

## Research Article

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# Optimal inclusion levels of palm kernel cake in diets for large and small ruminants: a meta-analysis

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**Abstract:** Inclusion of palm kernel cake (PKC) in ruminant diets is limited mainly due to inconsistent findings on its effects and optimal level. This meta-analysis evaluated the effects of PKC inclusion on performance, nutrient intake, nutrient digestibility, rumen fermentation, carcass traits, and milk production, and determined its optimal levels. A total of 51 papers were systematically selected from Google Scholar, ScienceDirect, and Springer Link following the PRISMA guidelines. The dataset was analyzed using the PROC MIXED procedure in SAS® OnDemand for Academics, with study variation treated as random effects, and PKC inclusion level as fixed effects. In large ruminants, PKC inclusion exhibited a quadratic effect ( $p < 0.05$ ) on crude protein intake (CPI), dry matter digestibility (DMD), and crude protein digestibility (CPD). However, dry matter intake (DMI) and average daily gain (ADG) were unaffected ( $p > 0.05$ ). In small ruminants, PKC inclusion had no significant effect ( $p > 0.05$ ) on DMI and CPI. Nonetheless, it exhibits a quadratic

influence on ADG ( $p < 0.05$ ). Optimal inclusion levels were defined as those providing the best production response (highest ADG and lowest FCR) while maintaining stable nutrient utilization. Optimal inclusion levels were identified as 106 g/kg DM (small ruminants) and 115 g/kg DM (goats) based on ADG, 139 g/kg DM (small ruminants) and 101 g/kg DM (sheep) based on feed conversion ratio (FCR), and 65 g/kg DM (dairy cattle) based on DMI. Optimal PKC inclusion levels maintain stable intake, growth performance, and production in both large and small ruminants despite its low palatability, whereas excessive levels may impair overall utilization. These findings provide evidence-based guidance for optimizing PKC use in ruminant diets and advancing sustainable livestock production systems.

**Keywords:** feed conversion; nutrient digestibility; meta-analysis; byproduct utilization; sustainability; ruminant

## 1 Introduction

Oil palm (*Elaeis guineensis* Jacq.), one of the world's most important commodities, generates tons of byproducts as potential feed ingredients [1, 2]. Palm kernel cake (PKC), a major by-product of the palm oil industry, is notable for both its quantity and nutritional value [3]. PKC contains 89.11–93.88 % DM, 93.95–96.77 % organic matter (OM), 16.5–22.51 % crude protein (CP), 2.91–9.66 % ether extract (EE), 59.9–78.9 % neutral detergent fiber (NDF), 40.56–52.7 % acid detergent fiber (ADF), 3.23–4.52 % mineral, 0.33–0.7 % calcium (Ca), and 0.56–0.69 % phosphorus (P) [4–9].

Given these characteristics, PKC represents a valuable feed ingredient for farmers in major palm oil-producing countries, including Indonesia, Malaysia, Thailand, Nigeria, Colombia, and Guatemala [10]. Over the past few decades, PKC has been widely used as a source of fiber, energy, and protein for cattle [11, 12], buffaloes [5, 13], goats [14, 15], and sheep [16, 17]. Optimizing non-conventional diet ingredients from agricultural byproducts is an efficient

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and sustainable strategy for ruminant diets. This aligns with the Sustainable Development Goals (SDGs), emphasizing efficient diet resources and a zero-waste production system [18]. Despite its potential, PKC is often associated with several disadvantages, such as high fiber content that may limit digestibility. PKC has 13.52–19.27% lignin [5–7, 11, 12] that resists degradation by rumen microorganisms [19]. This condition limits the utilization of the nutrients contained in PKC.

The dietary inclusion of PKC was generally associated with a linear decline in dry matter and nutrient intake [11, 20], body weight gain [12], and the nutrient digestibility of cattle [11, 21]. In small ruminants, such as goats, PKC reduced dry matter and nutrient intake [14, 22, 23], nutrient digestibility [6, 22, 23], and milk production [14]. Various studies have explored the use of PKC at different levels; however, the results remain inconsistent. For instance, Sani et al. [24] reported stable DMI at PKC levels of 50–200 g/kg DM using *Digitaria smutsii* hay as the basal diet, while Cruz et al. [25] (70–210 g/kg DM PKC; Tifton-85 grass hay) found a linear decline. Likewise, Lisboa et al. [11] and Santos et al. [26] (80–240 g/kg DM PKC; sugarcane bagasse) both observed decreasing DMI; however, ADG was unchanged in Lisboa et al. but exhibited a quadratic response in Santos et al., presenting contrasting findings. Including 80–240 g/kg DM PKC in the goats' diet decreased DM intake [14], where the basal diet was mainly composed of maize silage. Interestingly, contrasting results were discovered at approximately the same level (70–210 g/kg DM). Ribeiro et al. [6] and Oliveira et al. [27] found that PKC inclusion did not affect the DMI of goats using *Cynodon dactylon* and Tifton-85 grass hay-based diets.

These discrepancies highlight the need for a more rigorous and integrative approach to obtain a more accurate understanding. Furthermore, a firm conclusion on the optimal level of PKC remains difficult to determine, suggesting the need for more comprehensive meta-analysis approaches to tackle this issue. Meta-analysis offers a powerful approach to analyzing data from multiple studies, providing more reliable conclusions by integrating data from multiple sources [28]. This method has been widely used in ruminant nutrition research [29–32]. More comprehensible conclusions and comprehensive findings provide valuable insights for farmers and policymakers, encouraging informed decision-making.

Vargas and Mezzomo [33] conducted a meta-analysis to determine the optimal PKC inclusion levels in confined and grazing cattle diets. They found that the optimal level for confined cattle was 110.6 g/kg DM without affecting DMI. To our knowledge, no studies have assessed the optimal level of PKC inclusion for other ruminants, such as dairy cattle,

goats, and sheep, using a meta-analysis approach. This study extends previous work by integrating data across ruminant species and emphasizing the sustainable use of PKC as a local feed resource.

Therefore, the present study aimed to systematically and quantitatively assess the effects of PKC on ruminant performance and productivity through a meta-analysis, providing a recommended optimal level of PKC inclusion for large and small ruminants. This study establishes optimal inclusion levels of PKC in ruminant diets, contributing to improved feeding efficiency and sustainable farming practices.

## 2 Materials and methods

### 2.1 Literature search

This meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol [34, 35]. A comprehensive search of the research papers was conducted using the keywords 'palm kernel cake' and 'ruminant' to identify relevant studies related to the effects of PKC on ruminant performance, nutrient utilization, and production. The keywords were entered into three international scientific databases: Google Scholar (<https://scholar.google.com/>), ScienceDirect (<https://www.sciencedirect.com/>), and Springer Link (<https://link.springer.com/>). This process resulted in 980 papers from Google Scholar, 495 papers from Science Direct, and 633 papers from Springer Link. ScienceDirect allows the screening process to be conducted directly on its platform; thus, 303 papers were retained for further selection.

### 2.2 Selection process and inclusion criteria

This process was conducted to obtain papers aligned with the research objectives and carried out objectively and transparently according to the PRISMA guidelines. Papers retrieved using the specified keywords were entered into a Microsoft Excel<sup>®</sup> Sheet 2021 (Microsoft Corp, Redmond, WA, USA). Duplicate papers were identified using the Pivot-Table function in Microsoft Excel<sup>®</sup> Sheet 2021. A total of 106 papers were excluded during the screening process. Subsequently, the selection continued by assessing the relevance of each study based on its title and abstract. Through this process, 132 potential papers were subjected to full-text eligibility assessment using Mendeley Desktop 1.19.8 software. The full-text screening adhered to the following inclusion criteria; (i) papers reporting *in vivo* trials of PKC inclusion in ruminants, (ii) papers that reported or allowed

calculation of PKC inclusion levels in ruminant diets, (iii) papers published in English, (iv) peer-reviewed papers published in reputable journals, (v) no restriction on publication year, and (vi) papers with full-text availability. A total of 51 papers met the eligibility criteria and were included in the meta-analysis. The PRISMA flow diagram illustrating the selection process is presented in Figure 1.

The PICO elements of this meta-analysis were defined as follows. The population included ruminant species such as cattle, buffalo, goats, and sheep. The intervention was the PKC inclusion level. The comparator was a control diet without PKC or, when unavailable, the diet with the lowest inclusion level within each study. The outcomes evaluated animal performance, nutrient intake, nutrient digestibility, rumen fermentation, carcass traits, and milk production.

