

Manipulating concentrate level in the diet of tropical cattle to improve fiber utilization and mitigate greenhouse gas emissions

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ABSTRACT

This study evaluated the effects of concentrate level in diet, 10, 25, 40, and 60% forage dry matter (DM), on feed intake, nutrient utilization, weight gain (WG), and greenhouse gas (GHG) emissions in 12 male crossbred cattle (Red Sindhi × local, *Bos indicus*) 9-15 months of age in Southwestern Vietnam. The experiment was conducted for 6 months using a completely randomized block design. Animals were individually housed and fed *ad libitum* with rice straw, with or without elephant grass, supplemented with commercial concentrate. Results showed that as the concentrate level increased, consumption of feeds, digestible nutrients and energy, WG, and GHG emissions rose linearly ($P < 0.01$), whereas neutral detergent fiber (NDFD) and acid detergent fiber digestibility declined ($P < 0.05$). The DM, organic matter, and crude protein digestibility were not significantly affected ($P > 0.05$). The *in vitro* NDFD assessments exhibited similar trends to the *in vivo* data ($R^2 > 0.75$). GHG emissions per unit of live weight were significantly reduced ($P < 0.01$) as concentrate levels increased up to 60%, although the difference between the 40% and 60% groups was not statistically significant ($P > 0.05$). These findings suggest that a concentrate level of 40% forage DM offers an optimal balance between fiber utilization and GHG emission intensity. The *in vitro* technique using rumen fluid from slaughtered cattle with unknown dietary history and minimized chemical reagents may serve as a practical and ethical tool for evaluating fiber utilization in cattle nutrition studies.

Keywords: *Bos indicus*, Feedlot, Emission intensity, Fiber digestion, Rumen fluid reuse

INTRODUCTION

The greenhouse gases (GHG), including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), emitted from livestock production contribute significantly to global warming. According to the IPCC (2019, 2022), approximately 20% of total global GHG under livestock farm-gate emissions comes from enteric fermentation in cattle, contributing nearly 50% of agricultural methane and over 75% of agricultural nitrous oxide (IPCC, 2019; 2022). FAO (2023) estimates that agri-food systems release approxi-

mately 7.8 Gt of CO₂ equivalent (CO₂eq), about 30% of human-induced emissions, while livestock emissions are at ~6.2 Gt CO₂eq (~12% of global GHG). In Vietnam, livestock is estimated to account for over 6.3 million metric tons of CO₂eq annually, with ruminants responsible for 34.6% of this total (Monre, 2022). Vietnam's GHG inventory currently employs the IPCC (2019) Tier 2 approach, utilizing a fixed methane conversion factor of $6.5 \pm 1.0\%$ of gross energy intake (GEI), though this figure varies considerably with dietary concentrate level, fiber content, and energy density (Kaewpila and Sommart,

2016). Furthermore, IPCC (2022) emphasized that reducing GHG emissions is among the most effective short-term climate mitigation strategies, potentially limiting global warming by up to 0.3° C by 2050.

In response, many countries have adopted livestock-specific GHG control policies, including Vietnam, which has committed to achieving net-zero emissions by mid-century (Monre, 2022). Southwestern Vietnam, commonly referred to as the Mekong Delta (MD), spans approximately 40,922 km², with agricultural land occupying nearly 25,727 km². Pasture availability is limited, and cattle feed primarily consists of low-quality rice straw, while other forages, although abundant, are also nutritionally poor. The MD cattle herd reached approximately ~894 thousand in a national herd of ~6.33 million by 2023,—to meet the red-meat demands of ~17.5 million residents here (GSO, 2024). The predominant cattle in the region are Sindhi crossbred, derived from Red Sindhi sires and local dams, comprising ~90.2% of the herd (GSO, 2024). While well suited to the hot-humid delta climate and displaying greater frames than indigenous cattle, Sindhi crossbred cattle exhibit relatively low growth rates. Consequently, the implementation of concentrate-enhanced feeding strategies may improve growth performance, shorten feeding cycles, and potentially mitigate GHG emissions (Dung *et al.*, 2019; Hristov, 2024).

