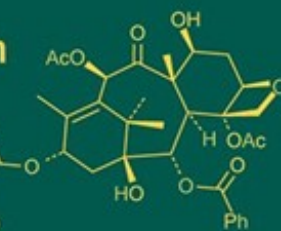
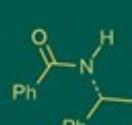


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Unconventional oil cakes in ruminant nutrition: Nutritional value, processing, rumen fermentation, methane mitigation and productive responses

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ABSTRACT

The increasing cost of conventional protein supplements and the need for locally available feed resources have renewed interest in underused oilseed by-products for ruminant feeding. This review evaluates neem, castor, guar, rapeseed-mustard, palm-kernel, sunflower, linseed, sal seed, rubber seed, camelina, hempseed, pumpkin seed and safflower cakes. Their feeding value depends on crude protein, fibre, residual oil, amino-acid profile, plant secondary metabolites and *anti*-nutritional or toxic compounds. Cakes such as castor, neem and rubber seed require particular attention to processing and safety, whereas cold-pressed cakes such as sunflower, linseed, camelina, hemp and pumpkin are mainly evaluated for protein, residual lipid, fibre and effects on animal products. Processing methods including heat treatment, washing, chemical detoxification, fermentation and biological treatment can improve the safety and utilization of selected cakes. Evidence from ruminant studies shows that appropriately selected and processed oil cakes can partially replace conventional protein supplements without impairing intake, digestibility or performance. Some also modify rumen fermentation, nitrogen metabolism, microbial populations, fatty-acid biohydrogenation and enteric methane production. Responses nevertheless vary with cake type, processing method, inclusion level, basal diet and animal category. The review emphasizes comparative feeding value, cake-specific metabolites, processing requirements, rumen effects, animal performance and practical use.

Keywords: Unconventional oil cakes, Alternative protein, Rumen fermentation, Plant secondary metabolites, Methane, Ruminants

1. Introduction

Ruminants depend on a complex microbial population in the rumen for the digestion of fibrous feeds. Bacteria, protozoa, anaerobic fungi and archaea convert dietary carbohydrates and nitrogenous compounds into products that can be used by the animal. This microbial system allows cattle, buffaloes, sheep and goats to utilize crop residues and other fibrous materials that cannot be efficiently used by monogastric animals. At the same time, rumen fermentation is associated with two important nutritional losses: formation of methane and excessive degradation of dietary protein to ammonia. Methane represents a loss of feed energy and is also an important greenhouse gas. Classical estimates indicate that enteric methane may account for about 2-12% of gross energy intake, depending on diet and production conditions (Johnson *et al.*, 1995) [1]; (Moss *et al.*, 2000) [2]).

Protein supplements are among the more expensive components of concentrate mixtures. Soybean meal, groundnut cake and other conventional cakes are widely used, but their price and competition with other uses encourage the search for alternative protein sources. Agro-industrial and oilseed-processing by-products are therefore important in tropical livestock production. Neem, castor, guar, rapeseed-mustard, palm-kernel, sunflower, linseed, sal seed, rubber seed, camelina, hempseed, pumpkin seed and safflower cakes differ markedly in composition and require cake-specific evaluation before inclusion in ruminant diets.

The main difficulty is that unconventional cakes cannot be judged only by crude protein content. Some contain bitter compounds, tannins, saponins, glucosinolates, ricin or other *anti*-nutritional factors. These compounds may reduce palatability and nutrient utilization when present at high levels. In moderate amounts, however, some plant secondary metabolites can alter rumen microbial activity in useful ways. Tannins may protect dietary protein from rapid ruminal degradation, while saponins can suppress protozoa and indirectly influence methane formation. Thus, the same compound may be beneficial at one concentration and harmful at another.

This review evaluates unconventional oil cakes as a group, comparing their nutritional value, cake-specific bioactive and *anti*-nutritional compounds, processing requirements, effects on intake and digestibility, rumen

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fermentation, methane production, microbial populations, animal health and recent in vivo responses in ruminants.

