Research Article

Common Agricultural Byproducts with High Potential as Beef Cattle Feed Associated with Methane Emissions in Some Districts of Lam Dong Province, Vietnam

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Abstract | Agricultural crop production in Lam Dong province generates substantial byproducts, many of which are discarded or not effectively reused, contributing to resource loss and environmental concerns. Utilizing these byproducts as beef cattle feed, especially those with potential to reduce methane emissions, could improve beef cattle industry sustainability. The objective of this study was to identify the most common agricultural byproducts at production units in agricultural crops (PUACs) and evaluate their potential as beef cattle feed based on chemical composition, nutritional value, and *in vitro* methane production. A cross-sectional survey was conducted at 90 PUACs across three districts in Lam Dong, including both integrated and non-integrated beef cattle systems (5 PUACs with and 5 PUACs without combining with beef cattle production activities per commune, and 03 communes/district). The Participatory Rural Appraisal method was used to collect information on byproduct availability, usage, and perceived constraints. Representative samples of promising byproducts were analyzed for chemical composition, nutritive value, and methane emissions. Results showed that the most prevalent byproducts ($P < 0.001$) rice straw (RS), sub-standard sweet potato tuber (SSSPT), sweet potato vines (SPV), sub-standard pumpkin fruit (SSPF), pumpkin vine (PV), passion fruit peel (PFP) and cocoa pod husk (CPH). Ratios of byproduct to main product of these byproducts were high (>21%), notably RS (109.84%), CPH (59.88%), and PFP (41.03%). Over half of PUACs (52.22-60.00%) burned or discarded wastefully these byproducts due to concerns about pesticide residues and feed quality ($P < 0.01$). Nutritional analysis showed SPV, PV, PFP, and CPH (forage group) had favorable compositions, similar to Napier grass and even better than rice straw. In the concentrate group, SPV and SSPF were comparable to commercial complete feed (CCF). Methane evaluation revealed that SPV, PV, and PFP (forage) and SSSPT (concentrate) generated lower emissions than Napier grass or CCF, respectively. In brief, these results suggest that SPV, PV, PFP, and CPH are promising forage byproducts to replace untreated RS or partially substitute Napier grass, owing to their prevalence, nutritional value, and methane emission reduction potential, while SSSPT and SSPF show great potential as concentrate alternatives partially.

Keywords | Agricultural byproducts, Beef cattle feed, Concentrate, Forage, Methane emission

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INTRODUCTION

It has been indicated that Vietnam generates abundant agricultural byproducts (>37 million tons/year), but less than 20% are utilized as animal feed (Truong, 2010; Hong, 2018; Nguyen *et al*., 2021a) and the majority of them have been dumped without treatment, not only causing waste but also polluting the environment. There has been a serious shortage of forage, especially in the dry season (Nguyen *et al*., 2021b) as well as a significant increase in the imported cost of animal feed ingredients (Hoai, 2022) which had, are having, and will continue to have a substantial impact on the local cattle industry. Recently, several studies have indicated that there has been a high potential for using local byproducts as cattle feed in several provinces (such as Dak Lak, Son La, Tien Giang, etc.) in Vietnam (Truong, 2010; Le *et al*., 2020; Le and Nguyen, 2024), but no one in Lam Dong province. Although the byproducts often contain poor nutrients (such as low CP, high fiber, low digestibility, etc), there is a significant improvement in nutritional values when they have been suitably processed or treated (Nguyen, 2008; Nguyen *et al*., 2021a). Using the byproducts as feed for cattle in combination with other ingredients contributes to creating more diversity in daily diets and stimulating better appetite for cattle (Nguyen, 2023). Previous studies have shown that the byproducts can partially (Nguyen *et al*., 2021a) or completely (Nguyen *et al*., 2021b) replace the forage for high-yielding crossbred beef cattle during the fattening stage during forage shortages or significant increases in concentrate feed costs to reduce farming costs and increase profits. Therefore, utilization of the byproducts as feed has been really necessary to solve the feed shortage and bring high economic efficiency by combining the locally available, cheap and byproducts in the daily diet for fattening cattle. Therefore, it is necessary to use byproduct sources reasonably for sustainable cattle production (Nguyen *et al*., 2021a).

Lam Dong is one of the provinces with a developed beef cattle industry in Vietnam, applying the program of hybridizing cattle and upgrading high-yielding cross-breeds, thus having a central role in the overall development of the national beef cattle industry (Nguyen *et al*, 2024). Therefore, there are many opportunities and potentials to develop the beef cattle industry in Vietnam in general and at LD under production conditions of household farms in the coming time. LD is a famous province of large agricultural production with abundant and diverse sources of byproducts (such as sweet potato tubers, pumpkins, passion fruit, bananas, cocoa pods, etc.) along with many processing factories, but the owners of farms and factories seem to not pay much attention to effective treatments for these byproducts and no previous study has been conducted in LD.

On the other hand, climate change is a major societal concern due to numerous causes, of which an increase in greenhouse effect is considered one of the main causes, especially the methane emission (CH_4, greatly affecting the greenhouse effect after CO_2) (IPCC, 2013). The combination of livestock and crop byproducts seems to be a potential circular agricultural system (byproduct sources as cattle feed and cattle manure as compost fertilizer for crops) in Vietnam in general and Lam Dong in particular, contributing to enhancing stable income for farmers. This not only creates a sustainable circular agricultural chain to increase the economic value of agricultural areas but also contributes to environmental protection (Nguyen, 2023). Several previous studies have shown that the positive solution of changing the cattle diet to reduce CH_4 emissions has been widely considered in many countries (Grainger and Beauchemin, 2011), as well as when livestock productivity increases through better nutrition, the total energy requirement will decrease and CH_4 will also decrease (Morgavi *et al*., 2023). In addition to adding feed additives to daily diets to reduce CH_4 emissions, it is also necessary to find out potential byproduct sources with low emission characteristics to supplement into daily feed for cattle.

