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Probiotics and oilseed cakes as feed additives in piglets nutrition

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ABSTRACT

Probiotics and oilseed cakes offer a promising approach to enhancing piglets nutrition and dietary absorption of nutrients. Four cold-pressed OSC - flax, pumpkin, hemp, and camelina - are recognized for their high protein and lipid content, balanced amino acid profiles, and essential fatty acids profile. Despite these advantages, certain antinutritional factors limit their inclusion in pig diets by affecting feed consumption and nutrient absorption. Probiotics, such as *Bacillus* species and lactic acid bacteria, present a viable solution to improve the OSC nutritional value by mitigating ANFs, with benefits on growth, health, and overall productivity. Using probiotics-oilseed cakes combination in piglets' feeding systems can enhance nutrient digestibility, zootechnical performance, gut health, and, finally, product quality, contributing to more sustainable and efficient animal production practices. Thus, this review paper aims to provide a comprehensive reference of the current applications of probiotics in piglets nutrition, specifically focusing on their integration into OSC-based diets.

Keywords: probiotics, oilseed cakes, piglets, benefits.

INTRODUCTION

Due to the high demand for swine meat, the pig sector plays a major role in the global economy (Szűcs & Vida, 2017). In addition to meat production, pork by-products are recognized for their high-quality proteins and rich mineral content, significantly contributing to proper human nutrition and health (Liu et al., 2018).

A key factor in swine farming is efficient feeding to optimize productivity and animal health. In this context, probiotics have emerged as a vital component of piglets' diets due to their ability to balance intestinal microflora, mitigate the impact of pathogenic bacteria, and improve overall gut health status (Jiang et al., 2024). According to Dasriya et al. (2024), a bacterium is recognized as a probiotic if it is non-pathogenic, capable of producing a viable cell count, beneficial to the host's health, and enhances digestive tract function.

Common probiotics include *Bacillus* spp. (e.g., *B. licheniformis, B. subtilis, B. amyloliguefaciens, B. megaterium*) *Lactobacillus* spp. (e.g., *L. plantarum, L. acidophilus*, *L. lactis, L. bulgaricus, L. helveticus, L. casei, L. salivarius*), *Bifidobacteria* spp. (e.g., *B. bifidum, B. infantis, B. breve, B. longum, B. animalis, and B. lactics*), *Enterococcus* spp. (e.g., *E. faecalis, E. faecium*)*, Streptococcus thermophilus,* and yeasts like as *Saccharomyces boulardii* and *Saccharomyces cerevisiae* (Mia et al., 2024).

The benefits of probiotics are closely tied to the dose of administration (Johansson et al., 2015). Typically, the recommended dosage for orally administered probiotics in piglet feed depends on the intended application and varies according to regulations in different countries. Generally, the dosage falls within the range of 10^6 to 10^7 colony-forming units (CFU) / gram of product, with a suggested daily intake of 10^9 CFU. Indeed, by enhancing immunity and promoting disease resistance, probiotics contribute to healthier and more robust animals, ultimately benefiting the efficiency and sustainability of piglet farming. These benefits are especially critical during the weaning phase - a stressful transition for piglets marked by dietary changes, environmental shifts, and abrupt separation from the sow (Wang et al., 2020). This stage often results in diminished feed intake, intestinal inflammation, and imbalances in microbiota during the gastrointestinal tract (GIT), which intensify the risk of diarrhoea and mortality rate (Tang et al., 2024). To maximize the benefits, probiotics can be combined with prebiotics to create enhanced formulations known as symbiotics, which provide higher effectiveness.

This overview explored the key benefits of probiotics administration and its effects on nutrition based on OSC to piglets' diets. For instance, OSC from flax, pumpkin, hemp, and camelina can serve as a prebiotic substrate for probiotics bacteria, yielding notable benefits in piglets feed. This approach is particularly valuable during the weaning stage, known as a critical and challenging phase in the piglet's life. In addition, piglets are exposed to a lot of unfamiliar factors, such as separation from the sow and the accommodation to a new diet, which induce considerable stress and serious changes in their growth and development (Sopková et al., 2016). These factors can result in drastic reductions in body weight (BW), an increased incidence of diarrhoea, and an unbalanced intestinal microbiota (Giang et al., 2012). Pluske et al. (2019) emphasized that various physiological and environmental factors during a weaning crisis significantly affect piglets' health and growth. Therefore, this study provides a comprehensive evaluation of existing research on potential strategies for repurposing by-products from the oil industry, particularly OSC, with a focus on their application in enhancing piglets' nutrition and health through the incorporation of prebiotics and probiotics in their diets.

