

Food waste as feed in dairy systems of Greater Bengaluru, India: Assessing the impacts on production, milk safety, and enteric methane emissions

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Abstract

Due to rapid urbanisation in India, many farmers have resorted to incorporating food waste (FW) into their cattle diets. However, the effect of feeding these FWs on milk yield, milk composition, fatty acid (FA) profile, heavy metal contamination of milk, and on enteric methane emissions remains unclear. Therefore, to understand how these parameters are affected by FW feeding, the present study was carried out with dairy farmers in the southern Indian megacity of Bengaluru. The study comprised 39 farmers who in total reared 75 cows on diets incorporating on average 23 % of FW, and 164 cows fed without FW inclusion, with repeated observations of some cows across seasons. During three visits in winter 2020 - 2021 (n=74 records), monsoon 2021 (n=61), and summer 2022 (n=104), feed intake, milk yield and quality were determined on a per-cow basis. Cows receiving FW-based diets showed higher dry matter intake and milk yield compared to non-FW-fed cows. Heavy metal concentrations in FW feeds were similar to or lower than those in conventional diets, and most milk samples remained within safe limits, except for lead (Pb), which exceeded World Health Organization thresholds in 20 % of samples from the FW group. Milk from FW-fed cows contained a higher proportion of unsaturated FA, while dry matter intake-based enteric methane emission estimations were similar between feeding groups. In conclusion, the higher milk yield and elevated levels of unsaturated FAs in milk from FW-fed cows suggest that FW can be a valuable alternative feed resource for dairy production. Although heavy metal concentrations in milk were generally low, Pb levels exceeded the safety threshold in some of the samples, which calls for close monitoring.

Keywords: circular feed resources, food waste management, milk quality, urban dairy farming

1 Introduction

Food waste (FW) and food loss are a pressing global issues with far-reaching implications for food security, environmental health, and economic stability across both developed and developing nations (Alexander *et al.*, 2017; Benyam *et al.*, 2021). While food loss occurs before retail, FW is generated at the retail and consumption levels. Globally, food loss and waste amount to approximately 1.3 billion tonnes per year, corresponding to about 132 kg per capita annually (UNEP, 2024). In India, per-capita FW is estimated at around 50–60 kg per year, translating into more than

70 million tonnes of FW annually, driven largely by rapid urbanisation, changing dietary patterns, and inefficiencies in food distribution systems (UNEP, 2024). FW generation is generally lower in low-income households and countries, such as India, Nepal, Bhutan, and Bangladesh, compared with higher-income nations including Australia, Denmark, Sweden, and Saudi Arabia (UNEP, 2024). However, the absolute volume of FW in India is substantial due to its large population size and increasing consumption of prepared and processed foods, particularly in urban areas; in these areas, FW generation is especially pronounced and often exceeds typical rural levels (JICA, 2015).

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Urban FW in India predominantly originates from households, restaurants, hotels, wet markets, and food processing units; it is largely composed of plant-based materials due to the predominance of vegetarian and cereal-based diets (Chauhan *et al.*, 2021). This waste stream typically includes cooked rice, vegetables, fruit residues, bakery waste, and other kitchen discards, making it nutritionally rich but highly heterogeneous (Chauhan *et al.*, 2021; Alam *et al.*, 2023). Countries differ markedly in their food loss and waste management strategies. For example, FW is entirely processed or treated in countries such as Germany, Belgium, and Norway, where strict segregation and valorisation policies are in place, whereas in many other countries, including India, Bangladesh, and Pakistan, FW is partially diverted to animal feed, often with limited or no formal treatment (Sarker *et al.*, 2022; Alam *et al.*, 2023; Alam & Islam, 2024).

This informal use is evolving alongside traditional disposal methods such as dumping, burning, landfilling, and composting (Reichenbach *et al.*, 2021a; Alam *et al.*, 2022). Recently, processing FW into animal feed has also emerged as a focal area for Indian start-ups, though formal guidelines remain unclear (Balaji, 2019; Chauhan *et al.*, 2021; Indiatv, 2023). The trend is largely driven by feed shortages within urban farming systems, a challenge intensified by rapid urbanisation (Seto and Ramankutty, 2016; Mundoli *et al.*, 2022).

When FW is repurposed as feed, questions of nutritional value and safety along with environmental considerations become relevant. Nutritionally, FW in India often contains 19.4 % crude protein and 268.4 g kg⁻¹ neutral detergent fibre (on dry matter basis), which is comparable with conventional feedstuffs (Alam *et al.*, 2023). However, safety issues are significant, as FW may contain contaminants such as heavy metals (e.g., cadmium (Cd), chromium (Cr), lead (Pb)), anti-nutritional factors like tannins, and foreign materials including glass, metal, and plastic debris from packaging. These contaminants pose risks to animal health and may compromise the quality and safety of animal-derived food products (Barik & Paul, 2017; Ma *et al.*, 2020).

