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PROSPECTS AND APPLICATION OF SOLID-STATE FERMENTATION IN ANIMAL FEED PRODUCTION – A REVIEW

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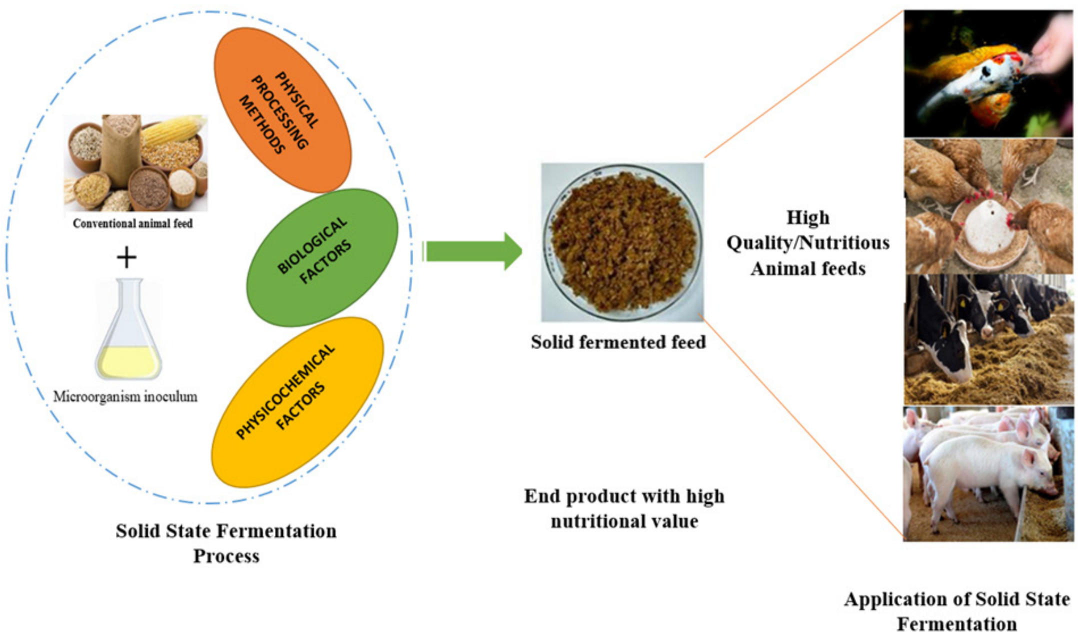
Abstract

Animal feed production has recently received significant attention in the food and livestock sectors due to its high nutritional value and substantial environmental potential. Extensive studies have been conducted to explore the effects of solid fermented feeds on different growth stages of animals but also on the health status of animals, the quality of animal products, and the composition of intestinal microflora to replace non-fermented feed production. The purpose of this review is to provide up-to-date existing trends, recent developments, and prospects of solid-state fermentation (SSF) practices for the production of animal feeds. Studies on enhancing nutritional factors by increasing the crude protein content, enzymes, and antioxidant activity of feed using physical processing methods on agro-industrial waste such as rapeseed meal, cottonseed, wheat bran, soybean meal, and legumes by mainly SSF are reviewed and discussed thoroughly.

Key words: solid-state fermentation, animal nutrition, solid fermented feed, feed composition

Graphical abstract



Solid-state fermentation (SSF) as a substitute for submerged fermentation (SMF) has gained lots of interest in the past decades, primarily due to its low cost and the ability to mimic the natural habitat of various microorganisms. SSF can be defined as a process that involves the growth of microorganisms in the absence or little free water within a solid medium. Regarding the definition of SSF, it is considered far more advantageous as associated with submerged fermentation. It has been widely used in several fields to produce enzymes, biofuels, food, feed, and secondary metabolites (antibodies, immune drugs) (Arora et al., 2018), with a significant disadvantage being the difficulty to control certain parameters such as agitation which hinders its application in industries, though the recent development and design of new bioreactors is a promising solution to these considerable shortcomings such as agitation and large scale production.

Nevertheless, various *in vitro* studies have also proven SSF to be a promising technology for enriching food products' nutritional and antioxidant properties, mainly cereals, legumes, and animal feed. Several cereal crop residues like wheat straw, paddy straw, and corn stover are used as bio feed and mostly contain lignin. One of the numerous applications of SSF is in animal feed production, which increases the nutritional properties of animal feed (Sun et al., 2023). Feed production has gained interest due to several global opportunities and challenges. There is a worldwide demand for animal feed, and it is expected to increase to 70% by 2050 due to population growth, increased income, and industrialization (Alexandratos and Bruinsma, 2012; Boland et al., 2013). In addition, animal welfare, environmental pollution minimization, use of novel ingredients, and ingredients unsuitable for human consumption concerning production efficiency are significant challenges facing the feed industry (Babinszky et al., 2019). Due to the high demand for high nutritional feeds, several methods are employed to produce quality feeds, one of which is SSF, which has been demonstrated to be a suitable alternative in animal feed production.

Moreover, some studies have reported solid fermented feed (SFF) to be a suitable alternative to feed additives such as antibiotics, and this has been possible because of 3 main reasons, which are: first, the structural cell walls breakdown due to the colonization of the microorganism; second, the release of specific metabolites (cellulase, protease, xylanase and phytase) secreted by microorganisms in the fermentation process (Cano y Postigo et al., 2021). Agro-industrial waste such as soybean meal, rice bran, wheat bran, cornmeal, groundnut husk meal, and flaxseed has intensively been used in animal feed production and the production of feed additives. Moreover, there has been increasing research on new agro-industrial waste for feed production and feed additives such as olive cake, tea dregs, ginkgo leaves, brewers spent grain, and okara (Chebaibi et al., 2019; Jiang et al., 2019; Ong and Lee, 2021; Wang et al., 2018 b). The main research methods used to improve SSF end-products can be divided into two groups. First is the mutation of microorganisms and the optimization of fermentation parameters. The other involves genetic recombination and metabolic engineering (Cao et al., 2018). Genetic engineering technology has made pronounced achievements in microbial breeding by employing advanced molecular genetic manipulation techniques; the safety of the strains is still questioned due to the introduction of foreign genes (Szyjka et al., 2017). The conventional random mutagenesis processes using physical and chemical mutagens are still the most straightforward and cost-effective techniques for improving strains (Câmara et al., 2019). Some mutagens, such as ultraviolet (UV), gamma radiation, atmospheric and room temperature plasma (ARTP), ethyl methanesulfonate (EMS), and 1-methyl-2-nitro-1-nitrosoguanidine (NTG) (Câmara et al., 2019; Gao et al., 2020; Montanari et al., 2019; Shu et al., 2020) have been applied in SSF to boost and improve the usage of SFF for animal nutrition.

It is widely acknowledged that SSF has enormous potential, but its application in the agro-industrial sector is less developed than SMF due to large scale production. However, as pointed out, animal feed may be best produced in SSF, as in soybean meal feed production for animals. This can be observed in its unique products containing high protein content, enzymes, essential amino acids, and secondary metabolites. Furthermore, SFF can be characterized based on its intended use, such as 1) fermented feed additives which have functional features (e.g., fermented therapeutic plants which promote animal immunity) (Ahmed et al., 2016; Yin et al., 2018). 2) fermented feed components that replace proteins or energy sources, reduce the anti-nutritional factors and improve feed efficiency. However, despite the critical corpus of research done in SSF, studies have yet to describe its application in the manufacture of animal feed; this review carefully curated recent research on the topic, which is exceptionally important to the sustainable growth of animal production. Besides, it provides a view of the main employed strategies in animal feeding and recent patents and innovations in this sector.

Factors affecting solid-state fermentation

Generally, two main factors affect the SSF process: biological and physicochemical. Nevertheless, we will introduce a third factor: the physical processing methods, which have received lots of interest due to their low cost and efficiency. Figure 1 shows a diagrammatic representation of the factors affecting solid fermentation.

Biological factors

These factors are associated with living things or organisms' biology, metabolism, and reproduction. These determine the behavior of the particular species in a specific way and are independent of each other. The different factors will be discussed as follows.

Type of microorganism and strain of microorganism

The choice of microorganisms is an essential factor in the SSF process. The most commonly used microorganisms for SSF are bacteria, fungi, and yeast. Each of them has a peculiar fermentation process; among these three microorganisms, fungi are the most suitable for SSF due to their hyphal growth and physiological, biochemical, and enzymological properties (Kar et al., 2010; Prado Barragán et al., 2016). However, bacteria have some advantages over fungi due to their rapid growth, their biomass and their metabolites which can easily be measured. Different organisms affect SSF processes differently as the end products differ from others. This can be observed in *Aspergillus* species where *Aspergillus niger* fermented rapeseed meal had a high decline in anti-nutritional substrates, thereby having a high crude protein and amino acid. In contrast, *Aspergillus wentii* could not decrease the anti-nutritional factors significantly in palm kernel meal (Muangkeow and Chinajariyawong, 2013; Changyou et al., 2016). Moreover, some bacteria strains like *Bacillus licheniformis* are mainly to produce alkaline protease, whereas *Bacillus subtilis* for their ability to produce neutral protease (Li and Wang, 2021).

Physicochemical factors

These factors are associated with the physicochemical expressions occurring in an SSF system. They affect most of the mechanisms involved in SSF, such as heat transfer. All these factors are not independent of each other. As such, it is crucial to determine the degree of influence a factor has on its counterpart. Moreover, we also need to consider some physicochemical factors that may not directly affect the system but affects the biological factor. Thus researchers have embarked on optimizing SSF parameters so as to obtain high value fermented end-products. We will therefore discuss the various aspects affecting SSF below.

