Impact of feed innovation on dairy water productivity and methane emissions in Nepal

ILRI RESEARCH REPORT

128

Impact of feed innovation on dairy water productivity and methane emissions in Nepal

Om Prakash Singh[1], Shivahari Ghimire[2], Pawankumar Jha[3], Bhola Shrestha[4], Anil Aryal[5], Santhosh Nepal[5], Cesar Patino[6], Yanamani Nepal[6], and Padmakumar Varijakshapanicker[6]

1 Banaras Hindu University, India
2 National Cattle Research Program, NARC, Nepal
3 National Buffalo Research Program, NARC, Nepal
4 Heifer International Nepal, Kathmandu
5 International Water Management Institute-Nepal Office, Kathmandu, Nepal
6 International Livestock Research Institute

December 2025

ILRI thanks all donors and organizations which globally supports its work through their contributions to the CGIAR Trust Fund

Editing, design and layout—ILRI Editorial and Publishing Services, Addis Ababa, Ethiopia.

Cover photo: ILRI/Yanamani Nepal (Biofermentation treatment of rice straw using lactic acid bacteria).

ISBN: 92–9146–869–X

Citation: Singh, O. P., Ghimire, S., Jha, P., Shrestha, B., Aryal, A., Nepal, S., Patino, C., Nepal, Y. and Varijakshapanicker, P. 2025. *Impact of feed innovation on dairy water productivity and methane emissions in Nepal.* ILRI research report 128. Nairobi, Kenya: ILRI.

Box 30709, Nairobi 00100 Kenya
Phone +254 20 422 3000
Fax+254 20 422 3001
Email ilri-kenya@cgiar.org

ilri.org
better lives, better planet through livestock

ILRI is a CGIAR research centre

Box 5689, Addis Ababa, Ethiopia
Phone +251 11 617 2000
Fax +251 11 667 6923
Email ilri-ethiopia@cgiar.org

ILRI has offices in East Africa • South Asia • Southeast and East Asia • Southern Africa • West Africa

Contents

Tables

Abbreviations and acronyms

CWP	Crop water productivity
CWR	Crop water requirement
DM	Dry matter
ET	Evapotranspiration
GE	gross energy
Ha	Hectare
LW	Liveweight
LWch	Liveweight change
LWP	Livestock water productivity
ME	Metabolizable energy
MJ	Megajoule
NARC	Nepal National Agricultural Research Council
NBRP	National Buffalo Research Program
WI	Water intake
WP	Water productivity

Acknowledgements

This work was conducted as part of the CGIAR Sustainable Animal and Aquatic Foods (SAAF) Science Program, with a contribution from the Policy Innovations Science Program. It was funded by CGIAR through contributions to the CGIAR Trust Fund, and AGCO Agriculture Foundation. CGIAR is a global research partnership for a food-secure future dedicated to transforming food, land, and water systems in a climate crisis.

Summary

This study assessed the impact of three livestock dietary regiments (T_0 with normal straw, T_1 with supplementary concentrate, and T_2 with biofermented straw) on milk water productivity using two approaches (dry matter and metabolizable energy) of estimating dairy water productivity based on partitioning of the total water depleted in feed production between residues and the main product. Methane emission was estimated using a mathematical model. The study was conducted at the Itahari institutional farm under the National Buffalo Research Program (NBRP) and at a commercial dairy farm in Tirahut, Nepal. Crop water requirement (m^3/ha) for feed and fodder production was estimated using the CROPWAT-8.0 model, except for oat (green fodder), where actual irrigation water data were utilized. At the Itahari (NBRP) location, milk water productivity was 0.550, 0.574, and 0.635 liters/m3 for T_0, T_1, and T_2 diets, respectively. In contrast, the Tirahut farm demonstrated higher milk-water productivity of 0.833, 0.781, and 1.143 liters/m3 for the T_0, T_1, and T_2 diets, respectively. In the case of methane emissions, the lowest emission (g/day) was from the biofermented straw-based diet. However, there were no significant differences among treatments. Despite improved diets (T_1 and T_2) leading to a marginal increase in milk yield at Itahari (NBPR), the net economic milk water productivity (USD/m^3) remained negative across all dietary treatments. Conversely, all dietary treatments at the Tirahut farm resulted in positive net economic milk water productivity, possibly due to better management. These findings suggest that while feed and fodder interventions are not economically justified under the current conditions at the Itahari (NBRP) location, they are both productive and economically viable at the Tirahut commercial farm.

1 Introduction

Livestock were first domesticated around 10,000 years ago and have since played a pivotal role in the advancement of human civilization (Salmon et al. 2020). Water remains a critical input in both food and feed production, directly supporting food supply and global food security. Driven by demographic expansion and rising economic prosperity, global demand for livestock-derived products is expected to increase by 35% by mid-century (Mekonnen et al. 2019). Over the past five decades, the global production of animal-sourced foods has more than tripled, a trend paralleled by a threefold increase in the cultivation of crops for animal (Heinke et al. 2020). Currently, nearly one-third of the world's cropland is dedicated to the production of feed and fodder crops (Steinfeld et al. 2006). The rising demand for agricultural commodities – including both crop and livestock-based – has intensified pressure on freshwater resources (Herrero et al. 2010). Moreover, water availability exhibits substantial spatial and temporal variability and is increasingly constrained in many regions of the world (Thoma, 2016; Drastig et al. 2021).

Enteric methane emissions from livestock are primarily determined by feeding level and feed quality. Thus, feeding and nutrition management are the most cost-effective means to reduce methane emission intensity (emissions per unit of animal product) (Aguirre-Villegas 2017) and improve animal productivity. A study conducted in India (NDDB, 2022), under a similar environment to Nepal, has demonstrated that improved feeding management results in higher milk yield, reduced methane emission intensity, and lower milk production costs.

The livestock sector not only contributes to nutritional security but also serves as a vital source of regular income and employment, particularly in rural areas. Therefore, enhancing its productivity and resource use efficiency is imperative to mitigate its environmental footprint and ensure the long-term sustainability of global food systems.

Enhancing crop water productivity (CWP) and livestock water productivity (LWP) is widely recognized as a key strategy for mitigating the adverse effects of water scarcity on sustainable livelihoods (Singh, 2005; Peden et al. 2007; Haileslassie et al. 2009; Rodell et al. 2009; Descheemaeker et al. 2010). Improvements in livestock productivity, feed-use efficiency, and the yield of feed and fodder crops significantly reduce the demand for critical resources such as land and water, thereby minimizing the environmental footprint of livestock production (Mekonnen and Hoekstra 2012; Steinfeld and Gerber 2010; Steinfeld et al. 2006). The direct consumption of drinking water by livestock is influenced by various factors, including climatic conditions, animal age, and the type and quantity of feed and fodder consumed (OMAFRA 2015; Higham et al. 2017a, b). The overwhelming majority of water use in the livestock sector is embedded in feed and fodder production, commonly referred to as "virtual" or "embedded" water. LWP is defined as the ratio of beneficial outputs and services derived from livestock to the volume of water depleted or degraded in producing those outputs (Haileslassie et al. 2011). It is estimated that more than 98% of the water used in the livestock sector is consumed indirectly through feed and fodder production, while only about 2% is used directly for drinking and servicing (Heinke et al. 2020). Therefore, accurately estimating the quantity and sources of feed and fodder required for livestock production, along with their associated water use, is essential for assessing total consumptive water use in the sector. Globally, the production of feed and fodder for the livestock sector is estimated to require about 4,387 km^3 of water annually (Heinke et al. 2020), underscoring the sector's substantial share of global freshwater use and the critical need for strategies to improve water-use efficiency.

Milk production from cows and buffaloes, particularly when reliant on cultivated feed and fodder, is among the most water-intensive agricultural systems – often exceeding the water requirements of many crop production systems (Singh 2004; Singh and Kumar 2009; Haileslassie 2011). However, the water-use efficiency of dairy production can be significantly improved by enhancing water-use efficiency in feed and fodder cultivation. Water use efficiency refers to the proportion of applied water that is productively consumed by the plants, primarily through transpiration (Drestig et al. 2021). In this context, improving water use efficiency directly contributes to reducing the water footprint of livestock production. Water productivity, a broader concept, is defined as the ratio of output (such as biomass, harvestable yield, or economic return) to the amount of water consumed. The numerator of water productivity can vary depending on the analysis objective (e.g., biological yield, market value), while the denominator may include measures of water use such as transpiration, evapotranspiration, irrigation water, or total water inflow (Molden 1997; Molden and Sakthivadivel 1997). Thus, water productivity provides a flexible yet robust framework for evaluating and comparing water use efficiency across different agricultural systems, including dairy production.

In the fiscal year 2021–22, Nepal's total livestock population (cattle and buffalo) was estimated at 12.55 million, with cattle accounting for 59% and buffaloes comprising 41% of the total (GoN 2023). Total number of lactating (in-milk) cows and buffaloes was about 1.22 and 1,67 million, respectively. During the same period, total national milk production was reported at 2.57 million tonnes, of which cow milk accounted for 1.10 million tonnes and buffalo milk for 1.47 million tonnes. The average daily milk production per lactating cow and buffalo was estimated at 2.47 kg and 2.41 kg, respectively (GoN 2023). These production levels are relatively low and considered economically suboptimal, highlighting the need for targeted interventions to enhance productivity and improve the economic viability of dairy farming in Nepal.

Pashupatinagar village in Mahottari District, Nepal, is considered a dry area, mainly due to an extended drought. The conventional and shallow wells run dry, leaving a significant portion of cultivable land unproductive due to insufficient water and minimal rainfall. The shortage of water for irrigation leads to parched fields, posing a grave concern for the community. Drought, intense heat, and the unavailability of drinking water are escalating in these areas, creating a challenging situation for villagers. In water-stressed regions, improving the water-use efficiency of dairy production is widely perceived as a non-negotiable option. If productivity can be improved through genetic, feed, and health improvement, more milk can be produced from the same animals with the same quantity of water, leading to higher water productivity (Singh and Kumar 2009; Bednarski et al. 2024; Hatew et al. 2023).