However, it is evident that ruminants have a biological ability to upcycle human-inedible food items into high-quality protein in the form of milk and meat, facilitated by their rumen microflora (Dou *et al.*, 2018; Matthews *et al.*, 2019; Ominski *et al.*, 2021). Although ruminants can efficiently utilise such food resources, the environmental implications of their inclusion in ruminant diets warrant careful evaluation. This is particularly important because the composition and contamination levels of FWs are highly heterogeneous and largely unregulated in urban feeding systems, potentially leading to variable nutritional outcomes and un-

intended risks to animal health, milk safety, and environmental emissions. This study addresses these aspects by investigating the effects of FW inclusion in dairy cows' diets on milk yield, milk composition, milk fatty acid (FA) profile, heavy metal contamination of milk, and estimated enteric methane emissions in Bengaluru, India.

2 Materials and methods

The survey procedures, farm monitoring, and sample collection received ethical approval from the Institutional Animal Ethics Committee (IAEC) at the National Institute of Animal Nutrition and Physiology (NIANP), Bengaluru, India, under approval number NIANP/IAEC/1/2020/6.

2.1 Study area

The study was carried out in the Greater Bengaluru area (latitude 12.9716°N, longitude 77.5946°E). As the capital of the State of Karnataka in southern India, Bengaluru is home to about 14.4 million people (WPR, 2025). Located on the Deccan Plateau, the city's elevation varies, with the southern part ranging between 600 and 900 m, and the northern part between 300 m and 600 m above sea level. Bengaluru experiences an annual average temperature of 26 °C, and from 1989 to 2018, it received an average annual rainfall of 1,146 mm (Guhathakurta *et al.*, 2020; WWO, 2020). In recent years, the Greater Bengaluru area was estimated to host around 137,000 cattle, collectively producing about 295,000 litres of milk per year (NDDB, 2015).

2.2 Farm selection, data recording and sample collection

In an earlier study (Alam *et al.*, 2022), a total of 145 dairy farms were visited to document their geographic locations, farm characteristics, and practices related to cattle feeding and housing. For the present study, a subset of 39 farms from this group was chosen using a stratified random sampling approach that accounted for urban (densely built-up areas) and peri-urban (loosely built-up areas) locations, as defined by Hoffmann *et al.* (2017) in the context of Bengaluru. The average herd size on these farms was 6.31 ± 4.27 cows, and the total number of lactating cows amounted to 239. Of these, 75 cows were fed FW (FW cow group) in combination with conventional feedstuffs, while the remaining 164 cows received only conventional feedstuffs (non-FW cow group) across different sampling seasons. All 39 farmers consented to participate in a comprehensive, day-long farm monitoring across three distinct seasons (winter: November 2020 – February 2021; monsoon: July – October 2021; summer: March – June 2022), resulting in a seasonal total of 74, 61, and

104 dairy cows monitored during winter, monsoon, and summer, respectively. Among the cows sampled multiple times, 35 were common between summer and winter, 34 between summer and monsoon, and 33 between monsoon and winter. A total of 19 cows were sampled across all three seasons (Alam *et al.*, 2025). Seasonal information is provided to indicate the sampling periods only; however, the primary objective of the study was to compare cows based on FW feeding status rather than to investigate seasonal effects.

Regarding breeds, the study included 29 Holstein Friesian cows with an average body weight (BW; mean $\pm$ SD) of $428 \text{ kg} \pm 68$, 19 Jersey cows ($369 \text{ kg} \pm 53$), 13 native zebu cattle ($373 \text{ kg} \pm 57$), and 178 crossbreeds involving combinations of Holstein and Jersey, Holstein and native, or Jersey and the All Black breed (a synthetic breed resulting from crosses between exotic (HF) sires with native cows, $399 \text{ kg} \pm 68$). In peri-urban areas, dairy cows were housed either in open sheds, loose housing, or were allowed to graze on various pasture lands during the day. In urban areas, cows were kept in concrete stables, tied to poles in open yards or on sidewalks, or permitted to scavenge on the streets during daylight hours. Hand milking was practiced twice daily on all 39 farms, both in the morning and evening (Alam *et al.*, 2023; Alam *et al.*, 2024; Alam *et al.*, 2025). During each monitoring visit, data were collected for each animal on breed, heart girth and body length (measured with a tape), along with daily milk yield, grazing duration (if applicable), and the types and quantities of feed provided.

The measurement of on-farm feed intake and milk yield, along with sample collection (feed and, milk), followed the protocols outlined by Reichenbach *et al.* (2021a) and Alam *et al.* (2024). A total of 124, 64, and 93 representative samples were collected from the different feed types across the farms. In addition, 239 milk samples were collected from individual cows during the day-long farm monitoring. During each farm visit, every meal consumed by each cow was recorded across a 24-hour feeding schedule. The weight of each feed portion was measured on an as-fed basis using a PCE-HS 50N hanging scale (capacity: 0.2 kg to 50.0 kg, accuracy $\pm 0.08 \text{ kg}$; Hampshire, UK). When possible, feed refusals were re-weighed to determine the actual feed intake per cow. Common diet components observed on the farms included pelleted concentrates, wheat flour (*Triticum aestivum* L.) (with or without bran), corn flour (*Zea mays* L.), chickpea husks (*Cicer arietinum* L.), groundnut cake, finger millet straw (*Eleusine coracana* Gaertn.), green maize (*Zea mays* L.), Napier grass (*Pennisetum purpureum* Schumacher), various locally grown grasses, and diverse FW sources (including household vegetable leftovers and inedible food items, wet market fruit and vegetable waste, sugar-

cane bagasse, and industrial fruit peels). For consistency in describing diet composition, all feeds except FW are designated as conventional feedstuffs.