Furthermore, there have been many studies over the world showing good results from using byproducts as feed for high-yielding beef cattle on growth performance, meat quality and gas emissions (Ali *et al*., 2019; Ianni *et al*., 2019; Marcos *et al*., 2019; de Araújo *et al*., 2021; Deng *et al*., 2023; Phoemchalard *et al*., 2024). It has also been indicated that there are various factors impacting the use of agricultural byproducts as feed for beef cattle such as farmers, beef, regions and byproduct kinds (Baba *et al*., 2019). In Vietnam, several studies have been conducted using local byproducts as feed for fattening beef cattle (Truong, 2010; Nguyen *et al*., 2021a, b) but there is still a lack and very limited research evaluating local agricultural byproducts with potential as feed related to methane emission in beef cattle industry in households in Vietnam condition. Therefore, it is essential to identify agricultural byproducts with high potential as beef cattle feed and low gas emissions in Lam Dong Province, aiming to develop feasible technical solutions that reduce feed costs, enhance productivity and profitability in beef cattle production, and mitigate methane emission, thereby contributing to the sustainable development of the beef cattle industry in Lam Dong Province and aslo in Vietnam.

MATERIALS AND METHODS

Location

This survey was carried out directly at production units in agricultural crops (PUACs) in 3 districts of Lam Dong (LD) from 10/2024 to 12/2024. Agricultural byproducts from the household beef cattle farms (HBCFs) were transferred and analyzed at Department of Animal Nutrition, Nong Lam University, HCMC, Vietnam. Measuring the methane emission by an *in vitro* rumen incubation was conducted in Research and Technology Transfer Center, Nong Lam University, HCMC, Vietnam.

Approach

Using retrospective data: From previous reports of the Department of Livestock, Veterinary and Fisheries of Lam Dong province on the PUACs in three districts of Lam Dong (Cat Tien, CT; Duc Trong, DT; Don Duong, DD) to estimate the number of the PUACs (sample size). Raw data were collected from direct interviews by using Participatory Rural Appraisal method with pre-printed questionnaires at the PUACs as a cross-sectional study model.

Survey implementation and data collection

The raw data were gathered from direct interviews using the pre-printed questionnaires and the samples were randomly collected at the PUACs through method of hierarchical nested sampling design with 3 levels (level 1 includes some districts in Lam Dong province, level 2 includes some communes in each district, and level 3 includes some PUACs in each ward/commune). Specifically, a total of 90 PUACs (N= 90; 45 PUACs with and 45 PUACs without combining with beef cattle production activities) were randomly surveyed in three districts of LD (CT, DT and DD) with 3 communes for each district and 10 PUACs for each commune (5 PUACs with and 5 PUACs without combining with beef cattle production activities). In fact, the CT, DT, and DD are among the most representative districts for beef cattle farming and for the PUACs in Lam Dong province. Therefore, these districts were selected, and within each district, three communes and 10 PUACs (randomly for each commune) were chosen as the hierarchical sampling to ensure representativeness of the current status of agricultural crop production activities at PUACs in Lam Dong.

Based on the results from the field survey, samples of agricultural byproducts with high potential as beef cattle feed were collected according to the sampling principles of the national standard regulations of Vietnam (TCVN 13052:2021). Three samples per ingredient type (one sample was randomly collected for each district) of some common main agricultural byproducts (such as sweet potato tuber, pumpkin, cocoa pod husk, passion fruit peel, etc.) to analyze some important chemical compositions and nutritional values (three replicates for each byproduct) to evaluate the potential as feed for household beef cattle farms (HBCFs).

Evaluation of *in vitro* methane (CH_4) emission of these common main agricultural byproducts (six replicates for each byproduct) at different times (12 and 24 hours) was applied in an *in vitro* rumen incubation to consider the possibility of gas emissions in HBCFs when using these byproducts. The procedure of the *in vitro* incubation system was performed as previously described (Inthapanya *et al.*, 2011; Nguyen *et al.*, 2022; Phuong *et al.*, 2023).

In this study, the independent variables were agricultural crop production activities at PUACs and the types of byproducts sourced from PUACs; while the dependent variables included the figures/data of PUACs, chemical composition, nutritional values, and *in vitro* methane emissions. Representative byproduct samples from the PUACs were analyzed in the laboratory for proximate composition and nutrient profiles, and subsequently evaluated for methane production potential using the *in vitro* gas production technique under strict controlled conditions. All experimental conditions such as incubation temperature, rumen fluid source, and incubation time, were kept constant across all samples.

Survey implementation and data collection

Parameters from the survey: Experience in agricultural crop production, distribution of byproducts from PUACs, the ratio of currently common byproducts compared to main products in PUACs, commonly applied treatment methods for byproducts at PUACs, and personal viewpoints from representatives of PUACs on the byproduct use as animal feed.

The chemical compositions of byproducts included dry matter (DM, analytical method according to TCVN 4326:2001/AOAC 934.01), crude protein (CP, TCVN 8125:2015/TCVN 4328-1:2007/AOAC 984.13), ether extract (EE, TCVN 8136:2009/TCVN 4331:2001/AOAC 920.39), crude fiber (CF, TCVN 4329:2007/TCVN 5103:1990/AOAC 962.09), neutral detergent fiber (NDF, TCVN 9590:2013/AOAC 973.18), acid detergent fiber (ADF, TCVN 9589:2013/AOAC 973.18), starch (TCVN 9587:2013/AOAC 996.11), sugar (TCVN 4594:1988/AOAC 985.29), ash (TCVN 7142:2002/AOAC 942.05), calcium (Ca, TCVN 1526-1:2007/AOAC 927.02) and phosphorus (P, TCVN 1525:2001/AOAC 965.17).

The nutritional values included total digestible nutrients (TDN, %) and metabolizable energy (ME, Mcal/kg DM). The values of the TDN and ME of the collected samples were calculated according to equations in the National Research Council's nutrient requirements for beef cattle (NRC, 1981, 2000). Capacity of *in vitro* methane emission of the common main agricultural byproducts included total gas production and methane emission at different times (12 and 24 hours).

Statistical analysis

Data from the cross-sectional study model were analyzed by using GraphPad Prism 8.3 statistical software (GraphPad Software Inc., San Diego, CA, USA). Quantitative values (Mean±SD) were compared using one-way ANOVA followed by the Tukey test, while qualitative ones (%) were compared using the $\chi 2$ test. Findings were considered significantly different at $P < 0.05$.

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RESULTS

Part 1: Evaluating the potential sources of local agricultural byproducts in some districts of Lam Dong province

General information about PUACs

The distribution of PUAC experience levels showed that the average distribution of experience of the PUACs was mainly at 6-10 years (38.9%), followed by 11-15 years (21.1%), 16-20 years (20.0%), over 20 years (13.3%), from 1-5 years (5.6%), and the lowest distribution of less than 1 year (1.1%) (Figure 1a; P < 0.001). Regarding the educational levels of the PUACs, it was mainly at secondary school (class 6-9) and high school (class 10-12) (34.4% at each level), followed by primary school (class 1-5) (23.3%) and the lowest distribution in tertiary education (college/university level) (7.8%) (Figure 1b; P < 0.001). The majority of working labor sources participating in production at these PUACs came from family members (65.6%), or combined family members with outside employed workers (33.3%) (Figure 1c; P < 0.001).

