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Review

Optimising Nutrition for Sustainable Pig Production: Strategies to Quantify and Mitigate Environmental Impacts

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Simple Summary: Pig farming plays an important role in global food production, but it faces growing challenges such as rising input costs, environmental pollution, and increasing pressure on natural resources. Life Cycle Assessment is a useful tool for measuring the environmental impact of food production and identifying where emissions originate. Feed and manure are the two main sources of emissions in pig farming. Ingredients like soybean meal, which are widely used in pig diets, are linked to deforestation and biodiversity loss in some parts of the world. In cooler regions, locally grown faba beans offer a more sustainable alternative, though their inclusion requires careful management due to nutritional limitations. Maintaining feed quality is also crucial, as post-harvest losses and contamination can impact productivity and animal health. Preserving grain with organic acids offers a safe and more energy-efficient method to traditional grain drying, helping reduce fossil fuel use while maintaining feed safety. Other dietary strategies, such as lowering protein levels, adjusting fibre sources, using feed additives, and supplementing sow diets, can improve digestion, reduce waste, and minimise pollution. Together, these strategies can offer practical ways to make pig farming more sustainable and efficient.

Abstract: The intensifying global demand for food presents significant challenges for sustainable pig production, particularly in the context of escalating input costs, environmental degradation, and resource scarcity. Life Cycle Assessment provides a comprehensive framework for quantifying environmental impacts and identifying production hotspots within pig production systems. Feed production and manure management are consistently identified as major contributors, emphasising the need for targeted interventions to improve sustainability. Although soybean meal remains a key protein source, its association with deforestation and biodiversity loss has prompting the search for more sustainable alternatives. In temperate climates, faba beans offer a promising, locally sourced option, though their wider adoption is limited by amino acid imbalances and anti-nutritional factors. Grain preservation is another critical consideration, as post-harvest losses and fungal contamination compromise feed quality and animal health. Organic acid preservation has emerged as a cost-effective, energy-efficient alternative to industrial drying, improving storage stability while reducing fossil fuel dependence. Additional nutritional strategies including crude protein reduction, carbohydrate source modification, feed additives use, and maternal nutritional interventions can enhance nutrient utilisation, intestinal health, and resilience while mitigating environmental impacts. This review discusses practical, feed-based strategies to support sustainable, resilient, and resource efficient pig production systems and contribute to global food security.

Keywords: swine; sustainability; life cycle assessment; nutrient utilisation; faba beans; grain preservation; organic acids; microbiota; maternal nutrition

1. Introduction

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The increasing global demand for food, driven by population growth, longer life expectancy, and improving living standards, presents significant challenges for sustainable agriculture. By 2050, food demand is projected to rise by up to 50% [1,2], necessitating innovative solutions to enhance production efficiency while minimising environmental impacts. Climate change, urbanisation, and land transformation further intensify resource constraints [3,4]. Both crop and livestock production face growing scrutiny due to their competition for natural resources as well as their contribution to air, water, and soil pollution [5,6]. Pig production plays a crucial role in global protein supply, accounting for approximately one-third of total meat consumption [7]. Pork remains a dietary staple, particularly in developing countries, providing high-quality protein and essential micronutrients [8,9]. However, modern pig production faces economic, environmental, and health-related challenges, including high input costs, resource limitations, and environmental emissions [10]. Additionally, concerns over antimicrobial resistance and feed safety emphasise the urgent need for sustainable interventions [11,12].

Achieving sustainable pig production requires balancing consumer demands, environmental responsibility, and economic viability [13]. Life Cycle Assessment (LCA) has emerged as a valuable tool for assessing sustainability in complex systems such as agriculture and food production [14–16]. It provides a quantitative framework for evaluating the environmental impacts associated with different stages of production [17]. By identifying key 'hotspots' in production, LCA facilitates the development of targeted mitigation strategies to reduce emissions and improve resource efficiency. This holistic approach allows for a comprehensive evaluation of the impacts associated, making it widely applicable in swine production systems [18].

Feed represents the largest economic and environmental cost in pig production, making ingredient selection and formulation critical [18–20]. Beyond influencing animal health, welfare, and productivity, feed composition impacts farm profitability, product quality, and environmental sustainability, particularly in terms of greenhouse gas (GHG) emissions, land use, non-renewable energy, and water quality [21,22]. Swine diets primarily rely on cereal grains and soybean meal (SBM) as key energy and protein sources. However, SBM production is directly associated with negative environmental and economic issues including deforestation, biodiversity loss, land degradation, transport-related emissions, and reliance on international trade [23,24]. In response, faba beans have received growing attention in Europe as regionally adapted, sustainable alternatives to imported soybean [24,25]. However, nutritional limitations, inconsistent availability, and preservation challenges hinder their widespread adoption [26].

With more than one-third of global food production lost post-harvest [27,28], improving grain preservation techniques is critical for ensuring feed safety and reducing waste. The high moisture content of feed commodities in temperate climates increases their susceptibility to mould and mycotoxin contamination, a problem expected to worsen with climate change [29,30]. While industrial drying is the most conventional method used, it incurs high financial and environmental costs due to its intensive energy requirements [31–34]. Organic acid preservation has recently emerged as a cost-effective, energy-efficient alternative, maintaining nutritional quality while reducing reliance on fossil fuel-intensive drying [35–37].

Beyond preservation, the inclusion of dietary organic acids plays a role in reducing reliance on in-feed antimicrobials [38]. Organic acids can enhance digestive function, modulate intestinal microbiota, reduce manure-related pollution, and improve growth performance in pigs, making them a valuable tool for sustainable production [39,40]. Other nutritional strategies, such as reducing crude protein (CP) levels, altering carbohydrate sources, and enzyme supplementation can also contribute to lowering manure-related emissions and odourous compounds by improving nutrient digestibility and intestinal microbial balance [41,42]. In addition to direct dietary interventions, maternal nutrition is gaining recognition as a proactive approach to improving offspring health and environmental sustainability. Enhancing sow diets during late gestation and lactation can improve offspring intestinal microbial colonisation and resilience, reducing post-weaning health challenges

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and reliance on in-feed antimicrobials [43]. Such interventions have the potential to promote lifetime improvements in digestive health, immune function, and overall production efficiency.

Both European Union (EU) and national policies are increasingly shaping the transition towards more sustainable production by encouraging innovations, emission reduction strategies, and improved resource management [44,45]. Adopting science-based interventions can support producers meet regulatory requirements and sustainability targets while maintaining economic viability. This review explores practical, feed-related strategies to enhance sustainability across the pig production chain. Specifically, it focuses on nutritional adjustments that reduce nutrient excretion, minimise odourous emissions, and support gut health; the potential of faba beans as sustainable alternatives for SBM; the dual role of organic acids as both grain preservatives and functional feed additives; and the impact of maternal nutrition on offspring development and performance. Through the lens of LCA, this review illustrates how these strategies can address key production hotspots and contribute to broader sustainability goals, ultimately supporting a more environmentally and economically pig sector, as depicted in Figure 1.

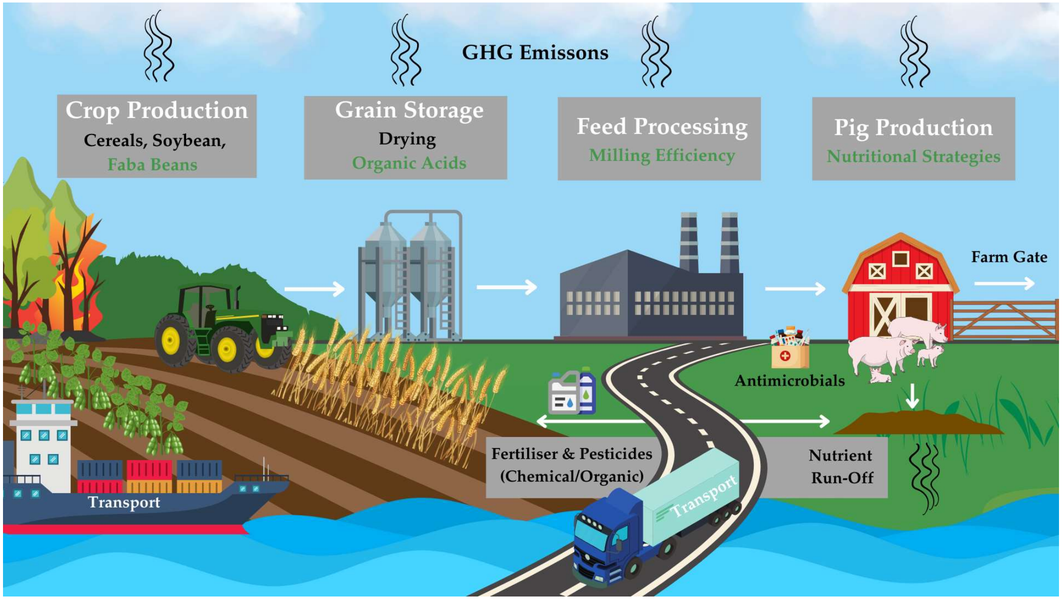

Figure 1. Schematic overview of the pig production chain from crop production to the farm gate, illustrating environmental hotspots and opportunities for intervention. Sustainable strategies include the use of regionally grown faba beans as alternatives to imported soybean, using organic acids for energy-efficient grain preservation, and applying targeted nutritional strategies to enhance gut health, feed efficiency, and nutrient management on farm. These interventions aim to lower greenhouse gas emissions, imported feed dependence, and nutrient losses across the system.