2 Methodology

In the present study, three diets were formulated and used in a feeding trial with buffalo in two locations:

- Control diet with normal rice straw (T_0)
- Improved diet 1 with normal rice straw + one kg more concentrate (T_1)
- Improved diet 2, where normal rice straw in T_0 is replaced with biofermented[1] straw (T_2)

The objective was to assess and compare the impact of the improved diets (T_1 and T_2) on milk yield and milk water productivity, with the overarching goal of identifying viable strategies to enhance dairy efficiency in water-constrained regions of Nepal.

The experiment was conducted within a typical mixed crop–livestock system, in which the primary sources of animal feed were crop residue, green fodder, and concentrate. While the specific composition of these feed resources may vary from farm to farm, the complexity they introduce poses a significant challenge for accurately estimating physical water productivity, which is generally defined as the ratio of total milk produced to the water used to grow the feed.

2.1 Experimental layout

This study utilized a combination of secondary and primary data sources. Secondary weather data and data on the nutritional composition of feed and fodder – specifically dry matter (DM) and metabolizable energy (ME) – were collected from Feedipedia (https://www.feedipedia.org) and other peer-reviewed literature (Kelly and Thomas (1978); Nwokolo (1987); Baking Business (2010); Huang et al. (2012); José et al. (2017); Baetge and Kaltschmitt (2018); Infonet (2024). Market prices for inputs and data on input prices (e.g., feed ingredients) and outputs (e.g., milk) were obtained from prevailing local market rates. Additionally, data on the proportion of main products and by-products were compiled from existing research studies (Saha et al. [2018]; Ramarao et al. [2020]; Kirti et al. [2022]; Joshi et al. [undated]; Saxena et al. [undated]). Primary data were collected through experiment-based observations and measurements at two locations in Nepal: (i) at the facilities of the National Buffalo Research Programme (NBRP) of the Nepal National Agricultural Research Council (NARC), located in Itahari, and (ii) a commercial buffalo farm located in Tirahut, Nepal.

The study was a randomized block design, conducted over a period of four weeks. Criteria used to select the experimental animals include that the animals be lactating, non-pregnant, or pregnant but in the first two trimesters or post-peak lactation (4–5 months). During the study period, three groups (T_0, T_1 and T_2 diets) of animals were managed:

1 Biofementation is a technology to upgrade quality of crop residues in which the residue is treated with lactic acid bacteria under anaerobic condition and fermented for 45 days.

a. Control diet (T_0): This feeding pattern reflects the common practice largely followed by most dairy farmers in the study area. Under this treatment, the quantity and types of feed and fodder (paddy straw, oats (forage), compounded feed, and wheat bran) and drinking water were provided to the sample buffaloes.

b. Improved diet-1 (T_1): Under this treatment, the quantity of compounded feed was changed. Under this feeding pattern, one kg more compounded feed was given to sample buffaloes (as recommended by a feed balancing tool developed by Heifer Nepal (https://livestocklab.ifas.ufl.edu/media/livestocklabifasufledu/pdf-/Scale-Up-Conf_FST--Poster_9.24.2018.pdf). The rest of the feeds and fodder (paddy-straw, oats (forage), and wheat bran) and drinking water were kept the same as in the case of T_0 treatment.

c. Improved diet-2 (T_2): Under this treatment, changes were made in paddy straw. The paddy-straw was upgraded using biofermentation technology (bio-fermentation breaks down the ligno-cellulose in the cell wall of paddy straw, and hence its nutritional quality is increased), and quantity was proportionally increased to maintain the DM content of paddy straw the same in all the treatments. The amount of the rest of the feeds and fodder (irrigated oats), compounded feed, and wheat bran) and drinking water was almost the same as in the T_0 diet.

Each group consisted of 10 animals, of which six were at the Itahari research farm and four at the Tirahut commercial farm (a total of 18 in Itahari and 12 in Tirahut). The 30 animals were randomly allocated to one of the three groups, balanced as much as possible for breed, live weight, parity, lactation period, milk yield, and pregnancy stage (if applicable) at the time of randomization.

2.2 Primary data collected

The primary data collected include the quantities of different types of feed (straw, oats forage, concentrate feed, compounded feed) consumed, water intake, fecal output, and milk yield. The trial duration was 28 days, with days 1 to 21 for acclimatization to the diet and experimental management, and sample and data collections during days 22 to 28. The study at the NBRP facilities in Itahari was conducted between 13 March and 9 April 2024, whereas the survey at Tirahut was conducted between 15 March and 11 April 2024. During the study, the buffaloes were housed in individual stalls within a shed (open sides and tall roof). The stalls have provision for feed and water troughs, and a rubber-covered floor. The floor allowed feces to be collected manually by scraping. During the first three weeks of the study (days 1-21), the buffaloes were released daily from the shed and enabled to exercise for approximately four hours in a yard with a soft floor. During the fourth week of the study (days 22–28), they were maintained permanently in the shed.

All the experimental diets were fed at 1.1 times the voluntary feed intake, whereas drinking water was offered *ad libitum*. Dietary treatments were fed twice daily (0800 and 1600 h), with the daily ration divided into two equal parts. At each feeding, all feed items were manually mixed with 20 kg of water. The buffaloes were manually milked twice a day (0800 and 1600 h). The experimental animals were weighed at the start of the study and then weekly. Animal weighing took place before the morning feeding. Animal liveweight (LW) was used for monitoring their well-being. Liveweight change (LWch) was of little interest in this study, given the short time frame.

Daily milk yields were calculated by adding the weights of morning and afternoon milk outputs. Milk aliquots (100 ml) were immediately analyzed for fat, protein, and lactose contents, whereas other subsamples were stored frozen for analyses of gross energy (GE) contents.

Samples of feed offered, and refusals were collected at two-day intervals. Subsamples of feed on offer and refusals were oven-dried (65°C, 72 h) until completely dry, and DM contents calculated. Daily feed amounts offered and feed refusals were calculated by multiplying each item's fresh weight by its DM content.

Daily water intake (WI) was calculated from the drinking water intake and the water intake in feed (the difference from the DM content of feed on offer). Water intake was determined from the weight of water offered and water refusal over 24-hour periods.

Samples of rumen fluid were collected at the end of the study (immediately after the morning milking and feeding on day 29) using orogastric tubing (SOP 4.40 Collection of Rumen Samples, ILRI). Rumen fluid was immediately analyzed for pH, then squeezed through two layers of cheesecloth, and subsequently, two subsamples (5 ml each) were collected and immediately stored frozen (-20 °C) without acid addition. One subsample was used for volatile fatty acid (VFA) analysis, and another for ammonia (NH_3) determination.

Fecal samples were collected seven times a day. In three-hour intervals during the daytime and four-hour intervals during the nighttime. The next day, all seven samples of each animal were mixed to make one sample per day per animal. For the final sample, a seven-day composite sample from each animal was mixed to produce one sample per animal.

Urine samples were collected during urination. Time separation was done to collect the urine samples. During the seven-day observation, urine samples from each animal were collected at approximately 2-hour intervals and combined. After completion of the observation period, the final urine sample was prepared by adding 10% H2SO4 to lower the pH to below 3. The recording was conducted by NBRP staff at the Itahari location and by a trained village livestock promoter at the Tirahut commercial farm.

2.3 Secondary data

The secondary data used in this study mainly include harvest index (Table 1), weather data (Table 2), production, dry matter content, and metabolizable energy data (Table 3).

Table 1: Harvest index (ratio between main product and by-products)

Name of the crop		Ratios	Reference
1. Paddy	Crop	Paddy grain (1.0): dry paddy straw (1.25)	Sirajuddin et al. (2017)
	Crop	Paddy grain (1.0): green paddy straw (3.0)	Singh et al. (1995)
	Grain	Rice (69%) + hull/husk (20%) + bran (11%)	Saha et al. (2018)
2. Wheat	Crop	Wheat grain (1.0): wheat straw (1.25)	Sirajuddin et al. (2017)
	Grain	Wheat flour (81%) + bran (19%)	Cui et al. (2013)
3. Maize	Crop	Maize grain (1.0): maize straw (1.34)	Adeoye et al. (2011)
4. Mustard	Crop	Mustard grain (1.0): mustard stalk (2.14)	Ramarao et al. (2020)
	Grain	Mustard oil (33%) + mustard cake (67%)	Ratio analysis of common oil crops (oil-mill-plant.com)
5. Soybean	Crop	Soybean grain (1.0): soybean straw (1.5)	Joshi, et al. (undated)
	Grain	Soybean oil (22.70%) + soybean cake (77.29%)	Ratio analysis of common oil crops (oil-mill-plant.com)
6. Sugarcane	Crop	Sugarcane (1.0): sugarcane top (0.10)	Mena (1987)
	Stem	Molasses (3.80%) + sugar (12.0%) + filter mud (3.60%) + bagasse (25.0% + straw (6.0%)	
7. Pigeon pea	Crop	Pigeon pea grain (1.0): pigeon pea stalk (3.18)	Kirti et al. (2022)
	Grain	Pulse (85.0%) + husk/chunni (15.0%)	Saxena, et al. (undated)

Table 2: Weather data (averaged between 1971 and 2000)

Month	Rain (mm)	Effective rain (mm)	Temperature (0C)		Humidity (%)	Wind (km/day)	Sunshine (hours)	Radiation (MJ/ m^3/ day)	ET_0 (mm/day)
			Min.	Max					
January	26.0	24.9	8.5	22.5	81	86	8.3	15.1	2.07
February	8.0	7.9	10.2	25.3	77	104	9.2	18.3	2.84
March	20.0	19.4	14.0	30.7	71	121	9.6	21.5	4.10
April	29.0	27.7	20.3	34.7	60	147	10.0	24.1	5.64
May	74.0	65.2	23.7	34.4	67	147	9.3	23.9	5.71
June	237.0	147.1	25.2	33.6	78	130	6.7	20.1	4.77
July	331.0	158.1	25.3	32.3	84	121	6.2	19.3	4.36
August	363.0	161.3	28.8	32.0	87	104	5.9	18.2	4.01
September	211.0	139.8	23.9	31.4	89	95	6.2	17.3	3.66
October	80.0	69.8	21.6	31.0	78	86	7.8	17.2	3.59
November	9.0	8.9	14.1	28.7	81	78	8.9	16.2	2.86
December	1.0	1.0	9.0	24.3	91	78	8.8	14.9	2.07
Total	1389.0	831.00	18.4	30.1	79	108	8.1	18.8	3.81

