BIOLOGY

BIOTECHNOLOGY AND BIONANOTECHNOLOGY

Статья поступила в редакцию: 23.06.2026
Статья принята к публикации: 29.06.2026
Статья опубликована: 07.10.2026

УДК 579.66:664.1.

Bioconversion of oil-and-fat industry by-products into non-traditional feed ingredients using microorganisms: an analytical review of substrates, strains and scientific findings

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Биоконверсия побочных продуктов масложировой промышленности в нетрадиционные кормовые ингредиенты с использованием микроорганизмов: аналитический обзор субстратов, штаммов и научных результатов

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Abstract

This analytical review systematizes current scientific evidence on the microbial conversion of oil-and-fat industry by-products into safe and nutritionally improved non-traditional feed ingredients. The review focuses mainly on cottonseed meal and cake, soybean meal, rapeseed meal, sunflower meal, palm-kernel cake and lipid-rich processing residues generated during vegetable-oil extraction and refining. Based on the comparative analysis of 28 legal, technical and peer-reviewed sources, the paper examines how solid-state fermentation, mixed-culture fermentation and enzyme-assisted bioprocessing change crude protein availability, reduce anti-nutritional factors, improve

Библиографическое описание: Алиева Г.В. кызы Биоконверсия побочных продуктов масложировой промышленности в нетрадиционные кормовые ингредиенты с использованием микроорганизмов: аналитический обзор субстратов, штаммов и научных результатов // Universum: химия и биология : электрон. научн. журн. 2026. 10(148). URL: https://7universum.com/ru/nature/archive/item/23442

For citation: Aliyeva G.V.Q. Bioconversion of oil-and-fat industry by-products into non-traditional feed ingredients using microorganisms: an analytical review of substrates, strains and scientific findings // Universum: Chemistry and Biology : electronic scientific journal. 2026. No. 10(148). Available at: https://7universum.com/ru/nature/archive/item/23442

digestibility and increase the functional value of feed materials. Bacillus subtilis, Lactobacillus plantarum, Saccharomyces cerevisiae, Candida utilis, Aspergillus niger and Aspergillus oryzae are identified as the most frequently investigated microorganisms. Scientific works show that microbial treatment can reduce free gossypol in cottonseed meal, degrade soybean antigenic proteins, lower glucosinolates and phytic acid in rapeseed meal, and hydrolyse mannan-rich palm-kernel cake. At the same time, the review emphasizes that fermentation cannot be considered a universal solution: its efficiency depends on substrate composition, strain safety, moisture, temperature, duration, post-drying conditions and feed-safety control. For Uzbekistan, where cottonseed and other oilseed by-products are available as local resources, microbial bioconversion may support circular economy, import substitution in feed protein and environmentally safer waste management, provided that it is integrated with veterinary, sanitary and toxicological assessment.

Аннотация

Данный аналитический обзор систематизирует современные научные данные о микробной конверсии побочных продуктов масложировой промышленности в безопасные и питательно улучшенные нетрадиционные кормовые ингредиенты. Обзор сосредоточен главным образом на хлопковом жмыхе и шроте, соевом шроте, рапсовом шроте, подсолнечном шроте, пальмовом ядровом жмыхе и богатых липидами технологических остатках, образующихся при экстракции и рафинации растительных масел. На основе сравнительного анализа 28 нормативных, технических и рецензируемых источников в работе рассмотрено, как твердофазная ферментация, смешанная культуральная ферментация и ферментативная биообработка изменяют доступность сырого протеина, снижают антипитательные факторы, повышают усвояемость и увеличивают функциональную ценность кормовых материалов. Bacillus subtilis, Lactobacillus plantarum, Saccharomyces cerevisiae, Candida utilis, Aspergillus niger и Aspergillus oryzae определены как наиболее часто исследуемые микроорганизмы. Научные работы показывают, что микробная обработка может снижать свободный госсипол в хлопковом шроте, разлагать соевые антигенные белки, понижать глюкозинолаты и фитиновую кислоту в рапсовом шроте и гидролизировать богатый манираном пальмовый ядровый жмых. Вместе с тем в обзоре подчеркивается, что ферментация не может рассматриваться как универсальное решение: её эффективность зависит от состава субстрата, безопасности штамма, влажности, температуры, продолжительности, условий сушки после ферментации и контроля безопасности кормов. Для Узбекистана, где хлопковые и другие масличные побочные продукты доступны как местные ресурсы, микробная биоконверсия может поддержать циркулярную экономику, импортозамещение в области кормового протеина и экологически более безопасное управление отходами при условии её интеграции с ветеринарной, санитарной и токсикологической оценкой.