MATERIALS AND METHODS

A structured data search was performed to identify relevant research articles from international databases, including ScienceDirect, PubMed, and Google Scholar. The search focused on scientific articles published in English and utilized the following keywords: probiotic, OSC (flax, pumpkin, hemp, and camelina), piglets, and benefits. Additional studies were identified by reviewing the reference lists of the collected studies and prior published research. The gathered literature was carefully accessed, explored, and evaluated. It was then systematically organized to focus on the current applications of probiotics in piglets' nutrition, particularly in diets incorporating different OSC.

RESULTS AND DISCUSSION

Effects of probiotics in piglets nutrition

In recent years, research has expanded significantly, focusing on the utilization of probiotics in piglets' nutrition. In this context, probiotics from *Bacillus, Lactobacillus, Enterococcus* groups, and yeasts have demonstrated significant benefits in the pig industry.

Studies have shown that piglets treated with *Bacillus* spp. as a source of probiotics improve absorption of nutritional compounds and ultimately exhibit a beneficial impact on their growth and health (Jäger et al., 2018). Moreover, numerous topics have shown that spore bacteria can produce extracellular enzymes (protease, amylase, cellulase, lipase, and phytase etc.) with significant effect on nutrient digestibility (Rambu et al., 2024; Sudan et al., 2022; Wang et al., 2021).

Similarly, research has shown that supplementing pigs with probiotics, including *Lactobacillus* strains (LABs), promotes the development of beneficial bacterial populations. Also, some LABs generate antimicrobial peptides and other bioactive compounds that can inhibit the growth of pathogenic bacteria such as *Enterobacteriaceae, Clostridium*, *Streptococcus,* and *Enterococcus* species (Zhang et al., 2023; Jiang et al., 2024). *Lactobacillus* generates bacteriocins with strong antibacterial activity, functioning either bactericidal or bacteriostatic against a range of foodborne pathogens (Ali et al., 2023). The production of bacteriocins may enhance the probiotic activity of intestinal *Lactobacillus*, potentially playing a direct role by positively modifying the gut microbiota or inhibiting certain GI pathogenic bacteria (Cotter et al., 2013). For example, in weaned piglets fed with *Lactobacillus*-based probiotics, the improved nutrient digestibility reduces the substrate available for microbial fermentation in the colon, leading to lower emissions of ammonia (NH_3), total mercaptans, and hydrogen sulfide (H_2S) (Zhao & Kim, 2015).

The production of metabolites like lactic, formic, butyric, and propionic acids by probiotic *Lactobacillus* can inhibit pathogen growth and stimulate the production of short-chain fatty acids (SCFAs) by reducing intestinal pH (Schokker et al., 2015; Cizeikiene et al., 2021). This process may influence fecal odor, microbial composition, and gut metabolites, although these effects are not yet fully understood. Besides, *Lactobacillus* can produce vitamins such as folate, riboflavin, and vitamin B12 (Linares et al., 2018). These vitamins have an important place in essential processes such as antioxidants and cell metabolism (Ali et al., 2023). The proteolytic enzymatic system of probiotics plays a pivotal role in hydrolyzing feed proteins into bioactive peptides, which can have functional benefits such as antimicrobial, antioxidant, and immunomodulatory properties. Selecting the appropriate bacterial strains or their products is essential for optimizing these benefits and adapting them to specific applications in animal nutrition and health.

Products based on yeast culture containing *Saccharomyces cerevisiae* as an excellent source with high-quality proteins, enzymes, vitamins, and nutrients, providing significant benefits to animal health (Yalçın et al., 2008). These products have been shown to enhance growth, microbiota and mitigate post-weaning diarrhoea in weaning piglets (Lee et al., 2021; Boontiam et al., 2022). Additionally, supplementing sow diets with probiotics based on yeasts has proven effective in reducing diarrhoea and decreasing mortality rates in newborn piglets (Donovan et al., 2021).

Zhang et al. (2019) observed that supplementing growing-finishing piglets' diets with brewer’s yeast hydrolysate led to a linear improvement in average daily gain (ADG) and feed conversion ratio. However, the diet did not significantly affect carcass weight, backfat thickness, or lean muscle. These results are essential aspects for optimizing the feed resources in swine production.

Included in young pigs' diets, probiotic products improved the intestinal integrity, stimulated the elongation of jejunal villi, enriched the gut microbiota with beneficial bacteria, and contributed to enhanced growth performance throughout the rearing period (Pupa et al., 2021). Consequently, significant changes were observed in the piglets’ life cycle. Some of the key benefits of incorporating probiotics into piglets' diets are illustrated in Figure 1.