### 2.3 Data extraction

The dataset was compiled from a total of 51 peer-reviewed research papers. Among these, 26 studies investigated the inclusion of PKC in diets of large ruminants (cattle and buffaloes), whereas the remaining 25 studies focused on small ruminants (goats and sheep). Considering that large and small ruminants differ in body size and physiological performance, the current meta-analysis was conducted separately for each group. A summary of the 26 studies on large ruminants and 25 on small ruminants is presented in Table 1, which includes the authors' names, year of publication, basal diet, animal type and breed, and country.

Descriptive statistics of the dataset, including mean, standard deviation, minimum, and maximum values, for large and small ruminants are presented in Table 2 and Table 3, respectively. Moreover, the chemical composition of PKC used in the included studies is summarized in Table 4.

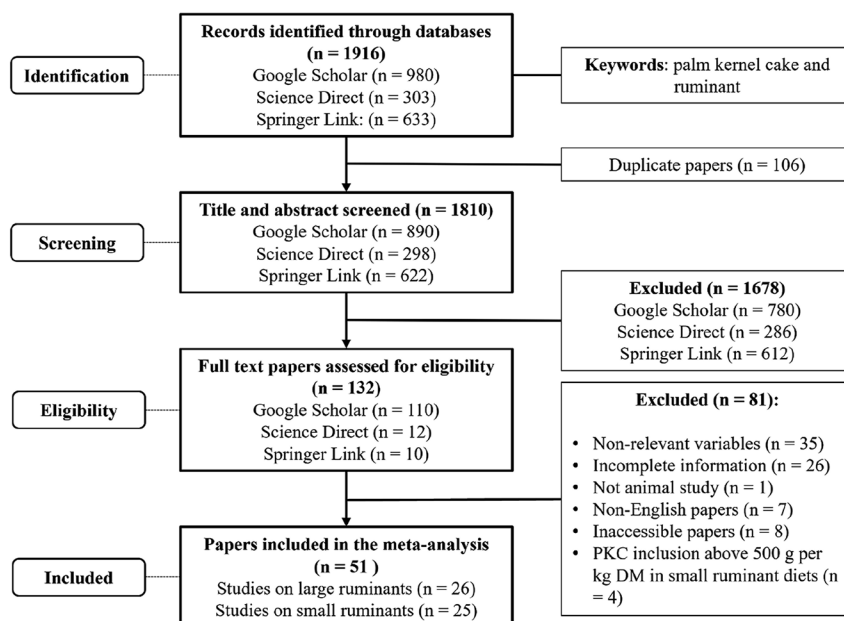
Detailed outcome data were also extracted, including nutrient intake, body weight gain, ADG, feed conversion ratio, feed efficiency, carcass production, and milk production as the primary outcomes, as they represent the direct production response to PKC inclusion. The secondary outcomes included nutrient digestibility, rumen fermentation, carcass composition, and milk composition, which describe physiological or metabolic responses. Some variables were reported in different units across studies. To ensure consistency, all values were converted into common units. PKC inclusion levels reported as percentages were converted to g/kg of dietary DM.

### 2.4 Statistical analysis

The database was analyzed using the mixed model methodology [68] in SAS<sup>®</sup> OnDemand for Academics. The different study was treated as a random effect, while the PKC inclusion level was treated as a fixed effect. The statistical model used was:

$$Y_{ij} = B_0 + B_1X_{ij} + s_i + b_iX_{ij} + e_{ij}$$

where  $Y_{ij}$  = dependent variable;  $B_0$  = overall intercept;  $B_1$  = linear regression coefficient of  $Y$  on  $X$ ;  $X_{ij}$  = value of the continuous predictor variable;  $s_i$  = random effect of study  $i$ ;



**Figure 1:** The preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram of the selection process.

**Table 1:** Description of the studies included in the database.

References	Basal diet	Animal	Breed	Country
<b>Large ruminants</b>				
Soares et al. [12]	<i>Urochloa brizantha</i> cv. Marandu	Cattle	Holstein Zebu crossbreed	Brazil
Soares et al. [36]	Sugarcane bagasse	Cattle	Holstein Zebu crossbreed	Brazil
Lisboa et al. [37]	Sugarcane bagasse	Cattle	Holstein Zebu crossbreed	Brazil
Salt et al. [21]	<i>U. brizantha</i> cv. Marandu	Cattle	Holstein Zebu crossbreed	Brazil
Kumar et al. [5]	Super Napier	Buffalo	Murrah	India
Sani et al. [24]	<i>Digitaria smutsii</i>	Cattle	Bunaji	Nigeria
Sani et al. [38]	<i>D. smutsii</i>	Cattle	Bunaji	Nigeria
Lisboa et al. [20]	Sugarcane bagasse	Cattle	Holstein Zebu crossbreed	Brazil
Lisboa et al. [11]	Sugarcane bagasse	Cattle	Holstein Zebu crossbreed	Brazil
Galvão et al. [39]	<i>Panicum maximum</i> cv	Dairy buffalo	Crossbreed buffaloes	Brazil
Huang et al. [13]	Elephant grass ( <i>Pennisetum purpureum</i> )	Buffalo	Crossbreed buffaloes	China
Latiefah et al. [40]	Rice straw	Cattle	Ongole crossbreed	Indonesia
Sukaryana et al. [41]	Elephant grass ( <i>P. purpureum</i> )	Cattle	Ongole crossbreed	Indonesia
Iqbal et al. [42]	Corn silage	Dairy cattle	Sahiwal Holstein crossbreed	Pakistan
Santos et al. [26]	Sugarcane bagasse	Dairy cattle	Holstein Zebu crossbreed	Brazil
Pimentel et al. [43]	Sugarcane	Dairy cattle	Holstein Zebu crossbreed	Brazil
Cruz et al. [25]	Tifton-85 grass hay ( <i>Cynodon spp.</i> )	Cattle	Nellore	Brazil
Sani et al. [44]	<i>Digitaria smutsii</i> hay	Cattle	Bunaji	Nigeria
Pimentel et al. [45]	Sugarcane	Dairy cattle	Holstein Zebu crossbreed	Brazil
Oliveira et al. [46]	Massai grass ( <i>Panicum maximum</i> cv. Massai)	Dairy cattle	Holstein Zebu crossbreed	Brazil
Pimentel et al. [47]	Sugarcane	Dairy cattle	Holstein Zebu crossbreed	Brazil
Tipu et al. [48]	Wheat straw	Buffalo	Nili Ravi	Pakistan
Cunha et al. [49]	Sugarcane	Dairy cattle	Holstein Zebu crossbreed	Brazil
Silva et al. [50]	Massai grass ( <i>P. maximum</i> cv. Massai)	Dairy cattle	Holstein Gir crossbreed	Brazil
Barbosa et al. [51]	<i>Pennisetum purpureum</i> Schum silage	Buffalo	Crossbreed Riverine buffalo	Brazil
Wong and Zahari [8]	–	Cattle	Sahiwal Holstein crossbreed	Malaysia
<b>Small ruminants</b>				
Buenabad-Carrasco et al. [52]	Wheat straw	Sheep	Dorper Pelibuey Katahdin crossbreed	Canada
Olawoye et al. [53]	Silage	Dairy goat	West African Dwarf	Nigeria
Ferreira et al. [14]	Maize silage	Dairy goat	Saanen and Anglo Nubian	Brazil
Rodrigues et al. [15]	Rice hulls	Goat	Cerossbreed Boer	Brazil
Rodrigues et al. [22]	Rice hulls	Goat	Boer × mixed breed crossbreed	Brazil
da Silva et al. [20]	Tifton-85 grass ( <i>Cynodon sp.</i> )	Goat	Crossbreed goats	Brazil
Ferreira et al. [54]	Maize silage	Dairy goat	Saanen	Brazil
Dwatmadji et al. [55]	<i>Pennisetum purpuroides</i>	Sheep	Thin-Tail	Indonesia
Md Ozman et al. [17]	Purple guinea grass silage	Sheep	Dorper	Malaysia
Olawoye et al. [56]	Silage	Dairy goat	West African Dwarf	Nigeria
Olawoye et al. [57]	Elephant grass ( <i>P. purpureum</i> ) silage	Dairy goat	West African Dwarf	Nigeria
Silva et al. [23]	Tifton-85 grass ( <i>Cynodon sp.</i> ) hay	Goat	Crossbreed goats	Brazil
Arief et al. [58]	Palm oil by-products	Dairy goat	Crossbreed Etawa	Indonesia
Ribeiro et al. [59]	<i>Cynodon dactylon</i> hay	Goat	Boer Indigenous crossbreed	Brazil
Oliveira et al. [27]	Tifton-85 grass hay ( <i>Cynodon spp.</i> )	Goat	Cerossbreed Boer	Brazil
Freitas et al. [16]	<i>U. brizantha</i> cv. Marandu and Tifton 85 ( <i>Cynodon dactylon</i> )	Sheep	Santa Inês crossbreed	Brazil
Santos et al. [60]	Elephant grass ( <i>P. purpureum</i> Schum) silage	Sheep	Santa Inês crossbreed	Brazil
Mayulu and Suhardi [61]	Palm oil by products	Sheep	Thin-Tail	Indonesia
Tona et al. [62]	<i>P. maximum</i> and <i>Gliricidia sepium</i>	Goat	–	Nigeria
Chanjula and Pengnoo [63]	<i>Paspalum plicatum</i> Michx. hay	Goat	–	Thailand
Etela and Suoware [64]	Guinea grass ( <i>P. maximum</i> )	Goat	West African Dwarf	Nigeria
Chanjula et al. [7]	Signal ( <i>Briachiaria humidicola</i> ) hay	Goat	Thai Native Anglo Nubian crossbreed	Thailand
Chanjula et al. [65]	<i>P. plicatum</i> Michx. hay	Goat	Thai Native Anglo Nubian crossbreed	Thailand
Nnadi et al. [66]	<i>P. maximum</i> and <i>Andropogon mucunoides</i>	Goat	West African Dwarf	Nigeria
Aina et al. [67]	<i>P. maximum</i>	Goat	West African Dwarf	Nigeria