Substrate

A substrate is a solid matrix containing a certain amount of water activity that can favor the growth of a particular microorganism. The choice of substrate is very crucial for the SSF process. A substrate is a matrix for the growth of microorganisms and a source of carbon, nitrogen and nutrients. There exist numerous substrates e.g biofuel co-products which include distiller grains and sugarcane bagasse, agro-industrial wastes which include oil seed meal, soybean hulls, and sugar beetroot pulp, and crop residues such as wheat straw and maize stover, as well as discarded fruit and vegetables, are also considered that have been used in the animal nutrition (Sun et al., 2024). It has been reported that fermentation products can be highly variable and appear to depend on the nature and characteristics of the substrates used (Canibe and Jensen, 2012). Moreover, since different microorganisms require different nutrients for optimal growth, some supplements are often added to a substrate to favor the development of a particular organism; such supplements are zinc, phosphorus, calcium, magnesium, and iodide (Farinas, 2015). One of the reasons why substrate is a significant factor in the SSF process was investigated by some researchers on the growth of Aspergillus oryzae. A study found that low water activity and osmosis made fungi produce defense metabolites such as glycerol, erythritol, and arabitol, which are helpful as bio-products (Ruijter et al., 2004).

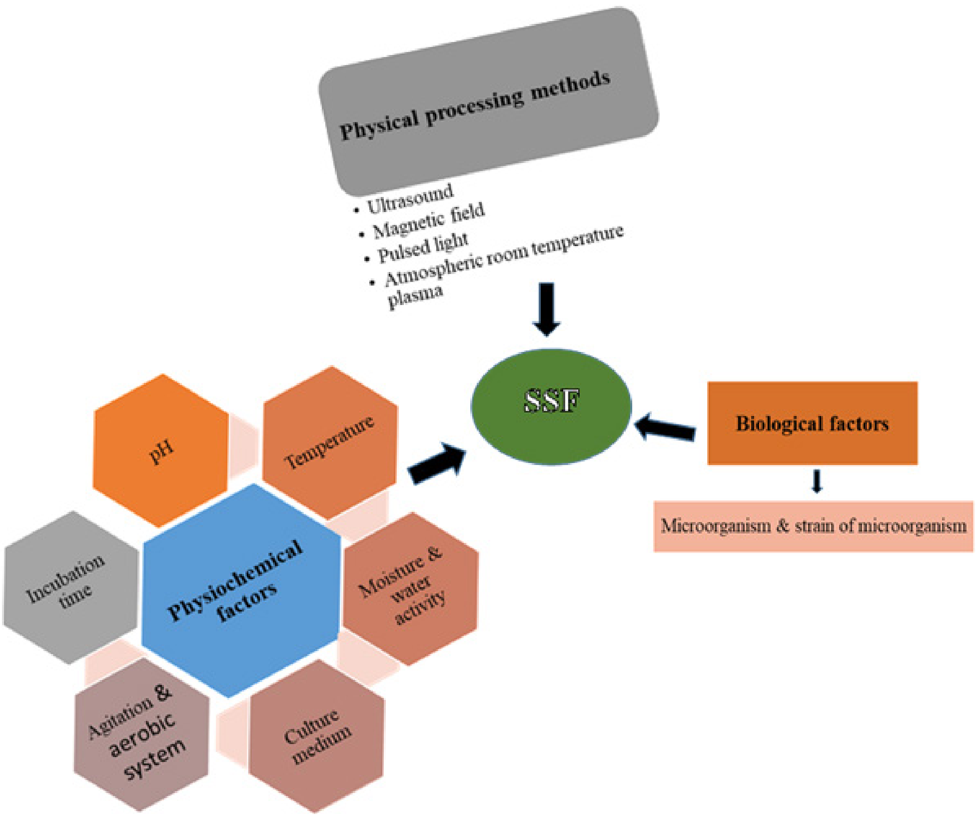


Figure 1. Factors affecting SSF

Temperature

One of the numerous characteristics of SSF is that they are developed in very narrow temperature ranges. The importance of temperature in the SSF process is that it could regulate the outcome of fermentation, such as enzyme inhibition increase or decrease of a particular metabolite (Carboué et al., 2020; Kumar et al., 2021). Furthermore, microorganisms have specific temperature ranges where they have optimal growth. For instance, the optimal growth of *S. cerevisiae*, *Lb. plantarum*, *R. oryzae*, *A. oryzae*, and *N. sitophila* for SSF is 28°C whereas the optimal growth of *Lactobacillus*, *B. licheniformis* and *yeast* (*Candida utilis*) was 30°C (Wang et al., 2019; Zhang et al., 2022 b). Several studies have investigated the optimum temperature at which SSF yield will be the highest. For instance, a study performed by Betchem et al. (2023) found that at 44°C the peptide, protease activity, and DPPH activity of rapeseed meal reached its maximum. Another investigation showed that at temperature of 37°C the mannanase yield reached its maximum hence increasing the synthesis of bioactive mannooligosaccharides (Rana et al., 2023). Consequently, temperature plays an important role in improving the nutritional aspect of agro waste which can be further used as ani mal feed due to the metabolic activity of the microorganism.

pH

pH is one of the critical factors of SSF; a study carried out by Cuadra et al. (2008) reported that the influence of pH in SSF with sugarcane bagasse as an inert support for the biosynthesis of cephalosporin C only occurred in a given range of pH of 6.4 to 6.8. Another study reported that pH between 4.5 and 5.5 markedly stimulated substrate biodegradability and biomass production (Nigam, 1990). Furthermore, an investigation showed the importance of pH as an SSF parameter to obtain high pectin yield at an optimum pH of 4.58 (Sosa-Martínez et al., 2023). Whereas, another found the optimum pH for high arachidonic acid production to be at 6 (Rayaroth et al., 2021). These mentioned go further to confirm the importance of pH in SSF and the need to optimize the factor to obtain the desired end-product.

Moisture content and water activity

The definition of SSF itself is characterized mainly by moisture content. The importance of water in SSF is because the composition of various microorganisms is about 70–80% water. Therefore, water is necessary for cell growth and metabolism. The primary limitation of SFF is the absence of readily available water. The decreased development of microorganisms is caused by reduced nutrition and metabolite transport and altered enzyme activity due to low moisture content. In contrast, excessive moisture content decreases the porosity of substrates, limits the movement of oxygen and heat, and increases the risk of contamination. Numerous documentation has eluded the importance of moisture content and water activity in SSF, giving moisture content and water activity in SSF to be 40–70% and below 0.95, respectively (Vandenberghe et al., 2021). The importance of moisture content in solid fermentation can be observed in the studies performed by Lou et al. (2023) and Dumandan and Arreola (2022) who demonstrated the effect of optimum moisture content 65% on aflatoxin B1 degradation in corn by *Ganoderma sinense* and 75% on enhancing l-lysine synthesis by *Bacillus megaterium* AECR 751 mutant in copra meal, respectively through solid fermentation.

Agitation and aerobic systems

These factors play a vital role in the SSF process, which is dependent on two phenomena that are (1) oxygen demand in the aerobic process and (2) heat and mass transfer. Agitation and aerobic systems are shortcomings of SSF, such as low yield end-product due to the lack of stirring, thus leading to the design of bioreactors which could be used in aeration and mixing. Nevertheless, these bioreactors have advantages and disadvantages, thus creating different types of bioreactors depending on their mode of operation, agitation, aeration, and desired by-product (Arora et al., 2018; Krishania et al., 2018). The design of bioreactors needs further investigation to increase the production of enzymes and neglect some of its disadvantages.

Incubation time

The incubation time is also essential in obtaining the desired end-product. Short fermentation time may result in less fermentation end-product possibly due to the lack of maturation of microorganisms (Gao et al., 2009). However, extensive fermentation time may also result in low yield due to the reduced growth of microorganism and the massive consumption of substrate nutrients. Several studies have optimized the fermentation parameters of SSF and each of them had a specific optimum incubation time for their experiments (Rui et al., 2017; Singh et al., 2020; Tuly et al., 2022 b). According to a previous study on the SSF of chicken feather, it was observed that the maximum enzyme activity and soluble protein was observed after five days of fermentation (El Salamony et al., 2024). Another study optimized the fermentation conditions and obtained optimum chlorogenic acid (82.3%) extraction after 48 h of fermentation compared to other fermentation times (Akpabli-Tsigbe et al., 2023). The above mentioned studies show the importance of incubation time during SSF.

Physical processing methods

These methods (ultrasound, magnetic field, pulsed electric field) are primarily non-destructive techniques recently applied during the fermentation process to improve the end-product yield of SSF. They are mainly used on microorganisms to break their DNA and cause mutation, thereby creating mutant species that are more efficient as compared to the wild type.

Ultrasound

Several articles and books have discussed the importance of ultrasound in the food industry (Huang et al., 2019; Yunliang et al., 2022). Ultrasound technology has recently been applied in the process of SSF and has shown interesting results, such as increasing the peptide content (150.68 mg/g) and enzyme yield (protease=330 IU, α-amylase=825 IU) of solid fermented products (Salim et al., 2019; Yucheng et al., 2021). Ultrasound technology (low-frequency ultrasound) has proven to have a positive effect on biological systems, such as (1) changing the cell membrane permeability and increasing cell growth rate; (2) changing the molecular conformation and amplifying metabolic processes; and (3) activation of intracellular signal transduction systems and variations to the secretion of metabolites inside the organism (Li et al., 2021). The effects, as mentioned earlier, of ultrasound on biological systems are the suggested mechanism of ultrasound, though the precise mode of action is still unclear. Ultrasound has been used as a pretreatment to improve the production of xylanase and cellulose (Leite et al., 2016) and the germination rate of *Bacillus amyloliquefaciens* from 15.67% to 67.33% (Wang et al., 2021).