Source: CROPWAT 8.0 Model

Table 3: Data on production, dry matter content, and metabolizable energy of main crops

Name of the crop		Production (kg/ha)	DM content (%)	ME (MJ/Kg DM)	Total DM equivalent (Kg/Ha)	Total ME produce (MJ/Ha)
Paddy	Grain	3,500.00	92.00	10.10	3,220.00	32,522.00
	Straw	4,375.00	88.94	7.01	3,891.13	27,276.79
Oat	Green fodder	60,000.00	39.10	7.64	2,3460.00	179,234.40
Wheat	Grain	2,700.00	87.00	13.10	2,349.00	30,771.90
	Straw	3,375.00	91.00	6.80	3,071.25	20,884.50
Maize	Grain	6,000.00	86.30	13.60	5,178.00	70,420.80
	Straw	8,040.00	29.60	8.40	2,379.84	19,990.66
Mustard	Grain	900.00	91.70	21.70	825.30	17,909.01
	Straw	1,926.00	90.00	8.00	1,733.40	13,867.20
Soybean	Grain	1,250.00	88.70	15.30	1,108.75	16,963.88
	Straw	1,875.00	24.00	9.20	450.00	4,140.00
Sugarcane	Sugarcane	50,000.00	23.20	9.00	11,600.00	10,4400.00
	Sugarcane top	5,000.00	26.80	8.00	1,340.00	10,720.00
Pigeon Pea	Grain	1,029.00	89.20	16.70	917.87	15,328.40
	Stalk	3,275.33	90.00	11.00	2,947.80	32,425.77

Source: Estimated by the author

2.4 Analytical tools

2.4.1 Estimation of milk water productivity

Livestock water productivity, specifically for milk production, was assessed as the ratio of livestock output (milk yield) to the volume of water depleted, i.e., evapotranspired (ET) water associated with the production of feed and fodder (Peden et al. 2007; Haileslassie et al. 2009; Descheemaeker et al. 2010). In crop production, water productivity is typically estimated by relating the total water consumed over the entire crop cycle – through evapotranspiration – to the crop output, either in physical terms (kg) or economic terms (Rs). Crops cultivated during the monsoon season predominantly rely on green water (rainwater stored in the soil), with minimal dependence on blue water (irrigation). Conversely, crops grown in winter and summer seasons generally require larger volumes of blue water, with limited or no contribution from green water sources. In the current study, consumptive water use – defined as the actual water utilized by the crop through evapotranspiration – was used as the basis for estimating crop water productivity, expressed in physical terms as kilograms of biomass or yield per cubic meter of water (kg/m^3). The functional relationship between water productivity in milk production and the corresponding inputs (feed and fodder and drinking water) and output (milk yield) can be described as follows (Singh 2004; Singh et al. 2004; Singh and Kumar 2009):

$$\sigma_{\mathrm{dairy\ j}} = \frac{Q_{\mathrm{mp}}}{\Delta_{\mathrm{milk}}} \quad (1)$$

Where; $\sigma_{\mathrm{dairy\ j}}$ is the milk water productivity expressed in liters/m^3. Q_{mp} is the average daily milk yield from livestock, Δ_{milk} is the total volume of water, including drinking water and the water embedded in feeds and fodder by sample buffalo.

Estimation of the total volume of water used (drinking and embedded water) was carried out by:

$$\Delta_{\mathrm{milk}} = \frac{Q_{\mathrm{df}}}{\sigma_{\mathrm{df}}} + \frac{Q_{\mathrm{gf}}}{\sigma_{\mathrm{gf}}} + \frac{Q_{\mathrm{cf}}}{\sigma_{\mathrm{cf}}} + \Delta_{\mathrm{dw}} \quad (2)$$

Where, Q_{df}, Q_{gf}, and Q_{cf} are the average quantity of dry fodder, green fodder, and balanced cattle feed used for feeding a livestock; σ_{df}, σ_{gf} and σ_{cf} are water productivity values (kg/m^3) of dry fodder, green fodder, and balanced cattle feed, respectively; Δ_{dw} is the daily drinking water consumption by livestock.

The estimated values of physical water productivity (kg/m^3) for both main and by-products of crops were incorporated into equation (2) to calculate the total volume of water used for milk production (Δ_{milk}). To allocate the total water used for crop production between main products (grain) and by-products (residue/fodder), the ME approach as suggested by Singh et. al. (2025) was used as it was found to be more functionally accurate estimate of water use efficiency compared to other methods, particularly in integrated crop livestock systems.

2.4.2 Estimation of crop water requirement

CROPWAT 8.0 is a decision-support tool developed by the Water Resources Development and Management Service of the Food and Agriculture Organization of the United Nations (FAO) for the estimation of reference evapotranspiration (ET_0), crop water requirement, irrigation scheduling, and irrigation water demand. The model is based on a suite of empirical and semi-empirical equations that utilize data on rainfall, soil characteristics, crop types, and climatic variables (Ewaid et al. 2019; FAO 2024; Patle and Panggeng 2024; Tewabe and Dessie 2020).

CROPWAT 8.0 is typically used in conjunction with CLIMWAT, a global climatic database that provides long-term monthly averages of vital meteorological parameters. These include mean daily maximum and minimum temperatures (°C), relative humidity (%), wind speed (km/day), sunshine hours (hours/day), solar radiation (MJ/m^2/day), monthly and effective rainfall (mm/month), and reference evapotranspiration (mm/day), computed using the Penman-Monteith method (FAO 2024a). The equation combines energy balance and mass transfer principles to provide a robust estimation of evapotranspiration. It incorporates the influence of climatic conditions on crop water use, thereby supporting accurate estimation of crop evapotranspiration, irrigation water requirements, and optimal irrigation scheduling (Feng et al. 2007; Stancalie et al. 2010; Surendran et al. 2015; Ewaid et al. 2019; Kibret et al. 2021; Patle and Panggeng 2024).

2.4.3 Estimation of reference evapotranspiration (ET_0)

Evapotranspiration (ET) is the combined process of water loss from the soil surface through evaporation and from plant surfaces through transpiration. These two processes occur simultaneously and are collectively referred to as evapotranspiration. In the present study, CROPWAT 8 was employed to estimate reference evapotranspiration

(ET_0) using the Penman-Monteith method, which is widely regarded as the standard approach due to its incorporation of both energy balance and aerodynamic factors (Smith et al. 1992; Allen et al. 1994, Allen et al. 1998; Doria et al. 2006; Zotarelli et al. 2010; Babu et al. 2015; Desta et al. 2015; Tewabe and Dessie 2020; Liu et al. 2022). The Penman-Monteith equation is as follows:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{273}\,U\,(e_a - e_d)}{\Delta + \gamma\,(1 + 0.34U_2)} \quad (3)$$

Where ET_0 is the reference crop evapotranspiration[2] (mm/day), R_n is net radiation at the crop surface (MJ/m^3/day), G is soil heat flux (MJ/m^3/day), T is average air temperature (^{0}C), U_2 is wind speed measured at 2 m height (M/S), e_a is saturation vapor pressure curve (kPa), e_d is actual vapor pressure (kPa), e_a - e_d is vapor pressure deficit (kPa), Δ is slope of the vapor pressure curve (kPa/^{0}C) and is the psychometric constant (kPa/^{0}C).

2.4.4 Estimation of effective rainfall

Rainfall is a critical determinant of crop water requirements, as it influences the extent of supplemental irrigation necessary to meet crop needs. A key parameter in this context is effective rainfall, defined as the fraction of total rainfall retained in the root zone and available for crop uptake (Allen et al. 1998; Memon and Jamsa 2018; Patle and Panggeng 2024). CROPWAT 8.0 was used to estimate effective rainfall using the model's standardized empirical equation, which accounts for rainfall distribution and soil water retention characteristics.

$$P_{effective} = P_{total}\,\frac{(125 - 0.20)\text{ x }P_{total}}{125}\text{ for }P_{total} < 250mm \quad (4)$$

$$P_{effective} = P_{total}(125 + 0.10)\text{ x }P_{total}\text{ for }P_{total} < 250mm \quad (5)$$

Where P is the precipitation in mm/month.

2.4.5 Crop water requirement (CWR)

Crop water requirement (CWR) is the amount of water required to meet a crop's evapotranspiration demand under specific climatic and agronomic conditions. It is estimated by multiplying the reference evapotranspiration (ET_0) by the crop coefficient (Kc), which accounts for the specific water needs of different crops and their growth stages (Allen et al. 1998; Adamtie et al. 2022). Kc represents the ratio of actual crop evapotranspiration (ETc) to ET_0. This coefficient is dynamic and varies across crop types and growth phases – such as the initial, development, mid-season, and late-season stages – reflecting the crop's physiological and morphological characteristics (Saha et al. 2025). Accurate estimation of Kc is essential for determining actual crop ETc and, consequently, for optimizing irrigation scheduling and overall water management.

$$ETc = Kc \times ET_0 \quad (6)$$

Where ETc is crop evapotranspiration (mm/day), Kc is crop coefficient, and ET_0 is reference crop evapotranspiration (mm/day).

The Kc value for different crops, which is used for feeding dairy animals in the study area, is presented in Table 4.

Table 4: Crop coefficients (Kc value)

Name of the crop	Crop coefficient (Kc) value in different growth stages of the crop		
	Initial	Mid	End
1. Paddy	1.00	1.15	0.70–0.45
2. Oats (forage)	0.15	1.10	0.15
3. Wheat	0.15 – 0.50	1.10	0.15–0.3
4. Maize	0.15	1.15	0.50–0.15

2 Reference evapotranspiration (ET_0) is the rate of water loss from a hypothetical, well-watered reference crop, like short grass, that is not limited by water or nutrient stress. It serves as a standard for calculating the water requirements of other crops and in hydrological studies.