Figure 1. Systemic diagram about the effects of probiotics products in piglets' diets

Instead, from an industrial standpoint, for an organism to be considered as a probiotic in piglet nutrition depends heavily on their stability, scalability, and cost-effectiveness of formulations (Dodoo et al., 2017). Strains intended for commercial use must exhibit a hight survivability during feed processing (e.g., pelleting or freeze drying, spray drying process), as well as adequate shelf life under various storage conditions. Also, the probiotic products must remain viable through the GIT of piglets, ensuring sufficient colonization and functional activity. Further, probiotics from *Bacillus* group have shown promise in this regard due to their spore-forming capacity (Dumitru et al., 2018; Rambu et al., 2024), which provides enhanced resistance and oxidative stress during feed manufacturing and storage (Cutting, 2011; Wang et al., 2017). Furthermore, encapsulation techniques and carrier matrices utilisation, such as OSC, can be used efficiently to improve probiotic strains stability and delivery (Łopusiewicz, et al., 2021; Ramadan et al., 2024). Additionally, significant modification of the immune response, following the probiotics inclusion in piglets' diets, is associated with infection resistance, which enhances the intestinal barrier function (Pistol et al., 2023). Some reports show that *Lactobacillus* and *Bacillus* spp. can improve the mucosal immune response, particularly in weaning piglets' crisis where the immune system is low developed (Deng et al., 2013; Du et al., 2018; Taranu et al., 2018). Together, the effects presented in Figure 1 contribute significantly to reducing morbidity, improving growth performance, mitigating inflammation, and promoting a well-gut homeostasis in piglets' life (Zhao et al., 2023).

Table 1 presents informative data on probiotic strains, dosage, and duration of use in piglet nutrition, providing details from previous studies. Beyond the findings summarized in Table 1, probiotic treatments are expected to replace antibiotics as a source of growth-promoting agents (Saha et al., 2024). Thus, research on the use of probiotics has grown significantly in recent years. A single strain or multiple strains of probiotics have been used to control diarrhea and promote growth and overall health status of piglets. The addition of probiotics in early life can improve growth performance and intestinal health microbiota, stimulating host immunity (Saha et al., 2024). Moreover, probiotics supplementation can be a good strategy to prevent diarrhoea, balance microbial flora, and improve nutrient absorption, followed by a reduction of lipid oxidation with a strong improvement of meat quality products (Bai et al., 2017). Further, the results illustrate the benefits of using different dietary protein sources in combination with probiotics bacteria products, which together provided significant advantages for piglets' nutrition. As can be observed, several studies (Table 1) were performed to evaluate the effects of a single or multiple probiotic strains in piglets weaning crisis. Notably, different probiotics, such as spore-forming bacteria, have been shown to improve intestinal health and growth efficiency, with a significant reduction of diarrhoea in young piglets (Hu et al., 2014; Wu et al., 2018; Tang et al., 2019; He et al., 2020; Park et al., 2020; Tian et al., 2021; Wang et al., 2021; Li et al., 2021; Tian et al., 2021; Sun et al., 2022; Júnior et al., 2023; Liu et al., 2023; Duddeck et al., 2023; He et al., 2023; Jia et al., 2023; Sudan et al., 2023).

Probiotics have various health benefits through different ways such as inhabiting gut pathogens bacteria, enhancing beneficial microflora in the gut, improving nutrient absorption, and supporting immune system regulation (Saha et al., 2024). The inclusion of *Lactobacillus* enhances growth performance and morphological intestinal structure, with a well intestinal function, which correspond to a better digestibility and absorption of nutrients (Chiang et al., 2015; Sopková et al., 2017; Zhao et al., 2017; Yi et al., 2018; Zhang et al., 2019; Li et al., 2019; He et al., 2019; Sun et al., 2021). For example, oral administration of *L. johnsonii* L531 (Log 10/mL) to newly weaned piglets reduced significantly *Salmonella* colonization in the colon and jejunum content, maintained metabolic homeostasis, thereby enhancing the gut health during the critical weaning period (He et al., 2019). Moreover, *Lactobacillus* strains like *L. plantarum* (CCM7512) and *L. fermentum* (CCM 7514) were supplemented to piglets from 28 days of age for 14 days, where changes in lipid metabolism and chronic diseases was observed (Sopková et al., 2017). However, *L. acidophilus* and *L. casei* in Sun et al. (2021) study improved significant piglets' growth, decreased intestinal inflammation, and oxidative stress. In addition, *L. casei* enhanced antioxidant capacity (Zhao et al., 2017), showing a similar effect to *L. delbrueckii*, as reported by Li et al. (2019), which also positively influenced the immune response in piglets. All findings presented in Table 1 suggest that supplementation with *Lactobacillus* strains can improve the health and productivity of piglets. Additionally, different probiotics based on yeasts, which its known as source of enzymes production, improve growth performance, blood parameters, intestinal microbiota, providing beneficial effects in piglets life (Trckova et al. 2014, Kiros et al., 2019; Subba et al., 2024).