Although the influence of the dietary concentrate on nutrient utilization and GHG emissions is well documented (Hristov, 2024), research under MD conditions remains lacking. A Vietnamese study by Dung *et al.* (2019) showed that higher dietary protein and concentrate improved intake and weight gain while lowering GHG emission intensity. Digestible fiber is a key indicator of the energy utilization efficiency of animals. Since humans cannot digest fiber, rumen microbes ferment structural carbohydrates to supply energy to ruminants (McDonald *et al.*, 2022). The *in vivo* trials are the best way to test digestibility, but they are labor-intensive and expensive. As an alternative, *in vitro* approaches such as the two-stage method modified by Goering and van Soest (1970) are frequently used, although they rely on rumen fluid from live animals and chemical reagents and raise ethical concerns, posing other challenges. To address these,

Mo and Thu (2025) developed an *in vitro* protocol using rumen fluid from slaughtered cattle, eliminating the need for fistulated animals and harsh reagents. Their results showed strong alignment with *in vivo* digestibility data ($R^2 > 0.80$), with reduced cost and improved animal welfare. These factors give rise to two fundamental inquiries. What dietary concentrate level enables Sindhi crossbred cattle in Southwestern Vietnam to achieve improved growth, lower GHG emission intensity, and efficient fiber utilization? Can a simplified *in vitro* digestion protocol effectively gauge dietary digestible fiber under tropical production settings?

MATERIALS AND METHODS

Study Site and Ethical Issues

A feeding experiment was conducted in 3 private smallholder cattle farms located in Southwestern Vietnam (9.654743, 105.194714; 9.525918, 105.211035; and 9.528395, 105.220781) from the autumn to winter. The area is characterized by a tropical monsoon climate, with distinct wet and dry seasons. The mean annual temperature is around 27°C and most of the rain falls between May and November. The *in vitro* experiment and sample analysis were done in the College of Agriculture, Can Tho University.

All animal-related procedures were carried out under Article 72 of the Vietnamese Law on Animal Husbandry (Law No. 32/2018/QH14), which provides guidance on animal welfare and ethics in scientific research. As such, no discomfort or harm was caused to the experimental animals throughout the study.

Animals and Feeds

Twelve crossbred male cattle (Red Sindhi × local) from 9 to 15 months of age were selected for the feeding and *in vivo* digestion trial. Before the experiment, animals were dewormed with ivermectin (0.25%) to ensure their health status.

Forage components included rice straw and elephant grass (*Pennisetum purpureum*), with the grass harvested daily at 45–60 days of regrowth. Rice straw was obtained once during the study period from nearby fields (winter-spring crop, variety OM7347). The concentrate used was a commercially formulated product purchased at

Table 1. The Chemical Composition (%DM, excluding DM) of Ingredients in Diets

Feedstuffs	DM	OM	CP	EE	NDF	ADF	ADL	ME, MJ/kgDM
Rice straw	85.2	84.8	5.34	1.13	72.1	40.6	7.47	7.28
Grass	12.8	88.8	9.01	2.04	71.2	37.0	5.88	8.56
Concentrate	86.4	89.8	16.3	9.23	45.0	22.6	4.33	10.8

DM: dry matter; OM: organic matter; CP: crude protein; EE: ether extract; NDF: neutral detergent fiber; ADF: acid detergent fiber; ADL: acid detergent lignin; ME: metabolizable energy.

the beginning of the trial. The chemical composition of ingredients is presented in Table 1.

Experimental Design and Feeding Management

The study employed a completely randomized block design with four dietary treatments. Three blocks based on differences in farms, initial live weight (LW), and ages of animals: in the first farm, LW ~ 105 kg, at 9 months old; in the second, LW ~ 132 kg, at 12 months old; and in the third, LW ~ 163 kg, at 15 months old. Each block had four animals corresponding to four treatments, totaling 12 male calves (3 animals per treatment). The dietary treatments were based on differing concentrate levels: 10, 25, 40, and 60% forage DM, calculated as % concentrate = (concentrate DM intake/forage DM intake) × 100. The proportions of rice straw and grass in the diets were adjusted so that the crude protein (CP ~ 9.04% DM), digestible CP (DCP ~ 5.56% DM), and metabolizable energy (ME ~ 8.54 MJ/kg DM) contents were almost equivalent. These nutrient levels are sufficient for the growth requirements of Sindhi crossbred cattle (Filho *et al.*, 2016).

