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The Kielanowski Institute of Animal Physiology and Nutrition, Polish Academy of Sciences, Jabłonna

REVIEW

Optimising nutrient utilisation in swine diets: The role of enzyme supplementation in alternative and traditional feedstuffs – A review

S. Sureshkumar[1,2], Y. Jungwon[1,2] and I.H. Kim[1,2,*]

[1] Dankook University, Department of Animal Biotechnology, Anseodong, Cheonan, Choongnam 31116, Republic of Korea
[2] Dankook University, Smart Animal Bio Institute, Cheonan, 31116, Republic of Korea

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* Corresponding author:
e-mail: inhokim@dankook.ac.kr

ABSTRACT. In recent decades, swine nutritionists have become increasingly concerned about the competition between human and livestock populations for limited animal and plant resources. Consequently, research efforts have shifted towards exploring alternative, cost-effective feedstuffs and evaluating their potential for incorporation into swine diets. In addition to investigating alternative ingredients such as barley, triticale, rye, pulses, and non-conventional oilseeds and their byproduct, advancements are also being made to improve the digestibility of conventional maize and soybean meal-based swine diets, which have long been the industry benchmark for energy and protein supply. However, monogastric animals like pigs lack or have insufficient levels of enzymes necessary to break down non-starch polysaccharides and other anti-nutritional factors present in cereals and oilseed coproducts, as well as in traditional feed ingredients. Therefore, the inclusion of enzymes into pig diets is essential to maximise nutrient utilisation from a complex feed matrix. Enzymes commonly employed in the feed industry include cellulase, β-mannanase, β-glucanases, xylanases, phytases, proteases, lipases, and galactosidases. The addition of phytase and protease supplements not only improves nutrient availability but also helps to mitigate environmental issues. This review provides an overview of current literature regarding the role of enzyme supplementation in optimising the sustainable use of both alternative and traditional feed resources. It describes the effects of these enzymes on pig performance, nutrient digestibility, and their broader environmental implications.

Introduction

Feed costs account for approximately 60–70% of total expenses in swine production (Patience et al., 2015a). Recently, the rising costs of feed ingredients have become a significant concern for livestock producers. To ensure the profitability of the pork industry, it is essential to implement effective strategies that improve nutrient availability and digestibility. The demand for maize and wheat cereal grains is expected to increase for human consumption in the coming years, driven by global population growth and an insufficient grain supply. A shortage of these cereal grains may lead to higher prices of animal feed. Consequently, it is necessary to explore cheaper alternative feedstuffs, such as barley, triticale, rye, pulses, as well as non-conventional oilseeds and their coproducts, for potential inclusion in swine feed formulations. Non-ruminant animals like pigs and poultry lack the enzymes required to hydrolyse non-starch polysaccharides (NSP) present in these feed ingredients, making it difficult for them to digest traditional cereal-based diets and their byproducts. This results in certain nutrients being unavailable to the animals. NSP levels are higher in byproducts compared to traditional cereal-based diets, and the nutrient quality of these coproducts is lower, leading to reduced animal performance (Bach Knudsen, 1997; NRC, 2012; Anderson et al., 2012). Therefore, research efforts should concentrate on improving the digestibility of traditional cereal-based diets and alternative, lower-cost feed ingredients. Moreover, other highly digestible nutrients such as protein, fat, and starch are often trapped in the NSP coating, restricting their accessibility and further impairing animal performance (Bach Knudsen, 1997; NRC, 2012). The coating also inhibits the activity of endogenous enzymes (Metzler et al., 2005; Choct, 2006; Slominski, 2013) and increases intestinal viscosity, negatively affecting digestibility.

