

Solid-state fermentation as a strategy to mitigate nutritional variability and improve the feeding value of commercial rapeseed meal

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Abstract

Rapeseed meal (RSM) is an important plant protein source for animal feeding, but its nutritional value is influenced by cultivar, dehulling and processing, while glucosinolates, phytic acid and fibre can limit its utilization in animal diets. This review synthesizes peer-reviewed studies from an animal nutrition and feed science perspective to examine the reported variation in RSM composition and the effects of solid-state fermentation (SSF) on its feeding value. Across the reviewed studies, crude protein (CP) ranged from 31.8% to 42.5%, glucosinolates from 15.5 to 75.6 $\mu\text{mol/g}$, phytic acid from 2.66% to 5.24%, and neutral detergent fibre (NDF) from 23.9% to 47.1%. These differences illustrate the influence of raw material characteristics and processing on the nutritional attributes of RSM. SSF using microorganisms belonging to *Bacillus*, *Lactobacillus*, *Saccharomyces* and *Aspergillus* reduced glucosinolates, phytic acid and fibre while generally increasing CP and peptide concentrations. The magnitude of these changes varied considerably among microorganisms and fermentation conditions. The reviewed evidence indicates that SSF is not simply a method for reducing individual anti-nutritional factors; it can simultaneously modify several characteristics that determine the nutritional usefulness of RSM. These changes make SSF a promising approach for upgrading RSM as an animal feed ingredient.

Keywords: Rapeseed meal, solid-state fermentation, animal nutrition, glucosinolates, phytic acid, fibre, protein quality

Introduction

The availability of economical and nutritionally suitable protein ingredients is an important consideration in animal nutrition. Rapeseed meal (RSM), obtained after oil extraction from rapeseed, represents an important alternative plant protein source to soybean meal. Its appreciable protein concentration and useful amino acid contribution make it relevant to feed formulation, particularly where diversification of protein sources is desirable (Cheng *et al.*, 2022; Zhu *et al.*, 2023) [3, 15]. However, the nutritional value of RSM cannot be defined by crude protein concentration alone. Its feeding value is influenced by fibre concentration, amino acid availability and the presence of anti-nutritional factors (ANFs), particularly glucosinolates and phytic acid. An additional challenge is that the composition of RSM is not uniform. Cultivar characteristics, dehulling efficiency and processing conditions can alter the relative proportions of protein and fibre and influence the concentration of ANFs (Cheng *et al.*, 2022; Konkol *et al.*, 2023) [3, 7]. This is important from an animal nutrition perspective because variation in the chemical characteristics of a feed ingredient can affect the precision with which diets are formulated. A high-protein RSM and a high-fibre RSM may therefore provide different nutritional contributions even when both are described simply as RSM. Similarly, differences in glucosinolate concentration can influence the suitability of the ingredient for inclusion in animal diets.

Processing strategies that improve the nutritional characteristics of RSM are therefore of considerable interest. Solid-state fermentation (SSF) uses microorganisms growing on a moist solid substrate and provides an opportunity to modify the composition of RSM

through microbial metabolism. Microorganisms used for RSM fermentation include species of *Bacillus*, *Lactobacillus*, *Saccharomyces* and *Aspergillus*. Their enzymatic activities can influence proteins, fibre, phytate and glucosinolates, thereby producing a fermented ingredient with characteristics different from those of the original RSM (Shi *et al.*, 2015; Shi *et al.*, 2016; Wang *et al.*, 2019; Zhu *et al.*, 2023) [9, 10, 11, 15].

The significance of SSF in animal nutrition therefore extends beyond the reduction of a single ANF. If fermentation can simultaneously improve several characteristics associated with feeding value, it may provide a useful biological approach for upgrading RSM. The present review examines the reported variation in the nutritional characteristics of RSM and synthesizes evidence on how SSF modifies these characteristics, with particular emphasis on the implications for the use of RSM as an animal feed ingredient.