**Table 2:** Descriptive statistics of the influence of palm kernel cake on large ruminants.

Variables	Unit	<i>n</i>	Mean	SD	Min	Max
<b>Nutrients intake</b>						
DMI	kg/d	79	9.32	3.58	2.13	17.60
OMI	kg/d	10	9.78	1.71	7.94	12.72
CPI	kg/d	34	1.23	0.33	0.83	2.19
EEI	kg/d	34	0.34	0.12	0.15	0.57
NFCI	kg/d	28	2.85	1.42	1.04	5.61
TDNI	kg/d	32	6.62	2.08	3.49	10.23
NDFI	kg/d	42	5.39	2.48	2.10	11.12
ADFI	kg/d	6	3.50	1.71	2.18	5.79
DMI	g/kg BW <sup>0.75</sup>	12	66.28	41.04	1.88	120.38
CPI	g/kg BW <sup>0.75</sup>	12	7.10	2.73	3.00	11.26
EEI	g/kg BW <sup>0.75</sup>	12	2.64	1.12	1.10	4.13
TCI	g/kg BW <sup>0.75</sup>	8	53.04	35.94	13.70	90.36
NFCI	g/kg BW <sup>0.75</sup>	8	14.11	7.47	4.60	26.74
TDNI	g/kg BW <sup>0.75</sup>	8	42.42	26.11	12.60	71.03
NDFI	g/kg BW <sup>0.75</sup>	12	44.86	28.39	9.60	79.00
<b>Rumen fermentation</b>						
pH		9	7.00	0.26	6.74	7.50
N-NH <sub>3</sub>	mg/dL	7	8.34	2.27	4.64	9.92
Total VFA	mmol/L	7	86.04	10.81	70.30	97.50
C <sub>2</sub>	mmol/L	6	51.48	3.97	44.40	55.13
C <sub>3</sub>	mmol/L	6	19.51	5.68	11.30	24.58
C <sub>4</sub>	mmol/L	5	12.03	2.36	8.28	14.69
Iso-C <sub>4</sub>	mmol/L	6	1.15	0.66	0.70	2.33
C <sub>5</sub>	mmol/L	6	1.09	0.36	0.52	1.44
Iso-C <sub>5</sub>	mmol/L	6	1.28	0.22	1.04	1.64
Ratio C <sub>2</sub> :C <sub>3</sub>		9	3.52	1.38	2.24	6.32
<b>Nutrients digestibility</b>						
DMD	%	53	59.39	7.79	44.00	75.80
OMD	%	14	63.09	6.40	53.30	77.60
CPD	%	53	62.02	7.39	42.94	76.13
EED	%	42	73.27	11.97	37.32	95.34
NFCD	%	32	73.28	16.94	36.31	98.03
TDND	%	20	64.22	4.78	54.37	72.99
NDFD	%	52	54.14	9.98	34.00	76.00
ADFD	%	12	46.62	13.40	24.70	73.10
Hemicellulose	%	6	62.32	9.25	49.89	74.63
<b>Performance</b>						
ADG	kg/d	50	0.96	0.30	0.48	1.54
FCR		50	7.66	2.58	1.81	14.83
FE		52	0.20	0.27	0.07	1.53
IW	kg	37	274.47	114.17	118.75	435.00
FW	kg	41	384.51	136.21	180.25	598.00
WG	kg	21	81.23	37.80	21.00	157.00
<b>Milk production and composition</b>						
MY	kg/d	17	10.60	2.12	7.86	13.90
Fat	%	21	5.07	1.79	3.20	8.89
Protein	%	21	3.37	0.44	2.90	4.01
Lactose	%	21	4.74	0.21	4.40	5.13
Total Solids	%	17	13.23	1.98	11.60	18.60

Table 2: (continued)

Variables	Unit	<i>n</i>	Mean	SD	Min	Max
<b>Carcass traits</b>						
HCW	kg/d	20	238.90	40.76	185.15	311.00
HCY	%	20	50.13	3.82	44.17	56.90
SFT	mm	12	3.82	0.91	2.60	5.50
Ribeye area	cm <sup>2</sup>	16	60.46	9.94	44.31	71.40
Carcass length	cm	8	135.19	6.71	128.50	145.00

*n*, number of studies; SD, standard deviation; Min, minimum; Max, maximum; BW<sup>0.75</sup>, metabolic body weight; DMI, dry matter intake; OMI, organic matter intake; CPI, crude protein intake; EEI, ether extract intake; NFCI, non-fiber carbohydrates intake; TDNI, total digestible nutrients intake; NDFI, neutral detergent fiber intake; ADFI, acid detergent fiber intake; TCI, total carbohydrates intake; DMD, dry matter digestibility; OMD, organic matter digestibility; CPD, crude protein digestibility; EED, ether extract digestibility; NFCD, non-fiber carbohydrates digestibility; TDN, total digestible nutrients; NDFD, neutral detergent fiber digestibility; ADFD, acid detergent fiber digestibility; ADG, average daily gain; FCR, feed conversion ratio; FE, feed efficiency; IW, initial weight; FW, final weight; WG, weight gain; N-NH<sub>3</sub>, ammonia concentration; VFA, volatile fatty acids; C<sub>2</sub>, acetate; C<sub>3</sub>, propionate; C<sub>4</sub>, butyrate; Iso-C<sub>4</sub>, isobutyrate; C<sub>5</sub>, valerate; Iso-C<sub>5</sub>, isovalerate; MY, milk yield; HCW, hot carcass weight; HCY, hot carcass yield; SFT, subcutaneous fat thickness.

$b_i$  = random effect of study on the regression coefficient of  $Y$  on  $X$  in study  $i$ ; and  $e_{ij}$  = the unexplained residual error. The CLASS statement was used to specify the study variable as it contained no quantitative information. The RANDOM statement was declared based on different studies. These models were weighted based on the number of replicates in each study, as described by Jayanegara et al. [69].

Model fit and accuracy were evaluated using  $p$ -values, root mean square error (RMSE), and Akaike Information Criterion (AIC). A significance threshold of  $p < 0.05$  was used. When  $0.05 < p \leq 0.10$ , the trend was considered a tendency toward significance. AIC was used to evaluate model fit, where lower AIC values indicated better goodness of fit, reflecting the model's balance and accuracy. Model accuracy and precision were further assessed by calculating RMSE using PROC GLM [68].

Linear and quadratic regression models were used to describe the response of all parameters to increasing PKC inclusion levels. The linear model was applied to identify a proportional relationship, while the quadratic model was used to detect curvilinear responses and determine the optimal inclusion level [70]. Optimal PKC inclusion level for parameters exhibiting a significant quadratic effect ( $p < 0.05$ ) was determined at the vertex of the quadratic curve, which represents the peak performance response. The optimal value was calculated using the first derivative of the quadratic regression function [70]:

$$Y = aX^2 + bX + c$$

$$\frac{dY}{dX} = 2aX + b = 0$$

$$2aX + b = 0$$

$$X = \frac{-b}{2a}$$

where  $X$  = optimal PKC inclusion level.