Table 1. The impact of probiotics on piglets development and functionality

Probiotic	Host age	Dosage (feed)	Time	Outcome	Ref.
Bacillus spp.					
B. subtilis	25 days	100 mg/kg feed; 200 mg/kg feed	42 days	↑ Diarrhoea rate	Liu et al. (2023)
B. subtilis	25 days	300 g/tone	42 days	↑BW_f, ↑ADG, ↑F/G	Hu & Kim (2022)
B. subtilis	26 ± 2 days	4×10^8 CFU/kg; 2×10^8 CFU/kg	28 days	↓Indice faecal, ↑ADG, ↑G/F	Hu et al. (2014)
B. subtilis	21 days	2.56×10^8 CFU/kg	28 days	↓Diarrhoea score, ↑ADG, ↑G/F	He et al. (2020)
B. subtilis	45 days	0.1%	28 days	↑BW_f, ↑ADG	Deng et al. (2020)
B. subtilis	25 days	1.44×10^7 CFU/kg	42 days	↑ADG, ↓Diarrhoea rate	Tian et al. (2021)
B. subtilis	25 days	500 mg/kg	42 days	↑ADG, ↑F/G	Tang et al. (2019)
B. subtilis	Weaned piglets (21 days)	1×10^8 CFU/kg	42 days	↑BW_f, ↑ADG, ↓F/G	Wang et al. (2021)
B. subtilis	Weaned piglets (21 days)	1.875×10^9 CFU/kg	14 days	↑BW_f, ↑ADG	Duddeck et al. (2023)
B. subtilis	Weaned piglets (21 days)	1×10^8 CFU/kg	14 days	↑BW_f	He et al. (2023)
B. subtilis	21 days	1×10^8 CFU/mL	28 days	↑ADG, ↓Diarrhoea rate	Jia et al. (2021)
B. subtilis	21 days	500 mg/kg	28 days	↑BW_f, ↑ADG, ↓Diarrhoea rate	Júnior et al. (2023)
B. subtilis	25 ± 2 days	1.0×10^7 CFU/kg	14 days	↑ADG, ↓ F/G	Li et al. (2021)
B. subtilis	21 days	0.05%	21 days	↑G/F, ↓ Diarrhoea rate	Park et al. (2020)
B. subtilis	NS	1.28×10^8 and 2.56×10^8 CFU/kg	19 days	↑ADG	Kim et al. (2019)
B. subtilis	45 days	0.1%	28 days	↑BW_f, ↑ADG	Deng et al. (2020)
B. subtilis	25 days	1.44×10^7 CFU/kg	42 days	↑ADG, ↓Diarrhoea rate	Tian et al. (2021)
B. subtilis	25 days	500 mg/kg	42 days	↑ADG , ↓ F/G	Tang et al. (2019)
B. subtilis	28 days	1×10^8 CFU/kg	42 days	↑BW_f, ↑ADG, ↓F/G	Wang et al. (2020)
B. subtilis	growing pigs (53.64 ± 5.04 kg)	1.8×10^8 CFU/mL	10 days	fermentation treatment enhance FSC nutritional value	Wei et al. (2024)
B. subtilis	NS	2.0×10^7 CFU/kg	28 days	↑ADG, ↓FCR, ↓Diarrhoea rate	Sudan et al. (2023)

B. coagulans	26 days	600 g/t	28 days	↑ADG,↓F/G, ↓Diarrhoea rate	Sun et al. (2022)
B. coagulans	7 days	1.0×10^8 CFU/kg	7 days	↓FCR	Zhang et al. (2023)
B. coagulans	24 days	400 mg/kg	28 days	↑ADG	Fu et al. (2021)
B. coagulans	21 days	2×10^8; 1×10^7 CFU/kg	21 days	↓ Diarrhoea rate	Wu et al. (2018)
B. coagulans	21 days	2×10^8 CFU/kg	14 days	↓ Diarrhoea rate	Wu et al. (2023)
B. amyloliquefaciens	28 days	5.0×10^7 CFU/kg	14 days	↑BW_f, ↑ADG, ↓ F/G	Du et al. (2022)
B. amyloliquefaciens	21 days	2.0 g/kg	28 days	↑ADG, ↑feed efficiency	Li et al. (2018)
B. amyloliquefaciens	21 days	1.0×10^7 CFU/kg	32 days	↑ADG, ↓Diarrhoea rate	Ji et al. (2013)
B. amyloliquefaciens	42 days	2.0×10^7 CFU/kg	28 days	↑ADG , ↓FI	Wang et al. (2024)
B. licheniformis	28 days	500 mg/kg	14 days	↑BW_f, ↑ADG, ↓Diarrhoea rate	Yu et al. (2022)
B. licheniformis	21 ± 1 days	1×10^7 and 1×10^8 CFU/kg	28 days	↑ADG, ↓F/G, ↓Diarrhoea rate	Cao et al. (2023)
B. licheniformis	28 days	500 or 1,000 mg/kg	28 days	↑ADG, ↓Diarrhoea rate	Yu et al. (2022)
B. licheniformis	21 ± 1 days	1,000 g/t	28 days	↑BW_f, ↑ADG, ↓Diarrhoea rate	Sun et al. (2023)
B. licheniformis	21 days	2×10^8 CFU/kg	17 days	Decreased faecal score	Xu et al. (2024)
B. toyonensis	24 ± 3 days	500 or 1,000 mg/kg	44 days	↑BW_f, ↑ADG, ↓Diarrhoea rate	Kantas et al. (2015)
B. cereus	28 ± 3 days	1×10^7 CFU/kg	35 days	↑BW_f, ↑ADG, ↓FCR, ↓Diarrhoea rate	Papatsiros et al. (2011)
Lactobacillus spp.					
L.plantarum NCIM 2374+*P. acidilactici* NCIM 5721	42 days	1×10^{11}CFU/mL	27 weeks	↑BW_f, ↑F/G	Ajay Kuriakose et al. (2024)
L. reuteri LR1	Piglets (21 days)	5×10^{10} CFU/kg	14 days	Improve morphological structure of the intestine; increase intestinal absorption area, digestibility of nutrients, and growth performance.	Yi et al. (2018)