2. Life Cycle Assessment in Pig Production

LCA is a standardised methodology used to systematically and quantitatively evaluate the potential environmental impacts of a product across all stages of its life cycle, from raw material extraction to use and disposal (cradle-to-grave)[46]. In pig production, LCA has been widely used to assess GHG emissions, resource use, and other environmental burdens. It helps identify hotspots for effective interventions, supports comparisons between products and production systems, and informs decision-making to develop more sustainable practices. As such, LCA has become a valuable tool for guiding improvements in the sustainability of pig production [47–53].

2.1. Methodology

LCA follows internationally recognised standards, including ISO 14040 (1997) and ISO 14044 (2006), and consists of four key phases. The first and arguably more important step is defining the

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goal and scope, which establishes the study's objective, the system boundary, the allocation method, and the functional unit (the reference to which all inputs and outputs are scaled). In pig production, 1 kg of live weight at the farm gate is commonly used (Figure 1), although alternative functional units such as carcass weight or protein content have also been reported [54–56]. The second phase, life cycle inventory (LCI), involves compiling data on elementary flows such as feed, water, and energy use, as well as emissions, nutrient losses, and waste generation [57]. Where primary farm-level data are unavailable, secondary sources including the literature or databases (Ecoinvent, Agribalyse, and Agri-Footprint) may be used [58–60]. However, variability in databases and data assumptions complicate comparability between studies [19]. The third phase, life cycle impact assessment (LCIA), translates or 'calculates' inventory data into impact categories, including global warming potential (GWP; also known as climate change), eutrophication potential (EP), acidification potential (AP), land use change (LUC), and non-renewable energy use, among others [61]. This phase can be largely automated using software packages such as OpenLCA, GaBi, and SimaPro [62–64]. The interpretation is the final stage, which involves testing model sensitivity, identify key hotspots, and provide recommendations or potential mitigation strategies based on the results obtained [65].

2.2. Limitaions and Opportunities

Despite its advantages, LCA faces several limitations in pig production that affect the comparability, reliability, and practical application of results. A major challenge is the lack of standardisation in system boundaries, allocation methods, and functional unit selection, which leads to significant variability between studies [19]. Differences in whether LCA studies follow cradle-to-farm-gate or cradle-to-slaughterhouse-gate approaches can yield vastly different results, making direct comparison difficult. Allocation methods for multi-functional process such as manure management and by-product utilisation further complicate assessments, as different approaches (e.g., economic, mass, or energy-based) can lead to varied impact estimations. The inclusion of LUC presents another issue. When LUC is considered, particularly in the context of SBM production and deforestation, GHG emissions from feed production increase substantially [66]. However, inconsistent methodologies appear, highlighting the importance of accurate LCA modelling when assessing the impacts of regional specific feed commodities. Additionally, data availability and quality remain key constraints, as primary farm-level data collection is often resource-intensive, accounting for 70-80% of the total time and cost of conducting an LCA [67]. While secondary datasets help address these gaps, they may not fully capture regional or temporal variation in feed production, manure management, and farming practices, potentially compromising the reliability of results.

Emerging tools such as artificial intelligence (AI) and machine learning have the potential to improve data processing, predictive modelling, and scenario analysis [68]. However, their integration into agricultural LCAs remains in its infancy and requiries further validation to ensure accuracy and reproducibility. Similarly, geographic information systems (GIS) are also being explored to analyse spatial variations in nutrient runoff, land use, and air pollution, which could enable more region-specific mitigation strategies [69]. Additionally, social factors such as labour conditions and animal welfare have historically been underrepresented in LCA models, however more recent studies have started integrating these aspects for a more holistic sustainability assessment [70,71]. Although these advancements may improve LCA applications in pig production, the inherent complexity and methodological inconsistencies remain challenges that must be addressed to ensure more robust, transparent, and actionable assessments.

2.3. Production Hotspots

The livestock sector is responsible for approximately 15% of global anthropogenic GHG emissions, with pork production accounting for around 9% of livestock-related emissions [72]. In the EU, agricultural GHG emissions primarily arise from enteric fermentation (45%), soil management (38%), and manure management (15%)[73]. Unlike ruminants, pigs produce relatively low emissions from enteric fermentation [74]. Instead, the most significant contributors to the environmental

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impacts of swine systems are feed and manure [18]. Therefore, optimising feed formulations and manure management are essential for reducing the sector's environmental footprint [75,76].

Feed production alone accounts for more 70% of the environmental impacts of the pig supply chain, driven by fertiliser and pesticide application, land use and LUC, energy-intensive processing, and the extensive transportation networks of globally sourced raw materials [18,20]. In particular, the environmental and economic burdens associated with SBM and grain preservation highlight the urgent need for more sustainable alternatives [77–79]. It was recently reported that feed-related changes implemented over the past two decades have reduced the GWP of pig production by 20-35% [18], demonstrating the substantial mitigation potential of feed-focused interventions.

Manure management is another major environmental hotspot, contributing to nitrogen and phosphorus losses, eutrophication, acidification, and ammonia volatilisation. Housing systems and manure storage conditions directly influence methane, ammonia, and nitrous oxide emissions, with flooring type, storage methods, and temperature playing key roles in emission rates [80]. While technologies such as slurry additives, anaerobic digestion, and low-emission slurry spreading (LESS) offer promising mitigation options, this review focuses on nutritional strategies as a practical and preventive approach to reducing nutrient excretion, emissions, and manure odour at the source. Optimising feeding practices and diet composition can minimise nutrient excretion, lower emissions, and significantly improve air, water, and soil quality [81,82].

3. Nutritional Strategies for Enhancing Sustainability of Pig Production

3.1. Feed Formulation and Ingredient Sourcing

The composition of pig diets is primarily determined by ingredient availability, nutritional value, and economic feasibility, which vary by region and production system [83,84]. Modern feed mills employ mathematical optimisation techniques to formulate least-cost diets while ensuring nutrient balance for optimal growth and feed conversion efficiency [85]. However, recent volatility in raw material prices, geopolitical unpredictability, and increasing scrutiny of the environmental impact of imported feedstuffs have intensified interest in alternative feed sources [24,25].

Cereal grains, such as maize, wheat, and barley serve as primary energy sources in pig diets. Maize is widely used due to its high starch content and digestibility. However, its production is resource-intensive, requiring substantial irrigation, fertiliser inputs, and land area, contributing to GHG emissions, eutrophication, and soil degradation [86]. The cultivation of maize in temperate climates is limited by the cooler temperatures and shorter growing season. In addition, it often requires the use of plastic film for crop establishment which increases soil temperature and promotes early growth, further adding to its environmental footprint [87]. As a result, wheat and barley serve as viable alternatives. Wheat provides a more balanced amino acid profile than maize, important for the total protein intake of pigs [88]. Barley contains a higher fibre content, which, although beneficial for intestinal health, can inadvertently reduce energy digestibility [89]. Non-starch polysaccharides in wheat and barley, such as arabinoxylans and β-glucans, can lower feed efficiency due to their resistance to enzymatic breakdown [90]. Additionally, phosphorus in cereals is largely bound to phytate, which is poorly digested by pigs, increasing phosphorus excretion and environmental risks. To mitigate these issues, diets are commonly supplemented with exogenous enzymes, which improve digestibility [91], enhance mineral bioavailability and reduce reliance on non-renewable resources [92].

Soybean meal remains the predominant protein source in pig diets due to its high digestibility, well-balanced amino acid profile, and consistent availability [93]. However, its reliance in Europe presents challenges, including price volatility, environmental degradation, and deforestation associated with large-scale cultivation in South America [94]. Given that feed production contributes 30–80% of the total carbon footprint of pig farming [18,20], research into alternative protein sources has gained momentum. More recently, circular economy models has driven interest in novel feed ingredients such as food waste, insect meal, and microalgae [95]. Studies suggest that integrating

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these ingredients into pig diets could significantly lower land use and emissions associated with feed production while simultaneously addressing food waste management challenges [24]. However, concerns regarding feed safety, regulatory approval, and consumer acceptance remain key barriers to widespread adoption [96,97]. Given these uncertainties, this review focuses on faba beans as regionally available and practical alternatives, providing a sustainable solution to reducing reliance on imported SBM.

Feed formulation also plays a crucial role in optimising nutrient retention and minimising the environmental burden of manure management. The composition of pig diets influences manure characteristics, influencing nutrient excretion, ammonia volatilisation, and odourous emissions [98]. Strategic modifications to dietary protein levels, carbohydrate sources, and the inclusion of feed additives can improve nutrient utilisation, thereby reducing excretion and minimising environmental impacts.