## 3 Results

### 3.1 Large ruminants

The current meta-analysis shows that the variation of PKC inclusion has a quadratic effect ( $p < 0.05$ ) on CPI, ether extract intake (EEI), non-fiber carbohydrate intake (NFCI), total digestible nutrient intake (TDNI), and NDFI. Nonetheless, DMI, OMI, and ADFI remained unaffected by the inclusion of PKC in large ruminants' diets (Table 5).

The result demonstrates a quadratic relationship ( $p < 0.05$ ) in DMD, CPD, NDFD, and hemicellulose digestibility with the various levels of PKC inclusion in the diets. It also showed a significant linear reduction ( $p < 0.05$ ) in NFC digestibility (NFCD) and TDN. However, no significant change ( $p > 0.05$ ) was identified in OM digestibility (OMD), EE digestibility (EED), and ADF digestibility (ADFD) (Table 6).

The diverse levels of PKC inclusion in large ruminants' diets did not significantly ( $p > 0.05$ ) influence the average daily gain (ADG), feed conversion ratio (FCR), weight gain (WG), and feed efficiency (FE) (Table 7).

Feeding PKC in large ruminants did not result in significant ( $p > 0.05$ ) change in all the rumen fermentation characteristics such as pH value, ammonia concentration (N-NH<sub>3</sub>), acetate (C<sub>2</sub>), propionate (C<sub>3</sub>), butyrate (C<sub>4</sub>), isobutyrate (iso-C<sub>4</sub>), valerate (C<sub>5</sub>), iso-valerate (iso-C<sub>5</sub>), and C<sub>2</sub>:C<sub>3</sub>

**Table 3:** Descriptive statistics of the influence of palm kernel cake on small ruminant.

Variables	Unit	<i>n</i>	Mean	SD	Min	Max
<b>Nutrients intake</b>						
DM	g/d	68	862.37	337.55	409.93	1,682.60
OM	g/d	24	843.50	327.90	409.80	1,597.40
CP	g/d	39	150.55	71.05	60.76	316.20
EE	g/d	28	40.79	23.42	20.70	107.80
NFC	g/d	25	280.88	148.80	96.50	633.80
TDN	g/d	29	602.24	291.04	238.30	1,390.00
NDF	g/d	32	382.17	205.21	127.90	877.20
<b>Performance</b>						
ADG	g/d	33	104.64	53.06	2.38	219.00
FCR (DMI/ADG)		30	7.03	3.02	3.52	14.64
FE (DMI/FT)		8	78.64	84.66	0.19	176.10
FE (ADG/DMI)		20	0.21	0.04	0.14	0.29
IW	kg	28	20.19	11.05	9.00	54.38
FW	kg	43	25.45	11.48	0.00	55.14
WG	kg	41	6.39	4.78	-1.72	13.60
<b>Rumen fermentation</b>						
pH		10	6.49	0.12	6.22	6.61
N-NH <sub>3</sub>	mg/dL	10	15.57	1.16	14.14	16.71
Total VFA	mmol/L	7	69.60	8.22	55.84	77.35
C <sub>2</sub>	mol/100 mol	7	67.93	5.81	59.10	71.88
C <sub>3</sub>	mol/100 mol	7	21.97	3.47	19.57	28.67
C <sub>4</sub>	mol/100 mol	7	6.91	1.49	5.60	10.04
<b>Milk production and composition</b>						
MY	mL/d	8	108.00	45.15	48.88	170.70
Fat	%	17	3.41	1.64	0.77	5.55
Protein	%	17	4.44	1.58	1.67	8.27
Lactose	%	12	4.22	0.81	2.27	5.24
Total solids	%	12	9.84	2.45	6.41	13.07
Ash	%	8	1.07	0.28	0.78	1.61
<b>Carcass production and composition</b>						
SW	kg	8	32.78	3.52	27.40	37.60
HCW	kg	16	11.69	3.60	2.20	16.40
CCW	kg	16	11.51	3.51	2.20	16.30
HCY	%	12	41.33	2.34	38.20	44.50
CCY	%	12	41.07	2.53	37.20	44.50
SFT	mm	8	1.79	1.17	0.60	3.10
Marbling		8	1.76	0.48	1.10	2.40
Loin eye area	cm <sup>2</sup>	8	9.91	4.11	5.30	15.00
CC		12	2.69	0.34	2.20	3.30
External length	cm	8	49.95	3.52	46.00	55.40
Leg length	cm	8	35.86	2.03	33.80	38.40

*n*, number of studies; SD, standard deviation; Min, minimum; Max, maximum; DMI, dry matter intake; OMI, organic matter intake; CPI, crude protein intake; EEI, ether extract intake; NFCI, non-fiber carbohydrates intake; TDNI, total digestible nutrients intake; NDFI, neutral detergent fiber intake; ADG, average daily gain; FCR, feed conversion ratio; FE, feed efficiency; IW, initial weight; FW, final weight; WG, weight gain; N-NH<sub>3</sub>, ammonia concentration; VFA, volatile fatty acids; C<sub>2</sub>, acetate; C<sub>3</sub>, propionate; C<sub>4</sub>, butyrate; MY, milk yield; SW, slaughter weight; HCW, hot carcass weight; CCW, cold carcass weight; HCY, hot carcass yield; CCY, cold carcass yield; SFT, subcutaneous fat thickness; CC, carcass conformation.

**Table 4:** Descriptive statistics of the chemical composition of palm kernel cake.

Chemical composition (%)	<i>n</i>	Mean	SD	Min	Max
DM	26	92.04	1.94	87.85	96.40
OM	12	95.39	2.00	91.29	97.87
Mineral	22	4.09	1.76	1.31	8.71
CP	26	15.67	2.37	9.98	22.51
EE	26	9.74	3.31	2.91	18.60
TDN	7	66.57	8.93	58.53	81.07
NFC	10	10.46	4.73	3.36	19.59
NFCap	5	9.61	3.56	3.32	11.68
NDF	10	70.18	5.33	59.90	78.90
NDFap	16	62.11	4.89	54.81	67.72
ADF	17	45.57	5.42	34.83	55.73
ADFap	4	31.12	4.56	28.84	37.95
iNDF	6	26.77	7.72	20.27	40.82
Hemicellulose	11	22.84	9.97	7.83	44.63
Cellulose	11	25.05	8.82	13.52	38.71
Lignin	21	16.30	2.64	11.38	19.83
NDIP (% CP)	5	23.72	22.64	1.31	49.44
ADIP (% CP)	5	10.29	12.69	3.12	32.50
ME (MJ/kg DM)	2	11.43	0.60	11.00	11.85
Silica	2	0.68	0.31	0.46	0.90
Calcium	2	0.34	0.01	0.33	0.34
Phosphorus	2	0.63	0.09	0.56	0.69
C6:0 (caproic)	2	0.20	0.14	0.10	0.30
C12:0 (lauric)	4	39.39	5.39	36.20	47.40
C13:0 (tridecanoic)	2	0.10	0.06	0.05	0.14
C14:0 (myristic)	4	18.80	1.43	16.66	19.52
C15:0 (pentadecanoic)	2	0.04	0.01	0.03	0.05
C16:0 (palmitic)	4	10.81	1.88	7.99	11.76
C17:0 (heptadecanoic)	2	0.08	0.02	0.06	0.09
C18:0 (stearic)	4	3.88	0.69	2.85	4.22
C14:1n-5 (myristoleic)	2	0.03	0.01	0.02	0.04
C16:1n-7 (palmitoleic)	2	0.05	0.01	0.04	0.06
C17:1n-7 (heptadecenoic)	2	0.05	0.04	0.02	0.08
C18:1n-9c (oleic)	3	17.79	3.42	13.84	19.76
C18:2n-6 (linoleic)	4	3.11	0.31	2.64	3.28
C20:3n-6 (eicosatrienoic)	2	0.04	0.04	0.01	0.06
C20:4n-6 (arachidonic)	2	0.09	0.01	0.08	0.09

*n*, number of studies; SD, standard deviation; Min, minimum; Max, maximum; DM, dry matter; OM, organic matter; CP, crude protein; EE, ether extract; TDN, total digestible nutrients; NFC, non-fiber carbohydrates; NFCap, non-fiber carbohydrates corrected for ash and protein; NDF, neutral detergent fiber; NDFap, neutral detergent fiber corrected for ash and protein; ADF, acid detergent fiber; ADFap, acid detergent fiber corrected for ash and protein; iNDF, indigestible neutral detergent fiber; NDIP, neutral detergent insoluble protein; ADIP, acid detergent insoluble protein; ME, metabolizable energy.

ratio, excluding total volatile fatty acids (VFA). The total VFA was decreased by a linear response ( $p < 0.05$ ) (Table 8).