Keywords: oil-and-fat industry by-products, cottonseed meal, solid-state fermentation, microbial protein, Bacillus subtilis, Saccharomyces cerevisiae, Aspergillus niger, gossypol, non-traditional feed, circular economy, feed safety.

Ключевые слова: побочные продукты масложировой промышленности, хлопковый шрот, твердофазная ферментация, микробный белок, Bacillus subtilis, Saccharomyces cerevisiae, Aspergillus niger, госсипол, нетрадиционные корма, циркулярная экономика, безопасность кормов.

Introduction

The development of livestock, poultry and aquaculture requires a stable supply of safe and digestible feed protein. At the same time, the oil-and-fat industry generates large quantities of secondary raw materials: cakes and meals after mechanical pressing or solvent extraction, soapstock, phosphatide concentrates, spent bleaching earth, acid oil and other residues. Not all of these streams are suitable for feed use; however, protein-rich meals and cakes from cottonseed, soybean, rapeseed, sunflower and palm-kernel processing can be valuable substrates for microbial upgrading if safety is strictly controlled. The scientific relevance of this topic lies at the intersection of feed technology, industrial biotechnology, waste minimization and circular economy.

In Uzbekistan, this direction is also connected with national regulatory priorities. The Law of the Republic of Uzbekistan 'On Waste' defines prevention of harmful effects on human health and the environment, reduction of waste generation and rational use of waste in economic activity as key objectives [1]. The Strategy for Transition to a Green Economy for 2019 – 2030 calls for rational use of natural resources and modernization of production systems [2]. In livestock production, the strengthening of the animal-feed base is reflected in Presidential Resolution PP-121 of 8 February 2022 [3], while veterinary and feed-additive safety are regulated through veterinary legislation and technical regulation [4, 5]. Therefore, research on the conversion of oilseed by-products into feed is not only a technological issue, but also a practical response to environmental policy, feed security and veterinary safety requirements.

Conventional use of oilseed meals is limited by anti-nutritional and toxic compounds. Cottonseed meal contains free gossypol; soybean meal contains antigenic proteins such as glycinin and beta-conglycinin, trypsin inhibitors and oligosaccharides; rapeseed meal contains glucosinolates, phytic acid and fiber; palm-kernel cake is rich in mannan and other non-starch polysaccharides. Microorganisms can partially solve these limitations by producing proteases, phytases, carbohydrases, organic acids and antimicrobial metabolites. As a result, fermentation may transform a low-value by-product into a more digestible feed ingredient with probiotic or postbiotic properties [6-11].

Level of scientific investigation. Research in this area has developed in several directions. The first direction is the fermentation of cottonseed meal, where studies by Xiong et al., Niu et al., Xu et al. and recent systematic reviews show that microbial treatment can reduce gossypol and improve broiler performance [7, 12-14]. The second direction is the fermentation of soybean meal. Mukherjee et al. summarized the role of fermentation in improving soybean-meal quality, while Yao et al. experimentally showed that Bacillus subtilis N-11 can reduce glycinin and beta-conglycinin and increase acid-soluble protein [8, 15]. The third direction is rapeseed meal bioprocessing, where Zhu et al. reported reductions in glucosinolates, phytic acid and crude fiber after microbial fermentation [9]. The fourth direction concerns palm-kernel cake and other fiber-rich oil by-products, where Aspergillus niger, mannanase-assisted systems and mixed cultures have been

studied to reduce mannan and improve nutrient digestibility [10, 16]. General reviews by Betchem et al., Canoy et al., Heuze et al. and others show that solid-state fermentation is currently one of the most promising approaches for upgrading agro-industrial residues into feed protein [6, 17, 18].