2.3 Estimation of body weight and feed dry matter intake while grazing

The BW of cows was estimated using a metric adapted version of Shaffer's formula as follows (Wangchuk *et al.*, 2018):

$$\text{Body weight (kg)} = (G2 \times L)/10838$$

where G2 represents the heart girth (in cm), L is the body length (in cm), and 10838 is the integrated conversion factor to obtain BW directly in kilograms.

In the present study, approximately 38 %, 24 %, and 6 % of the cows grazed on lakeshores, pasture land, and a combination of both, respectively, for an average of 7, 3, and 7 hours per day. The remaining cows were stall-fed with grass cultivated on the farm, purchased grass, or grass collected from lakeshores. For cows under grazing conditions, dry matter intake (DMI) was estimated following Schlecht *et al.* (2019) using the equation:

$$Y = t_e \times IR \times BW^{0.75}$$

where Y is the daily DMI from pasture (kg DM), t_e is the total grazing time in hours, IR is a fixed intake rate ($8 \text{ g DM h}^{-1} \text{ BW}^{-0.75}$), and $\text{BW}^{-0.75}$ is the metabolic BW to adjust for breed and seasonal variations. Finally, the total DMI from farm feed and pasture was calculated for each cow across all feed types.

2.4 Sample preparation and analysis

After sample collection (see section 2.2.), feed samples were placed in micro-perforated polyethylene bags. Freshly collected samples were weighed (range: 0.01–820 g; precision: 0.01 g; KERN ew WTM, Munich, Germany) before and after oven drying (at 60°C for 48–72 h; Equitron-stream series No. 7051-250; Mumbai, India). After drying, the samples were ground in a mixer grinder and passed through a 0.5 mm mesh sieve, and then stored in plastic zip-lock bags until further analysis. At each farm visit, milk yield was recorded for both morning and afternoon milking on an individual cow basis. Milk samples ($2 \times 25 \text{ ml}$ per cow and recording day) were collected from 74 cows in winter (19–28 February 2021), 61 cows during the monsoon season (20–31 July 2021), and 104 cows in summer (23–31 May 2022), respectively. These samples were transported to the Animal Nutrition Division laboratory at NIANP in a cool box with ice packs to maintain sample quality. From each collection day, one 25 ml sample was analysed for fat and protein

contents (Lactoscan Milk Analyzer, Softrosys Technologies, Bengaluru, India), while the second 25 ml sample was stored at -20°C for subsequent analyses of FA and heavy metals.

2.4.1 Heavy metal analysis

The concentration of Cd, Cr, and Pb in samples of feed and milk was measured using the procedure described by Alam *et al.* (2023). For feed, approximately 0.5 g of ground dry material was combined with 6 ml of concentrated HNO_3 , subjected to microwave digestion (Anton Paar GmbH, Graz, Austria), and subsequently diluted to a final volume of 50 ml. For milk, 3 g of sample was treated with 5 ml of concentrated HNO_3 , digested under the same conditions, and diluted to a final volume of 25 ml. After digestion, 1 ml of HCl and demineralised water were added to each sample, which was then filtered for detecting Cd, Cr, and Pb concentrations by inductively coupled plasma – optical emission spectroscopy (ICP-OES) using a Spectrogreen analyser (Spectro Analytical Instruments GmbH, Kleve, Germany). Calibration standards ($0.005\text{--}1.0\text{ mg l}^{-1}$) were prepared in a diluted HNO_3 and HCl matrix for feed and milk analyses. The instrumental detection limits were $0.000130\text{ mg l}^{-1}$ for Cd, $0.000752\text{ mg l}^{-1}$ for Cr, and $0.003022\text{ mg l}^{-1}$ for Pb. Analytical accuracy was verified with reference material (ERM®-CD281), for which obtained values were within certified ranges, and through an inter-laboratory comparison with results from AGROLAB LUFA GmbH (Kiel, Germany) for a subset of 5 % of the feed samples, confirming no significant differences.

2.4.2 Fatty acid analysis

Analysis of FAs in milk followed the method described by O’Fallon *et al.* (2007) and Alam *et al.* (2025). Fatty acid methyl esters (FAMES) were prepared by alkaline methanolysis of 1 ml milk using KOH in methanol with C13:0 as an internal standard. Samples were incubated at 55°C to allow saponification and hydrolysis, followed by acidification with H_2SO_4 . FAMES were extracted into hexane, separated by centrifugation, transferred to gas chromatography (GC) vials, and stored at -20°C until analysis.