Byproducts from the PUACs

As shown in Table 1, there were at least 17 types of byproducts from PUACs in Lam Dong, and the distribution of byproducts at PUACs was very different between districts in Lam Dong province or between PUACs associated with/without cattle husbandry (P < 0.001). Among them, rice straw (RS, 48.9%), sub-standard sweet potato tuber (or low-quality sweet potato tuber, SSSPT, 35.6%), sweet potato vines (including leaf and stem from aerial part of lateral and main stem) (SPV, 34.4%), sub-standard pumpkin fruit (SSPF, 30.0%), pumpkin vine (PV, 30.0%), passion fruit peel (PFP, 22.2%) and cocoa pod husk (CPH, 22.2%) were the most common by products (P < 0.001) among many byproducts created from current agricultural crop production activities at PUACs in LD. Furthermore, the ratio of these currently common byproducts to main products in PUACs was different among various types of ingredients (Table 2). The RS was a feed ingredient with a very high byproduct ratio (109.84%) compared to the main rice product, followed by the byproduct ratio of the CPH (59.88%), PFP (41.03%), SSPF and PV (21.66%), and the lowest byproduct group from the SSSPT and SPV (21.20%).

Commonly applied treatment methods for the byproducts at the PUACs

At least 6 treatment methods were being applied by the PUACs to handle the byproducts (Table 3). In particular, the most common method currently applied at the PUACs was the releasement into land for soil improvement (60.00%), followed by the burning (52.22%), feeding cattle (48.89%), supplying/selling to neighboring households/farms (37.78%), compost fertilizer (14.44%), and the lowest level was from deep litter materials (5.57%) (P < 0.001).

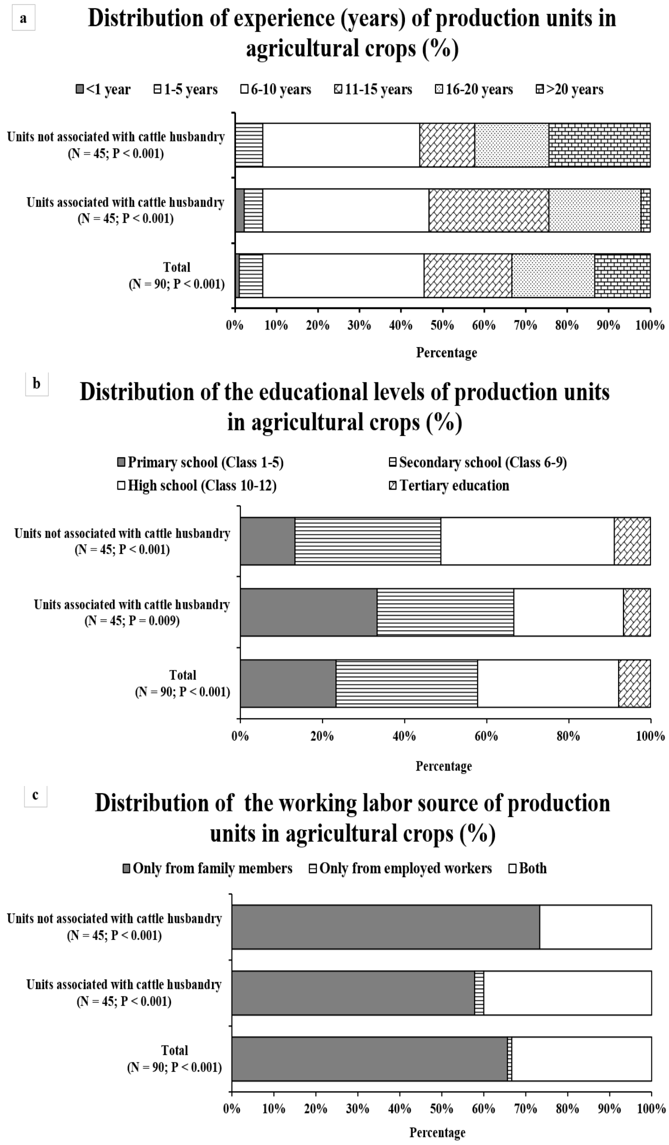

Figure 1: General information about PUACs (a, experience year; b, educational levels; c, working labor source).

Besides, a large proportion of the PUACs believed that the byproduct treatment method being currently applied at their PUACs was ineffective and wasteful (38.89%), although more than half of the PUACs still believed that the byproduct treatment being currently applied was effective (56.67%) compared to a very small proportion the PUACs with unconcern (4.44%) (P < 0.01; Table 4). The majority of the PUACs agreed that using byproducts as feed for cattle contributed to reducing the feed cost (100.00%) and to solving feed shortages (97.78%), but they were also very concerned about residual pesticides (90.0%) as well as about unsuitability/quality for cattle's feed (6.67%) (P < 0.01). There was a high percentage (100%) of the PUACs agreeing that there should be potential treatment solutions to increase the value/suitability/quality of byproducts for cattle feed (P < 0.01).

Table 1: Distribution of byproducts at PUACs (% unit).