Magnetic field

Magnetic fields have greatly improved the food industry and are generally used as physical non-thermal sterilization technology in food processing (Wang and Cui, 2019; Lin et al., 2019). Magnetic field treatment changes the properties of the culture medium. For example, it has been shown that increasing the strength of the magnetic field treatment reduces the conductivity of the spirulina culture solution and increases the NO_3-N content; this facilitates cellular uptake and metabolism (Deamici et al., 2018). Moreover, the magnetic field has proven to positively affect the structure of cellular genetic material, causing changes in genomic DNA and regulating gene transcription and expression of microorganisms improving fermentation (Fraga et al., 2019). Another study performed by Tuly et al. (2022 a) demonstrated the effectiveness of magnetic field-assisted fermentation in improving the functional and structural properties of mixed substrates (chicken feather powder and okara) by increasing the surface area for enzymatic action. A recent study on the use of magnetic field assisted solid fermentation showed improved protein digestibility of rapeseed meal through the exposure of hydrophobic groups present in rapeseed protein (Betchem et al., 2024).

Pulsed light

Pulsed light (PL) is an evolving technology used in food preservation in Japan since the late 1970s. Pulsed light applications on different microorganisms have different responses. These responses rely on factors such as the size and type of microorganism, the application time, and the pulsed light's intensity (Al Daccache et al., 2020). Nevertheless, its mechanism of action has yet to be fully explored through its vast industrial application. Some studies proved that low-intensity pulsed light stimulated the metabolic activities of certain microorganisms rather than destroying them (Mota et al., 2018; Wang et al., 2018 c). Another study showed the impact of pulsed light during the fermentation process of *Hanseniaspora* sp. isolated from apples in Lebanon increased glucose consumption in the medium, thereby reducing the fermentation period by one hour and increasing biomass concentration of *Hanseniaspora* sp. yeast (Al Daccache et al., 2020).

Atmospheric and room temperature plasma

Atmospheric and room temperature plasma (ARTP) represents one of the newest methods to solve mutation efficiency and the operator's health problem. ARTP produces various highly active, evenly distributed particles under atmospheric pressure. These particles can instantly act on the DNA strands of microbial cells and cause gene mutation through an incomplete gene repair process (Zhang et al., 2019). ARTP has been proven to be a dependable and effective microbial breeding method that leads to a high rate of random mutations. Its application has been proven successful in several studies involving diverse microorganisms to improve properties such as growth rate and produce valuable bio-products like cellular biomass, enzymes, peptides, and xylitol (Ottenheim et al., 2018; Zhang et al., 2019). ARTP mutagenesis and high-throughput screening was used to engineer *Corynebacterium glutamicum* toward high yield production of heterologous proteins (Meng et al., 2021).

Physio-chemical properties of SFF

The general characteristics of SFF are similar to those of SSF. That said, the SFF has a higher nutritional value than non-fermented feed. Several studies have shown the increase in crude protein, peptide content, low starch, and high amino acids of various fermented agro-industrial waste (Betchem et al., 2023; Jiang et al., 2021; Changyou et al., 2017 b; Changyou, et al., 2016). Nevertheless, SFF characteristics depend solely on the SSF process. Therefore, there can be no specific value to characterize the physical and chemical aspects of the solid fermented feed. Though, the following observations can be made for SFF. Table 1 shows some general characteristics of SFF.

Table 1. Characteristics of SFF

Characteristics	Examples	References
High crude protein content	Inoculated mixed feed (corn, soybean meal) with *Aspergillus niger* following two-stage fermentation had a 4.8% increase in crude protein.	(Changyou et al., 2016)
High organic acid content	Organic acid production reached a maximum of 123.0 g/kg dry weight of corncob during semi-solid fermentation.	(Mai et al., 2016)
High enzyme production	*Bacillus* species cultivated for five days on wheat bran were reported to have a high enzyme production, as high as 6900 U/g.	(Qureshi et al., 2016)
High amino acid content	Lactic acid bacteria (LAB) solid-state fermentation of wheat bran significantly increased the content of amino acids.	(Jiang et al., 2021)
Low anti-nutritional factors (ANFs)	*Aspergillus oryzae* and *Bacillus subtilis* afforded more excellent enhancement in the nutritional profile of okara and brewer's spent grain.	(Ong and Lee, 2021)
Low hemicellulose	Two-stage fermentation using *Bacillus subtilis* followed by *Enterococcus faecium* was performed on corn and soybean meal, and results showed a decrease in hemicellulose from 10.15 to 4.75%.	(Changyou et al., 2017 b)
High soluble protein content	The SSF process of *Bacillus subtilis* lwo on chickpeas increased the protease activity, resulting in the release of soluble proteins.	(Li and Wang, 2021)
High peptide content	*Bacillus licheniformis* mutant using solid-state fermentation at optimum conditions produced 185.99 mg/g peptides, using okara as substrate.	(Tuly et al., 2022 a)
High antioxidative activity	After three days of fermentation with *P. ostreatus* Perla and *Hericium erinaceus*, the antioxidant capacity increased two folds compared to unfermented nejayote at day 3 of fermentation.	(Acosta-Estrada et al., 2019)
High carbohydrate content	After 8 h of fermentation of black rice husk with *Saccharomyces boulardii,* the carbohydrate content increased by 10% compared to non-fermented black rice husk.	(Mirsalami and Mirsalami, 2024)
Decrease in dry matter	Two-stage fermentation using *Bacillus subtilis* followed by *Enterococcus faecium* was performed on corn and soybean meal, and results showed a reduction in dry weight from 89.09 to 88.06%.	(Changyou et al., 2017 b)

Application of fermented feed in animals

The use of SFF in animal nutrition has been acknowledged as more beneficial to animals than liquid fermented feed. One major advantage of SFF is its ability to improve animal digestion (Yang et al., 2021). During the fermentation process, the microbial activity helps break down complex carbohydrates, cellulose, proteins, and lignin into simpler forms that can be easily digested by the animals. SSF converts traditional feed into improved feed utilization and nutrient absorption, leading to better growth performance and feed conversion efficiency in animals. Furthermore, SSF improves the palatability of feed, by reducing the presence of antinutritional factors such as phytates which give a bitter taste when combined with other protein complex. Hence, the reduction of antinutritional factors makes SFF more attractive to animals and reducing the risk of feed wastage. Henceforth, it is essential to identify the recent advancements in producing high quality feed and propose techniques that can help improve animal nutrition through SSF. SFF is mainly provided to animals without adding other substances or additives (Yuan et al., 2017). Agro-industrial waste is often fed directly to animals after fermentation, but they are also used as substrate to produce feed additives such as enzymes (Leite et al., 2021).

Changes in nutritional value of SFF

Over the last few decades, there has been a significant increase in the utilization of solid fermented feed for livestock. Solid fermented feed has high nutritional value and provides several health benefits for livestock. However, the nutritional value of solid fermented feed has changed over the years due to several factors such as changes in feed formulation, the use of different microbial strains, and advances in fermentation technology. One of the most significant changes in the nutritional value of solid fermented feed is the increase in the crude protein content. This increase can be attributed to the use of high-protein feed ingredients, such as soybean meal, and the use of certain microbial strains that are known to increase protein synthesis during fermentation. Research studies suggest that the use of specific microbial strains, such as *Bacillus subtilis* or *Lactobacillus plantarum*, can lead to significant increases in crude protein content (Lu et al., 2022; Zhao et al., 2017). Similarly, the digestibility of solid fermented feed has also improved over the years. This is mainly due to improvements in fermentation technology. As stated above SSF improves the nutritional aspect of agro-industrial waste in different ways depending on the target end-product. It is true that SSF changes the nutritional value of feed raw materials, although in such feeds there are a number of changes that are often much more important than the increase in protein levels. The decrease in the fiber and non-starch polysaccharide content, which limit the digestibility of nutrients is another aspect which improves the nutritional content of SFF (Yang et al., 2021). Additionally, the reduction in the level of anti-nutritional substances such as glucosinolates, phytic acid and sinapine plays an important role in the nutritional value of SFF. Each microorganism affects the end-product of SSF in its path. Bacteria, especially *Bacillus* species, have been widely used on protein rich agro-industrial waste (Lu et al., 2022), whereas, fungi have been widely used on starch-rich substrate (Lin et al., 2018). Nevertheless, their effects are not limited to a particular substrate but depend on the desired yield. Moreover, the changes in the nutritional aspect of SFF have been attributed to the factors affecting SSF, a study attributed the change in antioxidant activity, protein and lipid to temperatures, pH and fermentation (Nguyen et al., 2022).

Effects of solid fermented feed on animals

SSF over the past decades has received enormous attention in the animal nutrition sector. Recently, researchers have carried out a large number of studies (*in vivo* and *in vitro*) to explore the applications of SSF in animal nutrition (Das et al., 2022; Jiang et al., 2021; Changyou et al., 2017 b; Zhang et al., 2022 a). SFF has been defined as a raw feed ingredient or commercial feed in which macromolecular substances and anti-nutritional factors are converted into more efficient and non-toxic nutrients by the metabolic activities of microorganisms. Moreover, due to the beneficial characteristics of SFF, it is therefore safe to use them to feed animals to meet the high demand of consumers for safe products. Consequently, it is crucial to explore the effects of SFF on animals.