The FA composition of FAMES was analysed using a GC system (Model 7890A; Agilent Technologies Inc., Singapore) equipped with a flame ionisation detector, a programmable temperature vaporiser injector, and a Supelco SP-2560 fused silica capillary column ($100\text{ m} \times 0.25\text{ mm} \times 0.20\text{ }\mu\text{m}$; Bellefonte, PA, USA). The FA fractionation conditions included an injection port temperature set to 250°C . The initial column temperature was held at 120°C for 2 min, then increased to 175°C at a rate of $10^{\circ}\text{C min}^{-1}$, with a hold of 10 min. It was subsequently raised to 210°C at $5^{\circ}\text{C min}^{-1}$

and held for 5 min, and then to a final temperature of 230°C at $5^{\circ}\text{C min}^{-1}$, with a hold time of 13 min. The detector temperature was maintained at 280°C , with GC-grade air, hydrogen, and nitrogen as carrier gases. Fatty acids were identified by comparing retention times with a commercial 37-component FAME standard mixture and quantified using the internal standard (CRM 47885; Sigma-Aldrich, St. Louis, USA).

2.5 Estimation of methane emission

Enteric methane emissions were estimated using the model developed by Alam *et al.* (2026), which utilises DMI as the sole predictive variable as follows:

$$\text{Enteric methane (g day}^{-1}\text{ cow}^{-1}) = 2.82 + 17.43 \times \text{DMI}$$

Measured and estimated DMI values obtained from the farm monitoring (sections 2.2 and 2.3) were used to calculate enteric methane emissions for each cow in the three monitoring seasons. The model was specifically designed for tropical conditions and developed using data exclusively from Indian dairy cattle, making it particularly applicable to the context of this study. Compared to other models formulated for tropical regions, the present model demonstrated superior predictive accuracy, as reflected by a high coefficient of determination ($R^2 = 0.78$), a low root mean square error (RMSE = 34), and a low relative prediction error (RPE = 9.9 %).

2.6 Statistical analysis

Statistical analyses were conducted using R software (version 4.2.1) (RCoreTeam, 2022). All variables were normally distributed and exhibited homogeneity of variances. A linear mixed model was fitted using the lme4 package in R (Bates *et al.*, 2015), applying residual maximum likelihood analysis (REML) to evaluate the fixed effects of FW type, season, and breed type. Farm ID and individual cow ID were included as random effects to compare dependent variables, including daily DMI (kg) from conventional feedstuffs, FW, and concentrates; daily milk yield (kg); milk fat and protein content (%); concentrations ($\text{mg kg}^{-1}\text{ DM}$) of Cd, Cr, and Pb in conventional feedstuffs, FW, and milk; daily intake (mg) of Cd, Cr, and Pb from conventional feedstuffs and FW; and the proportions (%) of saturated (butyric acid, caproic acid, caprylic acid, capric acid, undecylic acid, lauric acid, myristic acid, pentadecylic acid, palmitic acid, margaric acid, stearic acid, arachidic acid, heneicosanoic acid, behenic acid), monounsaturated (myristoleic acid, pentadecenoic acid, palmitoleic acid, heptadecenoic acid, oleic acid, elaidic acid, gondoic acid, erucic acid), and polyunsaturated (trans-9, trans-12 linoleic acid, linoleic acid, γ -linolenic

acid, α -linolenic acid, eicosadienoic acid, arachidonic acid) FAs in milk. The independent variable was feeding system, defined as FW cow group and non-FW cow group. A one-way ANOVA was applied to compare the concentrations of Cd, Cr, and Pb (mg kg^{-1} DM) in conventional feedstuffs. Estimated marginal means were calculated using the *emmeans* package (Midway *et al.*, 2020), and pairwise comparisons were performed using Bonferroni-adjusted post-hoc tests using *multcomp* package (Hothorn *et al.*, 2016). Differences were considered statistically significant at $p < 0.05$.

3 Results

3.1 Animal diets, milk yield and composition

The FW group exhibited a 4.4 % higher total DMI from both roughage and concentrate ($6.4 \text{ kg day}^{-1} \text{ TLU}^{-1}$) compared to the non-FW group ($6.1 \text{ kg day}^{-1} \text{ TLU}^{-1}$) ($p < 0.05$, Table 1, Table S1). The daily DMI from roughage alone was $4.3 \text{ kg day}^{-1} \text{ TLU}^{-1}$ in the non-FW group. In comparison, the FW group exhibited a slightly higher roughage DMI of $4.4 \text{ kg day}^{-1} \text{ TLU}^{-1}$, comprising 3.0 kg from conventional feedstuffs and 1.5 kg from FW sources. The FW contribution represented 23.4 % of the total diet and corresponded to an 8.0 % increase in roughage DMI relative to the non-FW group (Fig. 1).

