



International Journal of Research Publication and Reviews

Journal Homepage: www.ijrpr.com ISSN 2582-7421

Precision Swine Nutrition: Integrating Gut Microbiome, Functional Feed Additives and Data-Driven Feeding for Sustainable Pig Production: Review Article

Dr. Rajwardhan Chandrakant Nimbalkar¹, Dr. Yogeshwar Rajendra Nimbalkar², Dr. Vaibhav Pandurang Kharade^{3*}

¹MVSc, Poultry Science, ICAR- Central Avian Research Institute, Izatnagar, Bareilly,

²MVSc, Animal Reproduction Gynaecology and Obstetrics, KNPCVS, Shirwal, Satara,

³MVSc, Animal Nutrition, ICAR- Indian Veterinary Research Institute Bareilly.

Email: kharadevaibhav999@gmail.com

ABSTRACT:

Swine nutrition has to support rapid lean growth, reproductive performance, intestinal integrity and efficient nutrient use while controlling feed costs and nutrient losses. Because nutrient requirements change with body weight, age, genotype, health and reproductive status, a uniform diet may oversupply some nutrients and undersupply others. Precision swine nutrition combines phase-specific formulation, ingredient characterization, feeding-behaviour monitoring and data-supported adjustment. The gastrointestinal microbiome is particularly important around weaning, when dietary transition and stress can disrupt intestinal barrier function and microbial stability. This review synthesizes evidence on requirement-based feeding, amino-acid-balanced diets, dietary fibre and protein management, functional feed additives, alternative ingredients and emerging precision-feeding tools. Probiotics, prebiotics, organic acids, enzymes and phytochemicals have potential applications, but responses are product-, dose-, diet- and farm-dependent; they should not be treated as interchangeable replacements for sound management. Electronic feeders, individual identification and weight monitoring can reveal variation hidden by group averages, although these tools require calibration and reliable records. For India, locally available cereals, oilseed meals and agro-industrial by-products offer opportunities when their nutrient composition and safety are verified. Research priorities include affordable farm-level monitoring, validated gut-health indicators, regional ingredient databases and independent cost-benefit evaluation. An integrated nutrition programme is more likely to be sustainable when formulation, health management, biosecurity and measurable production outcomes are considered together.

Keywords: Swine nutrition; precision feeding; gut microbiome; post-weaning diarrhoea; functional feed additives; amino acid balance; feed efficiency; India

Review scope: This narrative review synthesizes selected peer-reviewed literature and authoritative reference works relevant to the topic. It is not presented as a systematic review; claims and recommendations should be checked against the cited original sources before journal submission.

1. Introduction

Feed is a major variable cost in pig production, and diet composition influences growth, reproductive performance, manure output and the environmental footprint of a unit of pork. Pigs differ in nutrient requirements with body weight, age, genetics, health, housing and production stage; therefore, a formulation developed for one group should not be assumed to fit all animals. Precision nutrition aims to reduce the gap between nutrient supply and actual requirement by combining accurate formulation with timely information on intake and animal response (NRC, 2012; Pomar and Remus, 2019).

The approach does not depend exclusively on expensive automation. Regular ingredient analysis, phase feeding, calibrated weighing, careful observation and good records are practical components of precision nutrition. Digital technologies can add value when they improve decisions that farmers or nutritionists can act upon, rather than merely generating more data.