Broilers

The feed of broilers consists primarily of grains (corn, soybean, barley, oats, rice, rye, sorghum) and protein supplements, and its production contributes up to 70% of the total production cost in commercial poultry. Feed ingredients such as wheat, soybean, barley, and rapeseed contain considerable amounts of non-starch polysaccharides (NSP) that cannot be easily digested by poultry due to the lack of endogenous hydrolyzing enzymes. However, using fermented agro-industrial by-products to replace corn and wheat soybean-based diets will help minimize production costs and improve feed quality. SFF has been proven to increase the nutritional factors of feeds. This is achieved by improving the solubility of essential amino acids (Borresen et al., 2012), increasing the digestibility of various nutrients such as organic matter, nitrogen, amino acids, fiber and calcium (Akinola et al., 2015; Ashayerizadeh et al., 2018). Moreover, the dietary addition of solid fermented canola meal improved feed intake, calcium digestibility, and retention of nutritional factors but negatively affected body weight gain and feed conversion ratio in broilers (Olukomaiya et al., 2021). Whereas different studies showed the positive effect on the growth performance of broiler chickens fed with fermented rapeseed meal (Ashayerizadeh et al., 2018; Elbaz et al., 2023). Additionally, broilers fed a canola diet with enzyme supplementation had an improved feed conversion ratio compared to the solid-state fermented canola meal diet at the end of 21 days (Olukomaiya et al., 2021). Solid-state fermentation using *C. crassa* decreased crude fiber, increased crude protein and amino acid contents of some agro-industrial by-products such as cassava pulp, banana bark, and rice bran which have proven to be potential feed ingredients (probiotics) as they improve the growth and immune system of broilers (Sugiharto et al., 2018).

Pigs

Researchers have focused on feeding pigs with liquid-fermented feed, but recently, significant focus has been given to feeding pigs with solid-fermented feed. Corn as an energy source and soybean meal (SBM) as a plant protein source are the most common feed ingredients in pig nutrition worldwide. Digestive utilization of energy in most pigs varies from 70% to 90%, and the rest (10% to 30%) is excreted in the urine, and feces are lost as body heat and gases in the gut of pigs (Noblet and Henry, 1993). Since animals cannot use all of the energy and nutritional factors contained in feed grains, hence a need for solid fermented feeds to maximize energy and nutritional factors utilization. Considering the beneficial impacts of SSF on feed safety, nutrient bioavailability, pig growth performance, and meat quality, fermented feed has been regarded as a novel substitute for antimicrobial growth promoters in pigs. Most studies showed a positive impact on protein digestibility in pigs (Hao et al., 2020; Wang et al., 2018 a), nevertheless, the effect depends much on the microorganisms used and the fermentation parameters. In a meta-analysis performed by Xu et al. (2019), SSF improved the crude protein of pig feeds with significant heterogeneity (SMD [95% CI] 1.209 [0.501, 1.917], I2=86.50%, PQ<0.001).

Nevertheless, in the same meta-analysis by Xu et al. (2019) fermented feed had no significant effects on the growth performance and nutrient digestibility in finishing pigs compared with the essential diet. In the subgroup analyses, fermented ingredients increased the growth performance of weaned piglets and growing pigs, and fermented additives stimulated the growth of pigs at all stages. Including wheat fermented with either *Lactobacillus plantarum* or *Lactobacillus buchneri* in the diets of piglets also increased the ileal digestibility of starch (Koo et al., 2018). Furthermore, including spontaneously fermented barley or wheat in growing pig diets improved the ileal starch digestibility of the diet (Jørgensen et al., 2010).

Ruminants

There is an increasing need to optimize the usage of unconventional feed ingredients for ruminants to guarantee sustainable use of resources. Agricultural waste products such as rice straw, soybean, and wheat straw have great potential to be used as ruminant feed. Solid-state fermentation can produce feeds for ruminants, providing a higher population of yeasts to enhance ruminal fermentation. In addition, the presence of lignin in these unconventional feeds hinders their efficient usage as a ruminant feed (Moore and Jung, 2001). Therefore, the application of solid-state fermentation to break lignin and make available nutritional ingredients in feed is essential for feed production. Several methods have been used in the past decades to break the lignin complex using different techniques such as physical and chemical treatment of feeds (Hendriks and Zeeman, 2009). Due to the high demand for safe and environmentally friendly animal feeds, SSF has been given enormous consideration due to its numerous advantages. The application of SSF for protein improvement of lignocellulosic residues has received significant attention due to its direct applicability to the fermented product for ruminant feeding purposes. A recent study demonstrated the beneficial effects of fermented soybean meal containing rumen-degradable protein on cattle's milk performance (Fessenden et al., 2020). Another *in vitro* study also showed that the replacement of fermented apple bagasse with alfalfa hay in an *in vitro* rumen habitat resulted in beneficial changes to living yeast colonies and lactic acid concentration, while not affecting other fermentative and microbial parameters of the *in vitro* rumen environment (Castillo et al., 2015). Another study also showed the significant effect of adding fermented yellow wine lees into the diet of cows, improving lactation performance, reducing diet costs, and increasing dairy farming income (Yao et al., 2020). Fungal fermentation of various substrates for ruminant feeding has been demonstrated to be able to degrade more than 50% of the lignin content of rice straw, oil palm frond, and sugarcane bagasse and 59–78% of the lignin content of wheat straw (Tuyen et al., 2013; Van Kuijk et al., 2015). The application of solid-state fermentation for ruminants has been mainly focused on the degradation of the lignin content of ruminant feeds.

Aquatic animals

Fish meal has been used over the past decades as the primary source of protein for fish feed. Due to the high demand for white meat (fish, crabs, shrimps) and the recent use of SSF in animal nutrition, more fermented feed has been used to replace the conventional fish meal, this is mainly because of its high protein content, moreover, fermentations enhance protein availability and digestibility. Up to date, the most commonly used feed replacement for fish meals has been fermented soybean meal. A study by Shao et al. (2019) showed a significant positive relationship between dietary fermented soybean meal and the growth of white shrimps. Whereas, another study performed by Rahimnejad et al. (2021) evaluated the optimum replacement level of fish meal with fermented soybean meal to be in the range of 26.9–37.1% by broken-line and second-order polynomial regression analyses based on the weight gain, feed efficiency, and lysozyme and superoxide dismutase activities in spotted seabass.

Furthermore, recent research has proven that soybean meal has a significant positive effect on the weight of aquatic animals (Rahimnejad et al., 2021; Shao et al., 2019; Sharawy et al., 2016; Shiu et al., 2015; Xu et al., 2020). Nevertheless, with the ongoing advancement in SSF, more suitable fish meal replacement may be achieved. A summary of some of the effects of solid fermented feed on animals is presented in Table 2.

Table 2. Effects of SSF on animals

Substrate	Microorganism	Product	Effect on the target organism	References
1	2	3	4	5
Rice bran	*Bacillus* and *Lysinibacillus* species	N/A	Offered a slightly better growth performance and survival in Pacific white shrimp	(Liñan-Vidriales et al., 2021)
Fermented rapeseed cake	*Bacillus subtilis* strain 87Y		Improved the digestibility of protein and minerals in piglets	(Czech et al., 2023)
Fermented soybean meal	*Bacillus pumillus SE5*	High crude protein and low ANF	Weight gain, feed efficiency, and lysozyme and superoxide dismutase activities in spotted seabass	(Rahimnejad et al., 2021)
Fermented dried soybean and/or fermented rapeseed meal	*Bacillus subtilis* and *Lactobacillus fermentum*	N/A	Low mortality rate, reduced incidence of diarrhea and improved nutrient digestibility in piglets	(Czech et al., 2021)
Cornmeal	*Ampelopsis isabellina* CCF 2412	Gamma-linoleic acid and beta-carotene	Increased fatty acids in breast muscles of chicken	(Marcinčák et al., 2018)
Fermented soybean meal	*Bacillus subtilis*	Reduced anti-nutritional factors	Reduced allergic immune response in broilers	(Cheng et al., 2019 a)
Fermented cottonseed meal	*Bacillus subtilis ST-141* and *Saccharomycetes* N5	Acid-soluble protein	Improved growth performance, increased serum immunoglobulin level and antioxidative abilities, and balanced cecal microflora in broilers	(Yongwei et al., 2017)
Fermented soybean meal	*Lactobacillus* species and *Clostridium butyricum*	N/A	Improved diarrhea incidence	(Cheng et al., 2019 b)
Fermented soybean meal	*Enterococcus faecium*	High crude protein and dry matter	Increased body weight gain, glucose level and immunity of piglets	(Muniyappan et al., 2023)
Fermented flaxseed cake	*Aspergillus niger* and *Candida utilis*	Higher crude protein and calcium	Reduced the level of TG, TC, HDL, and LDL and increased the weight of gizzards in ducklings	(Zhai et al., 2019)
Soybean meal	*Saccharomyces cerevisiae*	N/A	Improved digestibility and increased body protein and amino acids in Nile tilapia	(Hassaan et al., 2015)
Fermented soybean meal	*Bacillus subtilis* GR-101	High amount of ammonia nitrogen and small peptides	Improved calf performance by altering the rumen's fermentation products and the relative presence of some bacterial species.	(Feizi et al., 2020)
Rapeseed meal	*Aspergillus niger*	N/A	Improved the growth performance and nutrient digestibility of rapeseed meal for pigs	(Changyou et al., 2016)
Yellow corn, soybean meal, fish meal, dried whey, and soybean oil	*Bacillus licheniformis*	N/A	Improved feed conversion ratio, reduced fecal microbiota in weaning piglets	(Lin and Yu, 2022)
Fermented soybean meal	*B. amyloliquefaciens, L. acidophilus,* and *Saccharomyces cerevisiae*	Increased dry matter, crude protein, and TCA-SP	Improved the growth performance in broilers and their serum immunity, possibly due to altered fecal microbial composition.	(Li et al., 2020)

Table 2 – contd.