3.2. Nutritional Interventions for Minimising Nutrient Losses, Manure Emissions, and Odour

A key concern in intensive pig production is the inefficient utilisation of dietary nutrients, leading to excessive excretion in manure. This contributes to ammonia and odourous compound emissions, as well as eutrophication of water bodies [99]. To mitigate these challenges, precision feeding and nutritional strategies have been developed to optimise intestinal microbial populations, enhancing nutrient absorption while minimising waste output [100–102]. Approaches such as optimising dietary CP levels, altering carbohydrate sources, and integrating feed additives offer practical solutions for reducing emissions and improving sustainability in pig production [103]. These strategies not only decrease nutrient losses but enhance feed efficiency and support animal health, promoting a balance between animal welfare, environmental responsibility, and economic viability.

Swine manure has tremendous value as a natural fertiliser for crop production but must be managed to minimise GHG emissions and nutrient leaching [104]. A significant concern is the low nutrient retention efficiency in pigs. Research indicates that only 33% of ingested nitrogen and 37% of ingested phosphorus is retained, with the remainder contributing to environmental pollution [85,105]. Excess nitrogen and phosphorus are particularly problematic, as nitrogen volatilisation leads to ammonia emissions, while both nutrients lead to eutrophication of water bodies. These environmental concerns necessitate nutritional strategies that enhance both nitrogen retention and phosphorus utilisation, reducing their excretion into the environment.

The 'ideal protein' concept, introduced by Cole [106], advocates for lowering dietary CP levels and supplementing with synthetic amino acids to improve nitrogen efficiency. This strategy has been effective in reducing nitrogen excretion without compromising animal performance, although it may increase feed costs due to amino acid supplementation requirements [107]. A reduction of 1% in dietary CP has been associated with a 9% decrease in nitrogen excretion, along with lower AP and EP in LCA models [108]. Similarly, reducing CP from 18.5% to 15.5% in growing pigs improved nitrogen and phosphorus retention, enhanced daily gain, and further reduced AP and EP impacts [109]. Reducing CP from 20% to 12% has also been shown to lower urine production by 25%, leading to a more favourable manure composition with a lower urine-to-faeces ratio [101,103]. Since excess urinary nitrogen is primarily excreted as urea, microbial urease in manure converts it to ammonia, contributing to air pollution [110]. Studies suggest for every 1% reduction in dietary CP, ammonia emissions may be reduced by 8-12%, making CP reduction an effective strategy for mitigating environmental impacts [111–115]. However, care must be taken when formulating low-CP diets, especially for younger pigs, to avoid amino acid deficiencies and ensure growth is not compromised [116,117]. Although reducing nitrogen excretion lowers ammonia emissions, its effect on odourous compounds is inconsistent. Some studies suggest sulphur-containing amino acids contribute to offensive odours [118,119], increasing manure pH and promoting ammonia volatilisation [120,121]. While CP reduction clearly alters manure composition, its impact on gastrointestinal fermentation and odour production remains an area for further investigation.

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Dietary carbohydrate composition also influences intestinal microbial populations, which can affect odourous emissions. For example, substituting wheat with barley can reduce proteolytic metabolites and manure odour due to the presence of β-glucans [122,123]. Similarly, oat-based diets promote beneficial gut bacteria such as *Lactobacillus* and *Bifidobacterium*, altering volatile fatty acid profiles and reducing manure odour emissions [124]. Incorporating fermentable carbohydrates is an effective strategy for modifying the microbiota and reducing manure emissions [125]. Studies have shown that supplementing finisher pig diets with sugar beet pulp increases faecal output while reducing ammonia emissions by stimulating microbial nitrogen incorporation [101]. This lowers manure pH, thereby reducing ammonia volatilisation and subsequently decreasing air pollution [100]. However, fermentation effects vary based on carbohydrate structure. Rapidly fermentable fibres promote volatile fatty acid production and microbial activity, whereas less fermentable fibres primarily increase faecal bulk [126].

The use of feed additives such as enzymes, organic acids, and probiotics can also reduce nutrient excretion and manure-related emissions. Enzyme supplementation improves nutrient digestibility and efficiency, reducing the need for higher protein and phosphorus levels in feed. Phytase increases phosphorus bioavailability, lowering inorganic phosphorus requirements and excretion [92]. Protease and carbohydrase enzymes also enhance protein digestion efficiency, decreasing nitrogen excretion and subsequently ammonia volatilisation [127–130]. Organic acids also influence nutrient digestibility and fermentation processes by enhancing enzymatic activity, improving protein digestibility, and promoting beneficial microbial populations [131–134], which will be further discussed in Section 3.6. This reduces the substrates available for microbial proteolysis, thereby minimising ammonia and odourous metabolite production [121,135,136]. Another alternative is the introduction of dietary lactic acid bacteria through *Lactiplantibacillus plantarum* supplementation, which has been reported to improve distal gut microbiota composition, reduce protein-derived odourous compounds, and lower manure emissions [137]. This aligns with the broader understanding that saccharolytic fermentation displaces proteolytic fermentation, reducing noxious gas production while improving gut health [138,139]. While challenges remain in balancing nutrient utilisation and cost-effectiveness, ongoing research should apply LCA to evaluate the potential of dietary interventions to enhance environmental sustainability and animal productivity.

3.3. Integrating Faba Beans into Pig Diets: Opportunities and Challeneges

In response to the plant protein shortage in Europe, grain legume cultivation has expanded considerably over the past 15 years [140]. Over the next decade, legume production in the EU is projected to increase by more 80%, reflecting a strong shift towards sustainable protein sources[141]. These trends align with the European Green Deal objectives, which promote regional food autonomy and reduced reliance on imported soybean. Policy incentives supporting legume cultivation provide farmers new income opportunities and encourage diversification in agricultural production [142]. This renewed emphasis, and indeed availability in grain legumes, presents a practical approach to enhancing sustainable protein sourcing in livestock diets [143–146].

Beyond their role in nutrition, grain legumes or pulses such as faba beans, peas, and lupins possess nitrogen-fixing properties, which enhance soil fertility and reduce dependence on synthetic fertilisers [147,148]. Legumes also help decrease nitrate immobilisation during decomposition, making soil nutrients more readily available compared to cereals [149]. Research has shown that crops sown after grain legumes achieve higher yields with reduced fertiliser inputs [150], benefiting from the disruption of pest, disease, and weed cycles [151]. Unlike SBM, which is predominantly grown in tropical climates, legumes thrive in temperate regions, promoting circular economy principles and reducing transport-related emissions. However, some challenges remain, including variability in protein content, amino acid imbalances, and the presence of anti-nutritional factors (ANFs)[26]. Additionally, the high moisture content of pulses at harvest presents storage challenges, emphasising the need for effective preservation techniques to maintain nutritional integrity.

Faba beans (*Vicia faba L.*), also known as fava beans, field beans, horse beans, or broad beans, are the third most widely cultivated legume globally, after soybeans and peas [152]. Their increasing use in livestock feed is attributed to their high protein content (250–300 g/kg) and favourable amino acid profile [153,154]. Faba beans provide lysine and threonine levels comparable with SBM; however, they are deficient in sulphur-containing amino acids, such as methionine and cysteine, which may necessitate dietary supplementation depending on inclusion rates and overall feed formulation [155]. Furthermore, the various ANFs present in faba beans can impair digestion, reduce nutrient absorption, and affect pig performance.

Among these, vicine and convicine are two pyrimidine glycosides which can interfere with red blood cell metabolism and negatively affect pig growth and performance. However, low-vicine and convicine varieties are now being developed to mitigate these effects [26]. Faba beans also contain protease inhibitors, condensed tannins, and oligosaccharides. The Bowman-Birk inhibitor, reduces protein digestibility by interfering with trypsin and chymotrypsin, leading to higher endogenous nitrogen losses [156,157]. Although heat-sensitive and largely inactivated through processing, these inhibitors limit the maximum inclusion rates of raw faba beans in pig diets [145]. Condensed tannins, primarily concentrated in the hulls of coloured-flower faba bean varieties, can reduce palatability and protein digestibility by forming complexes with dietary proteins and digestive enzymes [158,159]. Although zero-tannin cultivars exist, they often exhibit poorer agronomic performance, including lower yield stability and reduced frost resistance [160]. Additionally, faba beans also contain high levels of non-digestible oligosaccharides such as raffinose and stachyose, which are highly fermentable in monogastric animal [161]. While moderate fermentation supports intestinal health, excessive intake can cause loose faces or diarrhoea, particularly in younger pigs, thereby limiting their inclusion in early-stage diets [26]. Furthermore, the higher crude fibre content of legumes can lead to increased nutrient excretion, raising concerns related to ammonia emissions and manure management [114].

Beyond genetic and processing challenges, environmental and agronomic factors such as soil quality, crop husbandry practices, and post-harvest processing also influence the nutritional composition and feed value of faba beans. Conventional high temperature drying is often necessary to reduce moisture content and prevent spoilage during storage. However, drying is energy intensive and costly, as discussed in Section 3.4. Additionally, dried beans can present handling and grinding challenges in feed mills, further affecting feed formulation efficiency. Organic acid preservation has emerged as a promising alternative to conventional drying, offering benefits for digestibility, storage stability, and overall nutritional value. Recently, grower-finisher pigs offered organic acid-preserved faba beans exhibited higher feed intake and final body weight compared to those consuming conventional SBM-based diets [36]. Further research is needed to optimise these benefits, particularly by integrating LCA to quantify the environmental implications of substituting SBM with faba beans and replacing conventional drying with organic acid preservation.