2. Major unconventional oil cakes used in ruminant nutrition

2.1 Neem seed cake

Neem seed cake is the residue remaining after oil extraction from *Azadirachta indica* seeds. It contains appreciable protein, but its direct feeding value is limited by bitterness and biologically active limonoids, including azadirachtin-related compounds, nimbin and salannin, together with tannins and other phenolics. Processing or detoxification is therefore important before substantial dietary inclusion. Ruminants can utilize properly processed neem cake as a partial protein substitute, and feeding studies in goat kids have reported acceptable growth and nutrient utilization when detoxified material replaced part of soybean meal. Its practical value is greatest in regions where neem seed is locally processed, but batch quality and the efficiency of detoxification should be verified before feeding (Prusty *et al.*, 2019) [3]. (Kumar *et al.*, 2016) [4]

2.2 Castor cake or meal

Castor cake is produced after extraction of oil from *Ricinus communis* seed and is attractive because the defatted residue is rich in protein. The major constraint is ricin, a highly toxic protein, along with ricinine and allergenic components. Raw castor cake should therefore not be regarded as a conventional feed ingredient. Physical, chemical or biological detoxification is required, and feeding recommendations must apply only to material produced by a validated detoxification process. Recent work in grazing sheep has evaluated detoxified castor cake as a replacement protein source, showing that the by-product can have nutritional value after appropriate processing. Its use should always be linked to quality control rather than to crude-protein concentration alone (Akande *et al.*, 2011; (Prusty *et al.*, 2019) [3]). [5, 6]

2.3 Guar meal

Guar meal is obtained during processing of *Cyamopsis tetragonoloba* and is a protein-rich agro-industrial by-product. Its feeding value depends on the proportion of germ and hull, residual galactomannan gum, processing method and concentrations of saponins and polyphenolic compounds. Excess residual gum can affect handling and digestion, whereas properly processed guar meal can replace part of conventional protein supplements. A recent study in Nagavali ram lambs evaluated graded replacement of soybean meal and reported useful growth and crude-protein digestibility responses, with the economic response depending on the replacement level. Guar meal is therefore a useful alternative protein source when its composition is known and diets are balanced for fibre and energy. (Shweta *et al.*, 2025) [7]

2.4 Rapeseed-mustard and canola-quality cake

Rapeseed-mustard cake is one of the most widely available alternative protein feeds in oilseed-producing regions. It provides protein and residual lipid, but glucosinolates and their degradation products are important limitations in high-glucosinolate material. Sinapine, sinapic acid, phytate and tannins may also influence palatability and nutrient availability. Low-glucosinolate canola-quality material has substantially improved feeding value. Processing and fermentation can further modify antinutritional compounds and rumen responses. In lactating dairy cows, fermented rapeseed cake reduced methane production without depressing digestibility or milk yield, and recent beef-cattle research also indicates that rapeseed cake can be incorporated without major loss of animal performance when diets are properly formulated (Rakita *et al.*, 2023) [8]; (Gao *et al.*, 2023) [9]. (Gao *et al.*, 2023; Folliard *et al.*, 2026) [9, 10]

2.5 Palm-kernel cake

Palm-kernel cake is an abundant by-product of palm-oil processing and contains moderate protein, residual lipid and a substantial fibre fraction rich in mannan. Its principal limitation is therefore often fibre

rather than a single toxic secondary metabolite. Inclusion level must be matched to animal species, physiological stage and the fibre concentration of the complete diet. A recent comparative meta-analysis in cattle, sheep and goats showed species-dependent responses in intake, digestibility and performance as dietary inclusion increased. Fermentation and other processing methods are being studied to improve fibre utilization; recent beef-cattle studies reported changes in nutrient degradation and rumen microbiota after feeding fermented palm-kernel cake. These findings support its use as a regional feed resource at controlled inclusion levels. (Vargas *et al.*, 2025; Mi *et al.*, 2025; Shen *et al.*, 2026) [11, 12, 13]

2.6 Sunflower cake

Sunflower cake is a useful protein and fibre source produced after oil extraction from sunflower seed. Cold-pressed material may retain appreciable residual oil rich in linoleic acid. Fibre concentration varies considerably with the degree of dehulling, and this variation is often more important nutritionally than crude protein alone. The cake also contains chlorogenic acid, caffeic acid and related phenolic compounds. These phenolics have antioxidant properties, although high concentrations can interact with proteins. Ruminant studies indicate that sunflower cake can replace part of conventional protein feeds, while residual unsaturated fatty acids may alter rumen biohydrogenation and the fatty-acid profile of animal products. Total dietary fat and fibre should therefore be considered when deciding its inclusion level (Rakita *et al.*, 2023) [8]. (Liu *et al.*, 2022) [14]