Name of the crop	Crop coefficient (Kc) value in different growth stages of the crop		
	Initial	Mid	End
5. Mustard	0.15	0.95 – 1.10	0.25
6. Soybean	0.15	1.10	0.30
7. Sugarcane	0.15	1.20	0.70
8. Pigeon pea (pulses)	0.15	0.95	0.25

Source: Allen et al. (1998)

2.4.6 Irrigation water used for oat crop production

Oat (forage) is cultivated by farmers primarily as a forage crop to provide green fodder for dairy animals. Due to multiple harvests throughout the crop's lifecycle, the oat plants are not allowed to reach full physiological maturity. Consequently, using the CROPWAT 8.0 model – which is designed for full-season CWR estimation – would result in an inaccurate assessment of actual water use. To address this limitation, the current study estimated the water requirement for oat cultivation based on the actual irrigation water volumes applied by farmers over the entire cropping period. The total volume of water used for oat production was quantified using the following expression, as suggested by Singh and Singh (2019):

$$\Delta \text{ crop} = I_n \text{ x } H_{pi} \text{ x } P_d \tag{7}$$

Where; Δ crop is total water used for crop production (m^3/ha); I_n is number of irrigation given to oats (forage) crop; H_{PI} is total hours of pump running for one irrigation; and P_D is pump discharge rate (m^3/hours).

The water productivity of oat (kg/m^3) production was determined by dividing the total green fodder yield (kg) by the total irrigation volume (m^3/ha) applied throughout the crop duration. The functional relationship representing oat forage water productivity can be expressed:

$$\sigma_{\text{oats (forage)}} = \frac{Q_{\text{oats (forage)}}}{\Delta_{\text{oats (forage)}}} \tag{8}$$

Where; $\sigma_{\text{oats (forage)}}$ is the water productivity of oat (forage) expressed in kg/m^3. $Q_{\text{oats (forage)}}$ is the oat (forage) production in kg/hectare, $\Delta_{\text{oats (forage)}}$ is the total volume of water used for oats (forage) production (m^3/ha).

2.4.7 Estimation of methane emissions

Enteric methane emissions from individual animals were estimated using feed intake parameters collected over Days 22–28. The equation used for estimating methane emission (Patra 2014) was:

$$CH_4 \text{ (MJ/d)} = -0.436 (\pm 0.665) + 0.678 (\pm 0.184) \times DMI + 0.697 (\pm 0.347) \times NDFI \tag{9}$$

where DMI and NDFI are dry matter intake (kg/d) and neutral detergent fiber intake (kg/d), respectively. Mean daily CH_4 emissions were expressed on an absolute basis (MJ/cow/d), as well as methane yield (per unit of gross digestible feed intake) and per unit of milk yield and live weight.

3 Results and discussion

3.1 Animal feeding pattern

The average quantity of feeds and fodder provided to the sample buffaloes under different feeding regimes at both locations is presented on a fresh matter and dry matter basis in Table 5. At both Itahari (NBRP) and Tirahut locations, the average daily feed and fodder intake by sample buffaloes on a dry matter basis was recorded as 15.87 and 15.48 kg/day for control diet (T_0), 16.72 and 16.38 kg/day for improved diet-1 (T_1), and 15.27 and 14.70 kg/day for improved diet-2 (T_2), respectively. Under the T_0 diet, the composition of feeds and fodder provided to buffaloes on fresh matter basis was paddy straw (28%), oat-forage (52%), compounded feed (16%), and wheat bran (4%) at both Itahari (NBPR) and Tirahut locations. Whereas for T_1 diet, the respective share was paddy straw (26.92%) oat (50%), compounded feed (19.23%) and wheat bran (3.85%). As for as T_2 diet is concerned, the feed and fodder composition comprised 40%, 43.33%, 13.33% and 3.33% for paddy straw, oat (forage), compounded feed and wheat bran, respectively, at both locations.

Table 5: Average quantity of feeds and fodder fed to the sample buffalo and ME use

Names of feeds and fodder	Quantity (fresh matter) of feeds and fodder (Kg/day/buffalo)		Dry matter (DM) equivalent of feeds and fodder fed to buffalo (kg/day/buffalo)		Metabolizable energy (ME) generated from feeds and fodder (MJ/day/buffalo)	
	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut
Control diet (T_0)						
1. Paddy straw	7.00	7.00	6.52	5.92	35.88	34.84
2. Oats (forage)	13.00	13.00	5.06	5.11	32.62	34.84
3. Compounded feed[1]	4.00	4.00	3.40	3.60	30.97	32.18
4. Wheat bran	1.00	1.00	0.89	0.86	7.65	8.03
Total	25.00	25.00	15.87	15.48	107.12	109.90
Improved diet-1 (T_1)						
1. Paddy straw	7.00	7.00	6.52	5.92	35.88	34.84
2. Oats (forage)	13.00	13.00	5.06	5.11	32.62	34.84
3. Compounded feed[1]	5.00	5.00	4.25	4.50	38.71	40.23
4. Wheat bran	1.00	1.00	0.89	0.86	7.65	8.03
Total	26.00	26.00	16.72	16.38	114.86	117.94
Improved diet-2 (T_2)						
1. Biofermented paddy straw	12.00	12.00	5.93	5.14	32.84	30.30
2. Oats (forage)	13.00	13.00	5.06	5.11	32.62	34.84
3. Compounded feed[1]	4.00	4.00	3.40	3.60	30.97	32.18
4. Wheat bran	1.00	1.00	0.89	0.86	7.65	8.03
Total	30.00	30.00	15.27	14.70	104.08	105.36

[1]: Balanced cattle feed (Shakti)

In case of T_2 diet, the feeding strategy was further enhanced by incorporating bio-fermented paddy straw – processed using microbial treatment to improve palatability and digestibility by breaking down complex carbohydrates. To maintain comparable DM levels across all diets, the proportion of paddy straw was increased to assess the impact of bio-fermented paddy straw on buffalo's milk production. The share of paddy straw, oat (forage), compounded feed, and wheat bran was 40.0%, 43.33%, 13.33% and 3.33%, respectively.

The DM content in feed and fodder is influenced by multiple factors, including plant variety, maturity stage, environmental conditions, and post-harvest handling. Since ME is strongly associated with DM content, these factors also indirectly affect ME availability. The estimated average daily ME intake per buffalo was 107.12 MJ, 114.08 MJ and 104.08 MJ under T_0, T_1 and T_2 diets, respectively, at Itahari (NBRP) location, whereas, it was 109.90 MJ, 117.94 MJ and 105.36 MJ for T_0, T_1 and T_2 diets, respectively, at Tirahut location.

3.2 Feeds and fodder equivalent embedded water used for milk production

Table 6 presents the quantity of embedded water – defined as the volume of water used in the production of feed and fodder – associated with milk production under different dietary interventions at both locations.

Table 6: Feeds and fodder equivalent embedded water use

Feeds and fodder	Control diet (T_0)		Improved diet-1 (T_1)		Improved diet-2 (T_2)	
	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut
1. Paddy straw	3.245	3.151	3.245	3.151	2.970	2.740
2. Oats (forage)	0.208	0.223	0.208	0.223	0.208	0.223
3. Compounded feed	3.202	3.202	4.003	4.003	3.202	3.202
4. Wheat bran	1.162	1.221	1.162	1.221	1.177	1.221
Total	7.818	7.797	8.619	8.597	7.558	7.386

The embedded water is calculated as follows:

(1) Calculate total ME production using the formula:
(Grain production x DM content in grain x value of ME per kg of DM) + (straw production x DM content in straw x value of ME per kg of DM).

(2) Calculate total water used (m^3) for crop production.

(3) Based on the above two, calculate crop (ME) water productivity

(4) Convert the feed and fodder fed to the dairy animal into ME value - (Quantity of Feed and Fodder x DM content x ME per kg of DM) for each feed and fodder

(5) Based on the above, estimate the embedded water used for milk production.

Under the T_0 diet, most of the embedded water originated from dry fodder (paddy straw), followed by compounded feed, wheat bran, and the least from green fodder (oat forage) at both Itahari (NBPR) and Tirahut locations. In contrast, under improved diets (T_1 and T_2), compounded feed emerged as the largest contributor to embedded water, followed by paddy straw, wheat bran, and oats (forage) at the Itahari (NBRP) and Tirahut locations.

In case of T_0 diet, total embedded water used for milk production was 7.818 and 7.797 m^3/day/buffalo at Itahari (NBRP) and Tirahut location, respectively, whereas, in case of T_1 diet, it was 8.619 and 8.597 m^3/day/buffalo, respectively. As for as T_2 diet is concerned, the embedded water used for milk production was estimated to be 7.558 and 7.386 m^3/day/buffalo at Itahari (NBRP) and Tirahut location, respectively.

Among the three dietary regimes, T_1 diet recorded the highest embedded water use, primarily due to the inclusion of an additional one kg of compounded feed per buffalo/day as compared to T_0 and T_1 diets. In the case of T_2 diet, the feeding strategy involved bio-fermentation of paddy straw. To maintain consistent DM intake, the quantity of paddy straw was proportionally increased as compared to T_0 and T_1 diets, though with a lower overall embedded water footprint than T_1 and T_0 diets.

3.3 Physical milk water productivity

Physical milk water productivity (liter/m^3) is intrinsically linked to the water efficiency of the feeds and fodder production, which constitutes approximately 98% of the total water used in milk production in the form of virtual water (Descheemacher et al. 2010; Singh 2004; Singh et al. 2004; Singh and Singh 2019; Singh and Kumar 2009; Haileslassie et al. 2011). In contrast, less than 2% of total water use is attributed to dairy animals' drinking water. The types and composition of feeds and fodder significantly affect milk water productivity, as supported by Gebreselassie et al. (2009).