1	2	3	4	5
Fermented soybean meal	*Bacillus subtilis, Lactobacillus,* and yeast	High crude protein, amino acid and lactic acid	Improved nutrient digestibility. an intestinal function in weaned pigs	(Yan et al., 2022)
Fermented okara	*S. cerevisiae, B. licheniformis,* and *L. plantarum*	Increased lactic acid and polysaccharides	Promoted growth by increasing average daily gain, improved antioxidant capacity by increasing superoxide dismutase.	(Tian et al., 2020)
Corn flour, rice flour, corn protein powder, and soybean meal	Engineered *Saccharomyces cerevisiae*	Increased dry matter, high 5-aminolevulinic acid	N/A	(Mao et al., 2020)
Rice hulls, wood shavings and millet bran	*Saccharomycetes, Lactobacillus, Bacillus subtilis,* and *Bifidobacterium*	N/A	Improved reproduction and increased the health of duck offspring	(Han et al., 2022)
Canola meal	*Aspergillus ficuum*	High crude protein	High feed intake, no body weight gain and feed conversion ratio	(Olukomaiya et al., 2021)
Okara	*Rhizopus oligosporus* and *Yarrowia lipolytica*	Decreased insoluble dietary fiber and phytic acid	N/A	(Vong et al., 2018)
Fermented rapeseed meal	*N/A*	Increased fatty acids and antioxidant activity	Positively affected the meat quality of turkey	(Drażbo et al., 2019)
Tea dregs	*Aspergillus niger* and *Trichoderma koningii*	Increased crude protein, crude fiber, neutral detergent fiber, and acid detergent fiber	N/A	(Cui et al., 2021)

Note: N/A = not available, ANF = anti-nutritional factor, HDL = high density lipoprotein, LDL = low density lipoprotein, TCA-SP = trichloroacetic acid soluble protein.

Challenges and future trends

The feed industry is constantly developing and using new fermentation technologies as effective alternatives to the conventional feed production technologies owing to exponential growth in consumer demand for quality, natural, high nutritional and safe feed composition. Although SSF technology has been proven to be a less expensive and environmental-friendly method to produce high-quality by-products, as far as the primary research is concerned, the results of many studies varied, and even opposite effects appear. In addition, the SSF repeatability could be better, which could be caused by several factors such as the type of microorganism, temperature, microorganism growth rate, different substrates, and other factors. On the other hand, despite various physical processing technology based on mutagenesis and the mixture of different microorganisms and substrates showing functional SSF high-yield end-product, many unclear underlying mechanisms remain to be investigated and studied systematically. Further research could be assisted by various disciplines such as bioinformatics, proteomics and non-destructive equipment, to enhance SSF yield. The limitation of SSF processes being a front-line biotechnological technique mainly applies to microorganisms that grow on solid matrices compared to solid foods. When performing SSF on a more extensive processing scale, the equipment employed in the laboratories could be more suitable. Therefore, achieving the scale-up of industrial processes is a technical challenge for researchers. Despite a few limitations, SSF has many applications and advantages in food and animal feed processing. It is a green and energy-saving technology that can improve the quality of feed products with natural color, flavor, as well as nutrients and texture.

Conclusion

The potential of solid-state fermentation is significant, which is why further study is being conducted. The progress in technologies, such as the production of bioreactors, has greatly enhanced solid fermentation. The utilization of physical processes such as ultrasonic and magnetic fields during solid-state fermentation (SSF) has enhanced the overall output yield. However, further investigation is required to explore the implementation of these physical processes in fermentation. Hence, additional investigation is necessary to further examine the influence of these physical mechanisms on microbes throughout the fermentation process, rather than solely prior to it. Furthermore, agro-industrial residues are a potential substrate for producing enzymes, peptides and improving their nutritional content by solid-state fermentation, which can be used to improve the welfare of animals. However, there is a need to explore all the different applications of SSF to maximize the low cost of animal feed production and enzyme synthesis.

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Conflict of interest

The authors declare that they have no competing interests.

CRediT authorship contribution statement

Garba Betchem: conceptualization, methodology, literature search, validation, formal analysis, investigation, data curation, writing – original draft, review and editing, visualization. Abdul Razak Monto: review and editing. Feng Lu: investigation. Laura Flavorta Billong: writing – review and editing. Haile Ma: supervision, resources, validation, project administration.

References

Acosta-Estrada B.A., Villela-Castrejón J., Perez-Carrillo E., Gómez-Sánchez C.E., Gutiérrez-Uribe J.A. (2019). Effects of solid-state fungi fermentation on phenolic content, antioxidant properties and fiber composition of lime cooked maize by-product (nejayote). J. Cereal Sci., 90: 102837.

Ahmed S.T., Mun H.S., Islam M.M., Ko S.Y., Yang C.J. (2016). Effects of dietary natural and fermented herb combination on growth performance, carcass traits and meat quality in grower-finisher pigs. Meat Sci., 122: 7–15.

Akinola O.S., Onakomaiya A.O., Agunbiade J.A., Oso A.O. (2015). Growth performance, apparent nutrient digestibility, intestinal morphology and carcass traits of broiler chickens fed dry, wet and fermented-wet feed. Livest. Sci., 177: 103–109.

Akpabli-Tsigbe N.D.K., Osabutey J., Mintah B.K., Tano-Debrah K., Ma Y. (2023). Cleavage of macromolecule (protein/polysaccharide)-phenolic bond in soybean cell wall through *Lactobacillus casei* and *Lactobacillus helviticus* mixed culture solid-state fermentation for chlorogenic acid extraction. Food Biosci., 55: 102903.

Al Daccache M., Koubaa M., Maroun R.G., Salameh D., Louka N., Vorobiev E. (2020). Pulsed electric field-assisted fermentation of *Hanseniaspora* sp. yeast isolated from Lebanese apples. Food Res. Int., 129: 108840.

Alexandratos N., Bruinsma J. (2012). FAO (2012) World Agriculture towards 2030/2050. In ESA Working Papers 12-03.

Arora S., Rani R., Ghosh S. (2018). Bioreactors in solid state fermentation technology: Design, applications and engineering aspects. J. Biotech., 269: 16–34.

Ashayerizadeh A., Dastar B., Shargh M.S., Mahoonak A.R.S., Zerehdaran S. (2018). Effects of feeding fermented rapeseed meal on growth performance, gastrointestinal microflora population, blood metabolites, meat quality, and lipid metabolism in broiler chickens. Livest. Sci., 216: 183–190.

Babinszky L., Horváth M., Remenyik J., Verstegen M.W.A. (2019). The adverse effects of heat stress on the antioxidant status and performance of pigs and poultry and reducing these effects with nutritional tools. In: Poultry and pig nutrition: Challenges of the 21st century, 8: 471–476.

Betchem G., Dabbour M., Tuly J.A., Billong L.F., Ma H. (2023). Optimization of fermentation conditions to improve the functional and structural characteristics of rapeseed meal with a mutant *Bacillus subtilis* species. Ind. Crops Pro., 205: 117424.

Betchem G., Dabbour M., Tuly J.A., Lu F., Liu D., Monto A.R., Dusabe K.D., Ma H. (2024). Effect of magnetic field-assisted fermentation on the *in vitro* protein digestibility and molecular structure of rapeseed meal. J. Sci. Food Agric., https://doi.org/10.1002/jsfa.13269

Boland M.J., Rae A.N., Vereijken J.M., Meuwissen M.P.M., Fischer A.R.H., van Boekel M.A.J. S., Rutherfurd S.M., Gruppen H., Moughan P.J., Hendriks W.H. (2013). The future supply of animal-derived protein for human consumption. Trends Food Sci. Techn., 29: 62–73.

Borresen E., Henderson A., Kumar A., Weir T., Ryan E. (2012). Fermented foods: patented approaches and formulations for nutritional supplementation and health promotion. Recent Pat. Food Nutr. Agric., 4: 134–140.

Câmara S.P., Dapkevicius A., Riquelme C., Elias R.B., Silva C.C.G., Malcata F.X., Dapkevicius M. (2019). Potential of lactic acid bacteria from Pico cheese for starter culture development. Food Sci. Techn. Int., 25: 303–317.

Canibe N., Jensen B.B. (2012). Fermented liquid feed – microbial and nutritional aspects and impact on enteric diseases in pigs. Anim. Feed Sci. Tech., 173: 17–40.

Cano y Postigo L.O., Jacobo-Velázquez D.A., Guajardo-Flores D., Garcia Amezquita L.E., García-Cayuela T. (2021). Solid-state fermentation for enhancing the nutraceutical content of agrifood by-products: Recent advances and its industrial feasibility. Food Biosci., 41: 100926.

Cao X., Luo Z., Zeng W., Xu S., Zhao L., Zhou J. (2018). Enhanced avermectin production by *Streptomyces avermitilis* ATCC 31267 using high-throughput screening aided by fluorescence-activated cell sorting. App. Micro. Biotech., 102: 703–712.