2.7 Linseed or flaxseed cake

Linseed cake supplies protein together with residual alpha-linolenic acid and is particularly interesting when the objective includes enrichment of milk or meat with beneficial fatty acids. Its bioactive fraction contains lignans, especially secoisolariciresinol diglucoside, as well as phenolic acids. Cyanogenic glycosides, phytate and mucilage are important antinutritional considerations, although their concentration and significance depend on processing. Recent dairy-cow studies with cold-pressed linseed cake reported favourable changes in milk fatty-acid composition and antioxidant-related traits. More recent cattle work also supports partial replacement of soybean meal with flaxseed cake without adverse rumen effects when the ration is balanced. Residual oil concentration should be monitored because excessive unsaturated fat can inhibit fibre digestion (Rakita *et al.*, 2023; Puppel *et al.*, 2023; Kokić *et al.*, 2024; Guo *et al.*, 2026) [8, 15, 16, 17]

2.8 Sal seed meal

Sal seed meal is produced after extraction of fat from *Shorea robusta* seeds and is relevant in forest-based production areas of India. Its use in ruminant diets is restricted mainly by tannins and the comparatively variable quality of the processed product. Tannins can bind dietary protein and carbohydrates, reducing their ruminal degradation; at excessive concentrations they may also reduce palatability and overall nutrient digestibility. Processing methods that lower tannin concentration improve feeding value. Sal seed meal is therefore better considered a locally available partial feed substitute than a direct replacement for high-quality conventional protein meals. Chemical analysis and gradual inclusion are advisable because composition can differ among processing systems (Prusty *et al.*, 2019) [3].

2.9 Rubber seed meal

Rubber seed meal is obtained from *Hevea brasiliensis* seeds after oil extraction. It can provide protein and energy, but cyanogenic compounds are a major safety limitation. Drying, heat treatment and other processing procedures are needed to reduce cyanide risk before feeding. The nutritional value also depends on residual oil and fibre. Ruminants may tolerate appropriately processed material better than monogastric animals because of rumen microbial metabolism, but this should not be used as a substitute for proper detoxification. Rubber seed meal is most relevant where rubber seed is locally abundant and where processors can provide a consistent, analysed product with low residual cyanogenic potential (Prusty *et al.*, 2019) [3].

2.10 Camelina cake

Camelina cake is a cold-pressed by-product of *Camelina sativa* and contains protein, residual oil rich in polyunsaturated fatty acids and several phenolic compounds. Its main antinutritional factors are glucosinolates, together with phytate and other secondary compounds. The glucosinolate profile differs from that of conventional rapeseed, and its feeding response depends on cultivar, processing and inclusion level. Ruminant research has examined camelina cake as an alternative protein and lipid source and as a means of modifying milk and meat fatty-acid composition. Because cold-pressed material may contain considerable residual oil, the complete dietary fat concentration should be controlled to avoid adverse effects on rumen fibre digestion (Rakita *et al.*, 2023) [8].

2.11 Hempseed cake

Hempseed cake is the residue from oil extraction of *Cannabis sativa* seed and is a source of protein, fibre, residual lipid, phenolic acids and flavonoids. Its nutritional limitations are generally associated more with fibre concentration and variable processing than with severe toxicity in approved low-THC feed material. A 2023 study in finishing goats evaluated increasing hempseed-cake inclusion as a replacement for soybean meal and found that nutrient digestibility, rumen fermentation and nitrogen-use efficiency were largely maintained, although microbial nitrogen supply changed at higher inclusion. These findings suggest that hempseed cake can function as an alternative protein source in small-ruminant diets when legal feed standards, composition and dietary fibre are considered (Rakita *et al.*, 2023) [8]; (Semwogerere *et al.*, 2024) [18].