The beneficial effects of dietary enzymes in high-fibre diets have been documented in many studies on animal nutrition (Thacker et al., 1992; Viveros et al., 1994; Saleh et al., 2005). The practice of using enzymes in swine diets dates back to the 1950 and is aimed to improve nutrient availability and digestibility (Adeola et al., 2011). Since then, numerous studies have investigated the application of various feed enzymes to increase the nutritional value of both alternative and traditional pig feedstuffs. Depending on specific dietary requirements, either a single enzyme or an enzyme cocktail are added to animal diets (Nguyen et al., 2019; Balasubramanium et al., 2020). For instance, xylanase supplementation led to improved ileal digestibility in growing pigs fed diets containing 30% wheat coproducts rich in NSP and crude protein (CP) (Nortey et al., 2007). Combining different enzymes enables the breakdown of a broader range of entrapped nutrients in a diet, ultimately improving feed efficiency. Emiola et al. (2009) showed that incorporating an enzyme cocktail containing xylanase, β-glucanase, and cellulase into a diet consisting of 30% wet distillers dried grain solubles (DDGS) and 65% barley increased the apparent total tract digestibility (ATTD) of dry matter (DM), nitrogen (N), and energy in growing pigs. However, the addition of a 0.01% dietary mixture of protease and probiotics to a maize-soybean meal-based diet did not result in any beneficial effects on growth performance or carcass characteristics in growing-finishing pigs (Min et al., 2019). Enzyme supplementation has proven more effective in diets containing sources relatively richer in fibre such as barley, oats, triticale, peas, rye, or wheat, while its use in maize-soybean meal-based diets is not recommended due to their lower content of non-starch polysaccharides. This review outlines the role of enzymes in swine diets and discuss their benefits in improving the nutritional value of both alternative and traditional feedstuffs.

Alternative animal feed sources

Oilseed meals

Alternative feed ingredients, including barley, sorghum, triticale, oilseeds other than soybean, oilseed coproducts and pulses can be used as substitutes for traditional feedstuffs such as maize, wheat and soybean meal. Numerous studies have demonstrated the benefits of these alternatives, including reduced feed costs and positive effects on carcass traits and pork quality (Shurson et al., 2012; Zijlstra and Beltranena, 2013a,b). Oilseed meals, byproducts of the oilseed crushing industry for biofuel or human consumption, can be utilised as dietary protein supplements. The most common canola is *Brassica napus*, whereas *B. juncea* is a newly developed species grown in warmer and drier areas of the Canadian prairies (Woyengo et al., 2014). In general, rapeseed meal contains more fibre and less CP and amino acids (AA) than soyabean meal (SBM). Additionally, it also contains glucosinolates, which may reduce feed intake and nutrient utilisation in pigs. The glucosinolate content in rapeseed meal varies between different processing methods, such as solvent-extracted rapeseed meal, expeller-pressed rapeseed meal, and cold-pressed rapeseed cake. This variation depends on the glucosinolate levels in the rapeseed seed itself and the extent of their breakdown during the toasting process (Woyengo and Naychoti, 2011). Similarly to SBM, full-fat soybean (FFSB) is a rich source of AA and energy. Studies demonstrated that including 30% toasted, extruded, or roasted FFSB in growing-finishing pig diets (30 to 100 kg BW) did not negatively affect growth performance and carcass weight (Zollitsch et al., 1993), but increased pork linoleic and linolenic acid contents. Montoya and Leterme (2010) reported that increasing the percentage of full-fat rapeseed (FFR) diet from 0 to 15% in diets with similar net energy (NE) and standardized ileaal digestibility (SID) AA content decreased average daily feed intake (ADFI) and increased the gain-to-feed ratio (G:F) of growing pigs, whereas Woyengo et al. (2012) found that the same inclusion levels of FFR in diets with similar composition linearly decreased the G:F ratio and carcass dressing percentage in growing-finishing pigs. However, formulations used in the trials were not consistent; for instance, FFR was replaced with wheat (Brand et al., 1999), wheat and SBM (Montoya and Leterme, 2010), or wheat and SBM balanced with barley (Woyengo et al., 2012).