Each animal was housed individually in a 3×2 m concrete-floored pen. The pen was equipped with separate feeders and drinking troughs. The pens were disinfected monthly using Virkon S. Animals were fed *ad libitum* twice daily, concentrate at 08:00 and 17:00, followed by forage. Clean drinking water was available at all times. The feeding trial lasted 6 months.

Feed Intake and *in Vivo* Digestibility

Feed intake was recorded daily as the difference between the amount of feed offered each morning and the refusals collected the following morning. The digestible nutrient intake was determined as the nutrient intake minus the nutrient excretion in manure. The live weights of the ani-

mals were measured individually (two times) at the beginning and end of the experimental period by a large scale to evaluate weight gain (WG).

In vivo digestibility was determined during 7 consecutive days in the middle of the experimental period. During this time, offered feed, refused feed, and feces were collected and weighed daily for each animal. Subsamples were taken and dried at 55°C for 24 hours, then ground to pass through a 1 mm sieve. These samples were pooled by animal and stored at -20°C for chemical analysis and *in vitro* digestion as required. The procedure for determining *in vivo* digestibility followed the method of McDonald *et al.* (2022). Digestible nutrients were estimated using the digestibility coefficient multiplied by nutrient content.

In Vitro Digestibility

Two different *in vitro* procedures were employed to assess digestibility. The first (*F_{in vitro}*) was conducted according to the conventional protocol by Goering and van Soest (1970). The second (denoted as *S_{in vitro}*) was adapted from Mo and Thu (2025). In this method, the incubation mixture consisted of 42 mL of rumen fluid, 8 mL of buffer solution, and 2 mL of reducing agent, without any added agents. Buffer and reducing solutions were prepared following the standard procedure of Goering and van Soest (1970). After anaerobic fermentation at 39°C in glass tubes, the residues were treated overnight with a neutral detergent solution at 85°C. They were then washed twice with hot water and twice with acetone, dried, and analyzed for neutral detergent fiber (NDF) as Goering and Van Soest (1970). Blank tubes containing only buffer and rumen fluid (without substrate) were used to adjust for background residues.

Rumen liquor source was collected from three slaughtered Red Sindhi × local crossbred cattle with unknown dietary backgrounds. Within

15 minutes post-slaughter, the rumen contents were removed by hand, strained through three layers of muslin cloth into pre-warmed flasks, and immediately transported to the laboratory to preserve microbial activity. The procedure for slaughtering animals was performed according to the Vietnamese standards (TCVN 12448: 2018), strictly guided by animal ethics and welfare issues.

Chemical Analysis

All samples were analyzed using standardized procedures to determine their chemical composition. DM was measured by oven drying at 105°C for 12 hours, while ash and organic matter (OM) were quantified through muffle furnace combustion at 600°C for 4 hours (method 942.05). Manure nitrogen (N) and CP ($N \times 6.25$) were analyzed by the micro-Kjeldahl method (method 984.13), and ether extract (EE) was extracted using a Soxhlet system with ethyl ether (method 920.39), as described in AOAC (1990). The fiber fractions, including NDF, acid detergent fiber (ADF), and acid detergent lignin, were determined following the protocol of Goering and van Soest (1970).

Non-fiber carbohydrates (NFC) were estimated using the equation: $NFC = OM - CP - EE - NDF$ as outlined by McDonald *et al.* (2022). Gross energy (GE), total digestible nutrients (TDN), digestible energy (DE), and ME were derived following Weiss and Tebbe (2019) guidelines, using the equations: $GE = CP \times 0.056 + EE \times 0.094 + (OM - CP - EE) \times 0.042$, $TDN = DCP + DNFC + 2.25 \times DEE + DNDF - 7$, $DE = 0.04409 \times TDN$, and $ME = 1.01 \times (0.04409 \times TDN) - 0.45$.