The results of the meta-analysis show that there is no significant ( $p > 0.05$ ) influence on milk yield (MY) and milk composition (fat, protein, lactose, and total solids) of large

ruminants consuming PKC (Table 9). The results demonstrate that all the carcass production and composition variables remained unchanged ( $p > 0.05$ ). Large ruminants consuming PKC did not vary in hot carcass weight (HCW), hot carcass yield (HCY), subcutaneous fat thickness (SFT), ribeye area (RA), leg length (LL), and carcass length (CL) (Table 9).

### 3.2 Small ruminants

It is revealed that no significant ( $p > 0.05$ ) result was found for DMI, OMI, CPI, EEI, NFCI, TDNI, and NDFI of small ruminants fed PKC (Table 10). The levels of PKC inclusion in small ruminants' diets exhibit a quadratic influence ( $p < 0.05$ ) on ADG, FCR, and FE (Table 11). The rumen fermentation characteristics (pH value, N-NH<sub>3</sub>, total VFA, C<sub>2</sub>, C<sub>3</sub>, and C<sub>4</sub>) remained unchanged ( $p > 0.05$ ) by the various levels of PKC inclusion in the small ruminants' diet (Table 12).

Apart from MY, which followed a quadratic response ( $p < 0.05$ ) to PKC inclusion, other milk composition (fat, protein, lactose, total solids, and ash) remained unaffected ( $p > 0.05$ ) (Table 13). PKC inclusion did not significantly ( $p > 0.05$ ) affect HCW, cold carcass weight (CCW), HCY, cold carcass yield (CCY), SFT, marbling, loin eye area (LA), carcass conformation (CC), external length, and LL. However, SW exhibited a quadratic response ( $p < 0.05$ ) (Table 14).

## 4 Discussion

### 4.1 Large ruminants

This meta-analysis found that PKC inclusion did not significantly affect DMI in large ruminants. Elevated levels of NDF and silica in the diet can reduce the acceptability and intake [5]. High-NDF diets may lead to earlier satiety due to rumen filling, thereby reducing feed intake [11]. Silica also contributes to feed stiffness and low palatability, which limits intake and digestion due to its indigestible nature.

These findings align with Soares et al. [12], who reported no change in DMI in heifers fed PKC, but noted a reduction in NFCI and TDNI. High EE content can also affect the ruminant intake rate. Diets containing over 4.5 % EE can restrict DMI, indirectly limiting other nutrient intake [71]. PKC contains 9.74 % EE, with lauric acid and myristic acid comprising 39.39 % and 18.8 %, respectively, limiting nutrient intake due to their amphiphilic nature. The fatty acid content of PKC may reduce palatability despite being less prone to rancidity [39].

**Table 5:** Regression equations on the influence of palm kernel cake on nutrient intake of large ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
DMI	kg/d	79	10.22	0.68	-0.0029	0.002447	0.241	1.96	312	L	0.013
OMI	kg/d	10	10.23	1.37	0.001078	0.003246	0.753	0.51	45.2	L	0.026
CPI	kg/d	34	1.31	0.09	-0.000007	0.000002	0.009	0.29	16.1	Q	0.148
					0.000566	0.000606	0.360				
EI	kg/d	34	0.30	0.04	-0.000002	0	<0.0001	0.08	-60.1	Q	0.241
					0.000821	0.00017	<0.0001				
NFCI	kg/d	28	3.56	0.58	-0.00002	0.000007	0.003	0.88	76.8	Q	0.246
					-0.00244	0.00186	0.205				
TDNI	kg/d	32	6.99	0.72	-0.00005	0.000012	0.001	1.49	111.5	Q	0.133
					0.004024	0.00302	0.196				
NDFI	kg/d	42	5.33	0.72	-0.00002	0.000007	0.001	0.89	117.3	Q	0.175
					0.007651	0.001692	<0.0001				
ADFI	kg/d	6	4.12	1.59	0.000214	0.002505	0.940	0.27	41.5	L	0.478
DMI	g/kg BW <sup>0.75</sup>	12	78.30	25.40	0.000173	0.000046	0.007	17.24	110.8	Q	0.220
					-0.1241	0.02687	0.002				
CPI	g/kg BW <sup>0.75</sup>	12	7.59	1.77	0.000022	0.000007	0.013	2.28	72.7	Q	0.004
					-0.01024	0.00383	0.032				
EI	g/kg BW <sup>0.75</sup>	12	2.53	0.71	-0.0002	0.001937	0.922	0.74	59.7	L	0.442
TCI	g/kg BW <sup>0.75</sup>	8	57.74	32.00	-0.0286	0.01636	0.155	2.55	65.2	L	-
NFCI	g/kg BW <sup>0.75</sup>	8	21.94	4.05	-0.08525	0.02845	0.040	5.31	65.4	L	-
TDNI	g/kg BW <sup>0.75</sup>	8	47.39	22.76	-0.0344	0.01858	0.138	2.82	65.6	L	-
NDFI	g/kg BW <sup>0.75</sup>	12	49.21	17.93	-0.04708	0.02784	0.135	11.77	110	L	0.441

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; BW<sup>0.75</sup>, metabolic body weight; DMI, dry matter intake; OMI, organic matter intake; CPI, crude protein intake; EEI, ether extract intake; NFCI, non-fiber carbohydrates intake; TDNI, total digestible nutrients intake; NDFI, neutral detergent fiber intake; ADFI, acid detergent fiber intake; TCI, total carbohydrates intake.

**Table 6:** Regression equations on the influence of palm kernel cake on nutrient digestibility of large ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
DMD	%	53	62.58	2.18	0.000081	0.00002	<0.000	8.52	337.8	Q	0.191
					-0.04775	0.008616	<0.0001				
OMD	%	14	64.91	3.06	-0.09552	0.04672	0.075	11.53	103.6	L	0.458
CPD	%	53	64.38	1.63	0.000062	0.000025	0.017	9.96	352.7	Q	0.719
					-0.03756	0.01087	0.001				
EED	%	42	69.72	3.12	0.02388	0.02208	0.289	16.45	326.5	L	0.960
NFCD	%	32	77.38	5.52	-0.08729	0.03202	0.012	13.21	244.3	L	0.082
TDN	%	20	66.24	2.22	-0.04261	0.0168	0.025	4.81	120.1	L	0.406
NDFD	%	52	56.46	2.48	0.000074	0.000033	0.031	12.46	372	Q	0.372
					-0.03285	0.01474	0.032				
ADFD	%	12	45.05	9.07	-0.04009	0.07983	0.633	16.03	109.6	L	0.002
Hemicellulose	%	6	60.54	10.92	-0.0001	0.000019	0.038	2.48	49.3	Q	0.268
					0.0689	0.006717	0.009				

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; DMD, dry matter digestibility; OMD, organic matter digestibility; CPD, crude protein digestibility; EED, ether extract digestibility; NFCD, non-fiber carbohydrates digestibility; TDN, total digestible nutrients; NDFD, neutral detergent fiber digestibility; ADFD, acid detergent fiber digestibility.

**Table 7:** Regression equations on the influence of palm kernel cake on the performance of large ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
ADG	kg/d	50	0.96	0.09	0.000168	0.000611	0.785	0.42	38.6	L	0.167
FCR		50	8.50	0.64	-0.00659	0.004224	0.128	2.94	223.6	L	<0.0001
FE		52	0.24	0.07	-0.00011	0.000094	0.248	0.07	-89.8	L	0.041
IW	kg	37	286.60	35.26	0.07605	0.04766	0.123	18.50	326.9	L	0.010
FW	kg	41	386.84	39.45	-0.00144	0.000614	0.026	63.27	431.1	Q	0.894
WG	kg	21	75.17	20.49	0.341	0.1411	0.022	33.21	198.4	L	0.339

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; ADG, average daily gain; FCR, feed conversion ratio; FE, feed efficiency; IW, initial weight; FW, final weight; WG, weight gain.