Aim and scope of the review. The aim of this review is to analyze and compare scientific findings on the microbiological processing of oil-and-fat industry by-products for non-traditional feed production. The review focuses on: (i) the main substrates generated by oilseed processing; (ii) microorganisms used for bioconversion; (iii) mechanisms of nutritional improvement; (iv) comparison of the results obtained by different researchers; and (v) technological and safety requirements for implementation in Uzbekistan.

Materials and methods

This paper is an analytical review. The methodological basis was a critical comparison of 28 sources, including legal acts of Uzbekistan, technical regulation, peer-reviewed review articles and experimental studies published mainly during 2012 – 2026. Sources were selected according to their relevance to four criteria: oil-and-fat industry by-products as feed substrates; microbial or enzyme-microbial processing; evidence of changes in nutritional quality or anti-nutritional factors; and implications for feed safety. The review does not present new laboratory experiments; instead, it summarizes and compares already published data.

The scientific literature was grouped by substrate type: cottonseed meal/cake, soybean meal, rapeseed meal, palm-kernel cake, sunflower meal and lipid-rich residues. Within each group, the microorganism, fermentation method, major biochemical effect and practical limitation were identified. Particular attention was given to solid-state fermentation because most oilseed meals are low-moisture substrates and can be processed without producing large volumes of wastewater [6, 17].

Results and analytical review

Oil-and-fat industry by-products as substrates for feed bioconversion

Oilseed meals are attractive substrates because they contain residual protein, fiber, minerals and biologically active compounds. Cottonseed meal is particularly relevant for cotton-growing regions; however, free gossypol limits its safe inclusion in diets. Soybean meal is nutritionally valuable but contains antigenic proteins and enzyme inhibitors. Rapeseed meal is cheaper than soybean meal in many regions but is restricted by glucosinolates and phytic acid. Palm-kernel cake is rich in fiber and mannan, which reduce digestibility. Sunflower meal has a favorable amino acid profile for some animal species but high fiber content can limit its use in poultry and young animals.

The central technological idea is not to treat these by-products as waste, but as secondary raw materials. In this sense, microbial processing corresponds to circular-economy principles: value is retained within the production chain, environmental load is reduced, and dependence on imported protein ingredients can decrease [1, 2, 6].

Microorganisms used for upgrading oilseed meals

Bacillus subtilis is one of the most widely used organisms because it produces extracellular proteases, amylases and other hydrolytic enzymes. It can degrade macromolecular proteins and reduce some anti-nutritional factors in soybean and cottonseed meals [8, 15]. Lactobacillus plantarum and related lactic-acid bacteria acidify the substrate, inhibit undesirable microflora and may improve palatability. Saccharomyces cerevisiae and Candida utilis contribute microbial biomass, B vitamins and protein enrichment and have been used for cottonseed meal fermentation [12, 19]. Aspergillus niger and Aspergillus oryzae are important fungal producers of cellulase, xylanase, phytase and protease; they are especially useful for fiber-rich substrates such as palm-kernel cake and soybean meal [10, 16, 20].

The choice of microorganism determines the final technological result. Bacterial fermentation is often faster and safer for industrial standardization, while fungal fermentation can hydrolyse complex fiber and phytate more effectively. Mixed-culture fermentation may combine these advantages, but it also requires stricter control of microbial compatibility, contamination, toxin formation and reproducibility [6, 17, 21].

Table 1.

Comparative analysis of scientific studies on microbial processing of oil-and-fat industry by-products