The physical milk water productivity under three distinct diets was evaluated at Itahari (NBRP) and Tirahut locations, and the results are summarized in Table 7. Across all diets, Tirahut consistently exhibited higher milk-water productivity than Itahari (NBRP), indicating greater efficiency in water use for milk production. Under the T_0 diet, the total water utilized per buffalo/day was estimated at 7.892 and 7.876 m^3 at Itahari (NBRP) and Tirahut location, respectively. Corresponding daily milk yields were 4.340 and 6.560 liters/buffalo, respectively. The milk water productivity – expressed as liters of milk produced per m^3 of water used – was calculated at 0.550 and 0.833 liters/m^3 at Itahari (NBRP) and Tirahut, respectively.

Table 7: Physical milk water productivity

Feeds and fodder	Control diet (T_0)		Improved diet-1 (T_1)		Improved diet-2 (T_2)	
	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut
1. Feeds and fodder (m^3/day/buffalo)	7.818	7.797	8.619	8.597	7.558	7.386
2. Drinking water (m^3/day/buffalo)	0.074	0.079	0.074	0.083	0.081	0.085
3. Total water used (m^3/day/buffalo)	7.892	7.876	8.693	8.680	7.639	7.471
4. Milk production (lt/day/buffalo)	4.340	6.560	4.990	6.780	4.850	8.540
5. Milk water productivity (lt/m^3)	0.550	0.833	0.574	0.781	0.635	1.143
6. Milk water footprint (m^3/lt)	1.818	1.200	1.742	1.280	1.575	0.875

Under the T_1 diet regime, the total water used for milk production was estimated at 8.693 and 8.680 m^3/day/buffalo at Itahari (NBRP) and Tirahut location, respectively, whereas milk production from sample buffalo was 4.990 and 6.780 liters/day/buffalo, respectively. The inclusion of one additional kg of balanced feed in T_1 diet, relative to the T_0 diet, led to an increase in water consumption of 0.801 and 0.804 m^3/day/buffalo, at Itahari (NBRP) and Tirahut location, respectively. This dietary enhancement resulted in incremental milk yield gains of 0.650 and 0.220 liter, respectively, as compared to T_0 diet at Itahari (NBPR) and Tirahut location, respectively. The physical milk water productivity for the Itahari (NBRP) and Tirahut locations was 0.574 and 0.781 liters/m3, respectively. The response to dietary improvement – measured in terms of milk yield per unit of water used – was more pronounced at the Itahari (NBRP) location, indicating a higher efficiency of the added balanced feed in improving water productivity at the Itahari (NBRP) location as compared to the Tirahut location.

Under the improved diet T_2, bio-fermented paddy straw was introduced into the feeding regime for the sample buffalo at both locations. The effect of this treatment was more pronounced at the Tirahut location compared to the Itahari (NBRP) location. The total water used for milk production under the T_2 diet was 7.639 and 7.471 m3/day/buffalo at Itahari (NBRP) and Tirahut location, respectively. Two key benefits were observed with the adoption of bio-fermented paddy straw: [a] reduction in total water use for milk production (-0.253 and -0.405 m^3/day/buffalo at Itahari (NBRP) and Tirahut location, respectively, when compared to T_0 diet; and [b] incremental milk yield of 0.510 and 1.980 liters/day/buffalo at Itahari (NBRP) and Tirahut location, respectively, relative to T_0 diet. As a result, the milk water productivity under the T_2 diet improved to 0.635 and 1.143 liters/m^3 at Itahari (NBRP) and Tirahut location, respectively, highlighting the enhanced efficiency of water use in milk production due to the integration of bio-fermented paddy straw.

3.4 Net economic milk water productivity

The net economic milk water productivity (USD/m^3) under different dietary treatments at both study locations is presented in Table 8. The results reveal a contrasting trend between the two locations. At Itahari (NBRP), the net economic milk-water productivity was negative across all diets, whereas at Tirahut it was consistently positive. Under the T_0 diet, the net economic milk-water productivity was estimated at USD -0.025/m^3 for Itahari, compared to USD 0.143 at the Tirahut location. With improved diet T_1, which included an additional one kg of compounded feed, the net productivity declined slightly to USD -0.030 /m^3 and USD 0.093/m^3 at Itahari (NBRP) and Tirahut location, respectively. However, with T_2 diet, where paddy straw was bio-fermented, Itahari (NBRP) recorded the lowest net economic productivity (USD -0.047/m^3), while Tirahut achieved the highest value of USD 0.247/m^3. The negative net economic water productivity observed at Itahari (NBRP) can be attributed to two main factors: (i) the cost of feeds and fodder exceeded the net income generated from milk sales; and (ii) lower milk yields were recorded from sample buffalo compared to those at Tirahut. These findings underscore the importance of both feed and fodder efficiency and milk production in improving the economic water productivity of the dairy production system.

Table 8: Net economic milk water productivity

Feeds and fodder	Control diet (T_0)		Improved diet-1 (T_1)		Improved diet-2 (T_2)	
	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut
1. Total water used (m^3/day/buffalo)	7.892	7.875	8.693	8.680	7.638	7.471
2. Milk production (liter/day/buffalo)	4.340	6.560	4.990	6.780	4.850	8.540
3. Milk price (USD/liter)	0.597	0.597	0.597	0.597	0.597	0.597
4. Gross income from milk (USD/day/buffalo)	2.591	3.916	2.979	4.048	2.896	5.099
5. Cost of feed and fodder (USD/day/buffalo)	2.787	2.787	3.239	3.239	3.257	3.257
6. Net income (USD/day/buffalo)	-0.196	1.129	-0.260	0.809	-0.361	1.842
7. Net economic milk WP (USD/m3)	-0.025	0.143	-0.030	0.093	-0.047	0.247

1 USD=I34 Nepalese Rupees (NPR)

At Itahari (NBRP) location, the cost-benefit analysis of feed interventions revealed economic inefficiencies across all dietary treatments. Under T_0 diet, the daily cost of feeds and fodder was USD 2.787/buffalo, which exceeded the corresponding gross income from milk production (USD 2.591/buffalo), resulting in negative net economic milk water productivity. For diet T_1, the cost of feeds and fodder increased by USD 0.452/day/buffalo over the

T_0 diet due to the inclusion of additional one kg balanced cattle feed, but this yielded only an incremental gross income of USD 0.388/day/buffalo from milk sales over T_0 diet, thereby sustaining a negative net economic milk water productivity of USD -0.030/day/buffalo. Similarly, under T_2 diet, which involved the use of bio-fermented paddy straw, the cost of feeds and fodder increased by USD 0.470/day/buffalo relative to the T_0 diet, while the associated gain in milk revenue was limited to USD 0.304/day/buffalo. This led to a negative net economic milk-water productivity of USD -0.047/day/buffalo. These findings suggest that at Itahari (NBRP), the enhancements in milk yield achieved through dietary improvement (T_1 and T_2) did not offset the additional cost of feed and fodder. Thus, feed- and fodder-based interventions under current conditions do not appear economically viable in this location.

At the Tirahut location, the highest net economic water productivity was recorded under T_2 diet reaching USD 0.247/m^3, while the lowest was under T_1 diet at USD 0.093/m^3. Under T_0 diet, the daily cost of feeds and fodder per buffalo was USD 2.787, which was lower than the gross income of USD 3.916/day/buffalo from milk sales, resulting in a positive net economic milk water productivity of USD 0.143/m^3. With the adoption of T_1 diet, the cost of feeds and fodder increased by USD 0.452/day/buffalo over T_0 diet, whereas the corresponding incremental gross income from milk production was USD 0.131/day/buffalo. Despite the relatively modest income gain, the net economic milk-water productivity remained positive at USD 0.093/m^3. In the case of T_2 diet, which involved feeding bio-fermented paddy straw, the cost of feed and fodder increased by USD 0.470/day/buffalo compared to the T_0 diet, while the gross income rose by USD 0.304/day/buffalo. This led to the highest net economic milk water productivity (USD 0.247/m^3) among all dietary intervention. These results indicate that the Tirahut location, and the increased feed and fodder costs associated with both (T_1 and T_2) dietary improvements, were effectively offset by higher milk revenues, making both interventions economically viable. It is important to note that the bio-fermented paddy straw under T_2 diet has a more substantial positive economic impact than the additional balanced feed provided under T_1 diet.

3.5 Economic viability of dietary improvement

An increase in milk yield from dairy animals – whether achieved through enhancements in the nutritional quality of feeds and fodder or through greater quantities of feed and fodder intake – does not necessarily translate into economic viability. While such interventions may improve physical milk-water productivity (liters/m3), they often incur higher feed and fodder costs, which may not be adequately compensated by the incremental income from enhanced milk production. Therefore, assessing the economic feasibility of dietary interventions is essential to ensure that any gains in milk yield result in positive net financial benefits for dairy animals.

The present study evaluated the economic sustainability of dietary improvements in buffalo feeding systems based solely on income derived from milk production. Other potential sources of income from buffalo rearing – such as revenue from dung and calf production – were excluded from the analysis. It is important to note that crop production and dairy farming are complementary enterprises because the by-product of one is used as an input for the other. Dung is a by-product of dairy farming and is commonly used by farmers as organic manure, providing a valuable nutrient input for crop production. Additionally, the market value of female buffalo calves significantly increases as they near lactation.

Uniform feeding protocols were maintained across both locations, with the quantity of feed and fodder administered per buffalo recorded at 25.0, 26.0, and 30.0 kg/day/buffalo under T_0, $T_{1,}$ and T_2 diets, respectively (Table 9). The findings revealed that net income from milk production was negative under all diets at the Itahari (NBRP) location. In contrast, positive net income was observed for all diets at the Tirahut location, indicating site-specific variations in the economic viability of dietary interventions.