District	Association with cattle husbandry	Percentage (%) of PUACs having the by products, namely																
		RS	SSSPT	SPV	SSPF	PV	PFP	CPH	KVF	WCB	CSB	WCR	WEP	WSY	WTM	WBP	WCC	SLT
CT (N = 30)	Yes (N = 15)	100.0	0.0	0.0	0.0	0.0	0.0	26.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	No (N = 15)	0.0	0.0	0.0	0.0	0.0	0.0	80.0	0.0	6.7	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0
	Average	50.0	0.0	0.0	0.0	0.0	0.0	53.3	0.0	3.3	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0
DD (N = 30)	Yes (N = 15)	93.3	66.7	66.7	53.3	53.3	26.7	0.0	20.0	13.3	26.7	20.0	26.7	13.3	0.0	6.7	0.0	6.7
	No (N = 15)	0.0	46.7	40.0	60.0	60.0	20.0	0.0	46.7	46.7	0.0	13.3	26.7	20.0	13.3	6.7	20.0	0.0
	Average	46.7	56.7	53.3	56.7	56.7	23.3	0.0	333	30.0	13.3	16.7	26.7	16.7	6.7	6.7	10.0	3.3
DT (N = 30)	Yes (N = 15)	93.3	60.0	60.0	40.0	40.0	40.0	0.0	0.0	0.0	26.7	20.0	0.0	0.0	0.0	0.0	0.0	0.0
	No (N = 15)	6.7	40.0	40.0	26.7	26.7	46.7	0.0	13.3	13.3	13.3	6.7	0.0	20.0	20.0	13.3	0.0	0.0
	Average	50.0	50.0	50.0	33.3	33.3	43.3	0.0	6.7	6.7	20.0	13.3	0.0	10.0	10.0	6.7	0.0	0.0
Total (N = 90)	Yes (N = 45)	95.6	42.2	42.2	31.1	31.1	22.2	8.9	6.7	4.4	17.8	13.3	8.9	4.4	0.0	2.2	0.0	2.2
	No (N = 45)	2.2	28.9	26.7	28.9	28.9	22.2	26.7	20.0	22.2	4.4	6.7	11.1	13.3	11.1	6.7	6.7	0.0
	Average	48.9^{a}	35.6^{b}	34.4^{bc}	30.0^{bc}	30.0^{bc}	22.2^{cdeh}	17.8^{deh}	13.3^{de}	13.3^{eh}	11.1^{hg}	10.0^{hg}	10.0^{hg}	8.9^{hgm}	5.6^{gm}	4.4^{gm}	3.3^{m}	1.1^{m}

Notes: RS, rice straw; SSSPT, sub-standard sweet potato tuber; SPV, sweet potato vine; SSPF, sub-standard pumpkin fruit; PV, pumpkin vine; PFP, passion fruit peel; CPH, cocoa pod husk; KVF, kohlrabi vine and fruit; WCB, waste cabbage; CSB, corn stalks byproduct; WCR, waste carrot; WEP, waste eggplant; WSY, waste soy; WTM, waste tomatoes; WBP, waste bell peppers; WCC, waste cucumber; SLT, sugarcane leaves and tops. Means with different superscripts within a row differ (P < 0,001).

Table 2: Ratio (%) of currently common byproducts compared to main products in PUACs (N = 90 PUACs).

PUACs	Rice straw	Sub-standard sweet potato tuber	Sweet potato vine	Sub-standard pumpkin fruit	Pumpkin vine	Passion fruit peel	Cocoa pod husk
Associated with cattle husbandry (N = 45)	109.91 ± 12.83	9.83 ± 1.66	10.66±1.77	11.69 ± 2.22	10.38 ± 2.21	40.90 ± 4.63	57.92 ± 7.12
Not associated with cattle husbandry (N = 45)	107.14 ± 0.00	11.10 ± 2.19	11.15 ± 2.04	11.31 ± 2.12	9.89 ± 2.90	41.15 ± 3.73	60.54 ± 6.83
Total	109.84 ± 12.69	10.35 ± 1.96	10.85 ± 1.86	11.51 ± 2.14	10.14 ± 2.53	41.03 ± 4.95	59.88 ± 6.77
P	0.832	0.07	0.48	0.653	0.624	0.895	0.521

Table 3: Currently common applied methods to treat byproducts at the PUACs.

Treatment methods	PUACs associated with cattle husbandry (N = 45)		PUACs not associated with cattle husbandry (N = 45)		Total (N = 90)	
	Quantity	%	Quantity	%	Quantity	%
Release into land for soil improvement	28	62.22^{b}	26	57.78^{ab}	54	60.00^{a}
Burning	15	33.33^{c}	32	71.11^{a}	47	52.22^{ab}
Cattle's feed	44	97.78^{a}	0	0.00^{d}	44	48.89^{ab}
Supplying/selling to neighboring cattle households/farms	13	28.89^{cd}	21	46.67^{b}	34	37.78^{b}
Compost fertilizer	0	0.00^{e}	13	28.89^{c}	13	14.44^{c}
Deep litter materials	5	11.11^{de}	0	0.00^{d}	5	5.57^{d}

Percentages with different superscript letters within a column differ (P < 0,001).

Part 2: Important chemical compositions and nutritional values of some common major agricultural byproducts

Regarding the forage group, PV (20.19% CP/DM), SPV (19.83% CP/DM) and PFP (10.62% CP/DM) contained quite high CP content compared to Napier grass (or King grass, 10.13% CP/DM), while the CP of SSPF (17.87% CP/DM) in the concentrate group were higher than that of commercial complete feed (16.50% CP/VKC) (Table 5; P < 0.001). Regarding EE value, PV (5.94%/DM) and SPV (4.09%/DM) in the forage group were higher than the Napier grass (2.64%), while the EE of SSSPT

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Table 4: Personal viewpoints from representatives of PUACs on the byproducts used as animal feed (N = 90 PUACs).

Personal viewpoint indicators about:	Classifications	Quantity	%	P
Effectiveness of currently applied byproduct treatment methods	Effective	51	56.67^{a}	< 0.01
	Ineffective and wasteful	35	38.89^{b}	
	unconcerned	4	4.44^{c}	
Using the byproducts as feed for cattle	Reduction of the feed cost	90	100.00^{a}	< 0.01
	Support to solve feed shortages	88	97.78^{ab}	
	Concerns about residual pesticides	81	90.00^{b}	
	Concerns about unsuitability/quality for cattle's feed	6	6.67^{c}	
Finding potential treatment solutions to increase the value/suitability/quality of byproducts for cattle feed	Necessary	90	100.00^{a}	< 0.01
	Unnecessary	0	0.00^{b}	

$^{a-c}$Values within each parameter with different superscript letters differ (P < 0.01).

Table 5: Chemical compositions of currently common byproducts with high potential as beef cattle feed.