Greenhouse Gas Estimations

Indirect GHG emission factors applied in this study included values for calf production (30.7 kg CO₂eq/kg LW; Basarab *et al.*, 2012) and for feed ingredients such as rice straw (0.072 kg CO₂eq/kg; Deka *et al.*, 2025), grass (0.018 kg CO₂eq/kg; Somjai and Suwan, 2020), and concentrate (0.27 kg CO₂eq/kg DM; Flachowsky, 2011). These data were sourced from published literature in which GHG emissions had already been expressed in CO₂eq. The original calculations were based on 100-year global warming potential values from IPCC (2007),

which were 25 for CH₄ and 298 for N₂O, relative to CO₂. To maintain consistency with the reference data, this study retained those conversion factors.

CO₂ emissions from animal respiration were estimated using the heat production (HP) method proposed by CIGR (2002). HP was calculated based on the animal's LW, WG, and GE. The heat output, which was initially measured in watts (W), was then converted to energy in kilojoules per day (kJ/d) and finally transformed to CO₂ volume (L/day) using the conversion factor of 21.75 kJ/L CO₂. This volume was further converted to mass (kg/day) using a gas density of 1.757 g/L under standard conditions of 32°C and 101.3 kPa.

Enteric CH₄ emissions (CH₄e) were estimated using the IPCC Tier 2 approach (IPCC, 2019), in which CH₄ output is derived from GEI and Y_m. The Y_m value was estimated using the empirical model proposed by Kaewpila and Sommart (2016), which incorporates the relationship between DE, ME, and GE: $CH_{4e} (kg) = Y_m / 100 \times GEI / 55.65$, and $Y_m = 37.7 + 19.71 \times DE / GE - 50.7 \times ME / DE$, where 55.65 MJ/kg is the energy content of methane.

CH₄ emissions from manure (CH₄f) were estimated as follows: $CH_{4f} = VS \times 0.1 \times 0.67 \times 0.02$, where VS is the daily excretion of volatile solids as the organic matter in manure, 0.1 represents the maximum methane-producing potential of manure, 0.67 is the conversion from m³ CH₄ to kg, and 0.02 is the methane conversion factor for dry manure systems (IPCC, 2019).

N₂O emissions from manure were calculated by summing direct emissions (N₂Od), those from volatilization (N₂Ov), and leaching (N₂OI), using the following formulas: $N_{2Od} = Nex \times 0.02 \times 44/28$, $N_{2Ov} = Nex \times 0.2 \times 0.01 \times 44/28$, and $N_{2OI} = Nex \times 0.3 \times 0.0075 \times 44/28$. Here, Nex refers to the N excreted per animal analyzed, as explained above. The constants used represent IPCC (2019) default values for N loss and conversion, while 44/28 is the molecular weight ratio used to convert N₂O-N to N₂O.

Statistical Analysis

All collected data were subjected to analysis of variance using the General Linear Model procedure (Stat>ANOVA>General Linear Model) in Minitab 21.3. Tukey's test was applied to detect

differences between treatment means. In addition, simple linear regression analyses (with *in vivo* as the dependent variable and *in vitro* - two methods $\times$ four incubation times - as the independent variable) and paired t-tests were used to assess the relationships and differences between *in vivo* and *in vitro* digestibility.

RESULTS AND DISCUSSION

Digestibility

The effects of different concentrate levels on the digestibility of nutrients, evaluated through both *in vivo* and *in vitro* methods, are presented in Tables 2 and 3. The results indicated that DM, OM, and CP digestibility were not significantly affected ($P > 0.05$) by treatments (Table 2). However, a clear linear trend was observed for NDFD and acid detergent fiber (ADFD) digestibility, which declined markedly ($P < 0.05$) with increasing concentrate levels (Table 2). The decline in fiber digestion, particularly NDF, was consistently detected by both *in vivo* and *in vitro* methods, although S_ *in vitro*

NDFD 12 hours had not been found yet ($P > 0.05$) (Table 3).