2.12 Pumpkin seed cake

Pumpkin seed cake is a protein- and oil-rich residue with phenolic compounds, flavonoids and a favourable amino-acid profile. Cold-pressed pumpkin cake can have relatively high protein concentration, but composition varies with seed variety, dehulling and oil extraction. Compared with rapeseed, sunflower and linseed cakes, direct ruminant feeding evidence remains limited. Its value in a review of unconventional oil cakes is therefore as a promising emerging feed resource rather than as a feed with a firmly established universal inclusion rate. Future ruminant studies should define ruminal protein degradability, effects of residual oil on fermentation, productive responses and economically practical inclusion levels (Rakita *et al.*, 2023) [8].

2.13 Safflower cake

Safflower cake is obtained after oil extraction from *Carthamus tinctorius* seed. Its crude-protein and fibre concentrations vary markedly with the extent of dehulling. Phenolic glucosides and other polyphenols contribute to the characteristic bitter taste of some safflower by-products and may influence palatability. Dehulled or better processed cake has greater feeding value because hull removal reduces fibre and concentrates protein. Safflower cake can therefore be considered a regional alternative protein source for ruminants, but its value should be assessed from actual chemical composition rather than a single tabulated average. Compared with major conventional cakes, more controlled ruminant trials are required to establish responses in intake, milk or growth performance and rumen fermentation (Frontiers, 2024) [27].

2.14 Comparative nutritional and safety considerations

These cakes differ widely in protein, fibre, residual oil and bioactive compounds. Neem, castor and rubber seed products need particular attention to detoxification and quality control. Guar, rapeseed-mustard, sunflower, linseed and several cold-pressed cakes are generally more practical protein supplements when their characteristic limitations are considered. Palm-kernel and sal seed meals are useful where locally available but are more constrained by fibre or tannins. Thus, feed value should be judged from chemical composition, processing method, palatability, safety and animal response rather than crude

protein alone. Comparative feeding characteristics are presented in Table 2.

3. Plant secondary metabolites, bioactive compounds and anti-nutritional factors

3.1 Integrated role of cake-specific plant metabolites

Oil cakes retain characteristic secondary metabolites from their parent seeds. Their effects are dose- and cake-dependent. Limonoids in neem contribute bitterness; ricin and ricinine make untreated castor cake unsafe; glucosinolates and sinapine constrain rapeseed-mustard products; cyanogenic glycosides require attention in linseed and rubber seed products; and phenolics, lignans and flavonoids occur in sunflower, linseed, hempseed and pumpkin cakes. Tannins and saponins are important in some cakes but should be interpreted within the complete chemical profile of each feed. Processing by heat, washing, fermentation, dehulling or other validated methods can reduce specific anti-nutritional factors, but excessive processing may also reduce protein quality. The cake-wise metabolites, their nutritional significance and supporting references are summarized in Table 1. (Francis *et al.*, 2002; Frutos *et al.*, 2004; McSweeney *et al.*, 2001; Patra *et al.*, 2009; Patra *et al.*, 2010) [19, 20, 21, 22, 23]

4. Effects on feed intake, growth and nutrient digestibility

The feeding value of an unconventional cake reflects the balance between nutrients supplied and anti-nutritional factors consumed. Moderate inclusion of a well-processed cake may maintain intake and growth, whereas bitterness, high fibre, residual toxins or excessive bioactive compounds can reduce palatability and digestibility. Responses therefore depend on cake type, processing, inclusion level, basal diet and animal species.

Processing can markedly alter animal response. Detoxified neem and castor products have been used in small ruminant diets without major loss of performance when appropriately processed, while untreated products are less suitable. Guar meal, rapeseed products, sunflower cake, linseed cake and hempseed cake have also been evaluated as partial replacements for conventional protein supplements. These studies support partial substitution rather than assuming complete equivalence with soybean meal.

Production stage is important. Growing animals may tolerate moderate inclusion without measurable loss of performance, whereas high-producing dairy animals require closer attention to amino-acid supply, energy density, fibre and residual oil. Consequently, tested inclusion levels should be reported rather than generalized as universal safe limits.