Non-maize grains

Coproducts, outputs from a manufacturing process or chemical reactions, can be converted into high-quality animal protein (Zijlstra and Beltranena, 2013a), thereby reducing the overall cost of feed production. Traditionally, in small-scale farming, pigs are often fed human food residues, regarded as alternative feedstuffs (Pond et al., 2001). More recently, these coproducts have gained attention as alternative feedstuffs, providing a means to improve the economic sustainability of the swine industry (Jha et al., 2013). Various animal sources and vegetable coproducts are used to formulate livestock feed. For instance, plant-derived ingredients include distiller's grain, molasses, maize gluten meal, maize germ meal, maize hominy, bakery co-products, brewer's yeast, citrus pulp, wheat middling, wheat bran, rice bran, cottonseed meal, sunflower meal, rapeseed meal, linseed meal, soy hulls and others. Wu et al. (2000) indicated that replacing maize with dehulled barley in a diet formulated to contain similar digestible energy (DE) and SID of AA resulted in comparable growth performance in growing-finishing pigs. Myer and Brendemuhl (2009) observed that a triticale-based diet yielded similar growth performance compared to a maize-based diet. Similarly, replacing maize with low-tannin sorghum in the growing-finishing pig diet did not decrease feed efficiency, total tract and ileal digestibility of N or gross energy (GE) (Cousins et al., 1981). Additionally, partial replacement of SBM in the diet with 20% (Gatta et al., 2013) or 30% field peas (Smith et al., 2013) did not cause any negative effects on growth performance or carcass traits in growing-finishing pigs. These findings support the possibility of using cheaper feedstuffs in swine diets.

Pulses and coproducts

Alternative feedstuffs are typically rich in NSP. Thus, to optimise the utilisation of these fibre- and NSP-rich feed ingredients, swine diet formulations should be based on NE and SID. Additionally, feed processing techniques such as particle size reduction, heat treatment, dehulling, air classification or enzyme supplementation can enhance the nutritional value and improve the digestibility of alternative feed components (Woyengo et al., 2014). However, certain processing procedures, including heat treatment, solvent-extraction, and expeller pressing may adversely affect nutrient quality (Zijlstra et al., 2001; Spragg and Mailer, 2007). For example, Zijlstra et al. (2010) observed that the appropriate supplementation of enzymes, tailored to the substrate, improved energy digestibility and nutrient utilisation. Plant-based alternative feedstuffs contain a significant proportion of P in the form of phytate, which is poorly digested by pigs (Woyengo and Nyachoti, 2011). Phytate reduces the availability of nutrients by binding to other dietary components or digestive enzymes (Woyengo et al., 2012). Additionally, fibre present in plant-based substitute feedstuffs limits nutrient utilisation in pigs (Woyengo and Nyachoti, 2011). To address these challenges, phytase and fibre-degrading enzymes (carbohydrases) can be supplemented to meals to improve the nutritional value of alternative feed sources (Zijlstra et al., 2010).

Characteristics and sources of enzymes

Enzymes are proteins with highly complex three-dimensional molecular structures. They play essential roles in metabolic processes and are synthesised by all living organisms, from simple unicellular forms of life to highly evolved animals and plants. Acting as catalysts, enzymes initiate or accelerate chemical reactions in the body that would otherwise proceed at a slow rate or not at all (Buhler et al., 2013). Their protein-based nature renders enzymes sensitive to high temperatures during feed production, as well as to denaturation due to pH changes and proteolysis by digestive enzymes in the gastrointestinal tract.

Hydrolysis of substrates in feedstuffs requires the use of specific enzymes, making it necessary to select enzymes based on the compounds present in feed formulations. Other factors influencing enzyme activities include moisture content, temperature, pH, enzyme and substrate concentration (Aehle, 2004), as well as barn hygiene and animal stress (Madrid et al., 2010). Large-scale enzyme production is achieved through continuous isolation, screening, and selection of appropriate microbes, culturing them in advanced fermentation systems, and optimising the extraction and purification processes (Wallis, 1996). Microorganisms that are commonly utilised in industrial enzyme production include bacteria such as *Bacillus subtilis, B. lentus, B. amyloliquifaciens*, *B. stearothermophils*, *Pseudoalteromonas arctica* (marine bacteria) and *Buttiauxella* spp. Additionally, fungi such as *Triochoderma longibrachiatum*, *Asperigillus oryzae* and *A. niger*, as well as yeast like *Saccharomyces cerevisiae* are employed in this process.