This inverse relationship is a well-known physiological response to high-concentrate diets. Rapid fermentation of soluble carbohydrates reduces ruminal pH, thereby impairing fibrolytic microbial activity (Mao *et al.*, 2024; Wang *et al.*, 2024). When the rumen pH drops below 6.0, fibrolytic microbes become less active, thus limiting fiber degradation (Bach *et al.*, 2023). This mechanism is indirectly supported by Mayulu *et al.* (2024), who reported that diets with lower fiber levels showed higher OM digestion, possibly indicating a shift in ruminal fermentation favoring non-fiber carbohydrate utilization. Despite a potential reduction in fiber digestion in this study, overall OM digestion remained relatively stable. This likely reflects compensatory effects from the improved non-fiber carbohydrate utilization of animals fed concentrates, as also reported in high-concentrate diets for goats and sheep by Elihasridas *et al.* (2024). Such nutrient substitution mechanisms allow animals to maintain a stable overall energy supply, even

Table 2. The *in Vivo* Digestibility (%) of Dietary Nutrients

Digestibility	Concentrate (% forage DM)				SEM	P
	10	25	40	60		
Dry matter	58.4	57.9	57.5	56.7	1.47	ns
Organic matter	60.0	60.0	60.1	60.8	1.46	ns
Crude protein	61.4	61.2	61.9	61.7	1.40	ns
Neutral detergent fiber	67.5 ^b	66.8 ^b	64.8 ^a	64.3 ^a	0.371	**
Acid detergent fiber	54.6 ^b	53.1 ^b	49.8 ^{ab}	45.3 ^a	1.47	*

SEM: standard error of mean; P: significant level - ns $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; ^{a, b} mean values with different superscripts are significantly different according to Tukey's test

Table 3. The *in Vitro* Digestibility (%) of Dietary Neutral Detergent Fiber

Techniques	Concentrate (% forage DM)				Analysis of variance		Regression analysis to <i>in vivo</i>		
	10	25	40	60	SEM	P	R ²	RSD	P
F_iv 12 h.	22.6 ^a	21.8 ^{ab}	20.5 ^{bc}	19.2 ^c	1.03	*	0.576	1.01	**
F_iv 24 h.	38.1 ^a	36.5 ^{ab}	32.9 ^{bc}	30.8 ^c	1.01	**	0.595	0.989	**
F_iv 48 h.	60.7 ^a	58.6 ^a	51.9 ^b	50.1 ^b	0.779	***	0.815	0.668	***
F_iv 72 h.	63.5 ^a	63.2 ^a	60.7 ^b	60.3 ^b	0.299	***	0.794	0.705	***
S_iv 12 h.	26.8	25.3	23.6	20.4	1.35	ns	0.475	1.13	*
S_iv 24 h.	35.0 ^a	32.1 ^{ab}	29.1 ^{bc}	27.0 ^c	1.21	**	0.577	1.01	**
S_iv 48 h.	53.9 ^a	52.5 ^a	42.8 ^b	41.2 ^b	1.01	**	0.650	0.919	**
S_iv 72 h.	59.5 ^a	58.5 ^a	55.3 ^b	54.7 ^b	0.538	**	0.751	0.775	***

F_iv: formal *in vitro* technique of Goering and van Soest (1970); S_iv: *in vitro* simplified reagents updated from Mo and Thu (2025); SEM: standard error of mean; P: significant level - ns $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; ^{a, b, c} mean values with different superscripts are significantly different according to Tukey's test; RSD: residual standard deviation; R²: coefficient of determination.