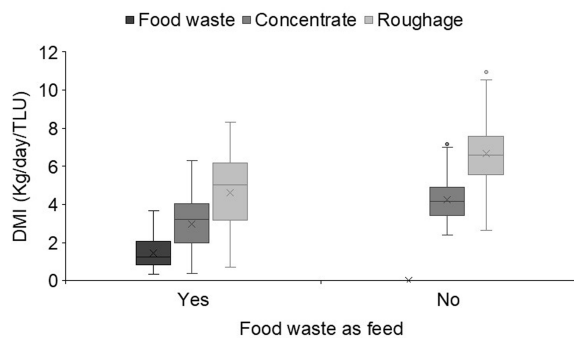


Fig. 1: Feed-specific dry matter intake (DMI; $\text{kg day}^{-1} \text{ TLU}^{-1}$) from food waste (FW), concentrate, and roughage in cows fed FW (Yes) or not fed FW (No). Boxplots depict the median (horizontal line), interquartile range (box), and minimum–maximum values (whiskers), with crosses indicating mean values and circles representing outliers. TLU = Tropical Livestock Unit (250 kg body weight = 1 TLU). FW as feed: yes = 75, no = 164.

The estimated daily enteric methane emissions, calculated from DMI, were higher in the FW group ($115 \text{ g day}^{-1} \text{ TLU}^{-1}$; SD = 21.4) than in the non-FW group ($109 \text{ g day}^{-1} \text{ TLU}^{-1}$; SD = 22.3). Although a slight variation was observed between the groups, the difference was not statistically significant.

Cows in the FW group produced 29.9 % more milk ($6.4 \text{ kg day}^{-1} \text{ TLU}^{-1}$) than those in the non-FW group ($6.1 \text{ kg day}^{-1} \text{ TLU}^{-1}$); however, this difference may partly reflect differences in the production characteristics of cows between the feeding groups. Milk fat content was 13.1 % lower in the FW group ($p < 0.05$), while milk protein percentage remained similar between the two groups.

3.2 Presence of heavy metals in feedstuffs, daily intake through feed, and effects on milk safety

There were no differences in Cd and Pb concentrations between FW and conventional feedstuffs (Table 2). However, the conventional feedstuffs had significantly higher concentrations of Cr, representing a 33.5 % increase compared to the FW group ($p < 0.05$).

Daily intake of Cd and Cr was significantly higher in the non-FW group compared to the FW group ($p < 0.05$; Fig. 2). Conversely, Pb intake was higher in the FW group than in the non-FW group, though this difference was not statistically significant ($p > 0.05$).

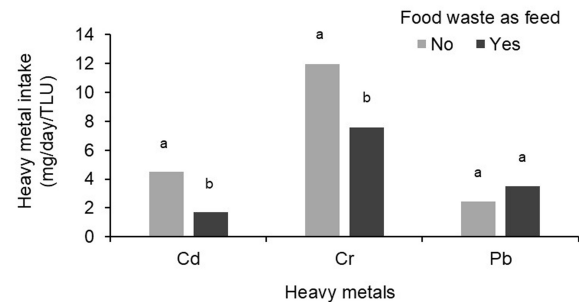


Fig. 2: Daily intake of cadmium (Cd), chromium (Cr), and lead (Pb) by dairy cows fed food waste (Yes) or not fed food waste (No) along with conventional feedstuffs. Season and breed type were included as fixed effects in the mixed model but showed no significant effects. ^{a–b} Mean values with different superscripts within the same column differ at $p < 0.05$. TLU = Tropical Livestock Unit (250 kg body weight = 1 TLU). Food waste as feed: yes = 75, no = 164.

No Cd was detected in the milk of either the FW or the non-FW group. In contrast, Cr and Pb concentrations were higher in the milk of the FW group than in that of the non-FW group (Table 3). The Pb concentration in milk of both groups approached the permissible threshold value of 0.020 mg kg^{-1} (Nag, 2010).

Table 1: Effects of food waste (FW) inclusion on daily dry matter intake (DMI), roughage and concentrate consumption, milk yield, and milk fat and protein content. Values are depicted as means and standard error of mean (SEM).

Variables	Food waste use as feed		p-value		SEM
	No (n = 164)	Yes (n = 75)	Season	Food waste group	
Feed intake					
Dry matter intake (kg day ⁻¹ TLU ⁻¹)	6.12	6.44	0.062	0.199	0.178
Roughage (kg DM day ⁻¹ TLU ⁻¹)					
Conventional sources	4.26	2.98	–	–	–
Food waste	–	1.46	–	–	–
Total roughage	4.26	4.44	0.063	0.072	0.147
Concentrate (kg DM day ⁻¹ TLU ⁻¹)	1.86	2.00	0.001	0.124	0.133
Food waste share in diet (%)	0	23.4	–	–	–
Production variables					
Milk yield (kg day ⁻¹ TLU ⁻¹)	5.24 ^b	6.85 ^a	0.023	0.003	0.394
Fat (%)	3.97 ^a	3.45 ^b	0.001	0.0013	0.151
Protein (%)	3.09	3.06	0.001	0.538	0.035

n = number of cows; TLU = Tropical Livestock Unit (250 kg body weight = 1 TLU); ^{a–b} Mean values with different superscripts within the same row differ at $p < 0.05$; Rows with SEM values were statistically tested, others are descriptive only; Breed types were included as fixed effects in the mixed model but showed no significant effects.