Materials and Methods

A focused narrative review of peer-reviewed literature concerning RSM composition, nutritional quality, and SSF was undertaken. The reviewed literature included studies addressing RSM composition, fermentation, and nutritional changes following SSF. Information relevant to animal nutrition was extracted concerning crude protein, amino acids, fibre fractions, glucosinolates, phytic acid, tannins, microorganisms used for fermentation and changes in nutritional characteristics following fermentation. The terminology used in the original studies was retained to distinguish RSM, rapeseed cake and canola meal where applicable.

Nutritional Variability of Rapeseed Meal and Its Relevance to Animal Nutrition

The nutritional characteristics of RSM vary considerably among the materials reported in the reviewed literature. Crude protein values ranged from 31.84% in rapeseed cake to 42.45% in RSM, while studies of RSM reported intermediate concentrations including 34.84%, 36.4%, 37.05% and 42.11% (Shi *et al.*, 2015; Shi *et al.*, 2016; Wang *et al.*, 2019; Wu *et al.*, 2021; Hu *et al.*, 2015; Liu *et al.*, 2026). Cheng *et al.* (2022) [3, 6, 8, 9, 10, 11] similarly described differences in protein concentration among rapeseed-derived materials and cultivars. These differences are nutritionally relevant because crude protein is an important determinant of the contribution of RSM to dietary protein supply. Protein concentration, however, does not completely describe protein quality. The reviewed literature indicates differences in amino acid composition, while processing can influence amino acid availability. Cheng *et al.* (2022) [3] reported variation in lysine and methionine concentrations between conventional and double-low RSM. They also highlighted that heat treatment may reduce lysine availability through Maillard reactions without necessarily changing total nitrogen. Consequently, reliance on crude

protein alone may overlook changes in the nutritional quality of the protein fraction.

Fibre represents another important source of variation. Reported NDF values ranged from 23.9% to 47.08% among the reviewed studies (Wang *et al.*, 2019; Shi *et al.*, 2016) [10, 11]. Dehulling can substantially influence fibre concentration because the hull fraction contributes considerably to the structural carbohydrate content of the meal (Cheng *et al.*, 2022) [3]. Thus, differences in processing can alter not only the concentration of protein but also the proportion of fibre accompanying that protein.

The greatest variation was observed for glucosinolates, with reported concentrations ranging from 15.51 to 75.6 µmol/g. Phytic acid was reported between 2.66% and 5.24%, while tannin concentrations of 1.32% and 2.67% were reported in two studies (Hu *et al.*, 2015; Zhu *et al.*, 2023) [15]. These components are particularly relevant to feed evaluation because they can influence the effective nutritional value of the ingredient. The combined variation in protein, fibre and ANFs demonstrates that RSM should be evaluated as a complex feed ingredient rather than on the basis of a single nutritional parameter.

Table 1: Reported variation in key nutritional and anti-nutritional characteristics of rapeseed-derived feed materials

Parameter	Reported values	Factors associated with variation	References
Crude protein (%)	31.84–42.45	Cultivar, dehulling, processing	Shi <i>et al.</i> (2015); Liu <i>et al.</i> (2026) [8, 9]
Glucosinolates (µmol/g)	15.51–75.6	Cultivar, processing	Konkol <i>et al.</i> (2023); Wang <i>et al.</i> (2019) [7, 11]
Phytic acid (%)	2.66–5.24	Cultivar, processing	Shi <i>et al.</i> (2016); Liu <i>et al.</i> (2026) [8, 10]
NDF (%)	23.9–47.08	Dehulling, processing	Wang <i>et al.</i> (2019); Shi <i>et al.</i> (2016) [10, 11]
Tannins (%)	1.32–2.67	Cultivar	Hu <i>et al.</i> (2015); Zhu <i>et al.</i> (2023) [15]

Values represent those reported across the reviewed studies and should not be interpreted as a single standardized commercial RSM specification.