L. plantarum (CCM7512) and *L. fermentum* (CCM 7514)	28 days	1 × 10^9 CFU/g	14 days	Regulating changes in lipid metabolism and vitality reduce the likelihood of chronic diseases.	Sopková et al. (2017)
Lactobacillus johnsonii L531	Weaned piglets (21 days)	10 ml, 1 x 10^9 CFU/ml	14 days	Controlling *Salmonella* infections and maintaining metabolic homeostasis; improve the intestinal health of piglets during the critical weaning period.	He et al. (2019)
L. acidophilus, L. casei, B. thermophilum and E. faecium	Weaned piglets (21 days)	2,5×10^7 CFU/g	25 days	Improve growth performance by reducing intestinal inflammation, oxidative stress, and morphological lesions.	Sun et al. (2021)
L. delbrueckii	Weaned piglets (21 days)	10 ml, 5×10^9 CFU/ml	-	Improve antioxidant capacity and immune response.	Li et al. (2019)
L. casei	Weaned piglets (21 days)	6 x 10^6 CFU/kg	-	Amelioration of liver damage by reducing pro-inflammatory cytokines; increase antioxidant capacity.	Zhao et al. (2017)
L. rhamnosus GG	Weaned piglets (21 days)	10 ml, 5×10^9 CFU/ml	7 days	Modulation of intestinal microflora; Improvement of the epithelial barrier	Zhang et al. (2019)
L. plantarum and *L. fermentum*	28 days	1 × 10^9 CFU/g	14 days	↓Chronic diseases, regulate lipid metabolism	Sopkova et al. (2016)
L. johnsonii, L. mucosae	Weaned piglets (21 days)	10^8 CFU/g/piglet		Improve growth performance and microbiota	Chiang et al. (2015)
Yeasts					
S. cerevisiae CNCM I-4407	Weaned piglets (28 days)	10^{10} CFU/g	14 days	Improve growth performances	Trckova et al. (2014)
Yarrowia lipolytica (YL) and *S. cerevisiae* (SC)+/- *probiotic (B. licheniformis*	Weaned piglets (28 days)	2 x 10^9 CFU/kg	56 days	Beneficial effects on blood parameters and intestinal microbiota, reducing the multiplication of coliforms bacteria and *E. coli.*	Czech et al. (2018)

+B. subtilis)					
S. cerevisiae	Weaned piglets (28 days)	2%	42 days	Increase performance growth	Subba et al. (2024)
S. cerevisiae	New-born piglets	5 x 10^9 and 2,5 x 10^{10} CFU/piglet	28 days	Improving growth performance and shaping the microbiota composition at the cecum level	Kiros et al. (2019)
S. cerevisiae autolyzed yeast (AY)	Castrated crossbred pigs	0.5% and 1% AY	9 weeks	Improving meat quality	Namted et al. (2021)
BW_f: final body weight (grams/individual); ADG: average daily gain (grams/individual/day); FI: average daily feed intake (g feed/individual/day); FCR: feed conversion ratio. F/G: feed/gain ratio; "↑" indicates an increase, while "↓" indicates a decrease; NS: not specified					

A well-balanced nutritional plan is essential for an animal's growth and development (Mia et al., 2024). The growth parameters such as body weight (BW), average daily gain (ADG), and feed conversion ratio (FCR) were improved, while diarrhoea rate was diminished. Overall, the growth performance of a pig farm is largely influenced by the productivity of piglets, where diarrhoea represents a major factor that contributes to the performance's reduction (Tang et al., 2024). So, providing the right amount of highly digestible feed is crucial, ultimately supporting the animal's growth and overall health.