Feed type	Ingredient	DM (%)	CP (% DM)	EE (% DM)	CF (% DM)	NDF (% DM)	ADF (% DM)	Starch (% DM)	Sugar (% DM)	Ca (% DM)	P (% DM)	Ash (% DM)
Forage	Napier grass	14.98 ± 0.86^{cd}	10.13 ± 0.68^{b}	2.64 ± 0.33^{bc}	33.15 ± 1.25^{a}	65.02 ± 1.35^{a}	40.22 ± 0.72^{ab}	0.00 ± 0.00^{b}	7.22 ± 0.71^{abc}	1.19 ± 0.56^{b}	1.03 ± 0.62	9.69 ± 1.34^{bc}
	PFP	13.80 ± 1.05^{d}	10.62 ± 1.46^{b}	1.22 ± 0.35^{cd}	30.70 ± 2.98^{ab}	45.87 ± 7.60^{b}	35.67 ± 4.30^{bc}	0.00 ± 0.00^{b}	12.30 ± 5.20^{a}	1.05 ± 0.60^{b}	0.71 ± 0.54	8.71 ± 1.85^{c}
	CPH	21.42 ± 0.94^{b}	8.00 ± 0.91^{bc}	0.67 ± 0.20^{d}	36.94 ± 1.86^{a}	49.12 ± 5.11^{b}	44.96 ± 3.33^{a}	1.06 ± 0.26^{ab}	10.55 ± 4.86^{ab}	0.76 ± 0.17^{b}	0.16 ± 0.04	8.88 ± 1.10^{c}
	SPV	14.77 ± 1.00^{d}	19.83 ± 1.10^{a}	4.09 ± 0.50^{b}	24.03 ± 2.58^{c}	38.09 ± 3.17^{b}	31.23 ± 2.11^{c}	0.28 ± 0.49^{ab}	5.55 ± 0.88^{abc}	2.43 ± 1.11^{ab}	0.78 ± 0.27	11.63 ± 0.85^{bc}
	PV	18.28 ± 1.26^{bc}	20.19 ± 1.36^{a}	5.94 ± 1.24^{a}	25.11 ± 3.67^{bc}	40.37 ± 2.66^{b}	33.15 ± 0.80^{c}	3.24 ± 2.77^{a}	3.04 ± 2.65^{bc}	3.19 ± 0.76^{a}	0.97 ± 0.23	16.08 ± 1.61^{a}
	Rice straw	87.54 ± 1.97^{a}	4.18 ± 0.51^{c}	0.91 ± 0.13^{d}	36.02 ± 1.10^{a}	69.76 ± 3.09^{a}	54.54 ± 0.99^{ab}	0.25 ± 0.43^{ab}	0.29 ± 0.50^{c}	1.03 ± 0.42^{b}	0.23 ± 0.09	12.98 ± 0.73^{ab}
	P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.036	0.005	0.004	0.054	< 0.001
Concentrate	CCF	87.00 ± 1.00^{a}	16.50 ± 0.50^{a}	4.23 ± 0.31^{b}	14.17 ± 0.76^{a}	29.47 ± 3.05^{a}	11.33 ± 2.39^{a}	28.73 ± 4.94^{b}	5.30 ± 1.20^{b}	1.10 ± 0.52	0.70 ± 0.45	8.18 ± 1.57^{a}
	SSSPT	32.42 ± 2.24^{b}	5.96 ± 0.58^{b}	8.70 ± 1.01^{a}	3.19 ± 0.79^{b}	5.36 ± 1.14^{b}	0.64 ± 1.11^{b}	71.89 ± 4.50^{a}	10.64 ± 5.37^{ab}	0.52 ± 0.33	0.58 ± 0.42	3.22 ± 0.55^{b}
	SSPF	9.55 ± 0.67^{c}	17.87 ± 1.34^{a}	8.05 ± 1.27^{a}	14.24 ± 2.31^{a}	22.53 ± 3.99^{a}	15.97 ± 2.05^{a}	15.35 ± 2.72^{c}	19.85 ± 4.80^{a}	0.52 ± 0.15	0.53 ± 0.09	8.85 ± 0.90^{a}
	P	< 0.001	< 0.001	0.002	< 0.001	< 0.001	0.001	< 0.001	0.015	0.166	0.844	0.001

Notes: PFP, passion fruit peel; CPH, cocoa pod husk; SPV, sweet potato vine; PV, pumpkin vine; CCF, commercial complete feed; SSSPT, sub-standard sweet potato tuber; SSPF, sub-standard pumpkin fruit; DM, dry matter; CP, crude protein; EE, ether extract; CF, crude fiber; NDF, neutral detergent fiber; ADF, acid detergent fiber; Ca, calcium; P, phosphorus. Different superscripts indicate significant differences in each type of feed (P < 0.01; three replicates for each byproduct).

(8.70%/DM) and SSPF (8.05%/DM) in the concentrate were higher than that of the commercial complete feed (4.23%/DM) (P < 0.01). Similarly, PV (3.24%/DM), CPH (1.06%/DM), SPV (0.28%/DM) and RS (0.25%/DM) had higher starch content than that of the Napier grass (0.00%/DM), while the starch of SSSPT (71.89%/DM) was higher than that of the complete feed (28.73%/DM) (P < 0.05). PFP (12.30%/DM) and CPH (10.55%/DM) had a higher total sugar ratio than that of the Napier grass (7.22%/DM), while the total sugar of SSPF (19.85%/DM) and SSSPT (10.64%/DM) was higher than that of the complete feed. PV (3.19 %/DM) and SPV (2.42%/DM) had higher calcium value than that of the Napier grass (1.19%/DM), but the calcium of SSSPT (0.52%/DM) and SSPF (0.52%/DM) were lower than that of the complete feed (1.10%/DM). PV (16.8%/DM), RS (12.98%/DM) and SPV (11.63%/DM) had higher total ash than that of the Napier grass (9.69%), while the total ash of SSPF (8.85%/DM) was higher than that of the complete feed (8.18%/DM) (P = 0.001).

In contrast, SPV (24.03%/DM), PV (25.11%/DM) and

PFP (30.70%/DM) had lower CF value than that of the Napier grass (33.15%/DM), while the CF of SSSPT (3.19%/DM) was lower than that of the commercial complete feed (14.17%/DM) (P < 0.001; Table 5). SPV (38.09%/DM), PV (40.37%/DM), PFP (45.87%/DM) and CPH had lower NDF than that of the Napier grass (65.02%/DM), while the NDF of SSSPT (5.39%/DM) and SSPF (22.53%/DM) were lower than the complete feed (29.47%/DM) (P < 0.001). SPV (31.23%/DM), PV (33.15%/DM) and PFP (35.67%/DM) contained lower ADF than that of the Napier grass (40.22%/DM) (P < 0.001), while the ADF of SSSPT (0.64%/DM) was lower than that of the complete feed (11.33%/DM) (P < 0.001). There were no differences in the P ratio among these ingredients (P > 0.05) in the forage and concentrate groups.