Solid-State Fermentation as a Nutritional Upgrading Approach

SSF provides a biological means of modifying RSM rather than simply removing a single undesirable component. The microorganisms used in the reviewed studies differed substantially in their enzymatic capabilities and were applied either individually or in combinations. *Bacillus* species were frequently used, including *B. subtilis*, *B. licheniformis*, *B. amyloliquefaciens* and *B. velezensis*. Lactobacilli, yeasts and *A. niger* were also used, with several studies employing mixed microbial systems (Chiang *et al.*, 2010; Shi *et al.*, 2015; Wang *et al.*, 2019; Wang *et al.*, 2022; Zhu *et al.*, 2023; Liu *et al.*, 2026) [4, 8, 9, 11, 12, 15].

The importance of the fermentation organism is illustrated by the different outcomes obtained among studies. Microbial growth can produce enzymes capable of acting on

proteins, fibre and phytate, while microbial metabolism can also contribute to glucosinolate degradation. *A. niger*, for example, was associated with secretion of glucoamylase, acid protease, xylanase and phytase, whereas bacterial systems can contribute proteases and other hydrolytic enzymes (Shi *et al.*, 2015; Shi *et al.*, 2016) [9, 10]. Mixed cultures may provide complementary metabolic activities, although their performance remains dependent on the substrate and fermentation conditions.

Fermentation conditions also differed markedly among studies. Reported temperatures ranged from 28 to 37°C and fermentation duration from 24 hours to 30 days, although many experiments were conducted over 48–96 hours. The differences in both microbial systems and processing conditions help explain why the magnitude of nutritional changes was not uniform among studies.

Table 2: Microorganisms and fermentation conditions reported for rapeseed meal

Study	Microorganism(s)	Culture type	Temperature	Fermentation duration
Chiang <i>et al.</i> (2010) [4]	<i>L. fermentum</i> , <i>E. faecium</i> , <i>S. cerevisiae</i> , <i>B. subtilis</i>	Mixed	30°C	30 d
Shi <i>et al.</i> (2015) [9]	<i>A. niger</i>	Single	34°C	72 h
Wang <i>et al.</i> (2019) [11]	<i>B. licheniformis</i> , yeast, <i>Lactobacillus</i>	Mixed	30°C	72 h
Wang <i>et al.</i> (2022) [12]	<i>B. subtilis</i> YY-4, <i>L. plantarum</i> 6026	Mixed	37°C	5 d
Zhu <i>et al.</i> (2023) [15]	<i>B. subtilis</i> , <i>S. cerevisiae</i> , <i>B. amyloliquefaciens</i>	Mixed	37°C	96 h
Liu <i>et al.</i> (2026) [8]	<i>B. velezensis</i> , <i>B. licheniformis</i> , <i>L. acidophilus</i>	Mixed	35°C	96 h

Nutritional Consequences of Solid-State Fermentation

The most consistent nutritional effect of SSF was the reduction of glucosinolates. Reductions ranged from 36.5% to 99.2% across the reviewed studies. Zhu *et al.* (2023) ^[15] reported a reduction from 47.67 to 0.26 µmol/g, while Wang *et al.* (2022) ^[12] reported a decrease from 75.17 to 6.15 µmol/g. Other studies reported reductions of 85.0%, 76.9%, 52.6%, 38.0% and 36.5% (Shi *et al.*, 2015; Wang *et al.*, 2019 ^[9, 11]; Wu *et al.*, 2021; Ahmed *et al.*, 2014; Konkol *et al.*, 2023) ^[1, 7]. These differences are important because they demonstrate that fermentation is not associated with a fixed degree of glucosinolate degradation. The response depends on the microbial system, substrate and fermentation conditions.

Phytic acid was also substantially reduced. Reported reductions ranged from 42.4% to 90.7%, while NDF and crude fibre were reduced in several studies. Wang *et al.* (2022) ^[12] reported a 90.7% reduction in phytic acid, whereas Shi *et al.* (2016) ^[10] reported an 86.1% reduction. Crude fibre reductions of 27.2%, 24.7% and 10.7% were reported by Zhu *et al.* (2023) ^[15], Hu *et al.* (2015) and Konkol *et al.* (2023) ^[7], respectively. These findings suggest that SSF can simultaneously target several components that influence the nutritional usefulness of RSM.