Effects of oilseed cakes on piglets' nutrition

In the last years, oilseeds have been used as a source of various vegetable oils for animal feed (Rakita et al., 2023). Oil industries have begun supplying protein-rich by-products for animal feed, leveraging the substantial quantities generated during the extraction (Singh et al., 2022).

Oilseed cakes (OSC) / meals are the by-products left after extracting most of the oil from oilseeds either by mechanical or solvent extraction, being an excellent and economical source of feedstuff for animals (Rakita et al., 2023).

The terms "cake" and "meal" are often used ambiguously in feed science literature, necessitating clear definitions to prevent misconceptions. Specifically, "meal" refers to the by-product remaining after oil extraction with organic solvents (e.g., hexane, xylene, toluene), whereas "cake" denotes the by-product obtained through mechanical pressing methods (Cakaloglu et al., 2018). Rich in fiber, protein (ranging from 14.40-63.20), essential fatty acids (FA), energy, carbohydrates, vitamins, minerals, and phytochemicals (Gupta et al., 2018), OSC were found to provide benefits and to have a potential role in animal growth and production of energy (Teh et al., 2014; Rakita et al., 2023). Moreover, due to their potential, OSC can be used as substrates to produce value-added products like enzymes and organic acids or can be successfully incorporated into diets to develop new products rich in nutrients (amino acids, bioactive compounds, pigments, enzymes, vitamins, antioxidants) (Ramachandran et al., 2009; Shim et al., 2015; Gupta et al., 2018; Singh et al., 2022). Founded on variety, growth conditions, and process of extraction, the OSC involve different physiochemical and functional properties that make them unique (Rani & Badwaik, 2021). Further, these by-products are recognized as low-processed materials that are safe (Petraru and Amariei, 2020).

OSC are indeed excellent sources of carbon and nitrogen, making them suitable substrates for microbial growth, including that of probiotic bacteria. While OSC is traditionally linked with fungal species for enzyme production, its utilization in the growth and metabolic activity of probiotic bacteria such as *Bacillus subtilis, Bacillus licheniformis, Lactobacillus*, and *Bifidobacterium* is gaining attention (Dumitru et al., 2024).

Oilseed cakes and probiotics effects on piglets' nutrition

Supplementing piglets' diets with OSC and probiotics enhances nutrient availability, promotes a balanced gut microbiota, and supports efficient metabolic processes, optimizing the utilization of dietary components. This synergistic approach between by-products such OSC and probiotics not only fosters growth but also supports sustainable livestock management practices (Mia et al., 2024).

OSC, a by-product of oil process extraction, is primarily utilized in animal nutrition due to its high protein level, nitrogenous compounds, bioactive constituents, and essential minerals (Kuna & Kata, 2024). The cold pressing technique plays a crucial role in preserving the aromatic profile, macro- and micronutrients, and other bioactive compounds (Krulj et al., 2021). However, the existence of antinutritional factors (ANFs) like cyanogenic glycosides, protease inhibitors, lectins, tannins, non-starch polysaccharides, and antigenic proteins poses challenges for its direct incorporation into animal feed. These compounds can negatively affect nutrient absorption and overall animal health, necessitating further processing or treatment to enhance their nutritional value and safety for livestock consumption (Yang et al., 2021; Xu et al., 2024). To mitigate these effects, incorporating probiotic bacteria into animal diets has emerged as a promising strategy. Probiotics not only degrade these ANFs but also act as natural bioregulators, optimizing digestive processes, preventing pathogen colonization (Gomes et al., 2012), and stimulating the immune system (Lee et al., 2014).

The use of probiotic products in piglets' diets, particularly when formulating feeds with OSC, offers a dual benefit. First, probiotics enhance the digestibility of the feed, thereby addressing one of the primary challenges in livestock nutrition. Second, they contribute to improved growth performance and overall well-being, emphasizing the need for nutritionally balanced and bioavailable feed. In this context, selecting suitable prebiotic substrates is essential for maximizing probiotic efficacy.

Research on the incorporation of OSC, specifically flax, pumpkin, hemp, and camelina, into piglets' diets, particularly in combination with probiotics, remains notably limited. Despite their rich composition in proteins, essential fatty acids, bioactive compounds, and fiber, these by-products have not been extensively studied for their potential as fermentable substrates for probiotic strains, such as those from the *Bacillus* and *Lactobacillus* groups.