Researchers / source	Substrate	Microorganism / method	Main reported effect	Practical significance	Ref.
Xiong et al.	Cottonseed meal	Candida utilis, solid-state fermentation	Evaluated growth and toxic response of broilers fed fermented vs. unfermented cottonseed meal	Shows that detoxification and animal-response testing must be combined	[12]
Niu et al.	Cottonseed meal	Bacillus subtilis fermentation	Improved production performance and reduced fat deposition in broiler chickens	Supports partial substitution of conventional protein feed	[13]
Esen et al.	Cottonseed meal	Systematic review of SSF studies	Summarized evidence that fermented cottonseed meal improves broiler growth while maintaining feed efficiency	Provides higher-level evidence for poultry feeding practice	[7]
Yao et al.	Soybean meal	Bacillus subtilis N-11, anaerobic SSF	Reduced glycinin and beta-conglycinin and increased acid-soluble protein	Demonstrates protein hydrolysis and ANF reduction	[15]
Mukherjee et al.	Soybean meal	Review of bacterial and fungal fermentation	Explained degradation of anti-nutritional factors and improvement of nutritional quality	Foundation for fermented soybean meal technology	[8]
Zhu et al.	Rapeseed meal	Multi-strain fermentation	Reduced glucosinolates, phytic acid and fiber; improved nutritional quality	Important for replacing part of soybean meal	[9]
Shuai et al.	Rapeseed meal	Fermented rapeseed meal in poultry diets	Reported increase in small-molecular proteins and reduction of glucosinolates	Connects chemical improvement with growth performance	[22]
Mi et al.	Palm-kernel cake	Aspergillus niger + mannanase	Reduced mannan and ADF; increased crude protein and digestibility in beef cattle trial	Shows enzyme-microbial synergy for fiber-rich residues	[10]

Researchers / source	Substrate	Microorganism / method	Main reported effect	Practical significance	Ref.
Liu et al.	Palm-kernel cake	Enzyme-bacteria pretreatment	Reduced anti-nutritional factors and enhanced nutritional value	Promising approach for high-fiber oil residues	[16]
Betchem et al.	Various agro-industrial residues	Review of solid-state fermentation	Generalized improvements in crude protein, enzymes, digestibility and antioxidant activity	Broad technological framework for feed production	[6]

Cottonseed meal: gossypol reduction and regional relevance

Cottonseed meal is the most important oilseed by-product for cotton-producing countries. Its feed use is limited by free gossypol, a phenolic aldehyde that can impair growth, reproduction and health when present above safe levels. Microbial fermentation can reduce free gossypol through adsorption, enzymatic transformation and binding with microbial proteins. Xiong et al. studied cottonseed meal fermented with Candida utilis and compared it with unfermented cottonseed meal and soybean meal in broilers, thereby showing that nutritional evaluation must include both chemical detoxification and animal safety response [12]. Niu et al. reported that fermented cottonseed meal improved broiler performance and affected fat deposition, indicating that fermentation changes not only toxicity but also metabolism [13].

Recent systematic evidence also supports the potential of fermented cottonseed meal. Esen et al. concluded that solid-state fermented cottonseed meal can increase body-weight gain and feed intake of broilers while maintaining feed efficiency [7]. Xu et al. noted that fermentation with Bacillus subtilis and Saccharomyces cerevisiae is associated with reduced free gossypol and improved nutritional value [14]. For Uzbekistan, this direction is especially important because cottonseed cake and meal are local by-products of the vegetable-oil industry; however, their usemust be accompanied by laboratory control of free gossypol, moisture, mycotoxins and microbial contamination.

Soybean meal: degradation of antigenic proteins and improvement of digestibility

Soybean meal is a standard plant-protein feed but contains anti-nutritional factors that reduce digestibility in young animals. Mukherjee et al. reviewed the role of fermentation in soybean meal and concluded that microbial processing can reduce anti-nutritional compounds and improve nutritional quality [8]. Yao et al. provided experimental evidence: after screening high-protease Bacillus strains, they identified Bacillus subtilis N-11, which increased acid-soluble protein and reduced glycinin and beta-conglycinin by 82.38 % and 88.32 %, respectively [15]. This result is important because antigenic proteins are one of the main reasons for intestinal irritation in piglets, calves and young poultry.

Fermented soybean meal research is useful as a technological model for other oilseed meals. The main mechanism is proteolysis: microorganisms break large storage proteins into peptides and amino acids. Simultaneously, microbial phytase and organic acids reduce phytate and improve mineral availability. However, soybean meal is more expensive than many local by-products; therefore, for Uzbekistan the main value of these studies is methodological: they show how strain screening, enzyme activity and product standardization should be organized.