While the integration of faba beans presents clear sustainability opportunities, potential trade-offs must be carefully managed. The displacement of conventional crops, variability in nutrient composition, and supply chain inconsistencies pose challenges that require attention. To enhance both performance and sustainability, technologies such as near-infrared spectroscopy (NIR) for real-time nutrient analysis and AI-driven feed formulation tools, are increasingly being utilised [68]. As research advances, faba beans hold strong potential as sustainable alternatives to SBM. However, future research should focus on optimising inclusion levels, improving processing technologies, and integrating LCA to comprehensively evaluate feed sustainability trade-offs. Addressing these challenges will be key to ensuring the successful adoption of faba beans as a viable, regionally produced protein source in pig production.

3.4. Importance of Grain Preservation for Feed Sustainability

While advances in plant genetics and agronomic practices have improved crop yields, corresponding efforts in grain preservation have lagged behind [162]. In fact, more than one-third of

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food produced worldwide is lost during the post-harvest phase due to inefficiencies in storage and preservation [32,163]. Poor post-harvest management not only compromises feed supply but also quality and contamination risks [164]. Thus, effective preservation strategies are essential for maximising production, reducing waste, and minimising resource inputs.

Preserving grain quality is also crucial for maintaining feed efficiency, nutritional integrity, and feed safety in swine nutrition. Effective preservation safeguards the physical, compositional, and sanitary attributes of grains, all of which influence their nutritional contribution to pig diets [165]. Physical properties such as grain size, hardness, and moisture content affect milling efficiency, storage stability, and digestibility; compositional factors including energy, protein, fibre, and mineral content, determine nutrient availability; while sanitary conditions, particularly fungal contamination, are critical for feed safety [166].

Moisture control plays a key role in preservation, as high moisture levels promote fungal growth, spoilage, and nutrient degradation [167]. In Europe, cereals, legumes, and oilseeds must be stored below 14%, 15% and 9% moisture content, respectively [168,169]. However, grains are often harvested at higher moisture levels, necessitating industrial drying to prevent degradation [166]. Fungal contamination remains a significant challenge, particularly under humid conditions. Field fungi, such as *Fusarium* spp., infect crops pre-harvest, while storage fungi, including *Aspergillus* and *Penicillium* spp., proliferate in improperly stored grains [170]. These fungi not only degrade grain quality but also produce mycotoxins, toxic compounds that impair livestock health and performance [171].

Pigs are particularly susceptible to mycotoxins due to their high cereal-based diets and limited detoxification capacity [172,173]. Aflatoxins (AF), produced from *Aspergillus*, cause hepatotoxic and immunosuppressive. Trichothecenes such as deoxynivalenol (DON), HT-2, and T-2 toxins, mainly from *Fusarium*, reduce feed intake, damage the gastrointestinal tract (GIT), and may cause vomiting [174,175]. Zearalenone (ZEN/ZEA), also from *Fusarium,* disrupts reproductive function due to its oestrogenic effects, while fumonisins impair liver and kidney function [176]. Ochratoxin A (OTA) produced from *Aspergillus* and *Penicillium*, is nephrotoxic and immunosuppressive, leading to long-term organ damage [177]. Although regulatory guidelines aim to mitigate mycotoxin risks in animal feed but enforcement and monitoring can vary by region [178]. Additionally, climate change is increasing the prevalence of toxin-producing fungi, thereby elevating contamination risks [30,179].

Biological detoxification methods, including enzymatic degradation and probiotic interventions, offer innovative solutions for mycotoxin mitigation in pig feed. Enzymatic treatments targeting mycotoxin deactivation, such as esterases and oxidoreductases, promote feed safety by neutralising toxic compounds before ingestion [180,181]. Certain microbial strains, such as *Lactobacillus*, *Bacillus*, and *Saccharomyces*, have been shown to degrade mycotoxins or reduce their bioavailability in the GIT [182]. Advancements in mycotoxin-binding agents, including activated clays and yeast-derived products, also contribute to minimising mycotoxin exposure in pig diets [183]. These adsorbents effectively sequester mycotoxins in the GIT, preventing their absorption and subsequent toxic effects. However, their efficacy varies based on mycotoxin structure, diet composition, and intestinal health, emphasising the importance of feed formulation and preservation [184,185].

Industrial grain drying remains the primary method for preventing microbial growth and spoilage in storage, yet industrial dryers are energy-intensive and heavily reliant on fossil fuels [31–34]. Drying lowers water activity, inhibiting microbial metabolism, but improper drying can lead to rehydration, uneven moisture distribution, and nutritional degradation [186,187]. Alternative drying methods, such as natural air drying, offer lower-cost solutions but depend on suitable climatic conditions, which can slow drying and increase fungal and pest risks [188]. Solar-assisted drying provides a renewable energy alternative, reducing operational costs; however its effectiveness is also limited by weather variability as well as high infrastructure costs [189,190]. Hybrid solar drying systems, which incorporate auxiliary heat sources, may enhance drying efficiency [191] but further research is required to ensure cost-effectiveness and consistent grain quality across varying environmental conditions. In temperate climates, the topical application of organic acids provides an

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effective alternative for grain preservation, inhibiting microbial growth and mycotoxin accumulation while maintaining nutritional integrity [192].

3.5. The Potential of Organic Acids as Grain Preservatives in Sustainable Pig Production

Organic acids and their salts are commonly used food preservatives due to their antifungal and antibacterial properties. Acids such as propionic, formic, and lactic acids, disrupt microbial cell membranes, preventing spoilage and reducing the need for energy-intensive drying processes [35]. By lowering pH and suppressing fungal activity, these acids effectively inhibit mould growth, extend shelf life, and reduce contamination risks, making them a viable alternative to traditional drying methods [193,194] Unlike drying, organic acid preservation does not rely on fossil fuel combustion, providing a more environmentally sustainable solution [33].

The process of preserving grain with organic acids is both straightforward and efficient. At harvest, the grain is transferred into a mixing auger or conveyor, where the acid is applied at a controlled concentration and mixed thoroughly to ensure uniform coverage before storage. This method not only preserves grain quality but also enables faster transfer into storage, easing pressure on harvest logistics and reducing operational costs. While concerns have been raised regarding equipment corrosion, acid volatility, feed palatability, and antimicrobial resistance, stabilised formulations incorporating multiple organic acids and their salts have successfully addressed these challenges while maintaining preservation efficacy [195,196]

Beyond storage stability, recent studies have demonstrated the significant nutritional and performance benefits of organic acid-preserved grain in pig diets, as summarised in Table 1. Preserved grains exhibit higher digestible and metabolisable energy values, leading to improved feed intake and daily gain in pigs [35,195]. Interestingly, pigs consuming preserved grain outperformed those receiving the same organic acid blend as a direct dietary additive [196], suggesting that the preservation process enhances bioavailability and efficacy. One possible hypothesis is that applying organic acids at harvest interacts with the grain while it is still biologically active, potentially modifying the structure of key components, such as starch and protein, in ways that enhance digestibility. Early acidification may also help retain functional compounds and prevent microbial contamination before storage creating a more favourable nutritional profile. In contrast, when organic acids are added at diet manufacture, they primarily act as acidifiers rather than influencing the grain's intrinsic properties. These findings suggest that incorporating organic acids at harvest may offer greater nutritional advantages than direct supplementation, ultimately enhancing grain quality and pig performance while reducing the need for energy intensive drying.

Besides nutritional advantages, organic acid-preserved grains positively influence intestinal health at key production stages. Weaned pigs consuming these grains exhibit enhanced nutrient digestibility and higher abundance of beneficial bacteria such as *Faecalibacterium*, contributing to enhanced gut microbial composition and reduced reliance on in-feed antimicrobials [195–198]. More recently, a study investigating the lifetime effects of organic acid-preserved grain from creep feed to finisher diets found that pigs offered preserved grain had higher daily gain, improved feed efficiency from two weeks post-weaning, and higher body weight from four weeks post-weaning. These pigs showed increased nutrient digestibility at four weeks post-weaning and again at slaughter [199]. They also had higher carcass weight and increased faecal abundance of *Faecalibacterium* at slaughter, suggesting that preserved grain may help reduce the days to slaughter and maintain a more beneficial GIT microbiome throughout production. These findings emphasise the dual benefit of organic acid preservation in maintaining feed quality while enhancing lifetime health, resilience, and herd productivity.

Integrating advanced preservation techniques is key to improving grain storage efficiency and minimising environmental impacts. Organic acid preservation provides an opportunity to optimise storage conditions, maintain feed quality, and reduce reliance on fossil-fuel drying methods. Future research should incorporate LCA to quantify the environmental trade-offs between different grain preservation methods. Addressing grain storage challenges is essential for ensuring a sustainable and

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cost-effective feed supply, reducing contamination risks, and supporting long-term productivity in swine production systems.