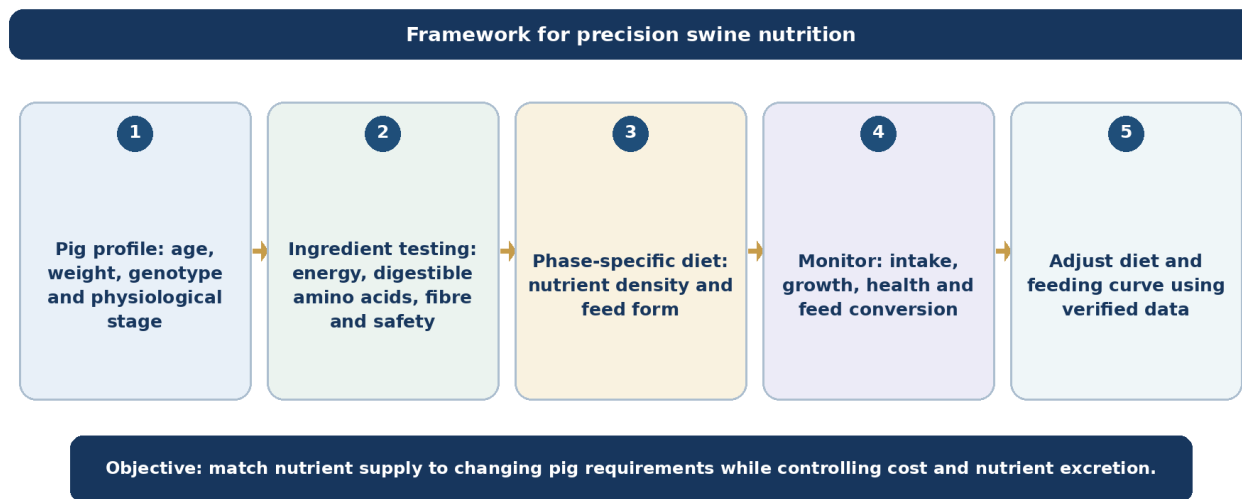


Fig. 1. Framework for precision swine nutrition. Conceptual synthesis of requirement-based formulation, individual monitoring and feedback adjustment.

Figure 1 illustrates the conceptual framework for this review. The arrows represent a management sequence and feedback relationship, not a claim that all effects occur uniformly across species or production systems.

2. Nutrient requirements across production stages

2.1 Nursery pigs and the weaning transition

Weaning combines separation from the sow, social mixing, changes in feed texture and ingredients, and exposure to a new environment. A temporary reduction in feed intake can limit intestinal development and make newly weaned pigs more vulnerable to diarrhoea. Diets should be palatable, digestible and correctly balanced for essential amino acids, minerals and vitamins. The transition should be planned, water access checked frequently and feeder space sufficient to allow pigs to learn to eat. Very high crude-protein concentrations can increase undigested substrate reaching the hindgut; reduced-protein diets may help when essential amino-acid balance is maintained (Han et al., 2024; Tang et al., 2024).

2.2 Grower–finisher pigs

During growth and finishing, the objective is to provide energy and digestible amino acids in proportions that support lean tissue deposition without unnecessary nutrient excretion. Lysine is commonly used as a reference amino acid, while the ratios of other indispensable amino acids must also be adequate. Requirements decline relative to body weight as pigs grow, so multiple feeding phases can improve nutrient matching. Feed conversion should be interpreted alongside average daily gain, carcass traits, health and the cost of the ration; a lower feed intake is not automatically beneficial if growth is compromised.

2.3 Gestating and lactating sows

Gestating sows require a controlled energy supply that supports pregnancy without excessive body-condition gain. Appropriate fibre can improve satiety and contribute to normal feeding behaviour. During lactation, energy, amino-acid and water requirements rise sharply because milk production is sustained by feed intake and mobilization of body reserves. Feeding decisions should therefore account for litter size, parity, ambient conditions, body condition and feed refusal. Group averages can conceal individuals that are over-conditioned, thin or consistently under-consuming.

Table 1. Main nutritional priorities and monitoring indicators across swine production stages.

Production stage	Main nutrition priority	Useful indicators	Common management risk
Nursery / weaning	Highly digestible diet; balanced amino acids; water access	Feed intake, faecal consistency, early weight gain	Abrupt diet change and excessive dietary protein
Grower–finisher	Energy and digestible amino acids matched to growth	Average daily gain, feed conversion, weight variation	Nutrient oversupply or poor feeder adjustment

Production stage	Main nutrition priority	Useful indicators	Common management risk
Gestating sow	Controlled energy; appropriate fibre and minerals	Body condition, refusals, litter outcomes	Over-conditioning or inadequate intake
Lactating sow	High nutrient density and unrestricted clean water	Feed intake, sow weight change, litter growth	Insufficient intake and loss of body reserves

3. Gut microbiome and intestinal health

3.1 Diet, microbial ecology and intestinal barrier

The intestinal microbiome participates in fermentation, metabolite production, immune development and maintenance of the epithelial barrier. Diet is one of the strongest manageable influences on this ecosystem. Protein source and level, fermentable carbohydrate, insoluble fibre, fat type, feed hygiene and transitions between diets can change the available substrates and microbial products. Microbiome associations should be interpreted cautiously: a shift in a bacterial group is not, by itself, proof of better health or improved production. Microbial data become more useful when combined with faecal consistency, growth, intake, inflammatory indicators and controlled diet comparisons (Han et al., 2024). The broader evidence on pig microbiota links nutritional inputs with growth and feed efficiency, but associations remain context-dependent (Gardiner et al., 2020; Hu et al., 2023; Pandey et al., 2023).