Enzymes from microbial sources

Enzymes play a crucial role as biocatalysts of metabolism and biochemical reactions, with some being extensively utilised as organic catalysts in many industrial-scale processes. Microbial enzymes, derived from bacteria, fungi, and yeasts, are particularly valued for their superior properties and widely explored for commercial applications (Pandey et al., 1999). In conventional catalytic reactions, the use of enzymes as biocatalysts, either in free or immobilised forms, depends on their specificity. Advances in metagenomics, biochemical reaction engineering, and protein engineering have facilitated the development of numerous novel enzymes for industrial applications. The quality and effectiveness of microbial enzymes have also been improved using a variety of molecular techniques, supporting their expanded use across various industries (Chirumamilla et al., 2001). *Pseudomonas*, *Bacillus*, and *Clostridium* are the primary producers of commercially significant proteases, while certain fungi have also been shown to produce these enzymes (Kumar and Takagi, 1999). Fungal species from the genera *Trichoderma*, *Penicillium* and *Aspergillus* are producers of xylanases, showing high activity over a wide range of temperatures (40–60 °C), and thus finding numerous applications in the industry (Ahmed et al., 2009). Vijayalakshmi et al. (2011) optimised and characterised culture conditions for producing alkalophilic and thermophilic extracellular protease enzymes from *Bacillus*. Liu et al. (2013) examined an extremely alkaline and oxidation-resistant keratinase from *B. licheniformis*, expressed in the recombinant *B. subtilis* WB600 expression system. Heterologous expression systems, including *Escherichia coli, Pichia pastoris* and *Bacillus* spp., have been employed to express active xylanase, enabling its commercial-scale applications (Prade, 1996; Jhamb and Sahoo, 2012). Additionally, researchers have cultured microorganisms using agricultural residues for cost-effective cellulase production of the required quality under submerged and solid-state fermentation conditions (Pandey et al., 1999).

Enhancing feed efficiency, livestock growth, and environmental sustainability with exogenous enzymes: Focus on alternative and traditional feed components

Alternative feed ingredients and improvement of traditional feed sources

Energy and protein are the main nutrients in animal diets. Maize and soybean meals are the traditional staple ingredients in swine diets, being the main energy and protein sources, respectively. Alternative feedstuffs other than maize, such as barley, wheat, sorghum, and oats, typically have higher fibre content compared to maize. On the other hand, alternative protein sources include oilseeds such as rapeseed, flaxseed and others. Maize SBM-based diets generally have lower NSP content, whereas diets formulated using non-maize SBM meals contain higher levels of NSP and anti-nutritional factors compared to grain-based diets. The application of exogenous NSP-hydrolysing enzymes in these alternative feed resources is a developing research area assessing the potential of these supplements in feeds (Spragg and Mailer, 2007; Kiarie et al., 2012; McAlpine et al., 2012; Rosenfelder et al., 2013). NSP present in pig diets are mainly complex carbohydrates consisting of 10–37% fibre, including cellulose, haemicellulose, pectins and β-glucans. These carbohydrates are not easily digested by monogastric animals due to the absence of enzymes capable of hydrolysing NSP (Adebiyi et al., 2010). The anti-nutritional effects of NSP arise because fat, starch and protein become trapped in an NSP coating in the cereal grain cell walls, hindering access of endogenous enzymes. In addition, the viscous nature of soluble NSPs increases digesta viscosity, which impairs nutrient digestibility and absorption, negatively impacting animal performance (Choct and Annison, 1992; Choct et al., 1995; Bedford and Schulze, 1998). To improve the nutritional value and availability of alternative feedstuffs, single enzymes or enzyme cocktails are added to animal feeds (Pettey et al., 2002). For instance, Omogbenigun et al. (2004) reported that the addition of a multi-enzyme blend (cellulase, galactase, mannanase, and pectinase) to a wheat-based diet of weaning pigs improved growth performance over a 38-day period. In a recent study, Laerke et al. (2015) compared the effects of xylanase supplementation in pig diets containing either wheat or rye. These authors found that arabinoxylan was more efficiently degraded in wheat-based diets, while the reduction in viscosity was higher in rye-based diets.