Changes in protein characteristics provide another dimension to the nutritional effect of fermentation. CP increased by 6.0–23.0% in studies reporting increases,

although Konkol *et al.* (2023) ^[7] found no significant change. Such increases should be interpreted carefully because they may result partly from dry matter losses and concentration effects, in addition to microbial protein synthesis. Therefore, an increase in CP concentration should not automatically be interpreted as a proportional increase in nutritionally available protein.

More pronounced changes were observed in peptide concentrations. Wang *et al.* (2019) ^[11] reported an increase from 11.9 to 66.0 mg/g, while Zhu *et al.* (2023) ^[15] reported an increase from 4.13% to 16.47%. Shi *et al.* (2016) and Wang *et al.* (2022) ^[10, 12] also reported substantial increases in peptide concentrations. These observations indicate that SSF can alter not only the quantity of nitrogenous material but also the molecular form in which part of the protein occurs.

Amino acid changes further support this interpretation. Shi *et al.* (2015) ^[9] reported increases in total amino acids and essential amino acids, including increases in methionine and threonine. Zhu *et al.* (2023) ^[15] reported increases in total amino acids together with increases in arginine, histidine and glutamic acid. Wang *et al.* (2019) ^[11] observed significant increases in several amino acids. Nevertheless, these responses were not identical across studies, indicating that amino acid modification is dependent on the fermentation system.

Table 3: Selected nutritional changes reported following solid-state fermentation of RSM

Component	Reported effect	Magnitude of change	Studies reporting the effect
Glucosinolates	↓ Reduced	36.5–99.2%	Ahmed <i>et al.</i> (2014); Shi <i>et al.</i> (2015); Wang <i>et al.</i> (2019, 2022) ^[1, 9, 11, 12] ; Wu <i>et al.</i> (2021); Konkol <i>et al.</i> (2023); Zhu <i>et al.</i> (2023); Liu <i>et al.</i> (2026) ^[7, 8, 15]
Phytic acid	↓ Reduced	42.4–90.7%	Shi <i>et al.</i> (2015, 2016); Zhu <i>et al.</i> (2023); Wang <i>et al.</i> (2022); Liu <i>et al.</i> (2026) ^[8, 9, 10, 12, 15]
Crude fibre	↓ Reduced	10.7–27.2%	Hu <i>et al.</i> (2015); Konkol <i>et al.</i> (2023); Zhu <i>et al.</i> (2023) ^[7, 15]
NDF	↓ Reduced	13.5–14.6%	Shi <i>et al.</i> (2016); Wang <i>et al.</i> (2019) ^[10, 11]
Crude protein	↑ Generally increased	6.0–23.0%*	Hu <i>et al.</i> (2015); Shi <i>et al.</i> (2015, 2016); Wang <i>et al.</i> (2019); Zhu <i>et al.</i> (2023); Liu <i>et al.</i> (2026); Konkol <i>et al.</i> (2023) ^[7, 8, 9, 10, 11, 15]
Peptides	↑ Increased	Up to approximately 5-fold	Shi <i>et al.</i> (2016); Wang <i>et al.</i> (2019, 2022); Zhu <i>et al.</i> (2023) ^[10, 11, 12, 15]
Total amino acids	↑ Increased	24.3% in Shi <i>et al.</i> (2015) ^[9] ; other increases reported	Shi <i>et al.</i> (2015); Wang <i>et al.</i> (2019); Zhu <i>et al.</i> (2023) ^[9, 11, 15]

Factors Affecting Fermentation

The nutritional response to SSF depends on the interaction between the microorganism, substrate characteristics and fermentation conditions. Differences among studies indicate that fermentation should not be regarded as a uniform treatment that produces an identical nutritional outcome in all RSM materials (Shi *et al.*, 2015; Wang *et al.*, 2019; Wang *et al.*, 2022; Zhu *et al.*, 2023; Liu *et al.*, 2026) ^[8, 9, 11, 12, 15].