Table 9: Economic viability of feeds and fodder improvement

Particulars	Control diet (T_0)		Improved diet-1 (T_1)		Improved diet-2 (T_2)	
	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut	Itahari (NBRP)	Tirahut
1. Quantity of feeds and fodder (kg/day/buffalo):						
a. Paddy straw	7.00	7.00	7.00	7.00	12.00	12.00
b. Oats (forage)	13.00	13.00	13.00	13.00	13.00	13.00
c. Compounded feed (Shakti)	4.00	4.00	5.00	5.00	4.00	4.00
d. Wheat bran	1.00	1.00	1.00	1.00	1.00	1.00
Total	25.00	25.00	26.00	26.00	30.00	30.00
2. Market price of feeds and fodder (USD/kg):						
a. Paddy straw	0.054	0.054	0.057	0.057	0.070	0.070
b. Oats (forage)	0.029	0.029	0.030	0.030	0.030	0.030
c. Compounded feed (Shakti)	0.423	0.423	0.425	0.425	0.424	0.424
d. Wheat bran	0.334	0.334	0.336	0.336	0.336	0.336
3. Market value of feeds and fodder (USD/day/buffalo)						
a. Paddy straw	0.381	0.381	0.396	0.396	0.842	0.842
b. Oats (forage)	0.381	0.381	0.384	0.384	0.384	0.384
c. Compounded feed (Shakti)	1.690	1.690	2.123	2.123	1.695	1.695
d. Wheat bran	0.334	0.334	0.336	0.336	0.336	0.336
Total	2.787	2.787	3.239	3.239	3.257	3.257
4. Milk production (liter/day)	4.340	6.560	4.990	6.780	4.850	8.540
5. Market price of milk (USD/liter)	0.597	0.597	0.597	0.597	0.597	0.597
6. Gross income from milk (USD/day/buffalo)	2.591	3.916	2.979	4.048	2.896	5.099
7. Net income from milk (USD/day/buffalo)	-0.196	1.129	-0.260	0.809	-0.361	1.842

1 USD = I34 NPR

At the Itahari (NBRP) location, the estimated daily cost of feeds and fodder was USD 2.787/buffalo, USD 3.239/ buffalo and USD 3.257/buffalo for T_0, T_1 and T_2 diets, respectively. The corresponding daily gross income from milk production was USD 2.591, USD 2.979 and USD 2.896/day/buffalo for T_0, T_1 and T_2 diets, respectively. As a result, net income from milk production was negative across all diets i.e., USD -0.196, USD -0.260 and USD -0.361/day/ buffalo under T_0, T_1, and T_2, respectively. These findings suggest that dietary improvements at the Itahari (NBRP) location were not economically viable. The additional income from increased milk yield was insufficient to offset the higher costs of enhanced feed and fodder inputs.

At the Tirahut location, the total daily cost of feeds and fodder per buffalo was estimated at USD 2.787, USD 3.239 and USD 3.257 for T_0, T_1, and T_2 diets, respectively. The corresponding gross revenues generated from milk production were USD3.916, USD4.048 and USD 5.099 per day per buffalo for T_0, T_1 and T_2 diets, respectively. This resulted in net daily incomes of USD 1.129, USD 0.809, and USD 1.842 per buffalo under, respectively, under T_0, T_1 and T_2 diets, respectively. Compared to control diet (T_0), T_1 diet led to a decrease in net income by USD 0.321/day/buffalo, while T_2 diet resulted in an increase in net income of USD 0.712/day/buffalo. These findings indicate that adding 1 kg of balanced feed to diet T_1 reduced profitability, whereas bio-fermentation of paddy straw (T_2 diet) significantly enhanced net revenue.

Despite similarities in the types and quantities of feed and fodder offered across locations, the economic outcomes diverged. Dietary improvements at the Itahari (NBRP) location were not economically beneficial, whereas the same interventions at the Tirahut location demonstrated clear economic advantages, particularly for bio-fermented paddy straw, thereby highlighting location-specific responses in the profitability of feed and fodder interventions.

3.6 Impact on methane emissions

The treatments did not show significant differences in methane production (g/day). Improved Diet 2 animals produced lower methane per day than Control and Improved Diet 2 because of lower dry matter intake, while Improved Diet 2 and Control produced similar levels averaged across locations (Table 10).

Table 9: Adjusted means of methane emissions in buffalo feeding trial

Location	Treatment	N animals	Average methane (g/D)	Std. Dev.	Average methane (g/kg DMI)	Std. Dev.
NBRP	Control	6	297	8.6	19.52	0.01
	Improved Diet 1	6	310	5.1	19.37	0.01
	Improved Diet 2	6	290	5.0	19.67	0.00
Tirahut	Control	3	276	10.6	19.58	0.01
	Improved Diet 1	4	288	16.7	19.52	0.03
	Improved Diet 2	4	262	7.1	19.77	0.00
		Probability				
		NBRP vs Tirahut	<0.0001		<0.0001	
		Ctl vs Imp1 vs Imp2	<0.0001		<0.0001	
Combined location	Control	9	289	0.2	19.54	0.01
	Improved Diet 1	10	301	0.22	19.46	0.01
	Improved Diet 2	10	279	0.22	19.67	0.01
		Ctl vs Imp1 vs Imp2	<0.0001		<0.0001	

Improved Diet 1= Feeding support tool-based diet; Improved Diet 2= Biofermented straw-based diet

Although the (treatment + location) interaction effect was significant, Improved Diet 2 has slightly higher methane in terms of g/kg dry matter intake (DMI) than the other two treatments in both locations because of lower dry matter intake in Diet 2 (dry matter content of biofermented straw was less because of higher moisture%). The interaction is caused by the methane g/kg DMI production in Tirahut being similar for Control and Improved Diet 1.

3.7 Water, food, and livestock nexus

The interdependence of water, food, and livestock resources in Nepal is particularly significant, given the country's heavy reliance on integrated crop-livestock farming systems and increasing pressures on natural resources. Livestock production depends heavily on feed and fodder, which require substantial water inputs to produce. Notably, most of the water utilized in the livestock sector is not consumed directly by animals but is instead embedded in the production of these feeds and fodder. In areas prone to water shortages, such as Pashupatinagar, improvements in feed quality—such as the use of bio-fermented straw—can increase milk production and improve water productivity. Optimizing the linkages among water, food, and livestock is crucial for promoting sustainable agricultural development and protecting rural livelihoods in Nepal.

The study examined the impact of feed innovation on dairy water productivity and methane emissions, providing valuable insights for sustainable livestock management. The research introduced improved feed innovations designed to enhance milk production while reducing resource use.

4 Summary and conclusions

The present study evaluated the effects of three dietary regimes, T_0, T_1, and T_2, on milk water productivity, using DM content and ME derived from feeds and fodder as analytical parameters. Methane emission was estimated using feed intake parameters. The total quantity of feed and fodder offered per buffalo/day was 25, 26 and 30 kg for T_0, T_1, and T_2, consistently applied across both locations viz., Itahari (NBRP) and Tirahut. At the Itahari (NBRP) location, the total embedded water associated with feed and fodder consumption was 7.892, 8.693, and 7.638 m^3/day/buffalo for T_0, T_1, and T_2, respectively. At the Tirahut location these values were slightly lower at 7.875, 8.680, and 7.471 m^3/day/buffalo for T_0, T_1 and T_2, respectively. These results offer insight into the water resource implications of dietary interventions in buffalo-based dairy production system. Results showed that though improved diet conditions, especially biofermentation, did not significantly improve milk production, they increased milk water productivity as less water was used compared to the control and the treatment with supplementation. Biofermentation also reduced enteric methane emissions, demonstrating a clear climate mitigation benefit.

The milk water productivity (measured in liters/m^3) at Itahari (NBRP) location was recorded as 0.550, 0.574, and 0.635 liters/m^3 for T_0, T_1, and T_2, respectively. In comparison, the corresponding values at the Tirahut location were 0.883, 0.781, and 1.143 liters/m^3, respectively. The addition of 1 kg of compounded feed under T_1 diet, elicited a greater milk yield response at Itahari (NBRP) than at Tirahut location. However, the beneficial effect of bio-fermented paddy straw in T_2 diet was more pronounced at Tirahut, indicating a location-specific advantage of this dietary intervention.

At the Itahari (NBRP) location, net economic milk-water productivity (expressed in USD/m^3) was negative across all dietary treatments. This outcome is primarily attributable to: (a) feed and fodder costs exceeding the income generated from milk sales, and (b) comparatively lower milk production per buffalo than that observed at Tirahut. In contrast, Tirahut demonstrated positive net economic milk-water productivity across all diets, suggesting that increased revenues from enhanced milk production effectively offset the higher feed and fodder expenditure.

The economic analysis indicates that even the baseline diet (T_0) was not economically viable at the Itahari (NBRP) location. Although dietary improvement (T_1 and T_2) led to modest increases in milk production, the incremental revenue failed to offset the additional costs of feed and fodder. Conversely, at the Tirahut location, dietary enhancements proved economically beneficial; the revenue from increased milk production not only covered the additional feed and fodder costs but also resulted in a substantial net income.

Despite the application of comparable feed and fodder types and quantities across both study locations, these findings underscore the location-specific nature of economic returns to dietary interventions. While feed improvement strategies did not yield the expected profitability gains at Itahari (NBRP), they significantly improved economic outcomes at Tirahut, where dietary improvement effectively maximized returns from milk production, possibly due to efficient management.

The results of the methane study did not statistically confirm the expected positive effect of including physically or biologically treated rice straw on enteric methane emissions. However, the covariate analysis revealed that both average milk yield and dry matter intake during the experimental adaptation period significantly affected key performance indicators, particularly milk yield and enteric methane emissions. There were a few inconsistent facts that suggest the straw biofermentation influenced the measured variables. First, the cattle diet containing bio-fermented straw resulted in higher fiber intake and digestibility, but these did not significantly translate into increased animal performance (milk yield), although methane emission per unit of fiber intake was lower than that of cattle fed on untreated or shredded straw. Second, the buffaloes fed on bio-fermented straw had inconsistently slightly higher methane emissions per unit of dry matter intake than in the other two treatments, primarily due to lower total dry matter intake in Diet T_2.

5 References

Adamtie, T. F., Mitku, D.T. and Hassen, A. 2022. Validations of CROPWAT-based irrigation practice for tomato productivity in the lowland hot humid area of Ethiopia. *American Journal of Life Science and Innovation* 1(1): 27–35. https://doi.org/10.54536/ajlsi.v1i1.426.