Rapeseed meal: glucosinolate and phytic-acid reduction

Rapeseed meal is rich in protein but contains glucosinolates and phytic acid. Glucosinolate breakdown products can affect thyroid function and feed intake, while phytate reduces phosphorus availability. Zhu et al. studied the improvement of rapeseed meal by mixed microbial fermentation and reported reductions in glucosinolates, phytic acid and crude fiber [9]. Shuai et al. further showed that fermented rapeseed meal can increase the share of small-molecular proteins and reduce glucosinolate content, connecting biochemical changes with animal growth and immune indicators [22].

Compared with cottonseed meal, rapeseed meal fermentation is less focused on detoxifying one dominant toxic compound and more focused on a complex improvement of protein, fiber and mineral availability. This means that the best strains are often mixed cultures or fungi-bacteria combinations rather than a single species. The technological challenge is to obtain stable glucosinolate reduction without producing undesirable metabolites.

Palm-kernel cake and other fiber-rich residues

Palm-kernel cake is not a typical Uzbek raw material, but it is scientifically important because it represents the fiber-rich group of oil-industry residues. Mi et al. showed that co-fermentation of palm-kernel cake with Aspergillus niger and mannanase reduced mannan and acid detergent fiber, increased crude protein and improved dry matter, crude protein and neutral detergent fiber digestibility in beef cattle [10]. Liu et al. also demonstrated that enzyme-bacteria pretreatment can reduce anti-nutritional factors in palm-kernel cake and improve its feeding value [16].

These studies show that fungal fermentation and enzyme assistance are especially useful when the limiting factor is fiber rather than toxicity. This conclusion is relevant for sunflower meal and other high-fiber oilseed meals. In such substrates, the main target should be cellulase, xylanase, beta-mannanase and phytase activity, not only crude protein increase.

Mechanisms of microbial improvement

The reviewed studies indicate five main mechanisms. First, protease-producing microorganisms hydrolyse large proteins into peptides, increasing acid-soluble protein and digestibility [8, 15]. Second, phytase and organic acids reduce phytic acid and improve mineral bioavailability [9, 20]. Third, fiber-degrading enzymes reduce cellulose, hemicellulose, beta-mannan and acid detergent fiber, which is important for palm-kernel and sunflower meals [10, 16]. Fourth, selected microbes may detoxify or bind anti-nutritional compounds such as gossypol or glucosinolates [7, 12-14, 22]. Fifth, microbial biomass itself enriches the substrate with protein, nucleotides, vitamins and biologically active metabolites [6, 17].

The practical effect of these mechanisms is not identical for all animal species. Poultry and piglets benefit most from protein hydrolysis and anti-nutritional factor reduction because their digestive system is sensitive to antigenic proteins and toxins. Ruminants may benefit more from fiber hydrolysis and rumen microbiota modulation. Aquaculture feed can benefit from replacement of fishmeal or soybean meal with fermented plant protein, but amino-acid balance and palatability must be carefully evaluated.

Technological scheme for non-traditional feed production

A scientifically justified process for converting oilseed by-products into fermented feed may include the following stages: raw-material receiving and testing; grinding and sieving; moisture adjustment; sterilization or hygienic heat treatment when necessary; inoculation with selected starter culture; solid-state fermentation under controlled temperature and aeration; drying at a temperature that preserves nutrients but stops uncontrolled microbial growth; milling; quality control; packaging and storage. For cottonseed meal, free gossypol must be included in the control program. For fungal fermentation, aflatoxins and other mycotoxins must be monitored. For all products, microbiological safety, moisture, crude protein, fiber, ash, amino acids and shelf-life stability should be determined.

Table 2.