The composition of the starting material is particularly important because differences in glucosinolate, phytic acid, fibre and protein concentrations provide different substrates for microbial activity. Likewise, microbial species differ in their enzymatic capabilities, while temperature and fermentation duration influence microbial growth and the extent of substrate degradation (Shi *et al.*, 2015; Shi *et al.*, 2016; Wang *et al.*, 2019) ^[9, 10, 11]. Consequently, the selection of an appropriate microbial system and control of

fermentation conditions are important for obtaining a predictable nutritional outcome.

Implications for Animal Nutrition

From an animal nutrition perspective, the principal value of fermented RSM lies in the simultaneous modification of characteristics that influence its feeding value. Reduction of glucosinolates, phytic acid and fibre can potentially improve the suitability of RSM as a feed ingredient, while changes in protein fractions and amino acid composition may influence nutrient availability (Ahmed *et al.*, 2014; Shi *et al.*, 2015; Shi *et al.*, 2016; Wang *et al.*, 2019) ^[1, 9, 10, 11].

However, chemical improvement should not automatically be equated with improved animal performance. The nutritional value of a fermented ingredient ultimately depends on how the observed compositional changes translate into nutrient digestibility, amino acid availability and animal responses. Studies with broilers and ducks have reported effects of fermented RSM on growth performance,

nutrient digestibility, intestinal characteristics, serum parameters and other biological responses (Chiang *et al.*, 2010; Fazhi *et al.*, 2011; Xu *et al.*, 2012; Hu *et al.*, 2015; Ashayerizadeh *et al.*, 2017; Wu *et al.*, 2021; Konkol *et al.*, 2023; Liu *et al.*, 2026) [2, 4, 5, 7, 8].

For feed formulation, fermented RSM should therefore be characterized according to its post-fermentation nutritional composition rather than evaluated solely from the characteristics of the original RSM. This is particularly important because the extent of nutritional modification differs among fermentation systems and starting materials (Cheng *et al.*, 2022; Wang *et al.*, 2019; Zhu *et al.*, 2023) [3, 11, 15].

Future Perspectives

An important limitation of the available literature is the lack of direct evidence on whether SSF can reduce variability among independent commercial RSM batches. Most studies have compared raw and fermented material from individual samples under specific experimental conditions. Such studies demonstrate nutritional modification but cannot establish whether fermentation produces a more consistent feed ingredient across commercially variable substrates.

Future studies should therefore evaluate multiple independent commercial RSM batches and apply the same fermentation conditions to each batch. Variability before and after fermentation should be quantified using appropriate statistical measures such as range, standard deviation and coefficient of variation. Standardization of analytical methods is also required because differences in methods for glucosinolate and fibre determination can complicate comparisons among studies.

Greater emphasis should also be placed on linking compositional changes with animal responses. Studies combining characterization of the starting RSM, controlled fermentation, nutrient digestibility and animal performance would provide stronger evidence for determining the practical feeding value of fermented RSM.

Conclusion

RSM is a valuable protein source for animal feeding, but its nutritional characteristics vary with cultivar, dehulling and processing. SSF can substantially modify this feed ingredient through reductions in important anti-nutritional components and fibre, together with changes in protein and peptide fractions. The available evidence therefore supports SSF as a promising approach for nutritional upgrading of RSM. However, nutritional improvement of individual batches should be distinguished from standardization of commercial RSM. Direct evidence that SSF reduces batch-to-batch variability is currently lacking. Further work using multiple commercial batches and standardized fermentation and analytical procedures is needed to determine whether SSF can provide not only improved nutritional quality but also greater consistency of RSM as a feed ingredient.