Table 1. The effects of organic acid-preserved grain on intestinal health, digestive function, and growth performance of pigs.

Production Stage	Organic Acid	Effects on Intestinal Health and Digestive Function	Effects on Growth Performance	Ref.
Exp. 1 and 2: Growing Exp. 3: Weaning	Organic acid-preserved grain (57% formic acid blend)	• Exp 1: Increased the diet DE and ME content. • Exp. 2: No effect on the CAID of amino acids or CP. • Exp. 3: No effect on the CATTD of DM, OM, GE, N, EE, P or Ca.	• Exp. 3: Increased ADFI and ADG during d 0-28 PW and final BW on d 28 PW.	[35]
Weaning (7-22 kg)	Organic acid-preserved grain (65% propionic acid blend)	• Reduced fecal scores and diarrhea incidence during d 0-21 PW. • Increased the CATTD of DM, OM, N, NDF, and GE on d 21 PW. • Increased the CAID of DM, OM, N, and GE on d 35 PW. • Reduced ileal *Streptococcus* and increased colonic *Faecalibacterium* on d 35 PW. • Reduced colonic BCFA on d 35 PW.	• Increased ADFI and ADG during d 0-35 PW and final BW on d 35 PW. • Preserved grain outperformed pigs supplemented with ZnO after d 21 PW.	[195]
Weaning (7-21 kg)	Organic acid-preserved grain (65% propionic acid blend)	• Reduced ileal *Escherichia* and increased ileal and colonic *Faecalibacterium* on d 10 PW. • Increased colonic propionate on d 10 PW.	• Increased ADFI and ADG during d 0-35 PW and final BW on d 35 PW.	[196]
Weaning (7-24 kg)	Organic acid-preserved grain (65% propionic acid blend)	• Increased ileal *Lactobacillus* and colonic *Faecalibacterium* and *Prevotella* on d 8 PW. • Preserved grain increased the CATTD of N in low CP diets (17%) on d 30 PW.	• No effect on ADFI but improved FCR during d 0-35 PW and increased final BW on d 35 PW.	[197]
Weaning (7-23 kg)	Organic acid-preserved grain (65% propionic acid blend)	• Increased duodenal VH on d 8 PW and tended to increase jejunal VH:CD. • Increased the CATTD of DM, OM, N, and GE on d 30 PW. • Increased colonic *Prevotellaceae* on d 8 PW	• Increased ADFI during d15-35 PW and improved FCR during d0-35 PW.	[198]
Suckling to Slaughter (3-120 kg)	Organic acid-preserved grain (65% propionic acid blend)	• Increased the CATTD of DM, OM, N, and GE on d 30 PW and at slaughter. • Increased faecal microbial diversity at weaning and d 30 PW, and increased *Faecalibacterium* at slaughter.	• No effect on ADFI, but increased ADG to slaughter, improved G:F from d 14 PW, higher BW from d 30 PW, and heavier carcass weight at slaughter.	[199]

ADFI, average daily feed intake; ADG, average daily gain; BCFA, branched-chain fatty acids; BW, body weight; Ca, calcium; CAID, coefficient of apparent ileal digestibility; CATTD, coefficient of apparent total tract digestibility; CP, crude protein; d, day; DM, dry matter; EE, ether extract; FCR, feed conversion ratio; GE, gross energy; G:F, gain-to-feed ratio; N, nitrogen; NDF, neutral detergent fibre; OM, organic matter; P, phosphorus; PW, post-weaning; VH, villus height; VH:CD, villus height-crypt depth ratio.

3.6. The Potential of Organic Acids as Functional Feed Additives in Sustainable Pig Nutrition

Amid ongoing environmental and economic pressures, maintaining herd health and productivity remains a critical challenge for the pig industry. Recent regulatory restrictions on in-feed antimicrobials and the EU ban of zinc oxide in piglet diets have further intensified these concerns [11,200]. These changes emphasise the urgent need for sustainable alternatives to support herd resilience and performance, particularly as impaired health status has a major impact on both the environmental footprint and economic viability of pig production systems [201]. Beyond preservation, increasing evidence indicates that the inclusion of dietary organic acids may support the transition to antimicrobial-free feeding, as recently reviewed by several authors [202–207]. Organic acids offer multifunctional benefits beyond pathogen control, including improved intestinal health, enhanced nutrient digestion, and better growth performance. Their antimicrobial effect stems from their ability to penetrate microbial cell membranes in their non-dissociated form, thereby disrupting cellular function and inhibiting pathogen proliferation [208–210]. Unlike inorganic acids, such as hydrochloric and phosphoric acid, which are highly corrosive and less biologically effective, organic acids are considered safer for long-term dietary use [211]. Short-chain fatty acids (SCFA), such as formic, acetic, propionic, and butyric acids, help maintain microbial balance and promote epithelial integrity. Medium-chain fatty acids (MCFA), such as caprylic and capric acids, act as antimicrobial agents and serve as energy sources, while tricarboxylic acids (TCA), such as citric and fumaric acid, contribute to metabolism and pH regulation [40]. Notably, SCFA serve as energy substrates for intestinal epithelial cells and influence immune modulation, inflammation, and digestion [39,196].

3.7. The Role of Organic Acids in Weaner and Grower-Finisher Diets

Organic acids have been extensively studied in swine nutrition for their multifaceted benefits across all stages of production. Their application is particularly prominent during the weaning transition, a critical period characterised by abrupt dietary changes, immature digestive and immune systems, and heightened susceptibility to enteric infections [212]. However, emerging research supports their benefits in grower-finisher pigs, reinforcing their broader utility in promoting gut health, nutrient efficiency, and sustainable production [38].

In weaned piglets, organic acids have been widely adopted as effective alternatives to in-feed antimicrobials due to their ability to lower gastric pH, inhibit pathogen proliferation, stimulate digestive enzymatic activity, and improve nutrient digestibility [213]. These effects help maintain intestinal integrity and microbial balance, reducing the incidence of post-weaning diarrhoea and improving feed efficiency [214,215]. Maintaining a low gastric pH is particularly important in early life [216,217], as piglets rely on microbial fermentation of lactose to maintain gastric acidity due to their underdeveloped endogenous hydrochloric acid secretion [218,219]. Post-weaning dietary changes elevate gastric pH, compromising the antimicrobial efficiency of the stomach [220], a challenge organic acids help counteract [40]. In addition to promoting acidification, organic acids support a healthy gut microbiota by stimulating beneficial bacteria like *Lactobacillus* and *Bifidobacteria* [221,222], while suppressing pH-sensitive pathogens like *Escherichia coli* and *Salmonella* [223]. Blended organic acid formulations are generally more effective than single-acid supplements, creating a more resilient microbial community [224]. These microbial shifts are often accompanied by reductions in *Enterobacteriaceae* populations and improved fecal consistency, both of which are indicators of enhanced gut health [225–227].

Weaning also disrupts intestinal morphology, typically resulting in villous atrophy and crypt hyperplasia, which impair nutrient absorption [228,229]. Organic acids can alleviate these effects by promoting epithelial cell turnover and supporting enterocyte metabolism [230,231]. Increases in villus height and villus height-to-crypt depth ratio have been observed, indicating enhanced intestinal function [232,233]. Another advantage of organic acids is their effect on feed intake and growth performance. By improving feed palatability, organic acids can encourage consumption [204,225,234], which is critical during the post-weaning period to minimise growth setbacks and support weight gain [235]. However, excessive inclusion rates may negatively affect palatability, underscoring the importance for optimised formulations [236].

While research on organic acids have largely focused on weaned piglets, growing evidence supports their efficacy in grower-finisher pigs. As pigs mature, their GIT becomes more resilient, making them less susceptible to dietary and environmental disruptions. Nevertheless, organic acids continue to enhance digestive efficiency and nutrient absorption during this later production stage [39]. During the grower-finisher stage, key objectives include maximising growth rates, feed efficiency, and carcass quality, while minimising environmental impact and production costs. Notably, GHG emissions during the finisher stage can be up to ten times higher than during the post-weaning period, primarily due to increased feed intake and manure output [51,237].

In older pigs, organic acids have been shown to improve protein and amino acid digestibility, enhance the absorption of key mineral such as calcium, phosphorus, magnesium, and zinc, and reduce nitrogen excretion [203,238,239]. These effects not only contribute to better performance but also reduced nutrient losses and emissions to the environment [134]. Although the gut microbiota in grower-finisher pigs is more stable than in weaned piglets, organic acids can still promote beneficial microbial shifts that support digestive health and feed utilisation. Despite growing interest in the use of organic acids during this stage, relatively few studies have evaluated their effects on carcass characteristics or meat quality parameters [205,240]. However, some evidence suggests that organic acids may reduce microbial shedding [223,241,242], indicating potential food safety benefits. These findings warrant further investigation into their broader impacts, including effects on meat quality attributes such as pH, colour, tenderness, water-holding capacity, and oxidative stability. While responses may vary depending on acid type, inclusion level, diet composition, health status, and age, the current evidence supports the efficacy of organic acids as a multifunctional nutritional strategy to enhance gut health, nutrient utilisation, and sustainability across all stages of swine production. A summary of the comparative effects of dietary organic acid inclusion during the weaning, growing, and finishing stages are provided in Table 2.