3.2 Post-weaning diarrhoea and nutritional prevention

Post-weaning diarrhoea is multifactorial. Pathogens, stress, reduced intake, feed composition, hygiene and immunity interact. Nutritional approaches include highly digestible ingredients, balanced and not excessive protein, appropriate fibre, adequate water, careful diet transitions and control of mycotoxins. The acid-binding capacity and processing properties of ingredients can also influence digestive conditions. Feed changes alone cannot replace veterinary diagnosis, all-in/all-out hygiene, cleaning, temperature control or appropriate disease prevention. The aim is to reduce avoidable nutritional pressure while managing infectious and environmental causes (Tang et al., 2024).

4. Functional feed additives: opportunities and limits

4.1 Probiotics, prebiotics and postbiotics

Probiotics are live microorganisms intended to confer a benefit when supplied in adequate amounts; prebiotics provide substrates selectively utilized by host microorganisms; postbiotics are preparations of inanimate microorganisms and/or their components. These categories differ in mechanism and cannot be treated as equivalent. Potential outcomes include improved intestinal barrier function, fermentation patterns or resilience during dietary transition. Interpretation requires attention to strain identity, dose, viability, storage, basal diet, pathogen pressure and trial duration. A result obtained using one product should not be generalized to all products in that class.

4.2 Organic acids, enzymes and phytogetic compounds

Organic acids are used to support feed preservation and gastrointestinal conditions, while exogenous enzymes can help release nutrients from substrates they are able to act upon. Phytogetic additives include selected herbs, spices, plant extracts and essential-oil components. A recent review found that phytoGENICS have been investigated for effects on growth, nutrient digestibility, gut health and meat quality, but also noted variation and inconsistent outcomes among formulations (Madesh et al., 2025). Product composition, processing stability, palatability and dose must therefore be considered. Additives should be tested against defined objectives such as feed conversion, faecal condition, growth or nutrient excretion.

4.3 Minerals, water and feed safety

Minerals are essential for growth, bone development, reproduction and enzyme function, but excessive supplementation can increase manure loading and cost. High-dose zinc and copper practices used historically to manage post-weaning challenges raise environmental and regulatory concerns in some jurisdictions. A precision approach uses requirement-based supply and considers interactions among minerals and ingredients. Mycotoxins, rancid fats, microbial contamination and poorly stored ingredients can undermine even a well-formulated diet. Feed safety is therefore a core part of precision nutrition, not an optional quality-control step.

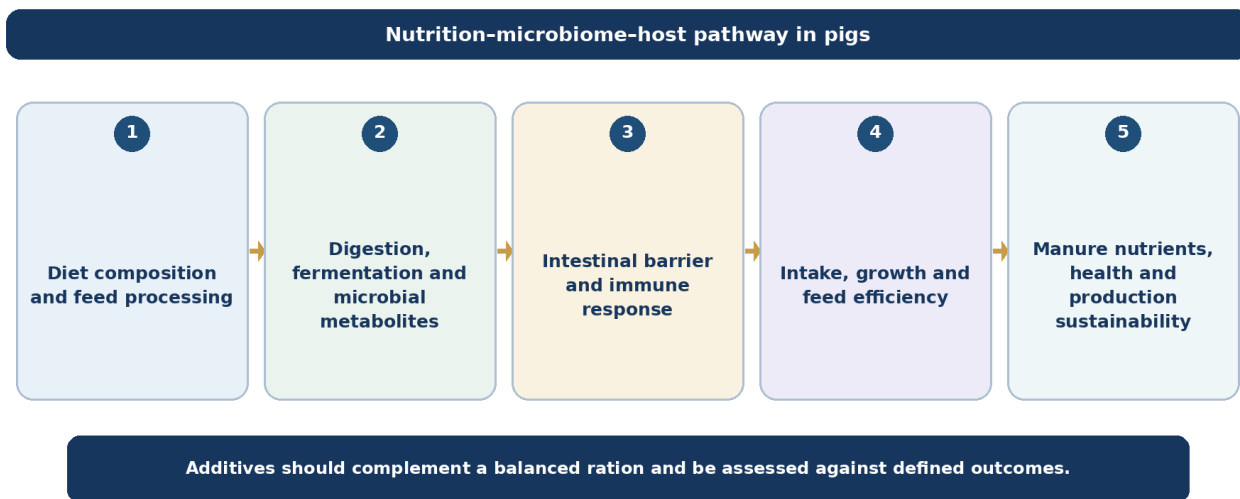


Fig. 2. Nutrition–microbiome–host pathway in pigs. The pathway emphasizes linked responses rather than a single-additive effect.

Figure 2 summarizes the biological or decision-making links discussed above. Practical application requires validation under the relevant species, management and environmental conditions.

Table 2. Functional feed additive classes in swine diets: proposed function and practical cautions.