Table 2: Average concentration of cadmium (Cd), chromium (Cr), and lead (Pb) in conventional feed and food waste (FW) used for dairy cattle feeding in Bengaluru, India.

Variable	Number of samples	Heavy metals (mg kg ⁻¹ DM)		
		Cd	Cr	Pb
Conventional feed*	262	0.22	3.67 ^a	0.92
Food waste [†]	19	0.22	2.75 ^b	0.99
SEM	–	0.09	2.09	0.43
EU threshold [‡]	–	1.00	–	5.00
WHO threshold [§]	–	–	1.304	–

^{a–b} Mean values with different superscript within the same column differ at $p < 0.05$; *Conventional feed: Pelleted concentrates, wheat flour (with or without bran), corn flour, chickpea husks, groundnut cake, finger millet straw, green maize, Napier grass, various locally grown grasses; [†]Food waste: Household vegetable and inedible food items, wet market fruit and vegetable waste, sugarcane bagasse, industrial fruit peels; [‡]EU threshold (López-Alonso, 2012); [§]World Health Organization threshold (Ramachandra et al., 2017).

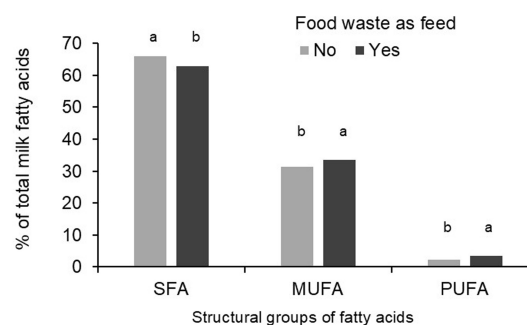
Table 3: Presence of cadmium (Cd), chromium (Cr) and lead (Pb) concentrations in milk from cows fed conventional feedstuffs or food waste–based feed in Bengaluru, India.

Concentration in milk (mg kg ⁻¹)	Food waste use as feed		SEM
	No (n = 164)	Yes (n = 75)	
Cd	0	0	–
Cr	0.010	0.012	0.002
Pb	0.019	0.021	0.005

n = number of milk samples

3.3 Concentrations of saturated and unsaturated fatty acids in milk

The concentration of saturated FAs in milk was 4.5 % higher in the non-FW group compared to the FW group. Mono-unsaturated and poly-unsaturated FAs were respectively 7.0 % and 45.8 % higher in the milk of the FW group ($p < 0.05$, Fig. 3).

**Fig. 3:** Effects of food waste feeding on saturated (SFA), monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids proportions in the milk of cows fed food waste (Yes) or not fed food waste (No) along with conventional feedstuffs. Values are expressed in percent of total fatty acids. Season and breed type were included as fixed effects in the mixed model but showed no significant effects. ^{a–b} Mean values with different superscripts within the same column differ at $p < 0.05$. Food waste as feed: yes = 75, no = 164.

4 Discussion

4.1 Dietary effects of food waste feeding on dry matter intake and milk production

In the Greater Bengaluru region, dairy farmers commonly incorporate FW into the diets of their cows. A higher DMI was found in the FW group than in the non-FW group of cows, likely due to the ready availability and minimal cost of FW, which encouraged farmers to include it more generously in the daily ration (Prajapati *et al.*, 2021; Reichenbach *et al.*, 2021b). A notably higher (14.3 %) intake of concentrates was observed in the FW group, where a substantial portion of the concentrate originated from mixed feeds containing corn flour, wheat flour, and chickpea husks. Although the higher concentrate intake may have contributed to the greater milk yield in the FW group, it alone is unlikely to account for the full 29.9 % difference, suggesting that diet composition and other animal- and farm-level factors also contributed. This may also indicate that farmers with limited possibilities for fodder cultivation or collection rely more heavily on concentrates. The inclusion of such nutrient-dense components likely contributed to improved production performance (Reichenbach, 2020; Daley *et al.*, 2022;), which was reflected in the 29.9 % higher daily milk yield of the FW group. To sustain milk production when cows are fed FW, the nutritional quality of FW must be comparable to that of conventional feedstuffs. Alam *et al.* (2023) reported that FW used in the same feeding systems contained 19.4 % of crude protein and 268.4 g kg⁻¹ DM of neutral detergent fibre, highlighting the potential of FW as a valuable feed alternative to conventional feedstuffs. However, FW is typically sourced from highly decentralised and heterogeneous urban waste streams, resulting in considerable variability in nutrient composition compared with regular roughages such as rice straw, wheat straw, or hay. This variability underscores the importance of careful selection, segregation, and supplementation of FW to ensure consistent nutritional supply and stable production performance in dairy cows.