**Table 8:** Regression equations on the influence of palm kernel cake on rumen fermentation of large ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
pH		9	7.02	0.11	-0.00094	0.000609	0.198	0.28	31.6	L	0.001
N-NH <sub>3</sub>	mg/dL	7	6.07	2.82	0.02707	0.02119	0.291	5.28	58.8	L	0.926
Total VFA	mmol/L	7	100.00	2.47	-0.1261	0.03036	0.025	9.44	61.7	L	0.912
C <sub>2</sub>	mmol/L	6	52.97	3.72	-0.07672	0.03523	0.161	3.06	46.3	L	-
C <sub>3</sub>	mmol/L	6	18.86	5.60	-0.02088	0.02525	0.495	1.77	45.8	L	-
C <sub>4</sub>	mmol/L	5	10.73	2.58	0.02283	0.05556	0.752	2.51	41.2	L	-
Iso-C <sub>4</sub>	mmol/L	6	1.64	0.59	-0.01223	0.008985	0.307	0.76	37.1	L	-
C <sub>5</sub>	mmol/L	6	1.03	0.34	-0.00287	0.005659	0.663	0.41	34.2	L	-
Iso-C <sub>5</sub>	mmol/L	6	1.56	0.12	-0.00664	0.006631	0.422	0.51	31.3	L	-
Ratio C <sub>2</sub> :C <sub>3</sub>		9	3.07	0.55	0.001919	0.001272	0.206	0.66	43.1	L	0.002

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; N-NH<sub>3</sub>, ammonia concentration; VFA, volatile fatty acids; C<sub>2</sub>, acetate; C<sub>3</sub>, propionate; C<sub>4</sub>, butyrate; Iso-C<sub>4</sub>, isobutyrate; C<sub>5</sub>, valerate; Iso-C<sub>5</sub>, isovalerate.

**Table 9:** Regression equations on the influence of palm kernel cake on milk production and composition, and carcass traits of large ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
<b>Milk production and composition</b>											
Milk yield	kg/d	17	10.54	1.10	0.002521	0.003952	0.538	0.76	66.7	L	-
Fat	%	21	5.16	0.82	0.001986	0.00216	0.375	0.41	60.1	L	0.506
Protein	%	21	3.42	0.19	-0.0003	0.000624	0.635	0.12	12.3	L	0.462
Lactose	%	21	4.79	0.09	-0.00082	0.000468	0.103	0.10	-1.8	L	0.685
Total solids	%	17	13.54	1.05	0.00285	0.002612	0.301	0.45	59.1	L	0.002
<b>Carcass traits</b>											
HCW	kg/d	20	239.59	19.29	0.07916	0.06548	0.248	23.01	173.4	L	0.505
HCY	%	20	50.47	1.84	0.000141	0.00523	0.979	1.69	88.8	L	0.029
SFT	mm	12	3.98	0.51	-0.00038	0.007701	0.962	1.76	58.2	L	-
Ribeye area	cm <sup>2</sup>	16	60.50	5.59	0.009093	0.01488	0.555	4.33	100.7	L	0.846
Carcass length	cm	8	136.07	6.23	-0.02883	0.03089	0.404	6.50	61.7	L	-

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; HCW, hot carcass weight; HCY, hot carcass yield; SFT, subcutaneous fat thickness.

**Table 10:** Regression equations on the influence of palm kernel cake on nutrient intake of small ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
DMI	g/d	68	949.73	77.59	-0.68	0.3895	0.087	300.62	912.2	L	0.514
OMI	g/d	24	927.31	123.27	-0.3791	0.7621	0.626	313.89	321.4	L	0.822
CPI	g/d	39	166.79	21.15	-0.1115	0.1339	0.412	71.07	415	L	0.987
E EI	g/d	28	38.57	7.74	0.04585	0.03267	0.177	17.28	230.2	L	0.069
NFCI	g/d	25	373.79	53.35	-0.525	0.3072	0.106	153.50	297.2	L	0.600
TDNI	g/d	29	638.58	107.12	0.178	0.5719	0.759	298.15	379.9	L	0.997
NDFI	g/d	32	370.26	65.82	0.414	0.2917	0.170	166.09	390.5	L	0.938

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; DMI, dry matter intake; OMI, organic matter intake; CPI, crude protein intake; EEI, ether extract intake; NFCI, non-fiber carbohydrates intake; TDNI, total digestible nutrients intake; NDFI, neutral detergent fiber intake.

**Table 11:** Regression equations on the influence of palm kernel cake on the performance of small ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
ADG	g/d	33	102.38	18.13	-0.00121	0.000174	<0.0001	51.05	309.5	Q	0.788
FCR (DMI/ADG)		30	7.17	1.32	0.2556	0.05716	0.000	2.68	137.5	Q	0.178
					0.000039	0.000014	0.011				
FE (DMI/Feeding time)		8	78.92	78.70	0.1159	0.1015	0.317	35.25	83.4	L	-
FE (ADG/DMI)		20	0.20	0.02	0.0000006	0	<0.0001	0.04	-44	Q	0.026
					0.000185	0.000078	0.034				
IW	kg	28	21.84	3.68	0.003824	0.003028	0.223	1.73	148.8	L	0.820
FW	kg	43	25.68	2.95	0.00143	0.007107	0.842	4.86	271.8	L	0.605
WG	Kg	41	6.49	1.41	0.001808	0.006693	0.789	4.64	231.8	L	0.480

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; ADG, average daily gain; FCR, feed conversion ratio; FE, feed efficiency; IW, initial weight; FW, final weight; WG, weight gain; DMI, dry matter intake.

**Table 12:** Regression equations on the influence of palm kernel cake on rumen fermentation of small ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC	
pH		10	6.59	0.08	-0.00048	0.000821	0.580	0.18	25.2	L
N-NH <sub>3</sub>	mg/dL	10	17.29	1.01	-0.01233	0.008836	0.212	1.90	59.1	L
Total VFA	mmol/L	7	65.45	12.94	0.02511	0.08628	0.790	6.47	60.6	L
C <sub>2</sub>	%	7	22.01	5.94	-0.00734	0.0148	0.654	1.16	49.3	L
C <sub>3</sub>	%	7	22.01	5.94	0.01899	0.04343	0.692	3.23	54.6	L
C <sub>4</sub>	%	7	7.46	4.12	-0.00072	0.03392	0.984	2.49	51.4	L

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; N-NH<sub>3</sub>, ammonia concentration; VFA, volatile fatty acids; C<sub>2</sub>, acetate; C<sub>3</sub>, propionate; C<sub>4</sub>, butyrate.

The decline in nutrient intake due to PKC inclusion affected the nutrient degradation process in the rumen. All nutrient intakes declined, except for EED, which increased at higher PKC inclusion levels. Crude fiber (CF) provides a physical filling effect, even though the other nutrients have not been optimally digested. In this study, ADFD showed a slight decreasing trend with increasing PKC inclusion,

reflecting the complexity of ADF digestion. This suggests that while NDF is digestible at certain levels, ADF remains a major inhibitor. Increased levels of NDF and ADF render the diet more indigestible by rumen microorganisms [21]. Although fiber affects DMD and CPD, the fat content of the diet contributes as an alternative energy source, as the fat composition in the PKC is degradable. Notably, PKC contains

**Table 13:** Regression equations on the influence of palm kernel cake on milk production and composition of small ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC	
Milk yield	mL/d	8	104.24	31.11	-0.00153 0.4273	0.000527 0.1858	0.044 0.083	61.10	85.1	Q
Fat	%	17	3.58	0.97	-0.00208	0.003644	0.580	1.15	76.4	L
Protein	%	17	4.01	0.83	-0.00093	0.006104	0.881	1.94	86.7	L
Lactose	%	12	4.56	0.57	-0.00356	0.003035	0.279	0.78	55.9	L
Total solids	%	12	10.64	1.38	-0.00118	0.01281	0.929	3.05	77.5	L
Ash	%	8	1.02	0.18	-0.00138	0.002332	0.585	0.49	39.2	L

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic.

**Table 14:** Regression equations on the influence of palm kernel cake on carcass production and composition of small ruminants.