Table 4. Consumption of Feeds, Digestible Nutrients, and Energy of Cattle

Daily Parameters	Concentrate (% forage DM)				SEM	P
	10	25	40	60		
Rice straw intake (kg dry matter)	0.384 ^c	1.01 ^{bc}	1.68 ^b	2.92 ^a	0.197	***
Grass intake (kg dry matter)	2.17 ^a	1.38 ^b	0.849 ^b	-	0.155	***
Concentrate intake (kg dry matter)	0.247 ^c	0.609 ^c	0.989 ^b	1.70 ^a	0.076	***
Dry matter intake (% of live weight)	2.06 ^c	2.22 ^{bc}	2.51 ^b	3.32 ^a	0.087	***
Digestible non-fiber carbohydrate (kg)	0.201 ^c	0.249 ^{bc}	0.318 ^b	0.457 ^a	0.017	***
Digestible protein crude (kg)	0.154 ^b	0.162 ^b	0.189 ^b	0.244 ^a	0.010	**
Digestible ether extract (kg)	0.041 ^c	0.059 ^c	0.081 ^b	0.125 ^a	0.004	***
Digestible neutral detergent fiber (kg)	1.30 ^b	1.31 ^b	1.43 ^b	1.78 ^a	0.060	**
Total digestible nutrients (kg)	1.55 ^b	1.65 ^b	1.88 ^b	2.45 ^a	0.081	***
Metabolizable energy intake (MJ)	23.7 ^b	25.2 ^b	28.7 ^b	37.5 ^a	1.22	***

SEM: standard error of mean; P: significant level - ns $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; a, b, c mean values with different superscripts are significantly different according to Tukey's test.

when structural carbohydrate degradation is compromised.

A notable methodological highlight in this study was the use of a newly developed simplified *in vitro* system (S_ *in vitro*), recently introduced by Mo and Thu (2025). Unlike conventional *in vitro* techniques (F_ *in vitro*), which require rumen fluid sourced from donor animals and involve multiple chemicals, the S_ *in vitro* employs a non-invasive rumen fluid protocol and significantly reduces the use of reagents. Despite its streamlined nature, the S_ *in vitro* yielded NDFD values highly correlated with *in vivo* measurements ($R^2 > 0.47$, $P < 0.05$), especially at 72 hours of fermentation ($R^2 = 0.75$, $RSD = 0.77$, $P < 0.001$) (Table 3), demonstrating its reliability. The study also found linear relationships between F_ *in vitro* and *in vivo* NDFD measurements ($R^2 > 0.57$, $P < 0.01$), and at 48 hours of fermentation, the regression has a higher $R^2 = 0.81$ ($RSD = 0.67$; $P < 0.001$) (Table 3). Strong correlations between S_ *in vitro*, F_ *in vitro*, and *in vivo* NDFD values affirm the robustness for evaluating fiber digestion of both *in vitro* systems, even though they consistently underestimated absolute NDFD values compared to *in vivo* data (21.0-61.9 vs. 65.9%, $P < 0.001$) (Table 3). These findings align with those of Lutakome *et al.* (2017), Wang *et al.* (2018), and Mo and Thu (2025) and validate the use of abattoir-sourced alternative rumen inocula in digestibility assessments. The S_ *in vitro* presents clear advantages for feed evaluation in low-resource and ethically constrained settings. It circumvents the need for fistulated animals, minimizes chemical waste, and facilitates applications in tropical

regions like the MD. The integration of simple and sustainable methods into nutritional studies is not only scientifically sound but also socially responsible.

The results confirm that higher concentrate inclusion compromises fiber utilization, particularly NDF and ADF. However, the overall energy remains stable, highlighting the nutritional adaptability of cattle to dietary shifts. The demonstrated reliability of the S_ *in vitro* approach highlights its practical potential as a low-cost, ethical, and effective alternative for routine fiber digestibility assessment under tropical production systems.

Consumption of Feeds and Nutrients

The effects of concentrate levels on the consumption of feeds, digestible nutrients, and ME of cattle are presented in Table 4. As the concentrate level increased, significant differences ($P < 0.01$ or 0.001) were observed in all measured variables, including feeds, digestible nutrients (NFC, CP, EE, NDF, TDN), and ME. Cattle fed the 60% concentrate consumed substantially more DM (3.32 %LW), DCP (0.244 kg/day), DNDF (1.78 kg/day), TDN (2.45 kg/day), and ME (37.5 MJ/day) compared to those fed the 10% concentrate, which showed the lowest values.