5. Effects on rumen fermentation and nitrogen utilization

Rumen ammonia reflects degradation of dietary protein and recycling of nitrogen. Some cake-associated phenolics, tannins, saponins and fermentation products can lower excessive proteolysis or alter protozoal activity, whereas highly degradable protein sources may increase ammonia. The desirable response is improved capture of dietary nitrogen into microbial protein without depressing fibre digestion.

Volatile fatty acids are the major energy-yielding products of rumen fermentation. Oil cakes can alter total VFA concentration and acetate:propionate ratio through their fibre, residual lipid and bioactive compounds. The response is not uniform; therefore, rumen pH, ammonia-N, VFA profile and digestibility should be interpreted together.

Recent work shows that responses are not driven only by tannins or saponins. Residual unsaturated fatty acids in sunflower, linseed, camelina and related cakes can influence biohydrogenation and hydrogen availability, while fermentation of rapeseed or palm-kernel products may modify substrate accessibility and the rumen microbial community.

6. Effects on enteric methane production

Methane is formed mainly by rumen methanogenic archaea using hydrogen released during fermentation. Oil cakes may influence methane through residual fatty acids, fibre, fermentation products and cake-specific secondary metabolites. A useful mitigation response should reduce methane intensity without reducing feed intake, nutrient digestion or productive performance.

In vitro studies show large variation among oilseed by-products, so animal studies are essential. Recent in vivo work with fermented rapeseed cake, rapeseed cake in beef cattle and processed palm-kernel products indicates that selected oilseed by-products can alter methane output or rumen fermentation while maintaining performance under defined feeding conditions. These responses cannot be extrapolated to all cakes or inclusion levels.

Methane reduction should not be interpreted as beneficial when it results from lower intake or poorer digestion. Future comparisons should report methane per unit of dry-matter intake or product output together with digestibility and performance.

7. Effects on rumen microbial populations

7.1 Bacteria

Rumen bacteria differ in sensitivity to plant metabolites and residual lipids. High concentrations may inhibit fibrolytic organisms, whereas moderate levels or fermentation processing may shift the community without impairing digestion. The direction of change depends on the compound, dose and basal diet.

Modern 16S rRNA sequencing allows community-level assessment of oil-cake responses. Recent studies of processed rapeseed and palm-kernel products suggest that changes in microbial composition may accompany altered fermentation and nutrient use. Functional interpretation, however, should be linked with VFA production, digestibility and animal performance.

7.2 Protozoa, methanogens and fungi

Protozoa contribute to feed breakdown but also engulf bacteria and support hydrogen transfer to associated methanogens. Saponin- or tannin-containing cakes may reduce protozoal activity, while residual lipids can influence methanogens and fibre-associated microbes. Anaerobic fungi are important for fibre degradation and may be sensitive to high concentrations of some secondary metabolites. Cake-specific microbial effects therefore require direct measurement rather than prediction from chemical composition alone.

8. Blood biochemistry, health and safety

Blood biochemical measurements are useful when unconventional feeds contain known toxic or *anti*-nutritional factors. Liver enzymes, renal indices, protein fractions and haematological variables can reveal subclinical effects that are not evident from growth alone.

Safety assessment is especially important for castor, rubber seed and high-glucosinolate rapeseed-mustard products. Ricin makes raw castor cake unsuitable for feeding, while cyanogenic compounds and glucosinolates require control through source selection and validated processing. Chemical analysis and processing verification should precede large-scale use.

Potential antioxidant or immune effects of phenolics, lignans and flavonoids should be interpreted cautiously. Evidence of antioxidant activity in extracts does not by itself establish a production benefit in ruminants; controlled feeding studies with relevant biomarkers are required.

9. Comparative practical value of major oil cakes

No single unconventional cake suits every production system. Guar meal, rapeseed-mustard products and selected sunflower or linseed cakes can be practical protein sources where locally economical. Palm-kernel cake is useful in regions with palm processing but its fibre limits high inclusion. Neem, castor, sal and rubber seed products require greater attention to processing and *anti*-nutritional factors. *Camelina*, hempseed, pumpkin and safflower cakes are promising alternatives, but their use should be based on batch composition, availability and species-specific evidence. A comparison of the nutritional value, limitations and practical considerations is given in Table 2.