Variables	Unit	n	Parameter estimates				Model estimates			M	Level vs animal
			Int	SE int	Slope	SE slope	p-value	RMSE	AIC		
SW	kg	8	33.85	2.50	-0.00009 0.01833	0.000013 0.00502	0.003 0.022	4.68	52.4	Q	-
HCW	kg	16	10.32	1.88	0.02381	0.0166	0.182	7.52	107	L	0.562
CCW	kg	16	10.16	1.83	0.02253	0.0162	0.195	7.29	106.4	L	0.569
HCY	%	12	42.09	1.42	-0.00285	0.00784	0.727	2.87	72.2	L	-
CCY	%	12	41.90	1.58	-0.00515	0.008675	0.571	3.15	74	L	-
SFT	mm	8	1.92	1.09	-0.00002	0.000967	0.984	0.30	37.6	L	-
Marbling		8	1.83	0.43	-0.0006	0.003494	0.871	0.96	45.7	L	-
Loin eye area	cm <sup>2</sup>	8	10.66	3.77	-0.00017	0.001794	0.846	1.42	52.7	L	-
CC		12	2.80	0.19	-0.00004	0.001902	0.928	0.63	43.3	L	0.044
External length	cm	8	51.41	3.11	-0.011	0.01107	0.377	3.08	59.1	L	-
Leg length	cm	8	36.39	1.85	-0.00365	0.003803	0.392	1.05	49.6	L	-

n, number of studies; Int, intercept; SE, standard error; RMSE, root mean square error; AIC, Akaike information criterion; M, model; L, linear; Q, quadratic; SW, slaughter weight; HCW, hot carcass weight; CCW, cold carcass weight; HCY, hot carcass yield; CCY, cold carcass yield; SFT, subcutaneous fat thickness; CC, carcass conformation.

high short and medium-chain fatty acids that are better digested and have higher uptake rates than long-chain fatty acids [72].

Xylan and mannan, the main non-starch polysaccharides (NSP) in PKC, are complex fibers that might reduce PKC's overall digestibility and utilization. PKC contains 13.91 % xylan and 28.78 % mannan of DM [73]. Xylan increases chyme viscosity, thereby interfering with enzyme access to substrates and reducing nutrient digestibility efficiency. Mannan forms a complex fiber structure that is tougher to digest by digestive enzymes as compared to other hemicelluloses, limiting nutrient digestibility. Although they generate VFA (acetate and propionate) during fermentation, the absence of enzymes like xylanase and mannanase can reduce fermentation efficiency [74, 75].

Furthermore, the high amount of neutral detergent insoluble protein (NDIP) and acid detergent insoluble protein (ADIP) in PKC also restricts crude protein (CP) degradation [76]. The heating process of palm oil before

mechanical extraction promotes protein denaturation and complex reactions between peptides and carbohydrates. This contributes to an increase in NDIP and ADIP in PKC, making it less digestible in the rumen [21].

Nutrient digestibility resulted in a noticeable impact on rumen fermentability characteristics. This meta-analysis found that greater PKC inclusion reduced total VFA concentrations. Since VFA is the main energy source for ruminants, this decline may affect productivity. In contrast, Kumar et al. [5] reported no change in total VFA in buffaloes fed PKC. Fortunately, PKC inclusion was also found to stabilize rumen pH. The reduced CPI might contribute to lower ruminal N-NH<sub>3</sub> concentration. Although CPD increased quadratically, N-NH<sub>3</sub> remained unaffected, consistent with previous findings [5, 40].

Increasing dietary PKC levels significantly reduced total VFA by 12.6 mmol/L per 100 g/kg DM PKC, whereas pH and N-NH<sub>3</sub> showed only slight, non-significant changes, with pH decreasing by about 0.09 units and N-NH<sub>3</sub> increasing by

2.7 mg/dL. These findings suggest that higher PKC inclusion may lower rumen fermentation activity, mainly reflected by the decline in total VFA, likely due to its high fat and fiber contents that limit the fermentation of rapidly degradable carbohydrates.

The unchanged WG and ADG suggest that even with reduced intake, animals can maintain growth by improving nutrient utilization. Enhanced digestibility may compensate for lower nutrient intake. This implies that performance is not compromised if digestibility improves. DMI is essential for growth in beef cattle [13]. However, in this case, improvement in digestibility helped maintain an optimal growth rate amid a decrease in intake. Our results are in agreement with Lisboa et al. [20], who found that reduced DMI in bulls fed PKC did not impair ADG or FCR. In fact, growth performance remained stable with up to 240 g/kg DM PKC inclusion. This suggests that a decrease in intake is not necessarily associated with a decrease in performance when digestibility is improved.

As a further observation, PKC inclusion showed a negligible effect on carcass and milk production. HCW and HCY remained stable, consistent with previous findings [37]. Since HCW is positively correlated with SW, this indicates no adverse effect. Similarly, MY was unaffected in cattle fed PKC. This is likely due to the lower DMI. The diet-to-milk conversion process relies on the amount and quality of nutrients digested by the animals [39]. Kumar et al. [5] supported this finding. They discovered that the PKC inclusion was unlikely to modify MY in buffaloes. This is partially due to the limited protein content in PKC.

PKC is low in lysine and methionine compared to other oil cakes. Both are crucial for milk synthesis in dairy buffaloes [5]. Despite this, milk composition remained unchanged. Although some studies report reductions in milk protein and lactose with PKC inclusion, this variation likely depends on diet composition and management [39], as milk fat is influenced by the acetate:propionate ratio [5], while milk protein and lactose depend on dietary CP and TDN [39].

## 4.2 Small ruminants

This meta-analysis highlights that PKC is a promising ingredient for small ruminants. Despite its low acceptance, it can still be utilized effectively at appropriate inclusion levels. Nutrient intake showed similar patterns to large ruminants, with DMI remaining stable. This suggests that PKC is less palatable and poorly accepted, likely due to its high CF content. Elevated CF content in the diet due to the inclusion of PKC restricts nutrient intake [15]. Higher NDF and lignin levels in PKC further limit utilization by increasing digestion time and

reducing nutrient intake [59, 77]. High-fiber diets cause delayed digestion and contribute to reduced DMI [17]. Previous meta-analysis reported that PKC reduces ADF digestibility quadratically in small ruminants, whereas CF and NDF digestibility remain unaffected [31].

Nutrient intake is influenced not only by feed type but also by animal species. Among domestic ruminants, goats are the most selective [78]. This explains why no effect was shown for DMI, since PKC is difficult for goats to tolerate [14]. Contrary to this meta-analysis, Ferreira et al. [14, 54] and Silva et al. [79] found that DMI, CPI, and TDNI in lactating goats decreased significantly with PKC inclusion. This rejection implies that PKC is simply unpalatable to goats. This suggests that even if total intake appears stable, rejection can still occur at higher inclusion rates. Since DMI affects other nutrient intakes, it also influences milk yield and composition [23, 54].

In ruminants, DMI is regulated by a chemotactic mechanism, where VFA absorption from the rumen triggers feeding signals, while nutritional imbalance can suppress microbial activity and digestion efficiency, lowering DMI [17]. Rumen fermentation produces acetate, propionate, and butyrate, primary energy sources for ruminants. In this study, total and partial VFA were not affected by PKC inclusion, consistent with Chanjula et al. [7]. Easily fermented substrates tend to increase propionate, while fibrous substrates increase acetate [80]. Lauric and myristic acids in PKC can interfere with rumen microorganisms. Both are main PKC fat components, which are amphipathic and toxic to rumen microorganisms [22, 81].

PKC inclusion also did not destabilize the rumen pH. It remained within the optimal range (6.22–6.61), supporting fermentation activity. Microbial growth peaks when rumen pH is between 6 and 7 [82]. This appropriate pH condition creates a conducive environment for microbial development. Rumen fermentation that occurs optimally is also signaled by the production of N-NH<sub>3</sub>. The concentration of N-NH<sub>3</sub> in the rumen highly depends on the protein content of the feed. Protein promotes microbial growth and replication, which ultimately leads to protein synthesis. The values obtained in this study (14.14–16.71 mg/dL) fall within the optimal range of 8.5–30 mg/dL McDonald et al. [83]. Although protein intake was unchanged, the 15.67% CP in PKC (Table 4) appears sufficient to maintain microbial activity and N-NH<sub>3</sub> concentration.

Optimizing production in animal farming is essential to maximizing the economic value. This meta-analysis revealed a quadratic decrease in ADG, with a gradual decrease initially and a more significant decrease at higher levels of PKC. Conversely, FCR increased quadratically, indicating reduced feed efficiency as inclusion levels rose. At low levels,

changes were minor, but higher inclusion resulted in more pronounced inefficiencies in converting feed to body weight.