Diets formulated with maize and SBM are considered highly digestible due to the low levels of anti-nutritional factors present in both feedstuffs (Smiricky et al., 2002). However, nutrient utilisation and digestibility were shown to increase with the supplementation of exogenous enzymes in maize-SBM-based diets in pig nutrition (Upadhaya et al., 2016a,b,c). Table 1 summarises the effects of single or multiple enzyme supplementation on alternative and traditional feedstuffs in different age groups of pigs.

Growth performance and digestibility in pigs fed alternative low-cost cereal-based diets supplemented with enzymes

A natural polymeric carbohydrate, starch, consists of multiple glucose units linked by α-glycosidic bonds (Singh et al., 2010; Tortoe et al., 2017). It is mostly composed of two structurally distinct polymers: amylopectin (branched -1,4 and -1,6 glycosidic bonds) and amylose (linear α-1,4 glycosidic bonds). Depending on the plant species, starch naturally contains 20–30% amylose and 70–80% amylopectin. Due to the presence of α-1,4 glycosidic bonds, amylopectin and amylose are both easily degraded by digestive enzymes found in animals (Black, 1999). Unlike starch, structural polysaccharides such as chitin, cellulose, and peptidoglycan are linked by β-glycosidic bonds, making them highly resistant to hydrolysis (Thacker and Campbell, 1999). Supplementation of a single enzyme such as β-glucanase to hulless barley-based diets for growing-finishing pigs was shown to improve nutrient digestibility (Spencer et al., 2007). Similarly, nursery pigs fed diets containing 30% DDGS supplemented with enzymes demonstrated improved growth performance (Inborr et al., 1993). Our previous study has also shown that growth performance and nutrient digestibility in finishing pigs were improved when fed a diet containing 5% palm kernel meal supplemented with carbohydrase cocktail (Ao et al., 2011). However, other studies on the supplementation of fibre- and starch-degrading enzymes in wheat or barley or peas-based diet did not show any effect on growth performance in pigs (Nonn et al., 1999). Recently, Boontiam et al. (2022) reported that the addition of up to 40% brewer grain meal, combined with a 0.1% enzyme cocktail (amylase, xylanase, β-glucanase, lipase, cellulase, β-mannanase, phytase, and pectinase) positively influenced growth performance, nutrient utilisation, and intestinal health of growing pigs. In addition, Ndou et al. (2015) found that the inclusion of xylanase in the ration exerted a beneficial effect on growth performance and digestibility in growing pigs fed diets with wheat and wheat bran or maize and maize DDGS supplemented with phytase. The observed positive effect on performance may be associated with the increase in nutrient digestibility resulting from NSP hydrolysis by the added enzymes, which release the entrapped nutrients from NSP present in feedstuffs (Thacker et al., 2013). Boontiam et al. (2022) demonstrated that a diet containing high levels of NSPs due to the inclusion of Brewer's Grain Meal (12.0519.23% crude fibre) and rice bran oil as an energy source (9.7914.84% ether extract) provided better substrates for enzyme activities (xylanase, β-glucanase, cellulase, β-mannanase, and lipase). Hence, enzymes supplemented with a low-cost cereal-based diet positively affected pig growth through improved nutrient utilisation.