Adeoye, P.A., Adebayo, S.E. and Musa, J.J. 2011. Agricultural post-harvest waste generation and management for selected crops in Minna, Niger state, north central Nigeria. Journal of Applied Sciences in Environmental Sanitation 6 (4):427–435

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration-guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No. 56, FAO, Rome, Italy https://www.researchgate.net/publication/235704197_Crop_evapotranspiration-Guidelines_for_computing_crop_water_requirements-FAO_Irrigation_and_drainage_paper_56.

Allen, R.G., Smith, M., Perrier, A. and Pereira, L.S. 1994. An update for the definition of reference evapotranspiration. *ICID Bulletin* 43(2): 1–34. https://www.researchgate.net/publication/237049120_An_Update_for_the_Definition_of_Reference_Evapotranspiration.

Babu, R. G., Babu, G. R. and Kumar, H. H. 2015. Estimation of crop water requirement, effective rainfall, and irrigation water requirement for vegetable crops using CROPWAT. *International Journal of Agricultural Engineering* 8(1): 15–20. https://doi.org/10.55003/cast.2022.04.23.011.

Baetge, S. and Kaltschmitt, M. 2018. Rice straw and rice husks as energy sources—comparison of direct combustion and biogas production. *Biomass Conversion Biorefinery* 8: 719–737. https://doi.org/10.1007/s13399-018-0321-y.

Baking Business. 2010. *Wheat flour fundamentals.* Bakingbusiness.com, 25 October 2010, 10:48. https://doi.org/10.5713/ajas.2012.12298.

Balan, P. and Joseph, A. 2021. Modelling the crop water requirement and irrigation scheduling of banana using CROPWAT 8 model: A case study of Manali watershed, Thrissur, Kerala. *International Journal of Farm Science*s 11(3): 1–9. https://doi.org/10.5958/2250-0499.2021.00024.0.

Blummel, M., Anandan, S. and Prasad, C.S. 2009a. Potential and limitations of byproduct-based feeding systems to mitigate greenhouse gases for improved livestock productivity", in Gowda, N.K.S., Senani, S., Raghavendra, B. and Pal, D.T. (Eds), *Diversification of Animal Nutrition Research in the Changing Scenario*, 13th Biennial Conference of Animal Nutrition Society of India, Volume 1, 17-19 December, Bangalore: 68–74, https://cgspace.cgiar.org/server/api/core/bitstreams/af831713-279c-4c87-a54d-8e020f650855/content.

Blummel, M., Samad, M., Singh, O. P. and Amede, T. 2009. Opportunities and limitations of food feed crops for livestock feeding and implications for livestock-water productivity. *The Rangeland Journal* 31(2): 207–212, https://hdl.handle.net/10568/146.

Cai, X.L. and Sharma, B. 2009. Remote sensing and census-based assessment and scope for improvement of rice and wheat water productivity in the Indo-Gangetic Basin, *Science in China Series E: Technological Sciences* 52(11): 3300–3308, https://hdl.handle.net/10568/24602.

Cui, S.W., Wu, Y. Ding H. 2013. The range of dietary fibre ingredients and comparison of their technical functionality. *Fibre-Rich and Wholegrain Foods*. Woodhead Publishing Series in Food Science, Technology and Nutrition. 96–119. https://doi.org/10.1533/9780857095787.1.96

Descheemaeker, K., Amede, T., Haileslassie, A. and Bossio, D. 2010. Analysis of water productivity gaps and effects of interventions on livestock water productivity in mixed crop livestock systems. *Experimental Agriculture* 46: Suppl. 00–00, https://hdl.handle.net/10568/3041.

Desta, F., Bissa, M. and Korbu, L. 2015. Crop water requirement determination of chickpea in the central vertisol areas of Ethiopia using FAO CROPWAT model. *African Journal of Agricultural Research* 10(7): 685–689. https://doi.org/10.5897/AJAR2014.9084.

Doria, R., Madramootoo, C.A. and Mehdi, B.B. 2006. Estimation of future crop water requirements for 2020 and 2050, using CROPWAT. In: 2006 *IEEE EIC Climate Change Conference*: 1–6. https://doi.org/10.1109/EICCCC.2006.277194.

Drastig, K., Vellenga, L., Qualitz, G., Singh, R., Pfister, S., Boulay, A.M., Wiedemann, S., Prochnow, A., Chapagain, A., De Camillis, C., Opio, C. and Mottet, A. 2021. Accounting for livestock water productivity - How and why? Land and Water Discussion Papers. Rome, FAO. https://doi.org/10.4060/ca7565en.

Ewaid, S. H., Abed, S. A. and Al-Ansari, N. 2019. Crop water requirements and irrigation schedules for some major crops in Southern Iraq. Water 11(4): 756, https://doi.org/10.3390/w11040756.

Faruq, M.D.O., Turash, S.A., Nasif, F. and Nahid, I.K. 2021. Estimation of crop water requirement for boro rice in Bandarban, Bangladesh based on CROPWAT 8.0 model. *Asian Journal of Plant and Soil Science* 6(1): 31–38, https://doi.org/10.56557/ajopss/2021/v6i147.

Feng, Z., Liu, D. and Zhang, Y. 2007. Water requirements and irrigation scheduling of spring maize using GIS and CROPWAT model in Beijing-Tianjin-Hebei region. *Chinese Geographical Science* 17: 56–63. https://doi.org/10.1007/s11769-007-0056-3.

FAO (Food and Agriculture Organization of the United Nations). 2024. CROPWAT. https://www.fao.org/land-water/databases-and-software/cropwat/en/ retrieved on 8 June 2024.

FAO. 2024a. CLIMWAT. https://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/ retrieved on 8 June 2024.

Gebreselassie. S., Peden D., Haileslassie, A. and Mpairwe, D. 2009. Factors affecting livestock water productivity: Animal scale analysis using previous cattle feeding trials in Ethiopia. *The Rangeland Journal* 31: 251–258.

GoN (Government of Nepal). 2023. Statistical information on Nepalese agriculture (2021–22), Statistics and analysis section, Planning and Development Cooperation Coordination Division, Ministry of Agriculture and Livestock Development, Singhadurbar, Kathmandu, Government of Nepal.

Haileslassie, A., Peden, D., Gebreselassie, S., Amede, T. and Descheemaeker, D. 2009. Livestock water productivity in mixed crop–livestock farming systems of the Blue Nile basin: Assessing variability and prospects for improvement. *Agricultural Systems* 102:33–40.

Haileslassie, A., Blümmel, M., Clement, F., Descheemaeker, K., Amede, T., Samireddypalle, A., Acharya, N. S., Radha, A. V., Ishaq S., Samad, M., Murthy, M. V. R., and Khan, M. A. 2011. Assessment of the livestock-feed and water nexus across a mixed crop-livestock system's intensification gradient: An example from the Indo-Ganga Basin. *Experimental Agriculture* 47(S1): 113–132.

Heinke, J., Lannerstad, M., Gerten, D., Havlík, P., Herrero, M., Notenbaert, A. M. O., Hoff, H. and Müller, C. 2020. Water use in global livestock production—Opportunities and constraints for increasing water productivity. *Water Resources Research* 56: 1–16. e2019WR026995. https://doi.org/10.1029/2019WR026995.

Herrero, M., Thornton, P. K., Notenbaert, A. M., Wood, S., Msangi, S., Freeman, H. A., Bossio, D., Dixon, J., Peters, M., Steeg, J. van de, Lynam, J., Rao, P. P., Macmillan, S., Gerard, B., McDermott, J., Seré, C. and Rosegrant, M. 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 327: 822–825.

Higham, C.D., Horne, D., Singh, R., Kuhn-Sherlock, B. and Scarsbrook, M. R. 2017a. Water use on non-irrigated pasture-based dairy farms: combining detailed monitoring and modelling to set benchmarks water use on non-irrigated pasture-based dairy farms: Combining detailed monitoring and modelling to set benchmarks. *Journal of Dairy Science* 100 (1): 828–840. http://dx.doi.org/10.3168/jds.2016-11822.

Higham, C.D., Horne, D., Singh, R., Kuhn-Sherlock, B., and Scarsbrook, M. R. 2017b. Temporal and spatial water use on irrigated and non-irrigated pasture-based dairy farms. *Journal of Dairy Science* 100 (8): 6772–6784. http://dx.doi.org/10.3168/ jds.2016-12200.

Huang, Q., Piao, X. S., Ren, P. and Li, D. F. 2012. Prediction of digestible and metabolizable energy content and standardized ileal amino acid digestibility in wheat shorts and red dog for growing pigs. *Asian-Australasian Journal of Animal Sciences (AJAS)* 25(12): 1748–1758. https://doi.org/10.5713/ajas.2012.12298.

Infonet. 2024. Animal nutrition and feed rations, https://infonet-biovision.org/animal-husbandry/animal-nutrition-and-feed-rations data retrieved on 14.08.2024

Joshi, A. L., Rao, A. Subba, Doyle P. T., Oosting S. J., Singh Mahendra, Harika A. S., Deinum B. and Ibrahim M. N. M. (Undated) Variation in the quantity and quality of crop residue. https://edepot.wur.nl/333851#:~:text=Grain%2Fstraw%20ratio%3Athe%20ratio,is%201000%2F1500%20i.e.%200.66

Kelly, N. C. and Thomas, P. C. 1978. The nutritive value of silages: Energy metabolism in sheep receiving diets of grass silage or grass silage and barley. *British Journal of Nutrition* 40, 205–219. https://www.cambridge.org/core/journals/british-journal-of-nutrition/article/nutritive-value-of-silages/9345B91F74C740429C5E59CFE0ADD97A

Khaydar, D., Chen, X., Huang, Y., Ilkhom, M., Liu, T., Friday, O., Farkhod, A., Khusen, G. and Gulkaiyr, O. 2021. Investigation of crop evapotranspiration and irrigation water requirement in the lower Amu Darya River Basin, Central Asia. *Journal of Arid Land* 13(1): 23–39. https://doi.org/10.1007/s40333-021-0054-9.