Technological comparison of microorganisms used for oilseed by-product fermentation

Microorganism	Main enzymes / functions	Suitable substrates	Advantages	Risks / control points
Bacillus subtilis	Protease, amylase, possible phytase	Soybean meal, cottonseed meal	Fast protein hydrolysis; industrially scalable	Strain identification and absence of toxin genes
Lactobacillus plantarum	Lactic acid, antimicrobial metabolites	Mixed meals, moist substrates	pH reduction; hygienic stabilization	Moisture control and drying stability
Saccharomyces cerevisiae	Microbial biomass, vitamins, enzymes	Cottonseed meal, mixed substrates	Protein enrichment; palatability improvement	Overgrowth if drying is insufficient
Candida utilis	Microbial protein, detoxifying capacity	Cottonseed meal	Useful for gossypol reduction studies	Feed-grade strain safety
Aspergillus niger	Cellulase, xylanase, phytase, mannanase	Palm-kernel cake, high-fiber meals	Strong fiber and phytate degradation	Mycotoxin control and strain certification
Aspergillus oryzae	Protease, amylase, phytase	Soybean and cereal-oilseed mixes	Traditional safe fermentation organism	Controlled culture purity required

Discussion

The comparison of studies shows that microbial bioconversion is most effective when the target limitation of the substrate is clearly identified. If the main problem is gossypol, as in cottonseed meal, the selected culture must be tested primarily for detoxification and animal tolerance. If the main problem is antigenic protein, as in soybean meal, protease activity and peptide formation are the most important indicators. If the main limitation is glucosinolate or phytate, as in rapeseed meal, mixed fermentation with phytase-producing strains becomes more relevant. If the limiting factor is mannan and fiber, as in palm-kernel cake, Aspergillus-based or enzyme-assisted systems are more effective.

The works of Xiong et al., Niu et al. and Xu et al. are important because they connect chemical detoxification of cottonseed meal with broiler performance and safety [12-14]. Yao et al. provide a more mechanistic model: the authors screened protease-producing Bacillus strains and demonstrated specific reductions in soybean antigenic proteins [15]. Zhu et al. and Shuai et al. show

that rapeseed meal fermentation requires simultaneous attention to glucosinolates, phytic acid, fiber and protein fractions [9, 22]. Mi et al. demonstrate a modern tendency: microorganism plus enzyme co-processing, which may be more predictable than relying on the microorganism alone [10].

The advantages of fermented feed ingredients are clear: better digestibility, lower anti-nutritional factors, possible probiotic/postbiotic effects, higher local-resource utilization and lower environmental pressure. Nevertheless, three limitations must be emphasized. First, crude protein increase after fermentation may partly result from dry-matter loss; therefore, true amino-acid improvement should be measured, not only nitrogen concentration. Second, microbial safety must be verified for each strain and batch. Third, feeding trials are indispensable: chemical improvement does not automatically mean improved animal performance.

For Uzbekistan, the most realistic starting point is cottonseed meal and cake. The country has local cottonseed-processing capacity, and the feed sector needs affordable protein ingredients. A pilot technology should therefore begin with starter cultures that have already shown gossypol-reduction potential, such as Bacillus subtilis, Saccharomyces cerevisiae or Candida utilis. The product should be standardized according to feed-safety regulations, including veterinary control, residual toxin control and hygienic indicators [4, 5].

Conclusion

The reviewed evidence confirms that oil-and-fat industry by-products can be converted into nutritionally improved non-traditional feed ingredients by selected microorganisms. Solid-state fermentation is the most suitable technological form for oilseed meals because it requires limited water, produces little effluent and fits the physical properties of cakes and meals. Bacillus subtilis is most effective for protein hydrolysis and soybean-meal improvement; Saccharomyces cerevisiae, Candida utilis and Bacillus-based systems are promising for cottonseed meal detoxification; Aspergillus niger and enzyme-assisted systems are suitable for fiber-rich residues such as palm-kernel cake; mixed cultures may be more effective for rapeseed meal because several anti-nutritional factors must be reduced simultaneously.

The scientific comparison also shows that no single microorganism or fermentation regime is universal. The substrate, target anti-nutritional factor, animal species and required safety level must determine the process. For practical application in Uzbekistan, fermented cottonseed meal is the most relevant direction. Future studies should include: selection of local safe strains; optimization of moisture, inoculum dose, temperature and fermentation time; determination of free gossypol and mycotoxins; amino-acid and digestibility testing; broiler, cattle or aquaculture feeding trials; and economic assessment of replacing imported feed protein. If these conditions are met, microbial conversion of oil-and-fat industry by-products may become an important element of sustainable feed production and circular bioeconomy.

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