Growth performance and digestibility in pigs fed coproducts supplemented with enzymes as alternative feed sources

Incorporating coproducts into the diets is part of the effort to create sustainable swine production systems, as well as to reduce feed costs per unit of pork production. The rapid adoption of coproducts in animal feeding is largely driven by unprecedentedly high prices of maize and SBM. However, feeding high levels of coproducts presents greater risks compared to traditional diets. This risk can be minimised by using modern feed formulation, feed enzymes, and processing techniques to achieve predictable results in pig growth, carcass traits, and pork quality. For instance, increased energy digestibility in swine has been observed with the inclusion of xylanase in diets containing wheat coproducts from flour milling, which are high in NSP and arabinoxylan content (Nortey et al., 2008). Additionally, the supplementation of xylanase in growing pig diets containing wheat coproducts improved ATTD and ileal digestibility of DM, CP and energy (Yin et al., 2000). The addition of an enzyme cocktail containing xylanase and β-glucanase to an energy-deficient feed with DDGS as a grain coproduct, has also been reported to improve total tract digestibility of DM, GE and nitrogen (Kiarie et al., 2012). Phytase supplementation increased ATTD and standardised total tract digestibility (STTD) of P, while lowering P excretion in the faeces by pigs fed diets containing rice coproducts such as rice bran, rice feed mill and broken rice (Casas and Stein, 2015). The inclusion

Table 1. Swine response to alternative and standard feedstuffs when supplemented with a single enzyme or a cocktail/blend of exogenous enzymes

Animal growth stage	Dose	Feed ingredients	Enzyme	Responses	Reference
Weaned pigs (25 days of age) challenged with *Escherichia coli*	1 g/kg feed	Maize-SBM-based diet	Lysozyme	No effect on growth performance, improved digestibility of DM and energy, reduced stress hormone levels and faecal *E. coli* counts	Park et al. (2021)
Growing pigs	500 units/kg diet	Maize starch-SBM-based diet	Phytase	Increased ATTD and STTD of Ca and ATTD of P	Gonzalez-Vega et al. (2015)
Growing pigs	1500 units/kg diet	Rapeseed meal 00-rapeseed meal 00-rapeseed expellers	Phytase	Increased digestibility of P in rapeseed meal, 00-rapeseed meal and 00-rapeseed expellers	Maison et al. (2015)
Growing-finishing pigs	1500 FTU/kg diet	Maize-wheat-SBM-based diet	Phytase	Increased body weight and ATTD of DM, nitrogen and energy and meat quality were no effects	Dang and Kim (2021)
Growing pigs	250 units/kg diet 4000 unit/kg diet	Wheat and maize DDGS	Phytase Xylanase	Increased ATTD of P but no effect on AA digestibility No effect on nutrient digestibility	Yáñez et al. (2011)
Growing pigs	400 unit/kg diet	Maize + SBM (hulled and dehulled)	Beta-mannanase	Reduced faecal coliforms but no effect on growth performance and nutrient digestibility	Upadhaya et al. (2016a)
Growing pigs	400 unit/kg diet	Maize + SBM (hulled and dehulled)	Beta-mannanase	Improved AID of Arg, His, Lys, Val and Gly and SID of Lys	Upadhaya et al. (2016b)
Growing-finishing pigs	1 g/kg feed	Hulled amylose barley and hulless low amylose barley	Multienzyme (beta-glucanase and beta-xylanase)	No effect on growth performance and carcass characteristics for both barley types	Prandini et al. (2016)
Xylanase + glucanase + cellulase	2200,1100 and 1200 unit/kg diet respectively	Wheat DDGS, barley, maize, SBM, RSM	Finishing pigs	Increased AID of DM, OM, energy, threonine, proline and serine	Emiola et al. (2009)
Finishing pigs	125 g/ton	Maize-SBM-based diet	Protease	Improved growth performance, and ATTD of nutrients and reduced stress-related hormones	Upadhaya et al. (2016d)
Finishing pigs	1 to 3 g/kg feed	Maize-SBM-DDGS-rape-seed-wheat-based diet	Protease	Linear reduction in feed conversion throughout experimental period, linear increase in nutrient digestibility, linear reduction in serum total protein concentration	Liu et al. (2019)
Cellulase + xylanase + beta-glucanase + protease	10000, 6000, 5000 and 12000 units/g respectively	Double-low rapeseed meal (extruded and non-extruded)	Finishing pigs	No effect on growth performance. Improved IgG and reduced malondialdehyde levels in serum in extruded RSM	Xie et al. (2012)
Cellulase	0.05% and 0.1% (12000 unit/g)	Maize + SBM	Lactating sows and piglets	DM and N digestibility increased, backfat thickness loss reduced, and ADG of piglets improved linearly	Upadhaya et al. (2016c)