Carboué Q., Rébufa C., Hamrouni R., Roussos S., Bombarda I. (2020). Statistical approach to evaluate effect of temperature and moisture content on the production of antioxidant naphtho-gamma-pyrones and hydroxycinnamic acids by *Aspergillus tubingensis* in solid-state fermentation. Biopro. Biosys. Eng., 43: 2283–2294.

Castillo Y., Ruiz Barrera O., Burrola-Barraza M.E., Arzola-Alvarez C., Corral-Luna A., Rodriguez-Muela C., Murillo-Ortiz M. (2015). Inclusion levels of fermented apple bagasse on *in vitro* rumen fermentation of alfalfa hay. J. Agric. Sci. Techn. A, 5: 40–46.

Changyou S., Jun H., Jianping W., Jie Y., Bing Y., Xiangbing M., Ping Z., Zhiqing H., Daiwen C. (2016). Effects of *Aspergillus niger* fermented rapeseed meal on nutrient digestibility, growth performance and serum parameters in growing pigs. Anim. Sci. J., 87: 557–563.

Changyou S., Jun H., Jianping W., Jie Y., Bing Y., Xiangbing M., Ping Z., Zhiqing H., Daiwen C. (2017 a). Solid-state fermentation of corn-soybean meal mixed feed with *Bacillus subtilis* and *Enterococcus* faecium for degrading antinutritional factors and enhancing nutritional value. J. Anim. Sci. Biotech., 8: 50.

Changyou S., Jun H., Jianping W., Jie Y., Bing Y., Xiangbing M., Ping Z., Zhiqing H., Daiwen C. (2017 b). Physicochemical properties analysis and secretome of *Aspergillus niger* in fermented rapeseed meal. Plos One, 11: e0153230.

Chebaibi S., Leriche Grandchamp M., Burgé G., Clément T., Allais F., Laziri F. (2019). Improvement of protein content and decrease of anti-nutritional factors in olive cake by solid-state fermentation: A way to valorize this industrial by-product in animal feed. J. Biosci. Bioeng., 128: 384–390.

Cheng Y.H., Hsiao F.S.H., Wen C.M., Wu C.Y., Dybus A., Yu Y.H. (2019 a). Mixed fermentation of soybean meal by protease and probiotics and its effects on the growth performance and immune response in broilers. J. Appl. Animal Res., 47: 339–348.

Cheng Y.H., Su L.W., Horng Y.B., Yu Y.H. (2019 b). Effects of soybean meal fermented by species and on growth performance, diarrhea incidence, and fecal bacteria in weaning piglets. Ann. Anim. Sci., 19: 1051–1062.

Cuadra T., Fernández F.J., Tomasini A., Barrios-González J. (2008). Influence of pH regulation and nutrient content on cephalosporin C production in solid-state fermentation by *Acremonium chrysogenum* C10. Let. Appl. Micro., 46: 216–220.

Cui Y., Li J., Dun D., Huijie L., Tian Z., Liu Z., Ma X. (2021). Solid-state fermentation by *Aspergillus niger* and *Trichoderma koningii* improves the quality of tea dregs for use as feed additives. PLoS One, 16: e0260045.

Czech A., Grela E.R., Kiesz M. (2021). Dietary fermented rapeseed or/and soybean meal additives on performance and intestinal health of piglets. Sci. Rep., 11: 16952.

Czech A., Wlazło Ł., Łukaszewicz M., Florek M., Nowakowicz--Dębek B. (2023). Fermented rapeseed meal enhances the digestibility of protein and macro- and microminerals and improves the performance of weaner pigs. Ani. Feed Sci. Techn., 300: 115656.

Das K.C., Mohanty S., Sahoo P.K., Sahoo S., Prakash B., Swain P. (2022). Inclusion of different levels of solid-state fermented mahua oil cake on growth, digestibility and immunological parameters of rohu (*Labeo rohita*). Aquaculture, 553: 738049.

Deamici K.M., Santos L.O., Costa J.A.V. (2018). Magnetic field action on outdoor and indoor cultures of *Spirulina*: Evaluation of growth, medium consumption and protein profile. Biores. Techn., 249: 168–174.

Drażbo A., Kozłowski K., Ognik K., Zaworska A., Jankowski J. (2019). The effect of raw and fermented rapeseed cake on growth performance, carcass traits, and breast meat quality in turkey. Poultry Sci., 98: 6161–6169.

Dumandan N.G., Arreola S.L.B. (2022). Enhanced production of l-lysine by *Bacillus megaterium* AECR 751 mutant in copra meal through solid-state fermentation. Biores. Tech. Rep., 20: 101270.

El Salamony D.H., Salah Eldin Hassouna M., Zaghloul T.I., Moustafa Abdallah H. (2024). Valorization of chicken feather waste using recombinant *Bacillus subtilis* cells by solid-state fermentation for soluble proteins and serine alkaline protease production. Biores. Tech., 393: 130110.

Elbaz A.M., El-sheikh S.E., Abdel-Maksoud A. (2023). Growth performance, nutrient digestibility, antioxidant state, ileal histomorphometry, and cecal ecology of broilers fed on fermented canola meal with and without exogenous enzymes. Trop. Anim. Health Prod., 55: 46.

Farinas C.S. (2015). Developments in solid-state fermentation for the production of biomass-degrading enzymes for the bioenergy sector. Renew. Sust. Energy Rev., 52: 179–188.

Feizi L.K., Zad S.S., Jalali S.A.H., Rafiee H., Jazi M.B., Sadeghi K., Kowsar R. (2020). Fermented soybean meal affects the ruminal fermentation and the abundance of selected bacterial species in Holstein calves: a multilevel analysis. Sci. Rep., 10: 12062.

Fessenden S.W., Ross D.A., Block E., Van Amburgh M.E. (2020). Comparison of milk production, intake, and total-tract nutrient digestion in lactating dairy cattle fed diets containing either wheat middlings and urea, commercial fermentation by-product, or rumen-protected soybean meal. J. Dairy Sci., 103: 5090–5101.

Fraga F.C., Valério A., de Oliveira V.A., Di Luccio M., de Oliveira D. (2019). Effect of magnetic field on the Eversa® Transform 2.0 enzyme: Enzymatic activity and structural conformation. Int. J. Biological Macro., 122: 653–658.

Gao J., Zhang H.J., Wu S.G., Yu S.H., Yoon I., Moore D., Gao Y.P., Yan H.J., Qi G. H. (2009). Effect of *Saccharomyces cerevisiae* fermentation product on immune functions of broilers challenged with *Eimeria tenella*. Poultry Sci., 88: 2141–2151.

Gao X., Liu E., Yin Y., Yang L., Huang Q., Chen S., Ho C.T. (2020). Enhancing activities of salt-tolerant proteases secreted by *Aspergillus oryzae* using atmospheric and room-temperature plasma mutagenesis. J. Agric. Food Chem., 68: 2757–2764.

Han T., Wang T., Wang Z., Xiao T., Wang M., Zhang Y., Zhang J., Liu D. (2022). Evaluation of gaseous and solid waste in fermentation bedding system and its impact on animal performance: A study of breeder ducks in winter. Sci. Total Environ., 836: 155672.

Hao L., Su W., Zhang Y., Wang C., Xu B., Jiang Z., Wang F., Wang Y., Lu Z. (2020). Effects of supplementing with fermented mixed feed on the performance and meat quality in finishing pigs. Ani. Feed Sci. Tech., 266: 114501.

Hassaan M.S., Soltan M.A., Abdel-Moez A.M. (2015). Nutritive value of soybean meal after solid-state fermentation with *Saccharomyces cerevisiae* for Nile tilapia, *Oreochromis niloticus*. Anim. Feed Sci. Tech., 201: 89–98.

Hendriks A.T.W.M., Zeeman G. (2009). Pretreatments to enhance the digestibility of lignocellulosic biomass. Biores. Tech., 100: 10–18.

Huang G., Chen S., Tang Y., Dai C., Sun L., Ma H., He R. (2019). Stimulation of low intensity ultrasound on fermentation of skim milk medium for yield of yoghurt peptides by *Lactobacillus paracasei*. Ultra. Sono., 51: 315–324.

Jiang K., Tang B., Wang Q., Xu Z., Sun L., Ma J., Li S., Xu H., Lei P. (2019). The bio-processing of soybean dregs by solid state fermentation using a poly γ-glutamic acid producing strain and its effect as feed additive. Biores. Tech., 291: 121841.

Jiang X., Liu X., Xu H., Sun Y., Zhang Y., Wang Y. (2021). Improvement of the nutritional, antioxidant and bioavailability properties of corn gluten-wheat bran mixture fermented with lactic acid bacteria and acid protease. LWT, 144: 111161.

Jørgensen H., Sholly D., Pedersen A.Ø., Canibe N., Knudsen K.E.B. (2010). Fermentation of cereals — Influence on digestibility of nutrients in growing pigs. Livest. Sci., 134: 56–58.

Kar S., Datta T., Ray R. (2010). Optimization of thermostable alpha-amylase production by *Streptomyces erumpens* MTCC 7317 in solid-state fermentation using cassava fibrous residue. Braz. Arch. Biol. Tech., 53: 301–309.

Koo B., Kim J.W., Nyachoti C.M. (2018). Nutrient and energy digestibility and microbial metabolites in weaned pigs fed diets containing *Lactobacillus*-fermented wheat. Ani. Feed Sci. Tech., 241: 27–37.

