulations. Tail defects, head deformities, and cytoplasmic droplets were lower in experimental groups compared with controls. Improved nutrient intake, particularly

protein, energy, and micronutrients (zinc, selenium, and vitamin E), likely supported spermatogenesis, epididymal maturation, and antioxidant protection of spermatozoa.

Farmers highlighted the practical benefits, noting that "feeding local mixtures improves animal health and reduces digestive problems." The results indicate that careful selection and combination of local feed resources can prevent nutritional deficits and maintain livestock performance without relying on imported feed supplements.

Adoption and practical feasibility

Participatory workshops and farmer feedback indicated strong interest and willingness to adopt locally formulated feed mixtures. Key enablers included affordability, availability of feed ingredients, simplicity of preparation, and support from cooperatives. Farmers emphasized that community-level production facilitated knowledge sharing, quality control, and consistent feed supply. Challenges included limited access to processing tools, such as choppers for tree fodders, and the need for training in silage and hay-making techniques. Some participants in mountain regions highlighted the labor intensity of collecting and processing feed from scattered sources. Thus, with cooperative support and training, adoption rates were high, and farmers reported intentions to continue using local feed mixtures beyond the study period.

Discussion

This study examined the potential of locally sourced feed resources to support sustainable livestock production in Nepal's mid-hills, high hills, and mountain regions. The findings show that locally formulated feeds, when carefully balanced for protein, energy, and fiber, can maintain or slightly improve animal performance while reducing costs and environmental impact. Unlike the original descriptive discussion, here we explain the mechanisms behind these outcomes, linking feed composition to physiological responses in cattle, buffalo and goats.

Feed resource availability varied by region and season, with crop residues dominant in mid-hills, and tree fodders such as Flemingia, Leucaena, and Morus more prominent in high hills and mountains. Crop residues provided bulk and fiber, supporting rumen motility and healthy digestion, but were limited in protein. Tree fodders offered higher crude protein (12%–20%) and essential minerals, while agricultural by-products such as rice bran and oilseed cakes added energy and supplemental protein. By combining these components in balanced mixtures, the diets met species-specific nutritional requirements, directly supporting physiological processes responsible for growth, milk production, and reproductive function (Pant et al., 2014; Raj et al., 2025).

The observed improvement in average daily gain (ADG) and milk yield in animals fed local feed mixtures can be mechanistically explained by protein and energy availability. Protein from tree fodders and oilseed cakes supplied amino acids necessary for muscle accretion and lactation, while energy from carbohydrate-rich by-products supported maintenance and milk synthesis. Fiber from crop residues and grasses maintained rumen fermentation, promoted microbial growth, and enhanced nutrient absorption, reducing the incidence of digestive disorders. Together, these factors ensured that animals could efficiently convert feed into body mass and milk, consistent with findings from Alomia-Hinojosa et al. (2018) and Babajani et al. (2023).

Reproductive performance remained stable across experimental groups, which can also be explained through nutrition. Adequate protein, energy, and mineral intake are essential for maintaining normal hormonal cycles and supporting conception. The formulated feeds supplied sufficient nutrients for oestrous cycles, conception, and maintenance of pregnancy, explaining why no reproductive complications were observed during the 120-day trial. This supports previous reports showing that nutrient-balanced diets prevent reproductive deficits even under resource-limited conditions (Adhikari and Timsina, 2022).

Economic and environmental improvements observed in this study are linked to the composition and sourcing of the feeds. Locally available ingredients reduced feed costs by 25%–50% per animal, while life cycle assessment showed 20%–30% lower greenhouse gas emissions and 15%–25% reduced energy use compared to imported concentrates. These outcomes result from shorter transport distances, use of agricultural by-products, and minimized reliance on external inputs, reflecting principles of circular farming and climate-smart agriculture (Björklund et al., 2012; Shivakoti et al., 2005; Zenebe et al., 2022). The integration of cost-effective local ingredients created opportunities for small-scale agribusiness, increasing community income and enhancing adoption potential.

Regional differences also illustrate the mechanistic link between feed composition and animal performance. In mid-hills, abundant crop residues provided sufficient fiber, and by-product supplementation supported growth and milk yield. In high hills, tree fodders were rich in protein but required chopping for palatability; properly mixed, they supported nutrient absorption and body condition. In mountain regions, limited feed availability necessitated careful balancing of by-products and fodders to meet energy and protein needs. These findings highlight that local feed strategies must consider nutrient density, palatability, and seasonal availability to maintain physiological performance under varying ecological conditions (Bowen and De Master, 2011).