This topic highlights the potential of probiotics, which can degrade ANFs such as tannins, glucosinolates, and trypsin inhibitors present in OSC, enhancing nutrient bioavailability, digestibility, and overall feed efficiency, making probiotic-enriched OSC a functional and sustainable feed alternative. Given the increasing demand for sustainable and high-quality livestock feed, this topic highlights the unexplored potential of integrating probiotics and OSC in piglets feed, offering a breakthrough strategy to enhance nutrient utilization, immune function, and overall production performance.

Further, agro-industrial by-products are promising biopolymers sources, recognized as natural encapsulating carrier matrix for efficient drying of probiotic cultures (Łopusiewicz et al., 2021; Wang, 2020). Regarding this, the addition of a probiotic source in a pig diet based on OSC, particularly for weaning piglets with underdeveloped digestive systems, presents a promising innovation and strategy for improving animal nutrition and husbandry practices.

Flaxseed cake (FSC) has shown significant potential as a prebiotic substrate, supporting probiotic growth and activity, which may further enhance its benefits in animal nutrition (Vaisey-Genser et al., 2003). When incorporated into piglet diets, FSC not only promotes the growth and activity of probiotic bacteria but also complements their ability to enhance nutrient availability and degrade ANFs. This synergy between FSC and probiotics represents a significant advancement in the development of functional feeds improving health and animal productivity. Together, these findings underline the importance of addressing ANFs through innovative nutritional strategies, such as probiotics and prebiotic-rich substrates like FSC addition, to optimize livestock feeding systems and promote sustainable animal production. Beyond animal nutrition, the valorisation of OSC, including FSC as a substrate to produce bioactive compounds like enzymes, antibiotics, biopesticides, biofertilizers, aroma compounds, biosurfactants, vitamins, or pigments, has important benefits for industry and consumers (Gupta et al., 2018).

The use of pumpkins in piglets' diets has not been widely investigated. However, González et al. (2019) reported that replacing up to 30% of the diet with *Cucurbita pepo* ferment does not impact weight gain. Instead, it leads to a 75% increase in feed intake, negatively affecting feed conversion efficiency.

Besides, the cucurbitacin (glycide) from pumpkin, known for their digestive and purgative properties due to their bitter compounds (Montesano et al., 2018), have likely contributed to their traditional use as antiparasitic agents (Yadav et al., 2010; Achilonu et al., 2018). Moreover, Bahramsoltani et al. (2017) highlighted the therapeutic potential of *Cucurbita* extract, demonstrating its efficacy in treating burns by reducing oxidative stress through its high mucilage content. These properties underline pumpkins' bioactive potential, which can be further enhanced when combined with probiotics. Also, incorporating probiotics alongside pumpkin-based feed or extracts could amplify these benefits. Probiotics, known for promoting GIT health and modulating the microbiome, may work synergistically with the bioactive compounds in pumpkin to enhance digestion, improve nutrient absorption, and support immune function. This combination could not only optimize the antiparasitic and digestive effects but also mitigate oxidative stress in tissues, potentially broadening the applications of pumpkin-probiotic formulations in animal health and nutrition. For example, González et al. (2019) observed that fermented *Cucurbita pepo* reduces the incidence of diarrhoea, thereby reducing the mortality and morbidity rates in piglets. Castro et al. (2022) affirmed that incorporating 10% pumpkin meal into the piglets' diet during the initial phase helps to reduce contamination from parasitic infections without affecting their performance. As part of a sustainable approach, pumpkin by-products, such as peel and pulp, can be effectively utilized in animal feed due to their high carbon content, making them attractive resources for producing value-added products (Gavril et al., 2024). A study examined cell viability in a substrate composed of pumpkin peel and pulp (30:70 *w/w*), preserved with *Lactobacillus casei* with an initial growth of 9 Log CFU/mL, followed by incubation at 37°C. After 24 hours of fermentation, an increase in cell viability demonstrated that pumpkin serves as an effective carrier substrate for probiotics and provides a suitable carbon source for the fermentation process (Genevois et al., 2016). Despite these promising findings, research on the inclusion of probiotic-supplemented PSC in piglets' diets remains limited, highlighting the need for further studies to explore its potential benefits for health and performance, especially in weaning piglets.