The increasing trend in nutrient intake across treatments likely reflects the combined effects of improved dietary palatability at high concentrate, high available energy density, and reduced physical bulk of the fiber fraction, which together stimulate voluntary feed intake and accelerate passage rate of digesta. These

physiological responses are consistent with findings from Han *et al.* (2024), who observed enhanced feed intake and rumen passage in growing beef cattle offered diets with higher concentrate inclusion.

Similarly, Quang *et al.* (2015) reported increased intake of both DM and NFC in Brahman crossbred cattle when dietary concentrate exceeded 45%, attributing the response to higher available energy and lower fiber. These outcomes align with current findings, particularly in the way DM, TDN, and ME intake increased in response to higher concentrate. The observed rise in digestible EE and NFC intake supports earlier reports showing that lipid- and grain-rich concentrate components may play a role in improving total digestible energy intake and growth performance (Elihasridas *et al.*, 2024).

Under tropical conditions, similar feed, nutrient, and energy intake responses have been documented. Quang *et al.* (2015) reported higher DM intake in Brahman crossbred cattle in South-eastern Vietnam, increasing from 4.02 to 6.43 kg/day with rising concentrate levels. A more recent Vietnamese trial by Phuong *et al.* (2024) found that supplementing fermented rice straw with dried brewer's malt significantly enhanced DM, CP intake, and WG in Sindhi crossbred cattle, indicating the potential use of energy-rich feed ingredients to improve consumption and performance under tropical conditions. It is also worth noting that the increase in digestible NDF and ADF intake across treatments reflects the absolute rise in total energy consumed. This suggests that even though dietary fiber content declined, the total fiber consumed still increased, a factor that may benefit rumen function when concentrate levels remain within moderate limits. Elihasridas *et al.* (2024) emphasized the importance of maintaining structural carbohydrates in high-concentrate diets to avoid metabolic imbalances.

Generally, the results from this study are consistent with existing evidence indicating that increasing dietary concentrate improves energy intake in tropical cattle. Such improvements in nutrient intake and energy availability are most effective when the dietary concentrate remains within a range that sustains ruminal health and fermentation stability (Han *et al.*, 2024; He *et al.*, 2024).

Growth Performance and Emission

The effects of different concentrate levels on growth performance and GHG emissions are summarized in Table 5. Higher concentrate levels significantly enhanced cattle growth performance. Final LW increased from 185 kg in the 10% group to 222 kg in the 60% concentrate group ($P < 0.001$), while WG rose sharply from 285 g/day to 493 g/day. Feed (103 to 113 gWG/kg of DM intake) and fiber (220 up to 278 gWG/kg of digestible NDF intake) utilization efficiency also improved, although there were insignificant differences ($P > 0.05$). Feed cost per kilogram of WG declined markedly ($P < 0.001$). This indicates a more efficient nutrient utilization at higher concentrate levels.

These align with earlier studies reporting increased growth rates and improved feed efficiency in cattle fed high-concentrate diets under tropical conditions. For instance, Quang *et al.* (2015) observed nearly a ten-fold increase in WG in Brahman crossbred cattle as concentrate levels increased from 0 to 67%. Han *et al.* (2024) also found that increased dietary concentrate enhances nutrient absorption more efficient, shortens fattening periods, and reduces production costs in crossbred cattle. Improved feed utilization efficiency in this study mirrors the trends reported by Silva *et al.* (2015), where increasing the concentrate led to better feed efficiency. However, these improvements may plateau or even reverse when concentrate levels exceed optimal thresholds. The overfeeding of concentrate may compromise rumen function, necessitating the balancing of non-fiber and fiber content in diets (Elihasridas *et al.*, 2024).