The simultaneous decrease in ADG and increase in FCR indicate reduced growth efficiency, as the additional nutrient intake does not result in proportional weight gain. Rodrigues et al. [22] reported similar results, identifying limited DMI as a primary factor. DMI will ensure adequate nutrient intake for animal growth [23]. DMI directly influences CPI and TDNI, which provide essential nutrients for growth and microbial fermentation.

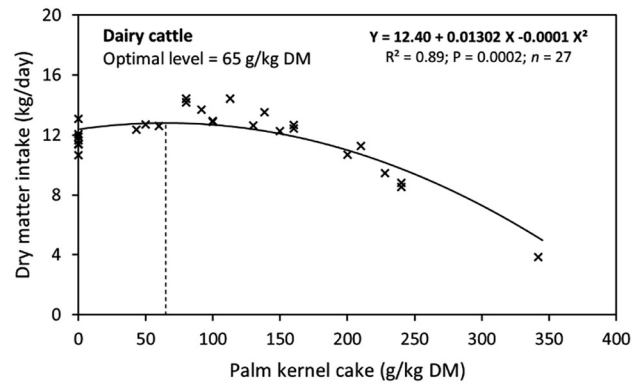
Increased NDIP, ADIP, and lignin from PKC reduce dietary quality and nutrient availability, ultimately impairing animal performance. PKC inclusion did not significantly affect carcass traits, morphometrics, or subjective carcass evaluation. However, SW declined quadratically, consistent with the ADG trend. High intake of feed rich in soluble carbohydrates enhances starch digestion in the small intestine. Free glucose obtained from the digestion process will be stored in adipose tissue [15].

MY increased at low PKC inclusion, reaching a maximum of ~134 mL/d at 140 g/kg PKC (Table 13), then declined at higher PKC levels, despite stable DMI and nutrient intake, indicating insufficient energy or protein supply for optimal milk production. At low inclusion levels, nutrient intake may still support milk synthesis. However, higher PKC levels reduce diet quality due to increased fiber and NDIP, limiting energy and protein availability for milk production.

These cumulative effects, particularly at high inclusion levels, reduce nutrient efficiency for milk production, which is evident in the quadratic decreasing pattern in MY, as shown by the declining MY trend. This suggests that even with unchanged total intake, shifts in nutrient profile due to PKC affect milk production efficiency [14].

### 4.3 Optimal PKC inclusion level in large and small ruminants

The findings of this meta-analysis suggest that the optimal level of PKC inclusion in large ruminants is strongly influenced by the type of animal and its production purpose. For dairy cattle, the best DMI was reached at 65 g/kg DM of PKC inclusion (Figure 2). This is due to the high fat and fiber content in PKC, which may affect feed efficiency in dairy cattle, making lower levels more appropriate. The saturated fatty acid content in PKC, such as lauric and myristic acid, reduces palatability and nutrient intake. Excessive inclusion of PKC in dairy cattle may lead to lower TDNI and CPI, which negatively affects milk production, as it can cause milk fat depression [84].



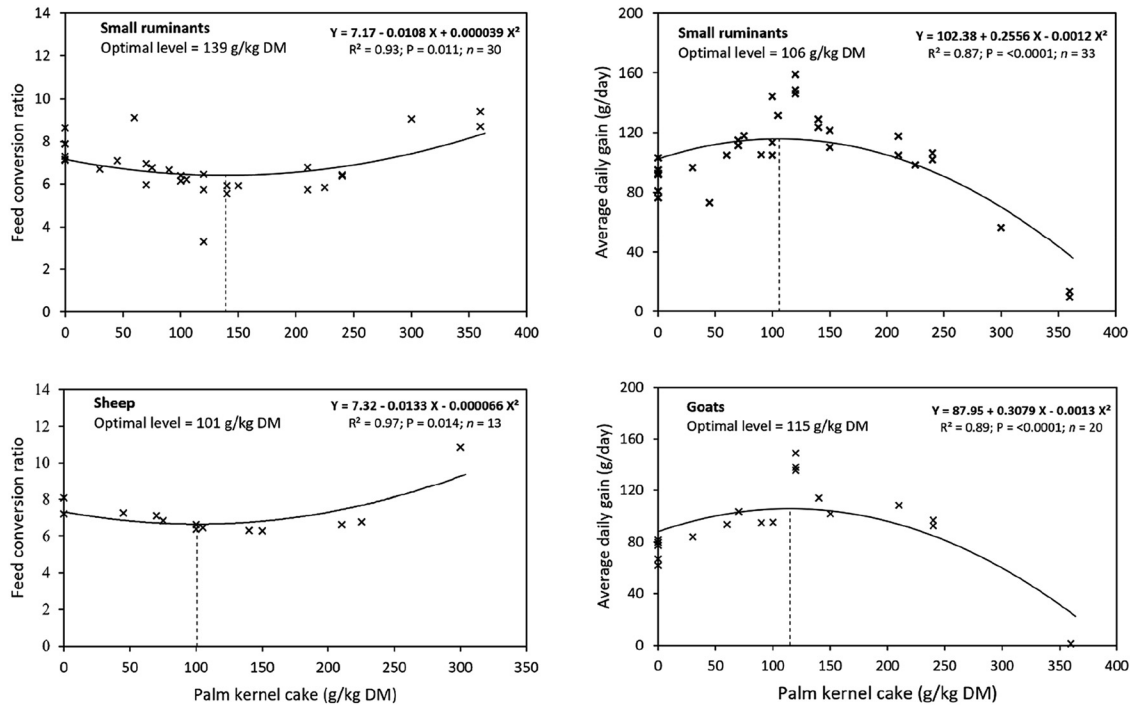
**Figure 2:** Estimating the optimal level of palm kernel cake inclusion for dairy cattle.

In contrast, beef cattle tend to be less feeder-selective, making it relatively acceptable for them to tolerate PKC in their diets with less impact on production. The saturated fatty acid content of PKC is also safer for beef cattle, as they do not encounter the risk of milk fat depression that often occurs in dairy cattle. Vargas and Mezzomo [33], through a meta-analysis, determined that the optimal PKC inclusion level for confined cattle was 110.6 g/kg DM without affecting DMI.

For small ruminants and goats (Figure 3), the optimal PKC inclusion levels to support ADG are 106 and 115 g/kg DM, respectively. Regarding FCR, the optimal levels are 139 g/kg DM for small ruminants and 101 g/kg DM for sheep. These findings emphasize the importance of adjusting PKC inclusion levels according to species and production objectives, whether for improving growth performance, enhancing feed efficiency, or ensuring better feed quality. Such adjustments support the effective use of PKC to achieve optimal production outcomes.

Based on previous studies, PKC inclusion in small ruminants has shown variable results according to animal type. Ferreira et al. [14] recommended the use of PKC up to 80 g/kg DM for dairy goats, while in feedlot goats, the recommended levels of PKC inclusion range from 107.7 to 120 g/kg DM to improve growth and meat quality [15, 23, 79]. The range of optimal levels of PKC inclusion for goats from previous studies ranges from 80 to 120 g/kg DM, depending on the production objective.

The buffalo dataset included treatment means from five studies, but not all response variables were consistently reported. For example, only three studies provided data on ADG and FCR at different inclusion levels. This limited coverage reduces statistical power and may not fully capture variability in responses to PKC levels. Additional studies examining growth performance and nutrient utilization at



**Figure 3:** Estimating the optimal level of palm kernel cake inclusion for small ruminants.

varying PKC inclusion levels in buffaloes are therefore needed to improve model reliability.

It should be noted that the calculated optimal PKC inclusion levels are based solely on intake and performance responses. Economic aspects, such as feed cost or profitability, were not considered because the included studies did not provide such data. Therefore, these optima represent physiological rather than economic recommendations, and future studies should incorporate cost-benefit analysis to determine economically optimal inclusion levels.

## 5 Conclusions

Incorporating PKC into ruminant diets may be advantageous at appropriate inclusion levels, whereas higher levels could reduce nutrient digestibility and impair animal performance. A balanced formulation is required to maintain the overall production performance of ruminants with minimal disruptive impact. Based on these findings, PKC can be included at 65 g/kg DM for dairy cattle and 101–139 g/kg DM for small ruminants, depending on their species. This insight can contribute to supporting the utilization of PKC as a sustainable feed ingredient. The current meta-analysis was unable to estimate the optimal inclusion levels of PKC for buffaloes, as the available data were insufficient. Further investigations are necessary to address this knowledge gap.

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**Data availability statement:** All data generated or analyzed during this study are included in this published article.

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