Class	Possible nutritional target	Evidence interpretation	Practical caution
Probiotics / direct-fed microbes	Microbial balance and gut-barrier support	Response depends on strain and diet	Check viable count, storage and product identity
Prebiotics / fermentable fibre	Microbial substrates and short-chain fatty acids	Fibre type and inclusion level matter	Excess may reduce energy density or intake
Organic acids	Feed hygiene and gastrointestinal environment	Effects differ by acid, dose and feed matrix	Consider palatability and mixing uniformity
Enzymes	Improved access to selected nutrients	Most useful for compatible substrates	Do not assume one enzyme works for all ingredients
Phytogenics	Bioactive, antioxidant and microbial effects	Published growth responses are inconsistent	Standardize active compounds and verify dose

5. Protein and fibre strategies for nutrient efficiency

Crude protein alone is an incomplete guide to protein adequacy. Formulating to digestible amino-acid requirements can support growth with less surplus nitrogen when all limiting amino acids are supplied. The response depends on digestibility coefficients, ingredient quality, energy supply and the pig's physiological stage. Dietary fibre is equally complex: fibre fractions differ in water-holding capacity, fermentability and effects on digesta flow. Moderate inclusion of selected fibres can support gut function and satiety, whereas excessive or poorly matched fibre may dilute dietary energy and reduce performance. These relationships are well established in reviews of fibre use and gut health in pigs (Montagne et al., 2003; Jha and Berrocoso, 2015; Pluske et al., 2018). Diets should therefore be designed around ingredient characteristics and animal response rather than a single crude-protein or crude-fibre target.

6. Alternative ingredients and circular feed use

Cereal grains, oilseed meals, bran, distillers' residues and other agro-industrial by-products may offer practical ingredients where supply chains are reliable. Their nutritional value can differ between batches because of crop variety, extraction method, processing, storage and contamination. Local availability does not guarantee suitability. Each ingredient needs representative sampling and evaluation of metabolizable energy, amino-acid profile,

fibre, anti-nutritional factors and mycotoxin risk. Fermentation and other processing methods can improve selected characteristics, but they introduce their own requirements for consistency and safety. Formulation should optimize the blend of ingredients instead of relying on a single “novel” feed as a universal replacement.

Table 3. Examples of ingredient opportunities and constraints for swine nutrition.

Ingredient group	Potential value	Key limitation	Evaluation before use
Cereal grains	Concentrated energy source	Mycotoxin and batch variation	Moisture, mycotoxin risk and energy value
Oilseed meals	Protein and amino acids	Amino-acid imbalance and anti-nutritional factors	Digestibility, processing and amino-acid profile
Bran and agro-industrial by-products	Local availability and circular nutrient use	Variable fibre, fat and contamination risk	Representative sampling and inclusion trials
Fermented ingredients	May improve palatability or nutrient availability	Process consistency and microbial safety	Batch control, shelf life and digestibility

7. Precision feeding and data-supported management

7.1 What should be measured?

Useful measurements include body weight and growth rate, individual or group feed disappearance, feed refusals, water use, health events, mortality, reproductive performance and feed cost. Electronic feeders can provide detailed intake records; RFID can link records to identified animals; camera-based systems may estimate weight or behaviour under suitable conditions. Data quality depends on calibration, animal identification, maintenance and consistent recording. Before investing, the farm should identify a concrete decision that the data are expected to improve.

7.2 From group formulation to individual adjustment

Precision feeding systems can adjust daily nutrient supply using estimated body weight, intake and growth trajectory. Such systems may reduce excess amino-acid supply and nitrogen output, but the benefits depend on accurate measurement, feeding-system design and the capacity to distribute diets individually. In many farms, two or three phases, improved feed testing and better group management may provide a stronger return than a complex system with poor data. Models should be evaluated on independent farm data and report both average accuracy and the frequency of operational errors (Pomar and Remus, 2019).

Table 4. Precision-feeding tools and their decision value in pig production.

Tool / data stream	Potential decision	Main limitation	Practical validation
Electronic feeder / RFID	Individual intake and feeding patterns	Capital, maintenance and incomplete readings	Compare recorded intake with feeder checks
Automated weighing	Growth curve and feeding-curve updates	Movement and identity errors	Repeat measures and manual verification
Feed analysis database	Diet adjustment to actual ingredients	Sampling and lab costs	Update after source or batch changes
Predictive analytics	Flag unusual intake or poor growth	Models may not transfer across farms	Validate prospectively against farm outcomes

8. Heat stress, welfare and environmental sustainability

Heat stress can reduce voluntary feed intake and alter feeding patterns. Pigs have limited ability to dissipate heat by sweating, so management of ventilation, stocking, drinker function and feeding schedule is important. Nutrient density may need to be reconsidered when intake declines, but concentrated diets must preserve amino-acid balance and digestive health. Feeding during cooler periods and ensuring fresh water are practical starting points. From an environmental perspective, precision protein and mineral supply can reduce avoidable nutrient excretion, while better feed conversion lowers the amount of feed required per unit of gain. These benefits should be measured, not assumed, because an intervention that increases cost or impairs growth may not improve whole-farm sustainability.