Furthermore, SPV (61.99%), PV (61.01%), and PFP (55.49%) had a higher proportion of total digestible nutrients (TDN) than that of the Napier grass (54.33%), while the TDN of SSSPT (92.67%) and SSPF (76.97%) were higher than that of the complete feed (73.58%) (Table 6; P < 0.001). Regarding ME values, SPV (2,236.5 kcal/kg DM), PV (2,201.3 kcal/kg DM) and PFP (2,002.2 kcal/kg DM) were higher than that of the Napier grass (1,960.0 kcal/kg DM), while the ME of SSWP (3,343.4 kcal/kg DM) and SSPF (2,777.2 kcal/kg DM) were higher than that of the complete feed (2,654.7 kcal/kg DM) (P < 0.001).

Part 3: *In vitro* gas emission of the common agricultural byproducts

Total quantity of gas emission of forage group at 12 hours of in vitro incubation was highest with cocoa pod husk (107.50ml), followed by passion fruit peel (98.30ml), pumpkin vine (83.30ml), Napier grass (63.33ml), sweet potato vine (60.00ml), and the lowest one from rice straw (35.83ml) (P = 0.001; Table 7). After 24 hours, passion fruit peel (483.30ml) was the highest byproduct for total

Table 6: Nutritional value of currently common byproducts with high potential as beef cattle feed.

Feed type	Ingredient	n (replicates)	Total digestible nutrients (TDN, % DM)	Metabolizable energy (ME, kcal/kg DM)
Forage	Napier grass	3	54.33 ± 1.12^{bc}	$1{,}960.3 \pm 140.6^{bc}$
	Passion fruit peel	3	55.49 ± 3.62^{abc}	$2{,}002.2 \pm 130.6^{abc}$
	Cocoa pod husk	3	48.39 ± 2.42^{c}	$1{,}781.5 \pm 87.4^{c}$
	Sweet potato vine	3	61.99 ± 2.40^{a}	$2{,}236.5 \pm 86.6^{a}$
	Pumpkin vine	3	61.01 ± 3.49^{ab}	$2{,}201.3 \pm 125.9^{ab}$
	Rice straw	3	41.15 ± 1.72^{d}	$1{,}473.6 \pm 147.9^{c}$
	P-Forage		< 0.001	< 0.001
Concen-trate	Commercial complete feed	3	73.58 ± 0.77^{b}	$2{,}654.7 \pm 27.7^{b}$
	Sub-standard sweet potato tuber	3	92.67 ± 0.39^{a}	$3{,}343.4 \pm 140.3^{a}$
	Sub-standard pumpkin fruit	3	76.97 ± 3.75^{b}	$2{,}777.2 \pm 135.2^{b}$
	P-Concentrate		< 0.001	< 0.001

Different superscripts indicate significant differences in each type of feed (P < 0.01).

Table 7: Total quantity of gas produced by byproducts at different times of in vitro incubation.

Feed type	Ingredient	n (replicates)	Total quantity (ml) of gas emission at different times	
			12 hours	24 hours
Forage	Napier grass	6	63.33 ± 19.66^{ab}	261.70 ± 64.30^{b}
	Passion fruit peel	6	98.30 ± 42.60^{a}	483.30 ± 119.60^{a}
	Cocoa pod husk	6	$107.50 \pm 36.^{6}a$	314.20 ± 74.70^{b}
	Sweet potato vine	6	60.00 ± 20.00^{ab}	235.00 ± 48.50^{bc}
	Pumpkin vine	6	83.30 ± 25.80^{ab}	275.00 ± 41.80^{b}
	Rice straw	6	35.83 ± 17.44^{b}	118.30 ± 31.90^{c}
	P-Forage		0.001	< 0.001
Concentrate	Commercial complete feed	6	500.00 ± 63.20^{c}	$1{,}136.70 \pm 69.50^{b}$
	Sub-standard sweet potato tuber	6	691.70 ± 49.20^{b}	$1{,}366.70 \pm 60.60^{a}$
	Sub-standard pumpkin fruit	6	860.00 ± 123.3^{a}	$1{,}511.70 \pm 177.80^{a}$
	P-Concentrate		< 0.001	< 0.001

Different superscripts indicate significant differences in each type of feed (P < 0.01).

Table 8: CH_4 emission from these byproducts at different times of in vitro incubation.

Feedtype	Ingredient	Methane production		
		Percentage (%)	Volume (ml)	Volume from 1g of ingredients (ml/g DM)
Methane production at 12 hours of incubation				
Forage	Napier grass	2.33 ± 0.29	1.50 ± 0.57^{ab}	0.12 ± 0.05^{ab}
	Passion fruit peel	2.30 ± 0.88	2.48 ± 1.92^{ab}	0.21 ± 0.16^{ab}
	Cocoa pod husk	2.70 ± 0.52	3.03 ± 1.34^{a}	0.25 ± 0.11^{a}
	Sweet potato vine	2.25 ± 0.39	1.36 ± 0.57^{ab}	0.11 ± 0.04^{ab}
	Pumpkin vine	2.35 ± 0.23	2.00 ± 0.74^{ab}	0.17 ± 0.06^{ab}
	Rice straw	1.92 ± 0.89	0.80 ± 0.68^{b}	0.07 ± 0.06^{b}
	P-Forage	0.407	0.017	0.017
Concentrate	Commercial complete feed	3.14 ± 0.62	15.93 ± 4.79^{b}	1.33 ± 0.40^{b}
	Sub-standard sweet potato tuber	2.36 ± 0.32	16.42 ± 3.33^{b}	1.37 ± 0.27^{b}
	Sub-standard pumpkin fruit	2.90 ± 0.58	25.05 ± 6.31^{a}	2.09 ± 0.52^{a}
	P-Concentrate	0.057	0.010	0.010
Methane production at 24 hours of incubation				
Forage	Napier grass	9.04 ± 1.31^{ab}	24.24 ± 9.24^{ab}	2.02 ± 0.77^{ab}
	Passion fruit peel	5.96 ± 0.78^{c}	29.38 ± 0.17^{a}	2.45 ± 0.85^{a}
	Cocoa pod husk	7.58 ± 1.32^{bc}	24.40 ± 8.04^{ab}	2.03 ± 0.67^{ab}
	Sweet potato vine	6.81 ± 1.02^{bc}	16.18 ± 4.43^{b}	1.35 ± 0.37^{b}
	Pumpkin vine	8.02 ± 0.82^{abc}	22.00 ± 3.71^{ab}	1.83 ± 0.31^{ab}
	Rice straw	10.20 ± 1.97^{a}	12.39 ± 4.90^{b}	1.03 ± 0.41^{b}
	P-Forage	< 0.001	0.004	0.004
Concentrate	Commercial complete feed	4.07 ± 0.41^{a}	46.31 ± 5.95^{ab}	3.86 ± 0.50^{ab}
	Sub-standard sweet potato tuber	2.66 ± 0.23^{b}	36.41 ± 4.09^{b}	3.03 ± 0.34^{b}
	Sub-standard pumpkin fruit	3.76 ± 0.48^{a}	57.02 ± 0.85^{a}	4.75 ± 0.90^{a}
	P-Concentrate	< 0.001	0.001	0.001