Table 2. The effects of dietary organic acid inclusion on intestinal health, digestive function, and growth performance of pigs.

Production Stage	Organic Acid and Inclusion Level	Effects on Intestinal Health and Digestive Function	Effects on Growth Performance	Ref.
Weaning (7-26 kg)	• OA1 (fumaric acid; 0.8-0.2%) • OA2 (Ca-formate, Ca-lactate, capric acid and caprylic acid blend; 0.3-0.2%) • Combination (OA1 + OA2)	• No effect on duodenal morphology or gastric, jejunal, ileal, cecal, or rectal pH on d 14 PW. • OA1 reduced jejunal villus height and cecal *E. coli* counts on day 14 PW • OA2 increased the relative weight of the large intestine on d 14 PW. • No synergistic effect of combination.	• No effect on ADFI, ADG, or FCR during d 0-42 PW	[216]
Weaning (9-18 kg)	Ca-formate, Ca-lactate, lauric, myristic, and capric acid and citric acid blend (0.3%)	• Upregulated the expression of jejunal amino acid transporters (EAAT3, CAT2) • Increased plasma IgG concentrations. • Increased the CAID of most amino acids. • Increased ileal and rectal *Lactobacillus* populations.	• Increased ADFI, ADG, FCR, and final BW during d 0-28 PW.	[221]
Weaning (8-32 kg)	• OA1 (formic and propionic acid blend; 0.1%) • OA2 (formic, propionic and butyric acid blend; 0.2%)	• OA2 increased VH in the ileum, while both OA increased jejunal VH:CD on d 35 PW. • No effect on CATTD of DM, GE, or CP during d 14 or d 35 PW. • Both OA increased fecal *Bifidobacteria* on d 14 PW.	• No effect on ADFI, ADG, or BW during d 0-35 PW. • OA1 tended to improve G:F overall.	[222]
Weaning (6-12 kg)	Fumaric, citric, malic, caprylic and capric acids blend (0.2% or 0.4%)	• Both levels reduced diarrhoea incidence during d 0-7, 7-14, and 14-21 PW.	• Both levels increased ADFI, ADG, G:F, and final BW before and after *E. coli* K88 challenge.	[226]

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Weaning (6-13 kg)	Sodium butyrate (0.05 and 0.1%)	• 0.1% increased villus height in the duodenum, jejunum and ileum and reduced jejunal crypt depth on d 21 PW. • 0.1% reduced duodenal/ileal, and colonic *E. coli* and duodenal/ileal *Clostridium*.	• 0.05% had no effect on performance • 0.1% increased ADFI, ADG, and G:F during d 0-21 PW and final BW on d 21 PW.	[230]
Weaning (9-20 kg)	• OA1 (blend of formic, acetic and propionic acids combined with MCFA; 0.3%) OA2 (phenolic compound, slow release C12, target release butyrate, MCFA and OA blend; 0.2%)	• Both OA reduced diarrhoea incidence during d 0-14 PW and d 0-28 PW. • OA1 increased serum IgM during d 0-14 PW. • OA2 reduced jejunal CD, while both OA increased jejunal and ileal VH:CD on day 28 PW. • OA1 increased the CATTD of DM, NDF and ADF during d 14-28 PW. • OA2 increased the CATTD of NDF, ADF, and P during d 0-14 PW and EE, and P during d 14-28 PW. • Both OA reduced fecal *E. coli* populations on d 28 PW. • Both OA increased total fecal VFA concentrations, including higher acetic, propionic, and butyric acid on d 28 PW.	• OA1 improved FCR during d 0-28 PW, • OA2 increased ADG during both d 0-14 and d 14-28 and improved FCR during d 0-28 PW.	[233]

Table 2. *Cont.*

Production Stage	Organic Acid and Inclusion Level	Effects on Intestinal Health and Digestive Function	Effects on Growth Performance	Ref.
Weaning (7-28 kg)	Formic acid (0.14 or 0.64%)	• No effect on gastric mucosa thickness, the number of parietal cells, or stomach weights on d 42 PW. • 0.64% increased jejunal microbial diversity on d 42 PW.	• Both levels tended to increase ADFI and FCR and increased ADG during d 0-21 PW.	[234]
Weaning (8-18 kg)	Butryic, fumaric and benzoic acid blend (0.5 and 1.0%)	• No effect on digesta pH. • Tended to have higher duodenal and ileal *Lactobacillus* populations and lower ileal *E. coli*.	• Increased ADG and FCR when challenged with *E. coli* K88.	[243]
Weaning (8-16 kg)	• OA1 (citric acid; 0.5%) • OA2 (formic, propionic, lactic, and phosphoric acids; 0.4%)	• OA1 increased serum IgG on d 28 PW. • Both OA reduced fecal *Salmonella* and *E. coli* populations on d 21 and 28 PW. • Both OA increased fecal *Lactobacillus* populations on d 14, 21 and 28 PW.	• OA1 reduced ADFI, increased G:F but had no effect on ADG during d 0-28 PW. • OA2 reduced ADFI, ADG and G:F.	[244]
Weaning (8-13 kg)	• OA1 (phenolic compound, slow release C12, target release butyrate, MCFA and OA blend; 0.2%) • OA2 (OA1 (0.2-0.4%) + formic, acetic, lactic, propionic, citric and sorbic acids and salt blend (0.6-0.4%)	• No effect on diarrhoea incidence. • Both OA increased serum IgG on d 14 PW and IgA on d 28 PW. • Both OA increased total antioxidant capacity on d 14 and 28 PW. • No effect on fecal microbial diversity. • Both OA increased the fecal abundance of Firmicutes and reduced Proteobacteria • Both OA increased the abundance of *Lactobacillus* and *Faecalibacterium*.	• OA1 had no effect on ADFI, ADG, FCR or final BW during d 0-28 PW. • OA2 improved overall ADG and FCR and final BW on d 28 PW.	[245]
Exp. 1: Weaning (7-24 kg)	• OA1 (phenolic compound, slow	• OA1 and OA2 reduced diarrhoea index during d 15-17 PW.	• No effect on ADFI, ADG, FCR or BW during d 0-42 PW	[246]

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	release C12, target release butyrate, MCFA, and OA blend; 0.2%) • OA2 (formic, acetic and propionic acids and MCFA blend; 0.3%) • Combination (OA1 + OA2)	• No effect on gastric, jejunal, or colonic digesta pH. • OA2 increased duodenal VH d 28 PW. • OA1 increased cecal acetic and propionic acid concentrations on d 28 PW. • All OA increased colonic acetic, propionic and butyrate concentrations. • OA1 and OA2 increased colonic *Lactobacillus*, while OA2 also reduced colonic *E. coli*.		
Exp. 2: Weaning (7-24 kg)	• OA1 (phenolic compound, slow release C12, target release butyrate, MCFA, and OA blend; 0.2%) • OA3 (formic acid blend; 0.3%) • Combination (OA1 + OA2)	• All OA reduced diarrhoea index during d 0-7, 7-14, 14-21, and 0-28 PW. • No effect on gastric, duodenal, jejunal, ileal, or colonic digesta pH on d 49 PW. • Combination increased ileal VH and acetic and propionic acid concentrations. • OA1 and OA3 increased microbial diversity. • Combination increased the abundance of *Prevotella* in the colon.	• All OA had improved ADG and FCR during d 43-49 PW.	

Table 2. *Cont.*

Production Stage	Organic Acid and Inclusion Level	Effects on Intestinal Health and Digestive Function	Effects on Growth Performance	Ref.
Weaning (6-20 kg)	Sorbic, benzoic, butyric, capric, caprylic, and lauric acid blend (0.2%)	• Increased ileal VH:CD on d 15 PW. • Tended to increase jejunal and ileal VH on d 30 PW. • Increased ileal VH on d 45 PW.	• Increased BW on day 30 and 45 PW. • Tended to increase ADG during d 0-45 PW.	[247]
Weaning (9-20 kg)	Benzoic acid, Ca-formate, fumaric acid blend (0.15%)	• Tended to reduce faecal scores during d 14-21 PW. • No effect on gastric, duodenal, jejunal, ileal, cecal, colonic or rectal pH. • Increased duodenal VH. • Increased the CATTD of CP, EE, Ca, and P on d 28 PW. • No effect on duodenal, jejunal, or ileal trypsin or chymotrypsin activity. • Increased fecal *Lactobacillus* populations on d 28 PW.	• Increased ADG during d 14-28 and d 0-28 PW but no effect on ADFI or G:F.	[248]
Weaning (7-25 kg)	Fumaric, citric, malic, caprylic and capric acids blend (0.1% or 0.2%)	• Linear reduction in faecal scores. • Increased the CATTD of DM and GE and tended to increase N. • Increased faecal *Lactobacillus* populations and reduced *E. coli* and *Salmonella*. • Tended to increase faecal *Bifidobacterium* and reduce *Clostridium perfringens*. • Reduced faecal ammonia.	• No effect on ADFI but improved ADG and G:F during d 0-42 PW.	[249]
Weaning (5-24 kg)	• OA1 (formic, acetic acid and ammonium formate blend; 0.2%) • OA2 (formic acid, acetic, sorbic, propionic, lactic and citric acids,	• OA2 reduced diarrhoea incidence during d 0-14, d14-49, and d0-49 PW. • OA2 tended to reduce CD and increase VH:CD in the duodenum on d 49 PW. • No effect on jejunum lipase, amylase or protease activity on d 14 or d 49 PW.	• OA1 increased ADFI and ADG during d 0-14 PW and tended to increase ADG during d 0-49 PW. • OA2 had no effect on ADFI, ADG, or FCR overall.	[250]