9. Implications for Indian pig production

Indian pig systems range from household and smallholder production to organized farms, with variation in breed, feed access, housing and veterinary support. Regionally available cereals, oilseed meals and by-products can contribute to diets, but their nutrient profiles should be verified and balanced. Smallholder-compatible improvements include clean and continuous water, accurate weighing, simple phase-feeding plans, safe storage, gradual diet changes and record keeping. Shared feed-analysis facilities and mobile advisory services could extend precision principles where individual automatic feeders are unaffordable. Local trials should assess profitability and animal performance under realistic management rather than assuming results from intensive overseas systems will transfer unchanged.

10. Research gaps and future directions

Priority research areas include standardized measurements of gut function, independent trials of additive combinations, reliable nutrient databases for region-specific ingredients, tools to detect under-consumption early and precision-feeding systems suited to variable farm scale. Future models should integrate biological knowledge with sensor data and report uncertainty so that recommendations can be reviewed by a nutritionist. Research should also address how diet, welfare, antimicrobial stewardship, carcass quality and manure nutrient losses interact. Comparative trials should report feed cost, mortality, growth, feed conversion and environmental indicators using consistent definitions.

11. Ration formulation in modern precision swine nutrition

11.1 Energy systems and digestible amino-acid balance

A useful formulation system distinguishes energy supply from the amino acids needed to deposit lean tissue, maintain organs and support reproduction. Crude protein is a useful screening measurement, but it does not reveal whether lysine, threonine, methionine plus cysteine, tryptophan or other indispensable amino acids are adequately supplied. When the protein source is variable, a diet can meet a crude-protein target yet remain deficient in one limiting amino acid. Conversely, a diet with excessive crude protein can increase nitrogen excretion without a proportional performance gain. Precision formulation therefore uses digestibility-adjusted amino acids and an appropriate amino-acid-to-energy relationship, with the ideal-protein concept providing a practical reference (NRC, 2012; Pomar and Remus, 2019).

Amino-acid requirements are not fixed numbers independent of context. Lean growth potential, sex, genotype, body weight, health status, thermal environment and feed intake alter the amount needed per day and the concentration needed in the diet. A pig that eats less during hot weather may receive less lysine even when the diet formula remains unchanged. Precision feeding should therefore distinguish nutrient concentration from absolute daily nutrient intake. Models can estimate daily requirements from weight and growth trajectory, but a model's apparent accuracy should not hide the uncertainty in body-weight estimation, feed wastage, ingredient digestibility or health-related changes in maintenance requirement.

11.2 From phase feeding to daily or individual adjustment

Conventional phase feeding divides production into discrete weight bands, each supplied a diet designed for the average pig. It is more accurate than one broad-phase diet, but the mean animal does not describe the whole population. Fast-growing animals can be under-supplied while slower-growing animals receive nutrients beyond their immediate needs. More phases can reduce this mismatch, although manufacturing, storage and delivery complexity increase. A two-diet blend or multiphase system can change nutrient density over time; individual electronic feeding can go further by assigning each animal its own daily mixture when identification, intake and delivery are measured reliably (Andretta et al., 2020).

The operational goal is not maximum technological complexity. A small farm may obtain useful benefits from accurately weighing a representative group, separating piglets by size, testing important feed ingredients, using clear feeding curves and reviewing feed conversion each batch. A commercial farm with individual stations may justify more precise models. In either setting, decisions should be made against a baseline: feed cost per kilogram of gain, variation in final weight, mortality, medication events, manure nutrient output and labour. A system that produces many alerts but does not change a feeding decision has limited practical value.

11.3 Model uncertainty and validation

Predictive models need external validation in herds different from those used for training. Performance can decline when breed, diet formulation, feeder design, housing, season or disease pressure changes. Models must also make uncertainty visible: an estimated daily requirement is not an exact biological measurement. An implementation study should report calibration, missing-data rates, the proportion of animals for which recommendations were followed, and whether the predicted gain was achieved after accounting for feed cost and management changes. Where model recommendations conflict with clinical signs or established feeding safeguards, the model should prompt review rather than automatically override the stockperson or veterinarian.