The observed differences in milk fat content (%) can be attributed to a dilution effect associated with higher milk volumes in the FW group. Such compositional shifts are commonly observed when increased milk yield results in a greater partitioning of dietary energy towards lactose synthesis and milk volume rather than milk fat concentration, reflecting changes in energy allocation and nutrient utilisation within the mammary gland (Daley *et al.*, 2022). In the present study, FW accounted for approximately 23 % of the diet (range: 6–52 %), suggesting that the level of FW inclusion may influence energy partitioning and, consequently, milk fat concentration. However, the optimal inclusion level

of FW to balance milk yield and milk composition requires further investigation through controlled feeding trials.

4.2 Effects of food waste-based feeding on milk quality, safety, and enteric methane emissions

Compared to the FW group, cows in the non-FW group received more forages, particularly green maize and mixed grasses, a feeding pattern that promotes *de novo* synthesis of saturated FAs in the mammary gland and allows more complete ruminal biohydrogenation of dietary unsaturated FAs (Bauman *et al.*, 2011). This likely explains the 4.5 % higher concentration of saturated FAs in the milk of non-FW cows. In contrast, the FW group consumed approximately 1.46 kg DM from FW along with a higher amount of concentrate feed and a reduced roughage consumption. FW often contains oil-rich and processed residues; particularly cooked and processed FWs are rich in unsaturated FAs that supply unsaturated lipids capable of partially bypassing ruminal biohydrogenation (Georganas *et al.*, 2020; Salami *et al.*, 2021). In the present study, this may have contributed to the markedly higher concentrations of mono- and polyunsaturated FAs (+7.0 % and +45.8 %, respectively) in milk of the FW group.

The lower forage and higher non-forage shares of FW diets may have reduced rumen pH and altered the microbial ecosystem, suppressing fibrolytic and biohydrogenating bacterial populations. Such microbial and fermentation changes likely decreased the extent of biohydrogenation, enabling a greater proportion of unsaturated FAs to escape ruminal conversion and be incorporated into milk fat (Fuentes *et al.*, 2009; Vargas *et al.*, 2023). Overall, these results suggest that replacing part of the forage with FW can beneficially alter the milk fatty acid profile, increasing unsaturation through both dietary lipid enrichment and changes in rumen biohydrogenation dynamics.

The concentrations of Cd and Cr were lower in FW compared to the conventional feedstuffs. This could be attributed to the fact that FW primarily originates from human food sources, where heavy metals are generally present at lower levels (Sadhya & Saha, 2023; Zhao *et al.*, 2024). In crops such as finger millet, a higher proportion of heavy metals tends to accumulate in the vegetative parts (e.g., straw) rather than in the edible grain. Consequently, human-consumed portions, which are the main contributors to FW, likely contain lower residual levels of Cd and Cr (Luo *et al.*, 2023). A similar pattern may also apply to other crop-derived food sources contributing to FW. In contrast, Pb concentrations were higher in the offered FW components. Although Alam *et al.* (2023) also reported higher Pb concentrations in food leftovers, the Pb concentrations observed in the present study

were lower. This difference may partly reflect the larger sample size ($n = 19$ vs. $n = 5$) and differences in the composition and sources of the FW samples.

Although Cr intake was significantly lower in cows fed FW-based diets compared to conventional feed-based diets, milk Cr concentrations were slightly higher in the FW group. This may indicate that the transfer of Cr from feed to milk is influenced not only by dietary intake but also by factors such as bioavailability, animal metabolism, physiological status, and environmental exposure. Previous studies have reported that heavy metal transfer from feed to milk is often variable and does not always directly reflect dietary concentrations (Hejna *et al.*, 2018; Rafiq *et al.*, 2022; Alam *et al.*, 2022). In addition, non-feed-related exposure sources, including drinking water, soil, or environmental contamination, may also contribute to milk Cr levels. Overall, the variation in heavy metal concentrations appears to reflect differences in the feed sources and their respective contamination levels, which are directly mirrored in the heavy metal intake levels of the two animal groups.

Although cows in both groups showed considerable intake of Cd, Cr, and Pb through feed, Cd was not detected in their milk. A similar pattern was observed by Yasotha *et al.* (2021), who reported that 73 % of milk samples collected from cows raised near industrial zones in the Erode district of Tamil Nadu, India, contained Cd levels below the detection limit, while the remaining samples showed only trace concentrations ($0.045 \text{ mg Cd kg}^{-1}$ milk). In another study, Roy *et al.* (2009) found Cd concentrations of 0.006 mg kg^{-1} in milk of cows from 19 districts in Haryana, India – well within the permissible safety limits. These findings indicate that Cd transfer into milk is minimal and unlikely to pose any significant health concern for consumers. The Cr concentration detected in milk from Bengaluru was markedly lower than that reported for cows raised in the industrial regions of Erode district, India (Yasotha *et al.*, 2021). This difference likely reflects variations in the Cr content of feed sources available in those industrial zones. With an average Cr concentration of 0.10 mg kg^{-1} , milk sampled from cows in the mining areas of Singhbhum, Jharkhand State (Giri & Singh, 2020), had a much higher level compared to the concentration of $0.01 \text{ mg Cr kg}^{-1}$ determined in milk samples from Bengaluru. Milk Pb concentrations in the present study mostly remained within the permissible limits; yet, 20 % of the milk samples collected from the FW group exceeded the threshold considered safe for human consumption (FAO/WHO, 2021). This observation is consistent with Yasotha *et al.* (2021), who found Pb levels in cow milk to be below safety limits in three out of four sites within the Erode district of India. Similarly, Roy *et al.* (2009) re-