Different superscripts indicate significant differences in each type of feed ($P < 0.01$; n = 6 replicates).

gas emission, followed by cocoa pod husk (314.20ml), pumpkin vine (275.00ml), Napier grass (261.70ml), sweet potato vine (235.00 ml) and the lowest one from rice straw (118.30ml) ($P < 0.001$). Regarding the concentrate group, the total quantity of gas emission at 12 hours of in vitro incubation was highest with sub-standard pumpkin fruit (860.00ml), followed by sub-standard sweet potato tuber (691.70ml), and lowest one from commercial complete feed (500.00ml) ($P < 0.001$; Table 7), while it also found the same trend in these three feeds at 24 hours (1,511.70; 1,366.70 and 1,136.70; respectively).

Ratios of methane emission from the total gas emission at 12 hours of different ingredients in forage or concentrate were quite similar in each group ($P > 0.05$; Table 8). The volume of methane production and quantity of methane/g dry matter were highest at cocoa pod husk (3.03ml and 0.25 ml/g DM, respectively), followed by passion fruit peel (2.48ml and 0.21 ml/g DM, respectively), pumpkin vine (2.00ml and 0.17 ml/g DM, respectively), Napier grass (1.50ml and 0.12 ml/g DM, respectively), sweet potato vine (1.36ml and 0.11 ml/g DM, respectively), and the lowest one from rice straw (0.80ml and 0.07 ml/g DM, respectively) ($P < 0.05$; Table 8). On the concentrate group, sub-standard pumpkin fruit (25.05ml and 2.09 ml/g DM, respectively) was the highest ingredient for the volume of methane production and quantity of methane/g dry matter, followed by sub-standard sweet potato tuber (16.42ml and 1.37 ml/g DM, respectively) and the lowest one from commercial complete feed (15.93ml and 1.33 ml/g DM, respectively) ($P = 0.01$).

After 24 hours of in vitro incubation, the ratios of methane emission of different ingredients in forage or concentrate were significantly different in each group ($P < 0.001$; Table 8). Especially, passion fruit peel (29.38ml and 2.45 ml/g DM, respectively) was the highest ingredient for the volume of methane production and quantity of methane/g dry matter in forage group, followed by cocoa pod husk (24.40ml and 2.03 ml/g DM, respectively), Napier grass (24.24ml and 2.02 ml/g DM, respectively), pumpkin vine (22.00ml and 1.83 ml/g DM, respectively), sweet potato vine (16.18ml and 1.35 ml/g DM, respectively) and the lowest one from rice straw (12.39ml and 1.03 ml/g DM, respectively) ($P < 0.01$). In the concentrate group, sub-standard pumpkin fruit (57.02ml and 4.75 ml/g DM, respectively) was the highest ingredient for the volume of methane production and quantity of methane/g dry matter, followed by commercial complete feed (46.31ml and 3.86 ml/g DM, respectively) and the lowest one from sub-standard sweet potato tuber (36.41ml and 3.03 ml/g DM, respectively) ($P < 0.01$).

DISCUSSION

In recent years, Vietnam faces a growing shortage of livestock feed, particularly forage resources, especially during the dry season (Nguyen *et al*., 2021a, 2025b). This situation is driven by the gradual reduction of grassland area and the rising cost of imported feed ingredients (Hoai, 2022), both of which have had- and will continue to have- a significant impact on the local cattle industry. A previous study reported that approximately 47.78% of beef cattle households experienced forage shortages and primarily relied on untreated rice straw as the most practical solution (Nguyen *et al*., 2025a), despite its inherently low nutritional value (Nguyen *et al*., 2025b). This highlights the urgent need to identify alternative agricultural byproducts with higher nutritional potential to supplement or replace the untreated rice straw, thereby contributing to the sustainable development of the cattle production system.

Part 1 of the survey revealed that agricultural production activities at production units in agricultural crops (PUACs) in Lam Dong have considerable potential for development. Most PUAC owners have been engaged in the agricultural crop production for over six years, possess educational backgrounds ranging from secondary/high school to college/university levels, and rely predominantly on family labor. Consequently, the byproducts generated from these PUACs are expected to remain stable in the coming years. Among the most common byproducts identified were the SSSPT, SPV, SSPF, PV, PFP and CPH, in addition to the RS. Notably, the RS appeared to be the most abundant byproduct in Lam Dong, with a byproduct to main product ratio exceeding 100%, consistent with a previous report by Tran *et al*. (2014), which recorded ratios ranging from 92 to 133%. Besides, production activities related to passion fruit, cocoa, sweet potato tubers and pumpkins also yielded substantial quantities of byproducts, with PFP and CPH exceeding 41% and SSPF, PV, SSSPT, and SPV exceeding 21% relative to their respective main products. However, more than 52% of these byproducts have been currently burned or wastefully discarded into the land without reuse, similar to earlier findings (Nguyen, 2008) where approximately 60% of agricultural by-products were not re-utilized, primarily due to concerns regarding their suitability or quality as cattle feed and potential pesticide residues. Such practices not only waste valuable resources but also negatively impact the living environment (Riseh *et al*., 2024). Therefore, these locally available byproducts represent a stable and promising alternative to address forage shortages for beef cattle in Lam Dong and, more broadly, across Vietnam.