FTU – phytase unut, SBM – soybean meal, AA – amino acids, ATTD – apparent total tract digestibility, ADG – average daily gain, AID – apparent ileal digestibility, DDGS – distillers dried grain solubles, DM – dry matter, Arg – arginine His – histidine, Lys – lysine, Val – valine, Gly – glycine, FTU – phytase units, SID – standardised ileal digestibility, RSM – rapeseed meal, OM – organic matter, SBM – soyabean meal, STTD – standardised total tract digestibility of pectinolytic enzymes in rapeseed meals has led to significant improvements in *in vitro* carbohydrate digestion (Pustjens et al., 2012). Moreover, xylanase addition to rapeseed meal was demonstrated to increase nutrient digestibility and growth performance in pigs (Fang et al., 2007). However, the addition of xylanase does not always seem to improve energy digestibility in DDGS, even though phytase has been shown to increase P digestibility (Yáñez et al., 2011). Several studies have failed to demonstrate positive effects of carbohydrate enzyme supplementation in diets containing DDGS for nursery pigs (Jones et al., 2010) and growing-finishing pigs (Widyaratne et al., 2009; Jacela et al., 2010). The inconsistencies in the effectiveness of carbohydrases added to livestock diets containing DDGS may be due to the differences in the age of experimental animals, nutrient concentrations, source and level of DDGS used, as well as doses of supplemental enzymes. Kerr et al. (2013) concluded that the lack of a positive effect of dietary enzyme addition on nutrient digestibility and growth performance in pigs may have been due to the low level of digestible fibre in the DDGS source.

Growth performance and digestibility in pigs fed maize-soybean meal-based diet supplemented with enzymes

The inclusion of exogenous enzymes has resulted in variable responses in nutrient digestibility and growth performance in pigs fed maize-based diets. Soybean and maize meals contain 4 and 0.5% galactose, and 1 and 0.3% β mannans, respectively (Hsiao et al., 2006). In addition to mannans and galactose, maize and soybean meals also contain xylose or arabinoxylan. Monogastric animals lack the ability to hydrolyse mannans, galactose, and arabinoxylan present in feed ingredients. Therefore, exogenous enzyme supplementation is necessary to degrade these substrates and release the nutrients trapped within the cell walls (Masey-O'Neill et al., 2014). Supplementation maize and soybean meal-based diets with carbohydrases was shown to improve feed efficiency and energy digestibility in weaning pigs (Kim et al., 2003). Our previous study on cellulase supplementation to maize-SBM diets demonstrated reduced backfat thickness loss, improved nutrient digestibility, and increased body weight of offspring in pigs (Upadhaya et al., 2016a). Enhanced weight gain and feed efficiency were also reported in growing pigs fed maize-SBM diets supplemented with recombinant β-mannanase (Upadhaya et al., 2016b). Likewise, improvements in apparent ileal digestibility (AID) values for DM, CP and GE were observed in pigs when β-mannanase was added to diets based on maize, SBM and palm kernel expeller (Upadhaya et al., 2016c). Mok et al. (2013) further noted that β-mannanase supplementation in a diet based on maize-SBM and palm kernel expeller increased the AID of leucine and phenylalanine when administered to growing pigs. The higher mannan content in palm kernel expeller, a substrate for β-mannanase has been identified as the reason for the observed outcome. On the contrary, our study showed no improvement in growth performance and total tract nutrient digestibility when β-mannanase was supplemented to a maize-SBM (hulled and dehulled) diet fed to growing pigs. We concluded that the lack of response could be due to insufficient substrate for enzymatic reactions (Upadhaya et al., 2016c). Protease supplementation to high- and low-density maize and SBM-based diets has been shown to positively affect growth performance and total tract digestibility of nutrients in finishing pigs (Upadhaya et al., 2016d) and weaning pigs (Tactacan et al., 2016).