ported that milk Pb concentrations were within acceptable limits (0.01 mg/kg) in six districts of Haryana State, while values above the permissible limit (0.10 mg kg^{-1}) were detected in 13 other districts. In contrast, longitudinal findings from Giri and colleagues indicated variability over time: Pb was undetectable in milk from cows in mining regions during an earlier study (Giri *et al.*, 2011), but exceeded safety thresholds a decade later (Giri *et al.*, 2021). Overall, variations in milk Pb concentrations across studies likely reflect environmental and management differences, including industrialisation, mining activities, urban traffic and the degree of heavy metal transfer from soil and water to fodder crops and subsequently to milk, which is also influenced by feeding practices (Nag, 2010; Wuana and Okieimen, 2011; Boudebbouz *et al.*, 2021). However, none of the mentioned studies, including our own, assessed heavy metal concentrations in soil or forage.

In the present study, the estimated daily enteric methane emissions were $115 \text{ g d}^{-1} \text{ TLU}^{-1}$ for FW cows and $109 \text{ g d}^{-1} \text{ TLU}^{-1}$ for non-FW cows. These values are within the lower range of previously reported methane emissions from Indian dairy cattle. For example, Alam *et al.* (2026) summarised data from 15 feeding trials across India and reported an average emission of $141 \text{ g d}^{-1} \text{ TLU}^{-1}$ (range: 88–245), while Sherasia *et al.* (2016) and Kannan & Garg (2009) observed $129 \text{ g CH}_4 \text{ d}^{-1} \text{ TLU}^{-1}$ and $122 \text{ g CH}_4 \text{ d}^{-1} \text{ TLU}^{-1}$, respectively, for crossbred and Gir cows in India. Lower emissions of $83 \text{ g CH}_4 \text{ d}^{-1} \text{ TLU}^{-1}$ were reported by Rajkumar *et al.* (2023) for indigenous Indian dairy cattle. The relatively moderate methane emissions estimated in the present study may therefore largely reflect the DMI levels of the cows, as DMI was the principal input used in the prediction equation (Beauchemin *et al.*, 2008; Knapp *et al.*, 2014).

4.3 Limitations of the study

The present study has several limitations. The unbalanced sample numbers between cows receiving only conventional feed or also FW may have influenced statistical comparisons. In addition, no history of metabolic disorders of the studied cows was recorded, although such information could provide further insight into potential side effects of FW-based feeding practices. Methane emissions were estimated using DMI-based prediction equations rather than direct measurement techniques, and part of the DMI was estimated using grazing-time equations. The use of a fixed intake rate for grazing cows may not fully account for variations in the intake of pasture vegetation on heterogeneous grazing sites such as lakeshore or pastureland within and around Bengaluru (Alam *et al.*, 2023). Therefore, the estimates of enteric methane emissions should be interpreted with caution.

5 Conclusion

The present study provides valuable insights into how urbanisation influences dairy feeding strategies and their effects on milk yield and composition in Greater Bengaluru. Incorporating FW into dairy cow diets was associated with increased milk yield, and greater proportions of unsaturated FAs compared to conventionally fed cows, indicating the potential of FW as an alternative feed resource in urban dairy systems. Heavy metal concentrations in feed and milk were generally within acceptable limits; however, Pb exceeded WHO thresholds in approximately 20 % of milk samples from the FW-fed group. This highlights the importance of careful source selection and regular quality control of FW materials designated for animal feeding, and suggests that not all FW sources are equally suitable for dairy cow feeding due to potential contamination risks. Therefore, source-specific assessment, appropriate processing and development of FW safety guidelines are essential. Further research should identify suitable FW inclusion levels and classify FW sources based on their nutritional composition. Overall, the study highlights the potential of carefully managed FW as a resource-efficient feeding strategy for dairy systems in land-constrained urban environments, while emphasising the need for accompanying safety regulations, source-specific FW assessments, and long-term animal health monitoring.

Supplement

The supplement (table S1) related to this article is available online on the same landing page at: <https://doi.org/10.17170/kobra-2026092412418>.

Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Informed consent statement

All interviewees participating in this study were fully informed about the study purpose and were assured that their information would be treated anonymously. Therefore, only persons giving explicit informed oral consent were interviewed.

Data availability

The datasets generated and/or analysed in the current study are available from the corresponding author for scientific purposes upon written request.

Declaration of generative AI and AI-assisted technologies in the writing process

AI-supported tools were used solely for language editing and grammatical correction. These tools did not influence the study design, data analysis, interpretation of results, or scientific conclusions.

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