Regarding emissions, total GHG per head tended to rise with increasing concentrate inclusion, primarily due to elevated enteric and manure-related emissions ($P < 0.001$). Moreover, indirect emissions from feed production were significantly higher ($P < 0.05$) in the 60% group, reflecting the higher carbon footprint of concentrate ingredients such as grains and meals (Niu *et al.*, 2016). However, emission intensity, expressed as kg CO₂eq per kilogram of WG or LW, either remained constant or declined, with a significant reduction ($P < 0.01$) observed in the per LW. This aligns with Li *et al.* (2024), who demonstrated that concentrate supplementation can reduce emission intensity by enhancing

Table 5. Growth Performance and Greenhouse Gas Emission Intensity of Cattle

Variables	Concentrate (% forage DM)				SEM	P
	10	25	40	60		
Initial LW, kg	134	133	134	133	1.21	ns
Final LW, kg	185 ^b	189 ^b	200 ^{ab}	222 ^a	5.04	**
WG, g/day	285 ^b	311 ^b	367 ^b	493 ^a	22.7	**
WG, g/kg DMI	103	106	112	113	6.75	ns
WG, g/kg DNDFI	220	238	265	278	16.5	ns
Feed cost, VND/kg WG	98577 ^d	74640 ^c	58424 ^b	40812 ^a	2507	***
Indirect emission						
Calves, kgCO ₂ eq	4114	4083	4114	4083	37.2	ns
Feeds, kgCO ₂ eq	80.9 ^b	74.5 ^{ab}	95.3 ^{ab}	111 ^a	7.21	*
Direct emission						
Exhaled, kgCO ₂ eq	25.8	25.5	26.6	28.3	0.957	ns
Enteric, kgCO ₂ eq	290 ^b	307 ^b	354 ^b	461 ^a	15.9	***
Manure, kgCO ₂ eq	45.2 ^b	43.7 ^b	51.3 ^b	63.6 ^a	1.91	***
Total emission						
kgCO ₂ eq/head	4555	4534	4641	4747	53.0	ns
kgCO ₂ eq/kg WG	8.58	8.04	7.92	7.56	0.485	ns
kgCO ₂ eq/kg LW	24.6 ^a	23.9 ^a	23.1 ^{ab}	21.4 ^b	0.425	**

LW: live weight; WG: weight gain; DMI: dry matter intake; DNDFI: digestible neutral detergent fiber intake; SEM: standard error of mean; P: significant level - ns $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; a, b, c, d mean values with different superscripts are significantly different according to Tukey's test.

growth rate and feed efficiency in tropical cattle systems. Enteric CH₄ emissions increased from 290 to 461 kg CO₂eq/head across treatments, consistent with increased energy intake availability (Hristov, 2024). Nevertheless, this absolute increase is offset by faster WG, resulting in lower emissions per unit of product. He *et al.* (2024) and Han *et al.* (2024) similarly emphasized that while high-concentrate diets may elevate total CH₄ output, they contribute to providing nutrients and energy intake and shorter production cycles, thereby lowering emission intensity. These emissions must be weighed against the benefits of reduced feeding duration and improved growth performance (Jiao *et al.*, 2014). Among the treatments, the 40% level emerged as the most balanced option, offering substantial gains in animal performance while maintaining moderate GHG intensity and lower feed cost (Table 5). This intermediate ratio appears particularly well-suited for cattle systems in the MD, where roughage quality is often poor and production efficiency is limited.

Overall, the results show that manipulating the concentrate level can simultaneously enhance cattle productivity and reduce GHG emission intensity, provided that dietary formulations are optimized for both non-structural

and structural carbohydrates. Moderate concentrate inclusion (e.g., 40% forage DM) may represent a sustainable and practical strategy for beef production in tropical low-input systems.

CONCLUSION

The study demonstrated that higher concentrate levels improved energy intake, weight gain, and feed efficiency while reducing the production cost. However, fiber digestibility, particularly NDF and ADF, declined. The study validated the effectiveness of a simplified *in vitro* method for evaluating fiber digestibility. It avoids using rumen fluid from fistulated animals and minimizes chemical use, with results aligned closely with *in vivo* methods. Although total GHG emissions increased, emission intensity per unit of LW product declined, highlighting improved environmental efficiency. The concentrate level of 40% forage DM emerged as the most balanced option. Further studies under commercial farm conditions are recommended to validate the scalability of this strategy.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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