Environmental impact of enzyme supplements

In addition to the economic advantages of low-cost feed formulation, enzymes also offer an environmentally friendly alternative, as they contribute to the reduction of pollution associated with animal production. The output of P is particularly high in intensive swine production, leading to environmental issues such as eutrophication and the adverse impact on marine life. Most of the phosphorus in typical feedstuffs is present as phytate/phytic acid, which is not digestible by livestock. Consequently, it is excreted in faeces into the environment. A typical swine diet contains between 8 g and 12 g of phytic acid per kg of feed (Selle et al., 2003). Earlier studies by Cowieson et al. (2006) and Yu et al. (2012) reported that phytate can bind proteins in the upper digestive tract, reducing their accessibility to endogenous proteases. Phytate-bound P, Ca, Zn and Cu may also indirectly influence the solubility of these substrates, limiting their availability for enzymatic digestion (Singh, 2008). Additionally, phytate has been demonstrated to exert an inhibitory effect on other endogenous proteolytic enzymes, thereby reducing protein digestibility (Guggenbuhl et al., 2012). Phytase supplementation in the diet liberates the P in feedstuffs, facilitating the release of other minerals (e.g., Ca, Mg), as well as proteins and AA bound to phytate. Phytase catalyses the removal of P from phytate, and thus aid in the absorption of P in the small intestine (Rojas and Stein, 2012; Patience et al., 2015b). Consequently, the release of feed ingredients bound to P, facilitated by the inclusion of phytase, reduces the quantity of inorganic P required in diet formulation, increases the bioavailability of P for the animals, and reduces its excretion into the environment. In addition to its role in reducing environmental pollution, the recent concept of phytase super-dosing at levels up to 2500 phytase units (FTU) has been shown to improve nursery pig performance (Dourmad and Jondreville, 2007).

Likewise, a significant quantity of undigested protein leads to the excretion of N-rich manure, which causes N gaseous emissions with a strong odour (Oxenboll et al., 2011), negatively impacting public health and the environment. Ferket et al. (2002) indicated that the intestinal microbial ecosystem and nutrient utilisation are key factors associated with faecal malodour and NH_3 emissions. Protease inclusion in the diet of animals can help mitigate the environmental problems related to manure management and disposal (Hoque et al., 2022). Our prior study also demonstrated a trend towards reduced H_2S and NH_3 emissions from pig faeces when protease was supplemented to maize-SBM-based diet (Sureshkumar et al., 2023).

Conclusions

The importance of exogenous enzyme supplementation in improving nutrient utilisation of high-fibre feedstuffs and coproducts used in swine diets has been well documented. The effects of enzymes are dependent on various factors, including diet composition, substrate specificity, type of enzyme (single or cocktail), moisture content, temperature, pH, enzyme concentration, substrate concentration, and the age of animals. The growth performance and nutrient digestibility of animals can be improved by including a single enzyme or their mixture to diets containing high-fibre ingredients such as cereals and their coproducts. Furthermore, the dietary incorporation of exogenous carbohydrate-digesting enzymes (haemicellulases, cellulases, xylanases, pectinases, β-glucanases, and α-galactosidases) can improve the digestibility of energy and nutrients in maize and wheat distillers dried grains with solubles in swine diets. What is more, the inclusion of a single enzyme or an enzyme blend in a conventional maize-soybean meal-based diet helps reduce the anti-nutritional factors present in those diets, thereby enhancing nutrient digestibility and performance traits of pigs.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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