Krishania M., Sindhu R., Binod P., Ahluwalia V., Kumar V., Sangwan R.S., Pandey A. (2018). Chapter 5 – Design of bioreactors in solid-state fermentation. In: Current developments in biotechnology and bioengineering, Pandey A., Larroche C., Soccol C.R. (eds.). Elsevier, pp. 83–96.

Kumar V., Ahluwalia V., Saran S., Kumar J., Patel A.K., Singhania R.R. (2021). Recent developments on solid-state fermentation for production of microbial secondary metabolites: Challenges and solutions. Biores. Tech., 323: 124566.

Leite P., Salgado J.M., Venâncio A., Domínguez J.M., Belo I. (2016). Ultrasounds pretreatment of olive pomace to improve xylanase and cellulase production by solid-state fermentation. Biores. Tech., 214: 737–746.

Leite P., Belo I., Salgado J.M. (2021). Co-management of agro-industrial wastes by solid-state fermentation for the production of bioactive compounds. Ind. Crops Prod., 172: 113990.

Li W., Wang T. (2021). Effect of solid-state fermentation with *Bacillus subtilis* lwo on the proteolysis and the antioxidative properties of chickpeas. Int. J. Food Microbiol., 338: 108988.

Li W., Ma H., He R., Ren X., Zhou C. (2021). Prospects and application of ultrasound and magnetic fields in the fermentation of rare edible fungi. Ultra. Sono., 76: 105613.

Li. Y., Guo B., Wu Z., Wang W., Li C., Liu G., Cai H. (2020). Effects of ferented soybean meal supplementation on the growth performance and cecal microbiota community of broiler chickens. Animals, 10: 1098.

Lin K.H., Yu Y.H. (2022). A field study of *Bacillus licheniformis*-fermented products on growth performance and faecal microbiota of weaning piglets. South Afr. J. Anim. Sci., 52: 718–729.

Lin L., Wang X., Cui H. (2019). Synergistic efficacy of pulsed magnetic fields and *Litseacubeba* essential oil treatment against *Escherichia coli* O157:H7 in vegetable juices. Food Cont., 106: 106686.

Lin W.C., Lee M.T., Lo C.T., Chang S.C., Lee T.T. (2018). Effects of dietary supplementation of *Trichoderma pseudokoningii* fermented enzyme powder on growth performance, intestinal morphology, microflora and serum antioxidantive status in broiler chickens. Italian J. Ani. Sci., 17: 153–164.

Liñan-Vidriales M.A., Peña-Rodríguez A., Tovar-Ramírez D., Elizondo-González R., Barajas-Sandoval D.R., Ponce-Gracía E.I., Rodríguez-Jaramillo C., Balcázar J.L., Quiroz-Guzmán E. (2021). Effect of rice bran fermented with *Bacillus* and *Lysinibacillus* species on dynamic microbial activity of Pacific white shrimp (*Penaeus vannamei*). Aquaculture, 531: 735958.

Lou H., Yang C., Li Y., Li Y., Li Y., Zhao R. (2023). Optimization of aflatoxin B1 degradation in corn by *Ganoderma sinense* through solid-state fermentation. LWT, 183: 114959.

Lu F., Alenyorege E.A., Ouyang N., Zhou A., Ma H. (2022). Simulated natural and high temperature solid-state fermentation of soybean meal: A comparative study regarding microorganisms, functional properties and structural characteristics. LWT, 159: 113125.

Mai H.T.N., Lee K.M., Choi S.S. (2016). Enhanced oxalic acid production from corncob by a methanol-resistant strain of *Aspergillus niger* using semi solid-sate fermentation. Process Biochem., 51: 9–15.

Mao Y., Chen Z., Lu L., Jin B., Ma H., Pan Y., Chen T. (2020). Efficient solid-state fermentation for the production of 5-aminolevulinic acid enriched feed using recombinant *Saccharomyces cerevisiae*. J. Biotech., 322: 29–32.

Marcinčák S., Klempová T., Bartkovský M., Marcinčáková D., Zdolec N., Popelka P., Mačanga J., Čertík M. (2018). Effect of fungal solid-state fermented product in broiler chicken nutrition on quality and safety of produced breast meat. Bio Med. Res. Int., 2018: 2609548.

Meng L., Gao X., Liu X., Sun M., Yan H., Li A., Yang Y., Bai Z. (2021). Enhancement of heterologous protein production in *Corynebacterium glutamicum* via atmospheric and room temperature plasma mutagenesis and high-throughput screening. J. Biotech., 339: 22–31.

Mirsalami S.M., Mirsalami M. (2024). Impact of solid-state fermentation utilizing *Saccharomyces boulardii* on the chemical composition and bioactive constituents of rice husk. J. Agric. Food Res., 15: 100957.

Montanari C., Tylewicz U., Tabanelli G., Berardinelli A., Rocculi P., Ragni L., Gardini F. (2019). Heat-assisted pulsed electric field treatment for the inactivation of *Saccharomyces cerevisiae*: Effects of the presence of citral. Front. Microbiol., 10: 1737.

Moore K.J., Jung H.J.G. (2001). Lignin and fiber digestion. J. Range Man., 54: 420–430.

Mota M.J., Lopes R.P., Koubaa M., Roohinejad S., Barba F.J., Delgadillo I., Saraiva J.A. (2018). Fermentation at non-conventional conditions in food- and bio-sciences by the application of advanced processing technologies. Crit. Rev. Biotech., 38: 122–140.

Muangkeow N., Chinajariyawong C. (2013). Diets containing fermented palm kernel meal with *Aspergillus wentii* TISTR 3075 on growth performance and nutrient digestibility of broiler chickens. Walailak J. Sci. Tech., 10: 131–147.

Muniyappan M., Shanmugam S., Park J.H., Han K., Kim I.H. (2023). Effects of fermented soybean meal supplementation on the growth performance and apparent total tract digestibility by modulating the gut microbiome of weaned piglets. Sci. Rep., 13: 3691.

Nguyen T., Lapoin W., Young M., Nguyen C.H. (2022). Changes in fermented soybean nutritional content generated under the different fermentation conditions by *Bacillus subtilis*. Waste Biom. Val., 13: 563–569.

Nigam P. (1990). Investigation of some factors important for solid-state fermentation of sugar cane bagasse for animal feed production. Enz. Microbial Tech., 12: 808–811.

Noblet J., Henry Y. (1993). Energy evaluation systems for pig diets: a review. Livest. Prod. Sci., 36: 121–141.

Olukomaiya O.O., Pan L., Zhang D., Mereddy R., Sultanbawa Y., Li X. (2021). Performance and ileal amino acid digestibility in broilers fed diets containing solid-state fermented and enzyme-supplemented canola meals. Ani. Feed Sci. Tech., 275: 114876.

Ong A., Lee C.L.K. (2021). Cooperative metabolism in mixed culture solid-state fermentation. LWT, 152: 112300.

Ottenheim C., Nawrath M., Wu J.C. (2018). Microbial mutagenesis by atmospheric and room-temperature plasma (ARTP): the latest development. Biores. Biopro., 5: 12.

Prado Barragán L.A., Figueroa J.J.B., Rodríguez Durán L.V., Aguilar González C.N., Hennigs C. (2016). Chapter 7 – Fermentative Production Methods. In: Biotransformation of agricultural waste and by-products, Poltronieri P., D'Urso O.F. (eds.). Elsevier, pp. 189–217.

Qureshi A.S., Khushk I., Ali C.H., Chisti Y., Ahmad A., Majeed H. (2016). Coproduction of protease and amylase by thermophilic *Bacillus* sp. BBXS-2 using open solid-state fermentation of lignocellulosic biomass. Biocatalysis Agric. Biotech., 8: 146–151.

Rahimnejad S., Zhang J.J., Wang L., Sun Y., Zhang C. (2021). Evaluation of *Bacillus pumillus* SE5 fermented soybean meal as a fish meal replacer in spotted seabass (*Lateolabrax maculatus*) feed. Aquaculture, 531: 735975.

Rana M., Kumar D., Angural S., Warmoota R., Mazumder K., Gupta N. (2023). Hyperproduction of a bacterial mannanase and its application for production of bioactive mannooligosaccharides from agro-waste. Proc. Biochem., 124: 13–23.

Rayaroth A., Tomar R.S., Mishra R.K. (2021). One step selection strategy for optimization of media to enhance arachidonic acid production under solid state fermentation. LWT, 152: 112366.

Rui X., Wang M., Zhang Y., Chen X., Li L., Liu Y., Dong M. (2017). Optimization of soy solid-state fermentation with selected lactic acid bacteria and the effect on the anti-nutritional components. J. Food Proc. Preserv., 41: e13290.

Ruijter G., Visser J., Rinzema A. (2004). Polyol accumulation by *Aspergillus oryzae* at low water activity in solid-state fermentation. Microbiology (Reading), 150: 1095–1101.

Salim A.A., Grbavčić S., Šekuljica N., Vukašinović-Sekulić M., Jovanović J., Jakovetić Tanasković S., Luković N., Knežević-Jugović Z. (2019). Enzyme production by solid-state fermentation on soybean meal: A comparative study of conventional and ultrasound-assisted extraction methods. Biotech. Appl. Biochem., 66: 361–368.

Shao J., Wang B., Liu M., Jiang K., Wang L., Wang M. (2019). Replacement of fishmeal by fermented soybean meal could enhance the growth performance but not significantly influence the intestinal microbiota of white shrimp *Litopenaeus vannamei*. Aquaculture, 504: 354–360.