10. Recent in vivo studies in ruminants

Recent controlled feeding studies and *meta*-analyses involving cattle, sheep and goats are summarized in Table 3. The study-specific references in that table correspond to the numbered reference list.

11. Recent research perspective and future directions

Recent research has moved from simple acceptability studies toward evaluation of rumen fermentation, methane, nitrogen efficiency, microbial ecology and product quality. Fermentation and other processing methods are receiving particular attention because they may reduce *anti*-nutritional factors and improve nutrient availability. (Ren *et al.*, 2026; Vujetić *et al.*, 2025; Grahovac *et al.*, 2025; Vichare *et al.*, 2024) [24, 25, 26, 27]

Important gaps remain. Composition varies among batches and extraction systems, so studies should report crude protein, fibre fractions, residual oil and relevant *anti*-nutritional compounds. Detoxification methods need chemical verification rather than relying only on normal animal performance.

More long-term studies are required in lactating cattle and buffaloes under tropical feeding systems. Future work should combine intake, digestibility, milk or growth responses, methane intensity, nitrogen balance, blood safety indices and rumen microbial measurements.

Economic and environmental assessment should accompany nutritional research. A locally available cake is useful only when processing, transport and quality control do not remove its cost advantage over conventional protein feeds.

12. Conclusion

Unconventional oil cakes can contribute to ruminant nutrition by supplying locally available protein, fibre, residual lipid and bioactive compounds. Their feeding value, however, varies widely. Guar, rapeseed-mustard, sunflower, linseed, palm-kernel and several cold-pressed cakes can partially replace conventional protein feeds when ration balance is maintained, whereas neem, castor, sal and rubber seed products require greater attention to *anti*-nutritional factors and processing.

Oil cakes should therefore not be evaluated on crude protein concentration alone. Safe and efficient use depends on extraction method, residual oil, fibre, cake-specific metabolites, detoxification, inclusion level and animal species. Recent ruminant studies support the value of selected processed cakes, but wider adoption requires standardized processing, chemical quality control and long-term in vivo evaluation.

Conflict of interest

The authors declare that there is no conflict of interest

Table 1. Plant secondary metabolites and *anti*-nutritional compounds in unconventional oil cakes

Oil cake	Major compounds	Nutritional/rumen relevance	References
Neem	Limonoids (azadirachtin-type), nimbin, salannin, tannins	Bioactive and bitter; processing improves feeding value	[3]

(continued on next page)

Oil cake	Major compounds	Nutritional/rumen relevance	References
Castor	Ricin, ricinine, phenolics	Ricin is highly toxic; use only adequately detoxified cake	[3, 5]
Rapeseed/mustard	Glucosinolates, sinapine/sinapic acid, phytate, tannins	Can affect palatability and thyroid function at excessive exposure; fermentation/processing can reduce constraints	[8, 24]
Sunflower	Chlorogenic acid, caffeic acid and other phenolics	Antioxidant phenolics; high concentrations may interact with protein	[8, 24]
Linseed/flaxseed	Lignans (SDG), phenolic acids, cyanogenic glycosides, phytate	Lignans are bioactive; cyanogenic glycosides are a safety consideration	[8, 24]
<i>Camelina</i>	Glucosinolates, sinapine-related phenolics, polyphenols	May limit high inclusion; composition varies with processing	[8]
Hempseed	Phenolic acids, flavonoids and other polyphenols	Potential antioxidant bioactivity; feeding response depends mainly on composition and inclusion level	[8]
Pumpkin seed	Phenolics and flavonoids	Potential antioxidant compounds; ruminant evidence remains comparatively limited	[8]
Sal seed	Tannins	Can reduce palatability and nutrient availability at high concentrations	[3]
Rubber seed	Cyanogenic compounds	Requires processing and attention to cyanide risk	[3]
Guar	Saponins, polyphenols; residual galactomannan	May affect palatability/digestion; processing and inclusion level are important	[3]
Palm kernel	Phenolic compounds; high mannan/fibre fraction	Secondary metabolites are less limiting than fibre; fermentation may improve utilization	[3, 12]
Safflower	Phenolic glucosides and other polyphenols	May contribute bitterness and affect palatability; dehulling and processing improve feeding value	[25]