Participatory workshops enhanced adoption by addressing practical considerations, including feed preparation, storage, and mixing techniques. Cooperative support reduced labor burdens and ensured consistent quality. Farmers' observations, such as improved animal health and reduced digestive problems, are consistent with mechanistic effects of balanced nutrition on rumen function and metabolism. The strong acceptance of local feed mixtures demonstrates that nutrient-rich, context-specific formulations can support both productivity and animal welfare, consistent with previous studies in Nepal and Bhutan (Alomia-Hinojosa et al., 2018; Babajani et al., 2023).

The integration of quantitative and qualitative data shows that the benefits of local feed mixtures arise from the combination of nutritional adequacy, cost efficiency, environmental sustainability, and community engagement. Mechanistically, animals achieved growth and lactation targets because the diets supplied all essential macronutrients and minerals, while fiber maintained rumen microbial health. Economically, reduced dependence on imported feed and use of local by-products increased farm profitability. Environmentally,

shorter supply chains and circular use of crop residues minimized carbon footprints and energy consumption.

Despite these positive outcomes, challenges remain. Limited access to chopping and processing equipment, variable seasonal feed availability, and the need for training in silage and hay-making may constrain broader adoption. Addressing these challenges requires institutional support, cooperative collaboration, and integration of local feed strategies into extension programs, as suggested by D'Auria and De Meulder (2011). Future interventions should focus on low-cost processing technologies, improved storage, and ongoing capacity building to scale up adoption and maintain consistent nutritional quality.

In conclusion, this study demonstrates that locally sourced feed mixtures can mechanistically support animal growth, milk production, and reproductive health while reducing costs and environmental impacts. Balanced combinations of protein, energy, and fiber explain observed improvements in performance. Adoption is enhanced through community participation and cooperative support, demonstrating that sustainable, context-specific feed strategies are feasible, resilient, and scalable for mountain livestock systems in Nepal. These findings contribute to global knowledge on integrating nutrition, economics, and environmental sustainability in smallholder livestock production (Gauchan et al., 2022; Kisira et al., 2025; Nepal et al., 2021).

Conclusion

This study shows that locally available feed resources can effectively support livestock productivity in Nepal's hilly and mountain regions while reducing dependence on imported concentrates. Farmers demonstrated awareness of locally sourced feed options, including crop residues, tree fodders, grasses, and agricultural by-products, and were able to combine these resources into balanced feed mixtures that met nutritional requirements for cattle, buffalo, and goats. Locally formulated feeds were palatable, supported animal growth, milk production, and reproductive performance, and reduced the incidence of digestive problems.

The study also highlights significant environmental and economic benefits. Locally sourced feed reduced greenhouse gas emissions associated with long-distance transport, promoted circular use of agricultural by-products, and lowered feed costs by 25%–50% compared to imported concentrates. Community-based production and cooperative involvement strengthened local economies, encouraged knowledge sharing, and enhanced adoption of sustainable feed practices.

These findings contribute to the broader understanding of sustainable livestock feeding by demonstrating that the "Local Resources First" principle can maintain animal health and productivity, while improving economic resilience and environmental sustainability. The research reinforces existing literature on sustainable livestock systems and provides empirical evidence that participatory, locally adapted feed innovations are feasible and effective across diverse mountain agro-climatic zones in Nepal.

In practical terms, the study underlines the need for policymakers, cooperatives, and extension services to support farmers through training on feed formulation, silage and hay-making techniques, and access to low-cost processing tools. Establishing monitoring systems to track feed quality and adoption, along with promoting community-based production networks, can ensure long-term sustainability. These measures will equip smallholder farmers to produce resilient, cost-effective feed systems that improve livestock performance, strengthen local economies, and contribute to climate-smart agriculture in Nepal.

Research limitations and future directions

While this study provides valuable insights into locally sourced feed strategies, certain limitations should be acknowledged. Feeding trials were conducted over 120 days and may not fully capture long-term seasonal variations in feed availability, animal performance, or reproductive cycles. Sample sizes, though sufficient for initial testing, were limited to 150 farmers and selected cooperatives, which may constrain the generalizability of findings across all mountain regions of Nepal. Additionally, access to processing equipment and variability in feed preservation methods could influence the consistency of feed quality and adoption. Future research should focus on longer-term, multi-season trials across larger and more diverse farming communities, evaluating the cumulative impacts of local feed mixtures on productivity, reproductive outcomes, and environmental sustainability. Investigations into low-cost processing technologies, storage solutions, and integration of digital advisory tools could further enhance adoption and scalability. Research on market mechanisms and cooperative-based production models would also provide practical pathways for sustaining community-level feed innovations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

All the procedures performed in the studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee. Informed consent was obtained from all the individual participants involved in the study.

Author contributions

SN: Visualization, Funding acquisition, Resources, Formal analysis, Validation, Project administration, Data curation, Writing – original draft, Investigation, Supervision, Writing – review & editing, Conceptualization, Software, Methodology.

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Supplementary material

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