Sharawy Z., Goda A.M.A.S., Hassaan M.S. (2016). Partial or total replacement of fish meal by solid state fermented soybean meal with *Saccharomyces cerevisiae* in diets for Indian prawn shrimp, *Fenneropenaeus indicus*, postlarvae. Anim. Feed Sci. Tech., 212: 90–99.

Shiu Y.L., Hsieh S.L., Guei W.C., Tsai Y.T., Chiu C.H., Liu C.H. (2015). Using *Bacillus subtilis* E20-fermented soybean meal as replacement for fish meal in the diet of orange-spotted grouper (*Epinephelus coioides*, Hamilton). Aquac. Res., 46: 1403–1416.

Shu L., Si X., Yang X., Ma W., Sun J., Zhang J., Xue X., De-pei W., Gao Q. (2020). Enhancement of acid protease activity of *Aspergillus oryzae* using atmospheric and room temperature plasma. Front. Microbiol., 11: 1418.

Singh R.S., Chauhan K., Kaur K., Pandey A. (2020). Statistical optimization of solid-state fermentation for the production of fungal inulinase from apple pomace. Biores. Tech. Rep., 9: 100364.

Sosa-Martínez J.D., Montañez J., Contreras-Esquivel J.C., Balagurusamy N., Gadi S.K., Morales-Oyervides L. (2023). Agroindustrial and food processing residues valorization for solid-state fermentation processes: A case for optimizing the co-production of hydrolytic enzymes. J. Environ. Man., 347: 119067.

Sugiharto S., Yudiarti T., Isroli I., Widiastuti E., Wahyuni H.I., Sartono T.A. (2018). The effect of fungi-origin probiotic *Chrysonilia crassa* in comparison to selected commercially used feed additives on broiler chicken performance, intestinal microbiology, and blood indices. J. Adv. Vet. Anim. Res., 5: 332–342.

Sun X., Urriola P.E., Shurson G., Tiffany D., Hu B. (2023). Enhancing feeding value of corn distiller's grains with solubles via fungal co-cultured solid-state fermentation for monogastric animal nutrition. Anim. Feed Sci. Tech., 303: 115673.

Sun X., Dou Z., Shurson G.C., Hu B. (2024). Bioprocessing to upcycle agro-industrial and food wastes into high-nutritional value animal feed for sustainable food and agriculture systems. Res. Conserv. Recyc., 201: 107325.

Szyjka S.J., Mandal S., Schoepp N.G., Tyler B.M., Yohn C.B., Poon Y.S., Villareal S., Burkart M.D., Shurin J.B., Mayfield S.P. (2017). Evaluation of phenotype stability and ecological risk of a genetically engineered alga in open pond production. Algal Res., 24: 378–386.

Tian Z., Deng D., Cui Y., Chen W., Yu M., Ma X. (2020). Diet supplemented with fermented okara improved growth performance, meat quality, and amino acid profiles in growing pigs. Food Sci. Nutr., 8: 5650–5659.

Tuly J.A., Ma H., Zabed H.M., Dong Y., Chen G., Guo L., Betchem G., Igbokwe C.J. (2022 a). Exploring magnetic field treatment into solid-state fermentation of organic waste for improving structural and physiological properties of keratin peptides. Food Biosci., 49: 101872.

Tuly J.A., Zabed H.M., Nizami A.-S., Mehedi Hassan M., Roknul Azam S.M., Kumar Awasthi M., Janet Q., Chen G., Akpabli-Tsigbe N.D.K., Ma H. (2022 b). Bioconversion of agro-food industrial wastes into value-added peptides by a *Bacillus* sp. mutant through solid-state fermentation. Biores. Tech., 346: 126513.

Tuyen D.V., Phuong H.N., Cone J.W., Baars J.J.P., Sonnenberg A.S.M., Hendriks W.H. (2013). Effect of fungal treatments of fibrous agricultural by-products on chemical composition and *in vitro* rumen fermentation and methane production. Biores. Tech., 129: 256–263.

Van Kuijk S.J.A., Sonnenberg A.S.M., Baars J.J.P., Hendriks W.H., Cone J.W. (2015). Fungal treated lignocellulosic biomass as ruminant feed ingredient: A review. Biotech. Adv., 33: 191–202.

Vandenberghe L.P.S., Pandey A., Carvalho J.C., Letti L.A.J., Woiciechowski A.L., Karp S.G., Thomaz-Soccol V., Martínez-Burgos W.J., Penha R.O., Herrmann L.W., Rodrigues A.O., Soccol C.R. (2021). Solid-state fermentation technology and innovation for the production of agricultural and animal feed bioproducts. Syst. Microbiol. Biomanufact., 1: 142–165.

Vong W.C., Hua X.Y., Liu S.Q. (2018). Solid-state fermentation with *Rhizopus oligosporus* and *Yarrowia lipolytica* improved nutritional and flavour properties of okara. LWT, 90: 316–322.

Wang C., Lin C., Su W., Zhang Y., Wang F., Wang Y., Shi C., Lu Z. (2018 a). Effects of supplementing sow diets with fermented corn and soybean meal mixed feed during lactation on the performance of sows and progeny. J. Anim. Sci., 96: 206–214.

Wang J., Cao F., Su E., Zhao L., Qin W. (2018 b). Improvement of animal feed additives of ginkgo leaves through solid-state fermentation using *Aspergillus niger*. Int. J. Biol. Sci., 14: 736–747.

Wang M.S., Wang L.H., Bekhit A.E.D.A., Yang J., Hou Z.P., Wang Y.Z., Dai Q.Z., Zeng X.A. (2018 c). A review of sublethal effects of pulsed electric field on cells in food processing. J. Food Eng., 223: 32–41.

Wang Y., Li J., Wei F., Liu X., Yi C., Zhang Y. (2019). Improvement of the nutritional value, sensory properties and bioavailability of rapeseed meal fermented with mixed microorganisms. LWT, 112: 108238.

Wang Y., Xu K., Lu F., Wang Y., Ouyang N., Ma H. (2021). Increasing peptide yield of soybean meal solid-state fermentation of ultrasound-treated *Bacillus amyloliquefaciens*. Innov. Food Sci. Emer. Tech., 72: 102704.

Xu B., Zhu L., Fu J., Li Z., Wang Y., Jin M. (2019). Overall assessment of fermented feed for pigs: a series of meta-analyses. J. Anim. Sci., 97: 4810–4821.

Xu C., Liu W., Zhang D., Liu J., Zheng X., Zhang C., Yao J., Zhu C., Chi C. (2020). Effects of partial fish meal replacement with two fermented soybean meals on the growth of and protein metabolism in the Chinese mitten crab (*Eriocheir sinensis*). Aquac. Rep., 17: 100328.

Yan H., Jin J.Q., Yang P., Yu B., He J., Mao X.B., Yu J., Chen D.W. (2022). Fermented soybean meal increases nutrient digestibility via the improvement of intestinal function, anti-oxidative capacity and immune function of weaned pigs. Animals, 16: 100557.

Yang L., Zeng X., Qiao S. (2021). Advances in research on solid-state fermented feed and its utilization: The pioneer of private customization for intestinal microorganisms. Anim. Nutr., 7: 905–916.

Yao K.Y., Wei Z.H., Xie Y.Y., Wang D.M., Liu H.Y., Fang D., Ma M.R., Liu J.X. (2020). Lactation performance and nitrogen utilization of dairy cows on diets including unfermented or fermented yellow wine lees mix. Livest. Sci., 236: 104025.

Yin J., Kim H.S., Kim Y.M., Kim I.H. (2018). Effects of dietary fermented red ginseng marc and red ginseng extract on growth performance, nutrient digestibility, blood profile, fecal microbial, and noxious gas emission in weanling pigs. J. Appl. Anim. Res., 46: 1084–1089.

Yongwei W., Qingqing D., Dang S., Weiwei W., Hang Z., Li W., Aike L. (2017). Effects of fermented cottonseed meal on growth performance, serum biochemical parameters, immune functions, antioxidative abilities, and cecal microflora in broilers. Food Agric. Immunol., 28: 725–738.

Yuan L., Chang J., Yin Q., Lu M., Di Y., Wang P., Wang Z., Wang E., Lu F. (2017). Fermented soybean meal improves the growth performance, nutrient digestibility, and microbial flora in piglets. Anim. Nutr., 3: 19–24.

Zhai S.S., Zhou T., Li M.M., Zhu Y.W., Li M.C., Feng P.S., Zhang X.F., Ye H., Wang W.C., Yang L. (2019). Fermentation of flaxseed cake increases its nutritional value and utilization in ducklings. Poultry Sci., 98: 5636–5647.

Zhang C., Qin J., Dai Y., Mu W., Zhang T. (2019). Atmospheric and room temperature plasma (ARTP) mutagenesis enables xylitol

over-production with yeast *Candida tropicalis*. J. Biotech., 296: 7–13.
Zhang A.R., Wei M., Yan L., Zhou G.L., Li Y., Wang H.M., Yang Y.Y., Yin W., Guo J.Q., Cai X.H., Li J.X., Zhou H., Liang Y.X. (2022 a). Effects of feeding solid-state fermented wheat bran on growth performance and nutrient digestibility in broiler chickens. Poultry Sci., 101: 101402.
Zhang D., Ye Y., Tan B. (2022 b). Comparative study of solid-state fermentation with different microbial strains on the bioactive compounds and microstructure of brown rice. Food Chem., 397: 133735.
Zhao H.M., Guo X.N., Zhu K.X. (2017). Impact of solid state fermentation on nutritional, physical and flavor properties of wheat bran. Food Chem., 217: 28–36.

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