Furthermore, the findings from Part 2 of this investigation showed that the chemical compositions and nutritional values of SPV, PV, PFP and CPH were superior to those of RS and comparable to Napier grass, while the nutrient profiles of SSSPT and SSPF closely resembled those of the commercial complete feed. Although RS is an abundant and inexpensive byproduct in Lam Dong and across Vietnam, it is classified as low-quality forage due to its poor nutrient content and low digestibility when left untreated (Phuong *et al*., 2024; Nguyen *et al*., 2025b). Recently, there have been many studies indicating that excessive inclusion of untreated RS in cattle diets can limit growth performance (Trach *et al*., 2001; Malik *et al*., 2015; Aquino *et al*., 2020; Phuong *et al*., 2024; Nguyen *et al*., 2025b). The nutritional analyses in the current study have shown that the important nutrients (including CP, EE, CFF, NDF, ADF, starch, and ash) as well as the total digestible nutrients and metabolizable energy were significantly higher in the SPV and PV than in Napier grass. It has also been demonstrated that the SPV or PV (including leaf and stem), separated from the root after harves, have been recognized as valuable forage sources for ruminants due to their high protein content and favorable nutrient balance (Ali *et al*., 2019; Deng *et al*., 2023). Similarly, the PFP is considered as the potential forage for cattle in previous years due to its beneficial nutrient composition (Correddu *et al*., 2020; Tran *et al*., 2020; Belmonte-Herrera *et al*., 2022). And the CPH has drawn increasing interest as a potential ruminant feed resource (Oduro-Mensah *et al*., 2020; Mael, 2024). In addition, the SSSPT and SSSF present promising concentrate feed alternatives for cattle due to high nutritional values, total digestible nutrients and metabolizable energy (Nguyen *et al*., 2021a; Valdez-Arjona and Ramírez-Mella, 2019). Therefore, the byproducts from PUACs are not only locally available but also possess favorable nutritional profiles, making them potentially well-suited for use in smallholder livestock systems through a low-cost, highly accessible, and practical approach.

Moreover, the findings from Part 3 of this investigation indicated that there was a substantial variation in gas/methane emission from different forage and/or concentrate ingredients, probably due to different chemical compositions, digestibility and ruminal fermentation characteristics of agricultural by products (García-Rodríguez *et al*., 2019; Pratama *et al*., 2022; Khairul *et al*., 2024). Among the forage group, the SPV emerged as the most valuable byproduct for mitigating total gas and methane emissions from ruminal fermentation as compared to other byproducts and even Napier grass, owing to its superior nutrient profile. Previous studies have reported that incorporating SPV at 15-20% of total dry matter intake can reduce methane production by 12-18%, largely due to enhanced fiber digestibility and its high polyphenol and flavonoid contents (Tadesse *et al*., 2024; Astati *et al*., 2025). The other byproducts investigated, including the PV, PFP and CPH, also exhibited notable potential for methane mitigation. It has also been demonstrated that PFP has been shown to contain bioactive compounds (such as flavonoids, polyphenols and/or tannins) which can have a positive effect on the ruminal microbiota and fermentation, as well as nutrient digestibility, consequently in the methane reduction (García-Rodríguez *et al*., 2019; Wanapat *et al*., 2024). Likewise, the CPH has been recognized for its potential to improve digestibility and lower methane output when appropriately processed and incorporated at optimal inclusion rates in ruminant diets (Laconi and Jayanegara, 2015; Dahunsi *et al*., 2019; Mael, 2024). In addition, the figures associated with methane production in the current study have demonstrated that SSSPT demonstrated strong methane mitigation potential, besides a noteworthy reduction capacity from the sub-standard pumpkin fruit as compared to the complete feed. In Vietnam, there have been some studies indicating that SSSPT has previously been identified as a viable methane-reducing feed ingredient in Boer crossbred goats (Truong and Tuan, 2024) or in high-yielding beef cattle when subjected to heat treatment, resulting in lower gas/methane emissions per unit of product (Nguyen *et al*., 2022).

However, the present study has only focused on the individual analysis of the chemical compositions, nutritional values and *in vitro* gas emission of the potential locally available agricultural byproducts rather than comprehensively evaluating their combination within one diet. Therefore, further investigations are urgently required to determine the optimal substitution levels of these byproducts based on the results from this current study for high-cost conventional ingredients, and to assess their impacts on growth performance and health of beef cattle. Additionally, investigations should be directed toward developing nutritionally balanced mixed feeds from these byproducts that are suitable for long-term storage at ambient temperature to minimize the feed cost for the beef cattle industry, especially household beef cattle farms.

CONCLUSIONS AND RECOMMENDATIONS

In summary, among the evaluated byproducts, sweet potato vine exhibited the highest potential among forage options, followed by pumpkin vine, passion fruit peel, and cocoa pod husk. These forages can serve as promising alternatives to untreated rice straw and may partially replace Napier grass in beef cattle diets. In the concentrate, sub-standard sweet potato tuber ranked highest in potential, followed by sub-standard pumpkin fruit, both of which can partially substitute for commercial complete feed on smallholder beef cattle farms. Notably, sweet potato vine and pumpkin vine in the forage, as well as sub-standard sweet potato tuber in the concentrate, showed not only favorable nutritional profiles but also significant potential for mitigating methane emissions. These results indicate that these selected PUAC byproducts can be feasibly applied in household cattle farms, offering a low-cost, accessible, and practical feed resource that supports both productivity and environmental sustainability in the beef cattle industry of Vietnam.

However, further research is required to explore, in greater depth and comprehensiveness, the formulation of nutritionally balanced mixed feeds from these byproducts that can be stored for extended periods at ambient temperature. Such studies should also evaluate the efficacy and optimal substitution levels of incorporating these byproducts into beef cattle diets on growth performance and overall health.

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NOVELTY STATEMENT

This study is the first to comprehensively evaluate individually common agricultural byproducts in Lam Dong province, Vietnam, as beef cattle feed, assessing both nutritional profiles and *in vitro* methane reduction potential. It identifies sweet potato vine, pumpkin vine, passion fruit peel, cocoa pod husk, sub-standard sweet potato tuber, and sub-standard pumpkin fruit as sustainable, cost-effective alternatives to conventional feed ingredients, with additional benefits of reducing methane emissions.

AUTHOR'S CONTRIBUTION

HTN and LVN: Responsible for the experimental, conceptualization, design, formal analysis, manuscript preparation, writing review and editing. PBTL, TPP, DKTN, NMTN and ANTD: contributed to the experimental design adjustment, field survey, collecting and analyzing data.

Generative AI and AI-assisted technology statement

The authors acknowledge that generative AI and AI-assisted technologies (such as Grammarly and ChatGPT) were used only to improve English grammar and minimize mistakes in this manuscript to ensure better quality. No AI technologies were used to generate, analyze, or interpret scientific data. The authors take full responsibility for the content and conclusions of this final manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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