Table 2. Comparative nutritional and practical characteristics of unconventional oil cakes

Oil cake	Main nutritional value	Important limitation	Practical consideration	References
Neem	Protein after processing	Limonoids, bitterness, tannins	Use processed/detoxified material; partial protein replacement	[3, 4]
Castor	High crude protein	Ricin, ricinine and allergens	Only validated detoxified material	[3, 5, 6]
Guar	Protein-rich by-product	Residual gum, saponins/polyphenols	Processing quality determines feeding value	[3, 7]
Rapeseed-mustard	Protein and residual oil	Glucosinolates, sinapine, phytate	Prefer low-glucosinolate/canola-quality or processed material	[8, 9, 10]
Palm kernel	Moderate protein and energy	High fibre and mannan	Use at controlled inclusion according to species and diet fibre	[3, 11, 12, 13]
Sunflower	Protein, fibre, linoleic-rich residual oil	Variable hull fibre; chlorogenic acid	Useful partial substitute; monitor total fat and fibre	[8, 14]
Linseed/flaxseed	Protein and alpha-linolenic acid	Cyanogenic glycosides, phytate, residual oil	Useful for protein and fatty-acid enrichment at controlled levels	[8, 15, 16]
Sal seed	Local energy/protein contribution	Tannins and variable quality	Processed material; gradual partial inclusion	[3]
Rubber seed	Protein and residual energy	Cyanogenic compounds	Require processing and cyanide control	[3]
<i>Camelina</i>	Protein and PUFA-rich residual oil	Glucosinolates, phytate	Control inclusion and total dietary fat	[8, 25]

(continued on next page)

Oil cake	Main nutritional value	Important limitation	Practical consideration	References
Hempseed	Protein, fibre and residual lipid	High fibre; variable processing	Evidence supports moderate replacement in goats	[8, 18]
Pumpkin seed	Protein and residual oil	Limited ruminant evidence; variable composition	Promising feed; establish inclusion from analysed composition	[8]
Safflower	Protein depending on dehulling	Fibre and bitter phenolic glucosides	Dehulled/processed cake has greater feeding value	[8, 27]

Table 3. Recent in vivo studies of unconventional oil cakes in ruminants

Cake/feed	Ruminant	Dietary treatment	Main response	Study type/year	Reference
Fermented rapeseed cake	Lactating dairy cows	2.65 kg/day; fermented treatment	CH ₄ production reduced about 12%; archaeal abundance decreased; digestibility and milk production maintained	In vivo, 2023	[9]
Rapeseed cake	Beef cattle	Rapeseed cake in concentrate	Enteric CH ₄ decreased; DMI not affected; no major loss of performance versus control	In vivo, 2026	[10]
Detoxified castor cake	Grazing sheep	Replaced soybean meal in concentrate	Nutrient intake and liver/kidney indices were maintained; dry-matter digestibility and average daily gain were lower than with soybean meal.	In vivo, 2024	[6]
Guar meal	Nagavali ram lambs	50, 75 or 100% replacement of soybean meal	Growth improved; CP digestibility highest up to 75% replacement; 75% was most economical in that trial	In vivo, 2025	[7]
Hempseed cake	Finishing goats	0-100 g/kg DM replacing soybean meal	Digestibility, rumen fermentation and N-use efficiency maintained; microbial N supply declined with inclusion	In vivo, 2023	[18]
Linseed cake	Organic dairy cows	300 g/day/cow	Improved beneficial milk fatty acids, fat-soluble vitamins and total antioxidant status	In vivo, 2023	[15]
Flaxseed cake	Simmental cows	40% replacement of soybean meal	ADG and CP digestibility improved; rumen fermentation, immunity and antioxidant status favourably affected	In vivo, 2026	[17]
Palm-kernel cake	Cattle, sheep and goats	Increasing dietary inclusion	Species-dependent intake/digestibility responses; ADG decreased progressively as inclusion increased	Meta-analysis, 2025	[11]
Fermented palm-kernel cake	Beef cattle	Processed PKC replacing part of corn/soybean meal	Improved nutrient degradation; altered rumen microbiota; 20% FPKC improved ADG and feed efficiency in a recent trial	In vivo, 2025 and 2026	[12]; [13]

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