12. Sow reproductive nutrition and early-life programming

12.1 Gilt development and sow body condition

Feeding programmes for replacement gilts and adult sows must balance body reserves with reproductive performance. Excessive energy intake during gestation can contribute to overconditioning, while inadequate intake may leave the sow unable to support pregnancy, lactation and subsequent recovery. Body-condition scoring, backfat measurement where appropriate, parity, litter history and expected litter size can help individualize feeding. Dietary fibre is useful for satiety and may support normal feeding behaviour in gestating sows, but fibre sources differ in fermentability, bulk density and energy value; the formulation must account for those properties rather than treating crude fibre as a uniform ingredient characteristic.

A sow's nutrition should be assessed across the reproductive cycle, not only during the current gestation. Feed intake in lactation, body-weight loss, return to oestrus, litter growth and sow longevity are linked outcomes. A low-cost ration that produces repeated excessive weight loss can raise replacement costs and reduce lifetime efficiency. Recording body condition at service, late gestation and weaning gives the farm a more useful picture than one end-point measurement. These records can be used to adjust feeding curves and to identify groups that need more careful assessment, such as young parity sows or animals rearing unusually large litters.

12.2 Lactation, water and milk output

Lactation is a period of high nutrient demand, and daily feed intake may not increase as rapidly as milk production early in lactation. Energy density, amino-acid balance, feed freshness, feeder access and water supply all influence voluntary intake. Water is often an overlooked component: inadequate flow, poor drinker placement or contaminated water can suppress intake and complicate interpretation of a feeding problem. An abrupt drop in sow feed intake should not be treated simply by changing the feed formula; farrowing complications, fever, lameness, heat stress, feeder malfunction and water availability must be checked.

The nutritional outcome for piglets depends on more than the sow diet. Colostrum intake, litter size, birth weight, competition at the udder, temperature, health and management shape early survival and growth. Nutrient supply to the sow may support milk production, but nutrition cannot compensate fully for poor farrowing supervision, inadequate thermal comfort or failure to ensure that small piglets obtain colostrum. Precision tools can help identify low-intake sows or piglets with poor growth trajectories, yet the measurements must be paired with observations of udder access, behaviour and health.

12.3 Creep feed and the post-weaning transition

Creep feed is intended to familiarize piglets with solid feed before weaning, but intake is often uneven within a litter. Feed disappearance from a feeder does not always equal ingestion by each piglet, and palatability, freshness, feeder design and opportunities to explore affect use. Where creep feeding is used, the main goal is to support a smoother dietary transition, not to force a high intake from every piglet. At weaning, the diet should be palatable, digestible and appropriately balanced, with a reliable supply of clean water and minimal unnecessary environmental change.

The post-weaning period warrants special attention because reduced intake can compromise intestinal barrier function, while undigested protein reaching the hindgut may support undesirable microbial activity in susceptible animals. The evidence reviewed by Han et al. (2024) and Tang et al. (2024) supports a multi-factor approach involving nutrient composition, feeding management, sanitation and pathogen control. It would be misleading to attribute every diarrhoea event to a single ingredient or to assume that one additive will work under all conditions. Clinical diagnosis, herd history and veterinary oversight remain essential when disease is persistent or severe.

13. Feed quality, ingredient variability and safety assurance

13.1 Ingredient analysis as a precision-nutrition foundation

Feed formulation is only as reliable as the ingredient data used. Moisture changes nutrient concentration on an as-fed basis; protein meals may vary in protein, amino acids, fibre and heat damage; cereal grains differ in energy and mycotoxin risk; and by-products change with the processing method. A feed database is a useful starting point, not a substitute for sampling the material actually delivered to the mill or farm. Sampling should capture variation between bags, silos, deliveries and storage layers. A poorly collected sample can produce a precise laboratory number that does not represent the batch. For Indian production systems, potentially useful ingredients include maize and other cereals, soybean meal, groundnut cake where quality is confirmed,

rice bran, broken rice and selected agro-industrial by-products. The value of a local ingredient depends on nutrient composition, seasonal price, antinutritional factors, fibre, mycotoxin exposure, processing quality and the ability to include it without compromising the amino-acid balance. Low price per tonne is not equivalent to low cost per kilogram of usable nutrient. Diet comparison should consider digestible energy and amino acids, pellet quality, growth response, feed conversion and safety rather than purchase price alone.