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	ammonium formate blend; 0.2%)			
Growing (19-28 kg)	Benzoic acid (0.5%)	• Tended to reduce jejunal pH. • Increased trypsin, lipase, and amylase activity in the jejunum after 14 days. • Reduced CD and increased VH:CD in the jejunum. • Increased the CATTD of DM, GE, CP, and EE.	• Increased ADFI, ADG and BW after 14 days.	[231]
Growing (23-50 kg)	Fumaric, citric, malic, caprylic and capric acid blend (0.1% or 0.2%)	• No effect on the CATTD of DM, N, or GE, or fecal ammonia during week 6.	• Increased ADG during the 6-week period.	[251]
Growing (23-54 kg)	Fumaric, citric, malic, caprylic and capric acid blend (0.1%, 0.2% or 0.4%)	• No effect on the CATTD of DM, N, or GE during week 6. • 0.2% increased faecal *Lactobacillus* but no effect on faecal *E. coli* populations during week 6 in any group.	• 0.2% increased ADG, and G:F during the 6-week period.	[252]

Table 2. *Cont.*

Production Stage	Organic Acid and Inclusion Level	Effects on Intestinal Health and Digestive Function	Effects on Growth Performance	Ref.
Finishing (48-93 kg)	Fumaric, citric, malic, caprylic and capric acid blend (0.2%)	• Reduced fecal pH, ammonia, and acetic acid concentrations. • Increased the CATTD of DM, GE, CP and EE in groups without dietary • antibiotic supplementation.	• Improved G:F over 6 weeks without dietary antibiotic supplementation. • Negative effect on G:F in antibiotic supplemented group.	[134]
Finishing (50-117 kg)	Fumaric, citric, malic, caprylic and capric acid blend (0.1% or 0.2%)	• No effect on blood serum parameters during week 6 or 12. • Linear increase in the CATTD of DM, N, and GE during week 12. • Linear reduction in faecal ammonia contents during week 6 and 12. • Linear increase in faecal *Lactobacillus* populations during week 6 and reduced faecal *E. coli* during week 6 and 12.	• Linear increase in ADG during weeks 0-6, weeks 6-12, and overall. • No effect on meat quality parameters (pH, water holding capacity, color, or drip loss).	[253]
Exp. 1: Weaning (6-22 kg) Exp 2: Grow-Finishing (24-140 kg)	Sodium diformate Exp 1: (0.4%, 0.6%, 0.8%, 1% or 1.2%) Exp 2: (0.25%, 0.5%, or 0.75%)	Exp 1: • No effect on faecal DM on d 9 PW • Linear reduction in faecal DM on d 24 PW.	• Exp 1: Linear increase in G:F during d 0-24 PW. • Exp 2: Linear increase in ADG and ADFI from d 60-93 and 93-117. Linear increase in G:F during d 93-117. • Exp 2: No effect on carcass characteristics	[254]

ADFI, average daily feed intake; ADG, average daily gain; BCFA, branched-chain fatty acids; BW, body weight; Ca, calcium; CAID, coefficient of apparent ileal digestibility; CATTD, coefficient of apparent total tract digestibility; CD, crypt depth; CP, crude protein; d, day; DM, dry matter; EE, ether extract; FCR, feed conversion ratio; GE, gross energy; G:F, gain-to-feed ratio; Ig, immunoglobulin; N, nitrogen; NDF, neutral detergent fibre; OA, organic acid; OM, organic matter; P, phosphorus; PW, post-weaning; VH, villus height; VH:CD, villus height-crypt depth ratio.

3.8. The Role of Organic Acids in Sow Diets

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There is growing recognition of the critical role maternal nutrition plays in shaping offspring development, health, and resilience both before and after weaning [255,256]. The sow's diet can influence foetal growth, colostrum and milk composition, microbial transmission, and immune system development, all of which contribute to neonatal survival and lifetime productivity [43,255]. While immediate growth improvements in offspring may are not always observed, long-term performance benefits have been reported [257]. Despite the logistical challenges of conducting longitudinal studies maternal dietary interventions hold significant potential for improving herd reliance and overall system sustainability. Among the various bioactive compounds explored in sow diets including probiotics, prebiotics, algae, milk products, and yeast derivatives [258–262], this review focuses on the role of dietary organic acids in sow nutrition.

Organic acid supplementation during gestation and lactation has shown beneficial effects on both maternal and neonatal gut health, nutrient digestibility, and immune status. Sows face increased nutritional demands during this period to support foetal growth and milk production. Organic acids have been shown to enhance nutrient digestibility, enhance the composition of colostrum and milk, and reduce pathogenic bacterial populations, making them valuable components for maternal feeding strategies [39]. For instance, citric acid supplementation during late gestation and lactation improved CP, calcium, and phosphorus digestibility, enhancing overall nutrient utilisation [263]. Similarly, organic acid blends increase the digestibility of dry matter, nitrogen, and gross energy during reproductive phases [264,265]. Improved nutrient absorption supports energy balance, prevents excessive tissue mobilisation during lactation, and reduces reproductive cycle delays, ultimately enhancing sow longevity and efficiency [266].

Additionally, organic acids can improve sow metabolic health and lactation performance. Supplementing a blend of formic, propionic, and butyric acids, as well as ammonium salts increased maternal feed intake, reduced the number of weak piglet born, and improved litter weaning weights [267]. It has also been reported that SCFA and MCFA supplementation enhanced maternal energy balance, reduced body weight loss, and supported milk production [268]. Colostrum and milk are critical sources of nutrients, immunoglobulins (Ig), antimicrobial peptides, and prebiotic compounds for piglets, all of which shape early immune responses and microbial colonisation [269,270]. Some studies have shown that organic acid supplementation can increase the Ig concentrations in colostrum and milk [263,264], enhancing plasma Ig concentrations in piglets and reducing pre-weaning mortality [271]. However, these effects may vary based on acid type, inclusion rate, and sow parity, as summarised in Table 3.

Besides digestion, organic acids, particularly those with antimicrobial properties, foster a favourable maternal intestinal environment. Increasing evidence suggest that early microbial establishment in piglets is a key determinant of long-term health trajectories, with some microbial transfer occurring in utero via amniotic fluid [272,273] but mostly through direct contact with maternal skin, mucosal surfaces, milk, and faeces after parturition [274]. Since piglets naturally ingest maternal faecal matter in the farrowing environment, modulating the sow's microbiota can influence early colonisation, reducing pathogenic bacterial load and promoting a healthier microbial profile [275,276]. Organic acids can promote beneficial bacteria such as *Lactobacillus* while reducing *Escherichia coli* populations in sow faeces during farrowing and lactation [264]. These microbial shifts enhance immune function, nutrient absorption, and microbial transfer to piglets, fostering healthier GIT development and resistance to infections during the challenging post-weaning phase [255,277].

Table 3. The effects of maternal dietary organic acid inclusion on sow and offspring gut health, digestive function and growth performance.

Supplementation Period	Organic Acid and Inclusion Level	Parity	Lactation Length	Main Effects on Sow	Main Effects on Offspring	Ref.
48 days	Citric acid	3.8	24 days	• No effect on ADFI or BW change during lactation.	• No effect on total piglets born/weaned	[263]