Kibret, E. A., Abera, A., Ayele, W. T. and Alemie, N. A. 2021. Performance evaluation of surface irrigation system in the case of Dirma small-scale irrigation scheme at Kalu Woreda, Northern Ethiopia. *Water Conservation Science and Engineering* 6:263–274. https://doi.org/10.1007/s41101-021-00119-8.

Kirti, Nikhil, Tekade Shyam P., Tagade Ankita Sawarkar Ashish N. 2022. Pyrolysis of pigeon pea (Cajanus cajan) stalk: Kinetics and thermodynamic analysis of degradation stages via isoconversional and master plot methods. *Bioresource Technology* 347. https://doi.org/10.1016/j.biortech.2021.126440

Kuo, S.F., Lin, B.J. and Shieh, H.J. 2001. CROPWAT model to evaluate crop water requirements in Taiwan, International Commission on Irrigation and Drainage.

Liu, Z., Liu, T., Huang, Y., Duan, Y., Pan, X. and Wang, W. 2022. Comparison of crop evapotranspiration and water productivity of typical delta irrigation areas in Aral Sea Basin. Remote Sensing 14(2): 249. https://doi.org/10.3390/rs14020249.

Mekonnen, M. and Hoekstra, A. 2012. A global assessment of the water footprint of farm animal products, *Ecosystems* 15: 401–415.

Mekonnen, M.M., Nealea, C.M.U., Ray, C., Erickson, G. E., Hoekstrad, A. Y. 2019. Water productivity in meat and milk production in the US from 1960 to 2016. *Environment International* 132: 1–12.

Memon, A. V. and Jamsa, S. 2018. Crop water requirement and irrigation scheduling of soybean and tomato crop using CROPWAT 8.0. *International Research Journal of Engineering and Technology* 5(9): 669–671.

Mena, A. 1987. The utilisation of sugar cane by-products as substitutes for cereal in animal feed. In Sansoucy, R., Preston, T. R. and Leng, R. A. (eds) Proceedings of the FAO Expert Consultation on the substitution of imported concentrate feeds in animal production systems in developing countries, FAO Animal Production and Health Paper – 63, Food and Agriculture Organization, Rome. https://www.fao.org/4/X6930E/X6930E07.htm

Molden, D. 1997. *Accounting for water use and productivity.* No. 42. Colombo, Sri Lanka, International Water Management Institute.

Nwokolo, E. 1987. Nutritional evaluation of pigeon pea meal. *Plant Foods for Human Nutrition* 37: 283–290, https://doi.org/10.1007/BF01092203.

Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). 2015. Water requirements of livestock. Factsheet, https://files.ontario.ca/omafra-water-requirements-livestock-23-023-en-2023-04-25.pdf.

Patle, G.T. and Tome, P. 2024. Assessment of crop water requirement and irrigation scheduling for selected crops in the Kohima district, Nagaland, India, *Water Practice and Technology* 19(3): 812–823, https://doi.org/10.11648/j.ajwse.20241003.12.

Patra, A.K. 2014. Prediction of enteric methane emission from buffaloes using statistical methods *Agriculture, Ecosystems and Environment* 195: 139–148.

Peden, D., Tadesse, G., and Misra, A. K. 2007. Water and livestock for human development. In Water for food, water for life: A comprehensive assessment of water management in agriculture: 485–514 (Ed D. Molden). London: Earthscan and Colombo: International Water Management Institute.

Ramarao, H.T., Chandranath, Babalad H.B., Hegde Yashoda. 2020. Growth, yield and oil quality of mustard in chickpea (Cicer arietinum) and mustard (Brassica juncea L.) intercropping system under different row ratio in Northern Transition Zone of Karnataka. *Indian Journal of Agricultural Researc*h 54(3): 322–328.

Huatai Oil Machinery. Nd. Ratio analysis of common oil crops. https://oil-mill-plant.com/edible-oil-making-information/oil-ratio-of-common-oil-crops.html#:~:text=Soybean,most%20important%20plant%20oil%20material

Rodell, M., Velicogna, I. and Famiglietti, J. S. 2009. Satellite-based estimates of groundwater depletion in India, Nature 460: 999–1002. https://doi.org/10.1038/nature08238.

Saha, D., Swati, S. and Navnath, I. 2018. Post-harvest processing and by-product utilisation of paddy, ICAR Winter School, October 05–25. https://krishi.icar.gov.in/jspui/bitstream/123456789/42006/1/05.pdf.

Saha, B., Mishra, A.K. and Umashankar. 2025), Determining crop water productivity for major crops in the Rarh region of West Bengal using the CROPWAT model and climatic inputs. *International Journal of Research in Agronomy* 8(5): 139–147.

Salmona, G. R., MacLeod, M., Claxton, J.R., Ciamarrad, U., Pica, Robinson, T., Duncan, A. and Peters, A. R. 2020. Exploring the landscape of livestock "Facts". Global Food Security 25: 1–7 https://doi.org/10.1016/j.gfs.2019.100329.

Saxena, K. B., Kumar R. V. and Rao P. V. (undated) Pigeonpea nutrition and its improvement. https://oar.icrisat.org/3164/1/PigeonpeaNutritionAndItsImprovement.pdf

Singh, R. B., Saha, R.C., Singh, M. Chandra, D., Shukla, S.G., Walli, T.K., Pradhan, P.K and Kessel, H.P.P. 1995. Rice straw – Its production and utilisation in India. In Singh Kiran and J. B. Schiere (eds.) Handbook for straw feeding systems, ICAR, New Delhi, India.

Singh, O. P. 2004. Water productivity of milk production in North Gujarat, Western India, paper published in the proceedings of the 2nd Asia Pacific Association of Hydrology and Water Resources (APHW) 1: 443–449, https://www.researchgate.net/publication/242200442_WATER_PRODUCTIVITY_OF_MILK_PRODUCTION_IN_NORTH_GUJARAT_WESTERN_INDIA.

Singh, O. P. and Kumar, M. Dinesh. 2009. Impact of dairy farming on agricultural water productivity and irrigation water use. In Kumar, M. Dinesh and Amrasinghe Upali A. (eds.), *Strategic Analysis of the National River Linking Project (NRLP) of India: Series – 4, Water Productivity Improvements in Indian Agriculture: Potentials, Constraints and Prospects*, International Water Management Institute, Colombo, Sri Lanka: 85–98, https://hdl.handle.net/10568/36846.

Singh, O. P. and Singh, P. K. 2019. Virtual irrigation water use in milk production: Results from water-abundant regions of India. *The Pharma Innovation* 8(4): 327–332. https://doi.org/10.2307/4415345.

Singh, O. P., Sharma Amrita, Singh Rahul, and Shah, Tushaar. 2004. Virtual water trade in dairy economy: Irrigation water productivity in Gujarat, *Economic and Political Economy* 39(31):3492–3497 https://hdl.handle.net/10568/41138.

Sighn, O. P., McCartney, M., Haileslassie, A., Padmakumar, V., Yanamani N., Shivahari, G., Bhola S., Pawankumar J., Aryal, A., and Nepal, S. 2025. Enhancing water productivity of dairying in the *terai* region in Nepal: A comparative analysis of water productivity assessment methods (under publication).

Singh, R. 2005. Water productivity analysis from field to regional scale: integration of crop and soil modelling, remote sensing, and geographical information. Doctoral thesis, Wageningen University, Wageningen, The Netherlands.

Sirajuddin, S.N., Saleh, I.K., Syawal, S. and Syamsinar. 2017. Identification of breeder factor has hot done fermentation of rice straw as cattle feed. *Entomology and Applied Science Letters* 4 (3): 12–15.

Smith, M. 1992. CROPWAT: A computer program for irrigation planning and management, Food and Agriculture Organization of the United Nations. https://doi.org/10.4236/gep.2020.89011.

Song, L., Oeurng, C., and Hornbuckle, J. 2015. Assessment of rice water requirement by using the CROPWAT model. In: The 15th Science Council of Asia Board Meeting and International Symposium, 6: 1–5.

Stancalie, G., Marica, A., and Toulios, L. 2010. Using earth observation data and the CROPWAT model to estimate the actual crop evapotranspiration, *Physics and Chemistry of the Earth, Parts A/B/C* 35(1–2): 25–30. https://doi.org/10.1016/j.pce.2010.03.013.

Steinfeld, H. and Gerber, P. 2010, Livestock production and the global environment: consume less or produce better? *Proceedings of the National Academy of Sciences* 107: 18237–18238.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. and Haan, C. 2006. Livestock's long shadow: Environmental issues and options. Food and Agriculture Organization, Rome. https://www.fao.org/4/a0701e/a0701e.pdf.

Surendran, U., Sushanth, C. M., Mammen, G. and Joseph, E. J. 2015. Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: A case study in Palakkad district of humid tropical Kerala, India. *Aquatic Procedia* 4: 1211–1219. https://doi.org/10.1016/j.aqpro.2015.02.154.

Tewabe, D. and Dessie, M. 2020. Enhancing water productivity of different field crops using deficit irrigation in the Koga Irrigation project, Blue Nile Basin, Ethiopia, *Cogent Food and Agriculture* 6(1): 1757226. https://doi.org/10.1080/23311932.2020.1757226.

Thoma, G. 2016. LEAP Partnership: introduction, achievements, and action plan. Presentation at "Global Conference on Sustainable Beef," 6 October 2016, Banff Springs, Canada.

Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W. and Morgan, K. T. 2010. Step-by-step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). Institute of Food and Agricultural Sciences, University of Florida. https://doi.org/10.32473/edis-ae459-2010.

92–9146–869–X

The International Livestock Research Institute (ILRI) works to improve food and nutritional security and reduce poverty in developing countries through research for efficient, safe and sustainable use of livestock. Co-hosted by Kenya and Ethiopia, it has regional or country offices and projects in East, South and Southeast Asia as well as Central, East, Southern and West Africa. ilri.org

CGIAR is a global agricultural research partnership for a food-secure future. Its research is carried out by 15 research centres in collaboration with hundreds of partner organizations. cgiar.org