13.2 Mycotoxins, rancidity and storage effects

Pigs can be affected by mycotoxins in contaminated grains and feed ingredients, and clinical signs can be nonspecific. Risk management includes appropriate crop and feed storage, moisture control, rapid handling of spoiled material, representative testing when warranted, supplier qualification and documentation of ingredient origin. Binding or biotransformation products are not interchangeable and should not be regarded as a universal solution to poorly controlled contamination. The choice of mitigation strategy depends on the toxin, feed matrix, dose, animal stage and local regulatory requirements. When an unexpected production decline occurs, feed analysis should be considered alongside infectious disease, water and ventilation checks. Storage conditions also influence fats and vitamins. Rancid lipids can reduce palatability and contribute to oxidative challenges, while prolonged storage under inappropriate temperature and humidity can degrade feed quality. Feed bins, augers and troughs require cleaning to reduce residue accumulation and mould growth. First-in, first-out stock management, batch identification and periodic inspection are simple measures that often offer a better return than adding multiple supplements to an inconsistent diet. Precision nutrition begins with predictable raw materials and sound hygiene.

13.3 Circular feed use requires traceability

Circular use of by-products can reduce waste and diversify feed supply, but it must be governed by ingredient safety and process consistency. Industrial by-products should be characterized for nutrients, salt, contaminants and processing aids. Materials from uncontrolled sources, including untreated food waste, can introduce pathogens, foreign objects, residues or highly variable composition. Any recycled ingredient must comply with applicable rules and be processed, stored and transported under defined hygiene controls. The objective is to recover nutrients responsibly rather than transfer risk from a waste stream into meat, manure or farm workers.

A practical quality assurance record should identify the supplier, production date, batch, analysis certificate, inclusion rate and any corrective action. When feed conversion or health outcomes change abruptly, such records help link the event to a specific ingredient batch. This is especially important in smallholder settings where feed may come from several local sources and formal testing may be limited. Cooperative feed testing and extension services can reduce this barrier by sharing laboratory costs and delivering understandable formulation advice.

14. On-farm implementation: measurements, economics and workforce

14.1 A tiered measurement hierarchy

Not all farms need cameras, RFID readers or individual feeders. A tiered approach starts with reliable feed purchase and usage records, body-weight sampling, water availability, health records and batch-level growth. The next level adds feed laboratory analysis, pen-level feed intake, automated weighing and feeder monitoring. Advanced systems may capture individual intake, behavioural indicators and model-based estimates of requirements. This hierarchy helps separate the underlying nutritional objective from the equipment that may support it. A basic measurement system used consistently can be more valuable than an expensive installation that is poorly maintained.

Every measurement should connect to a decision. Body weight should inform sorting and diet phase; feed refusals should prompt checks of palatability, water and health; heat alerts should prompt a defined review of ventilation, water and feeding time; and changes in manure or diarrhoea should trigger a structured investigation. The data pipeline needs named responsibility: who checks sensor accuracy, who reviews alerts, who changes a formula, and how the response is documented. Without that operating routine, technology creates records but not precision.

14.2 Cost-benefit evaluation and adoption barriers

Economic evaluation should include installation, software, maintenance, staff training, calibration and downtime, alongside feed savings, improved uniformity, reduced medication, labour and nutrient losses. Benefits may be uneven across farms: precision feeding is more likely to pay where ingredient costs are high, animals vary substantially, diets can be adjusted accurately, and a reliable data system is already present. A pilot should define baseline metrics, a comparison group where feasible, an observation period that covers normal variability, and a stopping rule if performance deteriorates. Vendor claims should be tested against the farm's own outcomes and total cost of ownership.

Smallholder and backyard systems may benefit from shared services rather than individual automation. Options include cooperative feed analysis, standard ingredient libraries, mobile ration calculators, regional extension support and shared access to weighing equipment. For these users, the interface should explain recommendations in plain language and show the assumptions behind the answer. Digital tools should accommodate connectivity interruptions and local feed ingredient names, and provide a manual fallback. The Indian setting is diverse; an implementation strategy designed for a large integrated farm cannot be copied unchanged into every village pig-production system.

14.3 Worker competence, animal welfare and biosecurity

Feeding precision depends on the people who operate the system. Stockpersons need to recognize altered appetite, lameness, coughing, abnormal faeces and heat stress, and know when a nutrition issue may actually be a veterinary problem. Automated gates and feeders must not cause injury, restrict access for subordinate pigs or create competition that disproportionately affects smaller animals. Maintenance and cleaning routines should be designed around animal movement and biosecurity. A system that increases stress or prevents access to feed and water may undermine the intended benefit even when its formulation mathematics is sound.

Records of ration changes should include the reason for the change, the person responsible, the date, and the measured outcome. This creates a learning cycle and reduces repeated trial-and-error changes. In controlled experiments, diets are often prepared accurately and animals are monitored intensively; commercial farms face dust, variable feed flow, illness, staffing changes and equipment breakdown. Field validation must include these normal constraints. Model performance and animal welfare should be treated as co-equal evaluation endpoints.