References

1. Ahmed A, Zulkifli I, Farjam AS, Abdullah N, Liang JB. Effect of solid-state fermentation on nutrient content and ileal amino acids digestibility of canola meal in broiler chickens. *Italian Journal of Animal Science*, 2014;13(1):3293.
2. Ashayerizadeh A, Dastar B, Shams Shargh M, Sadeghi Mahoonak AR, Zerehdaran S. Fermented rapeseed meal is effective in controlling *Salmonella enterica* serovar Typhimurium infection and improving growth performance in broiler chicks. *Veterinary Microbiology*, 2017;201(1):93-102.
3. Cheng H, Liu X, Xiao Q, Zhang F, Liu N, Tang L, *et al.* Rapeseed meal and its application in pig diet: A review. *Agriculture*, 2022;12(6):849.
4. Chiang G, Lu WQ, Piao XS, Hu JK, Gong LM, Thacker PA. Effects of feeding solid-state fermented rapeseed meal on performance, nutrient digestibility, intestinal ecology and intestinal morphology of broiler chickens. *Asian-Australasian Journal of Animal Sciences*, 2010;23(2):263-271.
5. Fazhi X, Lvmu L, Jiaping X, Kun Q, Zhide Z, Zhangyi L. Effects of fermented rapeseed meal on growth performance and serum parameters in ducks. *Asian-Australasian Journal of Animal Sciences*, 2011;24(5):678-684.
6. Hu Y, Wang Y, Li A, Wang Z, Zhang X, Yun T, *et al.* Effects of fermented rapeseed meal on antioxidant functions, serum biochemical parameters and intestinal morphology in broilers. *Food and Agricultural Immunology*, 2015;27(2):182-193.
7. Konkol D, Jonuzi E, Popiela E, Sierzant K, Korzeniowska M, Leicht K, *et al.* Influence of solid-state fermentation with *Bacillus subtilis* 67 strain on the nutritional value of rapeseed meal and its effects on performance and meat quality of broiler chickens. *Poultry Science*, 2023;102(8):102742.
8. Liu Y, Li S, Chen X, Zhang X, Zhao A, Chen Z, *et al.* Effects of fermented rapeseed meal on growth performance, antioxidant capacity, and immune function in broiler chickens. *Animals*, 2026;16(5):765.
9. Shi C, He J, Yu J, Yu B, Huang Z, Mao X, *et al.* Solid state fermentation of rapeseed cake with *Aspergillus niger* for degrading glucosinolates and upgrading nutritional value. *Journal of Animal Science and Biotechnology*, 2015;6(1):13.
10. Shi C, He J, Yu J, Yu B, Mao X, Zheng P, *et al.* Physicochemical properties analysis and secretome of *Aspergillus niger* in fermented rapeseed meal. *PLoS ONE*, 2016, 11(4):e0153230.
11. Wang Y, Liu J, Wei F, Liu X, Yi C, Zhang Y. Improvement of the nutritional value, sensory properties and bioavailability of rapeseed meal fermented with mixed microorganisms. *LWT-Food Science and Technology*, 2019;112(1):108238.
12. Wang Y, Sun H, Liu X. A novel fermented rapeseed meal, inoculated with selected protease-assisting screened *B. subtilis* YY-4 and *L. plantarum* 6026, showed high availability and strong antioxidant and immunomodulation potential capacity. *Foods*, 2022;11(14):2118.
13. Wu Z, Chen J, Ahmed Pirzado S, Haile TH, Cai H, Liu G. The effect of fermented and raw rapeseed meal on the growth performance, immune status and intestinal morphology of broiler chickens. *Journal of Animal Physiology and Animal Nutrition*, 2021;106(2):296-307.
14. Xu FZ, Zeng XG, Ding XL. Effects of replacing soybean meal with fermented rapeseed meal on performance, serum biochemical variables and intestinal morphology of broilers. *Asian-Australasian Journal of Animal Sciences*, 2012;25(12):1734-1741.
15. Zhu X, Chen Y, Hao S, Jin S, Li X. Improvement of the Nutritional Quality of Rapeseed Meal through Solid-State Fermentation with *B. subtilis*, *S. cerevisiae*, and *B. amyloliquefaciens*. *Fermentation*, 2023;9(5):492.