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(d90 of gestation)	(0.5, 1.0, or 1.5%)			• 1.5% increased the CATTD of CP and Ca • 1.0 and 1.5% increased serum IgG, IgA, and IgM concentrations. • 1.5% increased CP, IgA, and IgM concentrations in colostrum and milk (d 14 post-partum).	• No effect on mortality, birth weight, or weaning weight.	
41 days (d95 of gestation)	Fumaric, citric, malic, caprylic, and capric acid blend (0.1 and 0.2%)	4.0	21 days	• No effect on ADFI, BW loss, or BF change during lactation or wean-to-oestrus interval. • 0.2% increased the CATTD of DM, N, and GE. • 0.2% increased plasma IgG at weaning. • 0.2% increased faecal *Lactobacillus* and reduced *E.coli* at farrowing and weaning.	• No effect on total piglets born/weaned • No effect on mortality, growth, or faecal scores during lactation. • 0.2% increased plasma immunoglobulin level	[264]
70 days (d73 of gestation)	Fumaric, citric, malic, caprylic and capric acid blend (0.1 and 0.2%)	3.3	28 days	• No effect on ADFI, BW loss or BF change during lactation. • No effect on the CATTD of DM, N or GE. • Linear increase in faecal *Lactobacillus* at farrowing and weaning. • Linear decrease in faecal *E.coli* at weaning.	• No effect on total piglets born/weaned, pre-weaning mortality, or faecal scores during lactation. • Linear increase in ADG and weaning weight. • Linear increase in faecal *Lactobacillus* and linear reduction in *E.coli* at weaning.	[265]
51 days (d85 of gestation)	Formic, propionic, butyric acid and ammonium salt blend (0.25%)	4.4	21 days	• Increased ADFI during lactation however BW and BF were not recorded. • No effect on serum antioxidant status. • No effect on colostrum or milk composition.	• No effect on total piglets born/weaned • Reduced number of low-birth-weight piglets (<0.7kg) but no effect on mortality • Increased litter weight/piglet BW at weaning.	[267]
29 days (d107 of gestation)	Formic, acetic, lactic, citric, propionic, sorbic, caprylic, capric and lauric acid blend (0.1 and 0.3%)	2.6	21 days	• 0.3% increased ADFI and reduced BW and BF loss during lactation. • No effect on the wean-to-oestrus interval. • No effect on the faecal microbiota pre-farrowing or post-partum, but *Clostridium perfringens* was reduced on d 7 of lactation.	• No effect on total born/weaned. • Reduced mummified piglets at birth. • Both levels increased piglet ADG during lactation and BW at weaning. • No effect on the faecal microbiota on d 7 post-partum or at weaning.	[268]

Table 3. *Cont.*

Supplementation Period	Organic Acid and Inclusion Level	Parity	Lactation Length	Main Effects on Sow	Main Effects on Offspring	Ref.
52 days (d85 of gestation)	Sodium butyrate (0.1%)	3.0	22 days	• Increased ADFI during lactation. • Reduced wean-to-oestrus interval.	• Reduced pre-weaning mortality, diarrhoea incidence, jejunal CD, and the expression of inflammatory cytokines in the colon at weaning.	[271]

				• Increased fat, CP, IgA, IgG, and IgM concentration in colostrum • Sow microbiota not analysed.	• Increased the expression of tight junction proteins in the colon at weaning. • Increased colonic microbial diversity and plasma IgA, IgG, and IgM concentrations at weaning.	
35 days (d100 of gestation)	Butyric (Tributyrin 0.05%)	N/A	21 days	• Reduced total parturition time • No effect on ADFI or BF change during lactation. • Increased the CATTD of DM, GE, and EE. • No effect on colostrum or milk composition. • Increased faecal microbial diversity and the abundance of *Lactobacillaceae, Oscillospiraceae and Christensenellaceae*	• No effect on total piglets born/weaned, pre-weaning mortality, or growth during lactation. • Reduced diarrhoea incidence during lactation. • Increased microbial diversity and faecal *Lactobacillus* at weaning.	[278]
N/A Entire cycle	K-diformate and formic acid (0.8 and 1.2%)	3.4	28 days	• Reduced BF loss during gestation. • Increased ADFI during lactation. • No effect on BW or BF change during lactation. • 1.2% inclusion increased CATTD of ash and EE • K-diformate tended to increase milk fat	• No effect on total piglets born/weaned. • Increased birth and weaning weight.	[279]
32 days (d108 of gestation)	Citric and sorbic acid blend (0.05 or 0.1%)	1.5	25 days	• No effect on ADFI or BF change during lactation or wean-to-estrus interval. • Linear tendency to reduce lactation BW loss. • 0.05 and 0.1% increased the CATTD of DM.	• No effect on total piglets born/weaned. • No effect on pre-weaning mortality. • 0.1% increased piglet ADG and reduced diarrhoea incidence during lactation. • 0.1% increased offspring weaning weight.	[280]
N/A Late gestation	Sodium butyrate (0.05% or 0.1%)	3.6	N/A	• No effect on ADFI, BW loss, milk composition, or blood clinical chemistry during lactation. • IgG and IgA in colostrum tended to increase in supplemented sows.	• No effect on total piglets born/weaned, pre-weaning mortality, or growth during lactation. • 0.1% increased ADFI, ADG, BW, and G:F increased in offspring PW.	[281]

Table 3. *Cont.*

Supplementation Period	Organic Acid and Inclusion Level	Parity	Lactation Length	Main Effects on Sow	Main Effects on Offspring	Ref.
26 days (d110 of gestation)	Sorbic, formic, acetic, lactic, propionic and MCFA blend (0.3%)	4.8	21 days	• No effect on ADFI or BW loss during lactation. • Reduced BF loss during lactation. • No effect on weaning-to-oestrus interval.	• No effect on total piglets born/weaned, or pre-weaning mortality. • Increased piglet ADG during lactation. • No effect on growth from weaning to d 35 PW.	[282]

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				• Reduced faecal *Streptococcus suis* on d 7 post-partum	• Reduced *Clostridium perfringens* on d 7 PW.	
40 days (d100 of gestation)	Organic acid-preserved grain (65% propionic acid blend)	3.2	26 days	• No effect on ADFI, BW loss, or BF change during lactation. • Increased the CATTD of DM, OM, N, NDF, and GE. • Reduced faecal Proteobacteria and increased *Oscillospiraceae and Christensenellaceae* at farrowing.	• No effect on total piglets born/weaned, pre-weaning mortality, or growth during lactation. • Reduced faecal scores during lactation. • Reduced faecal Proteobacteria on d 10 post-partum and increased *Lactobacillus* at weaning. • Increased ADG and FCR from weaning to slaughter.	[283]

ADFI, average daily feed intake; ADG, average daily gain; BF, back-fat thickness; BW, body weight; Ca, calcium; CATTD, coefficient of apparent total tract digestibility; CD, crypt depth; CP, crude protein; d, day; DM, dry matter; EE, ether extract; FCR, feed conversion ratio; GE, gross energy; G:F, gain-to-feed ratio; Ig, immunoglobulin; K, potassium; N, nitrogen; NDF, neutral detergent fibre; OA, organic acid; OM, organic matter; PW, post-weaning.

More recently, tributyrin supplementation (butyric acid + glycerol) from day 100 of gestation resulted in shorter parturition duration, enhanced digestibility of dry matter and fat, and increased milk fat and protein content by day 20 of lactation. Notably, piglets born to supplemented sows exhibited lower diarrhoea incidence and increased plasma IL-10, IL-6, and IgA levels, suggesting improved immune function. Faecal microbial analysis revealed greater microbial diversity, with increased *Lactobacillaceae*, *Oscillospiraceae*, and *Christensenellaceae* in sows, and a higher prevalence of *Lactobacillaceae* in piglets [278]. In a similar context, offering sows organic acid-preserved grain (65% propionic acid blend) from day 100 of gestation has recently been shown to deliver multifaceted benefits. Sows fed preserved grain had increased digestibility of dry matter, nitrogen, neutral detergent fibre, and gross energy. At farrowing, their faecal microbiota showed increased abundance of *Oscillospiraceae*, and *Christensenellaceae*, both of which are associated with enhanced fibre fermentation and gut health [284,285]. Piglets born to preserved grain fed sows exhibited lower faecal scores during lactation, greater faecal *Lactobacillus* at weaning, and superior post-weaning growth and feed efficiency extending through to slaughter, compared to those from sows fed conventionally dried grain diets [283]. These findings suggest that incorporating preserved grain into sow diets offers a promising nutritional strategy for enhancing maternal digestive function, modulating both maternal and neonatal gut microbiota, and improving the health and performance trajectory of offspring. Importantly, this approach is not limited to sows, but can be applied across the entire farm system, from gestation and lactation to creep and finisher diets, offering a cohesive, farm-wide strategy for improving efficiency.

4. Conclusion

The future of sustainable pig production depends on a multifaceted approach that optimises feed efficiency, minimises environmental impact, and maintains economic viability. By leveraging Life Cycle Assessment, producers can identify and implement best practice to improve sustainability metrics while maintaining production efficiency. Concerns around conventional soybean meal and energy-intensive grain preservation methods, such as industrial drying, highlight the need for sustainable alternatives, like faba beans and organic acid preservation. These approaches not only reduce greenhouse gas emissions but also support circular economy principles by promoting locally sourced and energy-efficient feed ingredients. Nutritional interventions are central to reducing the environmental footprint of pig farming. Strategies such as lowering crude protein levels, altering carbohydrate sources, and incorporating feed additives help reduce nitrogen excretion, ammonia,

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and odourous compound emissions. Organic acids offer dual benefits as both preservatives and functional additives, improving digestive health, growth performance, and herd resilience, making them promising alternatives to in-feed antimicrobials. Additionally, the inclusion of organic acids in maternal dietary strategies have shown promising effects on offspring microbiota, immunity, and growth, reinforcing the importance of holistic nutritional management throughout the production cycle. Although challenges remain in balancing cost-effectiveness, nutrient composition, and large-scale implementation, ongoing research continues to refine sustainable feeding strategies. Future advancements in feed formulation, preservation techniques, and microbiome-targeted nutrition will be key to enhancing sustainability. By aligning scientific innovation with practical application, the industry can move towards a more resilient, environmentally responsible model that ensures long-term food security and economic stability.

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