Including cakes in feed mixtures is a strong strategy to control the fatty acid profile (PUFA) of animal-derived products, enhancing desirable PUFA levels for human nutrition. Nowadays, the use of hemp seed cakes (HSC) (*Cannabis sativa L.*) in animal nutrition as feed ingredient has significantly developed due to its numerous benefits (Aloo et al., 2024). HSC presents a high protein content, while it contains 9-20% lipids, 6-7% dietary fiber, vitamins, and minerals (Capcanari et al., 2023); further, it is also rich in essential FAs, PUFA respectively linoleic (LA) and alpha-linolenic acid (ALA), antioxidants (polyphenols) with antimicrobial, antifungal, anti-inflammatory, and immunomodulatory properties (Kamle et al., 2024). Details on the HSC composition can be found in diverse research topics (Burton et al., 2022; Zając et al., 2019). Studies examining the effects of HSC with probiotic bacteria supplementation in pigs' diets are limited. Liu et al. (2024) reported the capacity of hemp seed to develop a gel through probiotic fermentation (*Lactobacillus acidophilus, Lactobacillus bulgaricus, Lactobacillus plantarum, Lactobacillus casei, and Streptococcus thermophilus*) with significant attention due to their dietary, functional, and nutraceutical properties (Vichare & Morya, 2024). Although research on HSC inclusion in piglets' diets remains limited, Kamle et al. (2024) reported that a maximum inclusion level of 10% is permissible. However, based on established assimilation limits, standard feed formulations typically incorporate hemp seed or HSC at levels ranging from 2-5%. This inclusion strategy presents multiple opportunities for the animal feed industry, supporting sustainable feed production while harnessing the nutritional and functional benefits of hemp-derived ingredients.

Camelina (*Camelina sativa* (L.) Crantz) is a fast-growing annual plant from the *Brassicaceae* family, known for its adaptability to various climatical conditions, low nutrient demands, and natural resistance to numerous pests and diseases (Hilbrands et al., 2021). One of its key by-products, Camelina seed cake (CSC), is obtained through the cold extraction of oil and holds potential for livestock nutrition due to its high crude protein content (30-35%) and residual oil levels (10-20%) (Nain et al., 2015). However, the primary challenge in incorporating CSC into monogastric diets, especially for young animals, is the presence of ANFs. These include glucosinolate levels of 34-36 μmol/g and antitrypsin factor content ranging from 12-28 TIU/mg, which may limit its direct application in feed formulations (Woyengo et al., 2017).

Research on the inclusion of CSC in pig diets, particularly during the weaning phase, remains highly limited. Smit & Beltranena (2017) reported that incorporating 6% CSC during the first 28 days post-weaning led to a decline in piglet growth performance. Similarly, the low nutrient digestibility of camelina cake in experimental diets could contribute to the decreases in pigs' growth (Li et al., 2021; Hilbrands et al. 2021). Li et al. (2021) reported decreased ADG and FI in growing-finishing piglets when CSC was included at a 10% dietary level, while Hilbrands et al. (2021) observed a decline in daily weight gain in the experimental groups containing 10% or 15% CSC. These findings suggest that the limited nutrient availability in CSC may negatively impact growth performance, emphasizing the need for further research to optimize its use. Given the observed challenges associated with CSC inclusion in piglet diets, such as decreased FI and growth performance, there is growing interest in strategies aimed to improve its nutritional quality and digestibility. One promising solution involves the use of probiotics, particularly beneficial bacterial strains such as *Bacillus* spp. and *Lactobacillus* spp., which may contribute to mitigating some negative effects and enhancing feed utilization.

Probiotics have been shown to enhance gut health and nutrient absorption, mitigating the negative effects of fiber content, ANFs, such as glucosinolates and antitrypsin factors present in CSC to hurt thyroid activity (Luise et al., 2024). Also, these products play a crucial role in improving the digestibility of CSC by facilitating microbial fermentation and enzyme production. This process helps break down complex compounds, enhancing nutrient bioavailability and mitigating potential negative effects on piglet growth performance. To further optimize CSC inclusion, it is recommended to introduce it into piglet diets once they have reached a weight of 11-15 kg (approximately two weeks post-weaning). At this stage, the gut is more developed, and the enzymatic profile has fully adapted to a plant-based diet, improving the animal's ability to process CSC efficiently. This combined approach, strategic timing of CSC introduction, and probiotic supplementation can help maximize its nutritional benefits while minimizing its limitations in piglets' nutrition.

In summary, the swine agricultural sector plays a vital role in the global economy, contributing not only through meat production but also by providing nutritionally valuable by-products. Ensuring optimal productivity and health in swine farming requires an efficient feeding strategy, particularly during the sensitive weaning phase, where piglets face significant stress and health challenges.

CONCLUSION

In conclusion, the incorporation of probiotics alongside OSC in piglets' diets involves a sustainable strategy to enhance feed digestibility, growth performance, and gut health. This synergistic combination represents a novel and nutritionally valuable strategy for advancing health and farm efficiency. Although OSC are rich in beneficial nutrients, its ANFs can limit its efficacy. Probiotic products help overcome these limitations by improving nutrient absorption and microbial balance, optimizing animal health and productivity. Despite these promising results, further studies are necessary to refine probiotic formulations, determine appropriate OSC inclusion levels, and assess the long-term effects on animal health and performance. Moving forward, the integration of probiotics with OSC represents an innovative and sustainable solution to improving piglet nutrition, enhancing overall productivity, and minimizing feed costs, all while supporting environmentally responsible livestock practices.

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