15. Nutrient losses, sustainability and a research agenda

15.1 Nitrogen and phosphorus efficiency

Dietary nitrogen and phosphorus not retained in animal tissues are excreted, increasing manure management needs and potentially contributing to environmental loading. Formulating protein around digestible amino-acid requirements can reduce unnecessary nitrogen supply while protecting growth when all limiting amino acids and energy needs are met. Phosphorus formulation should distinguish total from digestible or available phosphorus and account for phytate-bound phosphorus in plant ingredients. Phytase and other feed technologies may improve phosphorus availability in suitable diets, but their benefit depends on enzyme activity, matrix assumptions and processing conditions.

Improved nutrient efficiency is not achieved by lowering a nutrient without regard to requirement. Severe restriction can reduce growth, impair bone development or compromise reproduction. The appropriate target is adequate nutrient supply with minimal avoidable excess. Manure nutrient analysis, feed records and animal performance can be considered together to evaluate whether a reformulated diet has achieved the expected improvement. Where manure is recycled into agriculture, its nutrient value may be useful, but application rate, storage and runoff controls are still required.

15.2 Responsible reduction of antimicrobial dependence

Nutrition contributes to resilience and may reduce some risk factors for enteric disease, but feed additives should not be marketed or used as replacements for diagnosis, vaccination, sanitation, ventilation or responsible veterinary treatment. Nutritional strategies such as appropriate fibre, amino-acid balance, water hygiene and selected microbial products can support gut function, especially around weaning. Evidence for any additive should be assessed by product strain or formulation, dose, basal diet, health status and outcome measured. Improvements in faecal score do not automatically prove lower antimicrobial use or long-term productivity unless those outcomes are measured directly.

The use of pharmacological mineral levels and medically important antimicrobials in livestock feed is subject to evolving regulatory requirements and should be checked against current local law and veterinary policy. A prudent review should avoid implying that an intervention is universally permitted or safe. Feed manufacturers and farms need documented ingredient approvals, withdrawal requirements where applicable, and procedures for avoiding cross-contamination. One Health outcomes require simultaneous attention to animal health, food safety, farm-worker exposure and environmental release.

15.3 Priority questions for Indian research

Future Indian studies should compare precision feeding against well-managed conventional phase feeding, using economic and biological outcomes rather than model accuracy alone. Priorities include locally calibrated ingredient matrices, region-specific mycotoxin surveillance, performance of balanced low-protein diets, sow lifetime productivity, low-cost methods to estimate intake, and validation of gut-health biomarkers under different housing and health conditions. Trials should include commercially relevant breeds and smallholder systems, report diet composition and ingredient quality, and describe management sufficiently for replication. Multi-site studies are preferable when a technology is intended for broad national adoption. An especially valuable direction is to connect data streams that are usually studied separately: feed composition, daily intake, body-weight trajectory, gut-health indicators, environmental conditions, manure nutrient output and farm economics. Such integration can identify when the constraint is diet formulation, delivery, water, health or thermal stress. Research should also establish transparent rules for missing sensor data, uncertain predictions and recommendations that conflict with clinical assessment. Precision swine nutrition is most useful when it is explainable, reversible and grounded in animal requirements.

16. Emerging directions: microbiome-informed and computational nutrition

16.1 From microbial taxonomy to function

The gut microbiome is best interpreted as a functional community rather than a list of organisms. Different taxa can perform overlapping metabolic roles, and the abundance of a microbe does not necessarily indicate the rate at which its pathway is active. Metagenomics identifies genetic potential, while metatranscriptomics and metabolomics can indicate expressed functions and products. For swine nutrition, the relevant questions include whether the diet promotes beneficial carbohydrate fermentation, maintains mucosal integrity, supports short-chain fatty-acid production and reduces the substrate available to opportunistic pathogens. These measurements can make mechanistic hypotheses stronger, but they are not yet substitutes for well-defined animal outcomes.

A microbiome-informed feeding programme should link microbial measurements with intake, faecal characteristics, gut morphology where ethically and practically possible, immune markers, growth and medication use. Sampling time, faecal versus intestinal samples, storage conditions, sequencing pipeline and diet composition can create major differences between studies. Accordingly, microbial signatures should not be transferred from one farm to another without external validation. The useful future product may be a small, reliable panel of functional indicators rather than expensive sequencing of every animal. Researchers should report negative findings and avoid treating microbial diversity as an objective that must always be maximized.

16.2 Nutrigenomics and individual nutrient response

Nutrigenomic approaches examine how nutrients influence gene expression, metabolic signalling and phenotype. In pigs, candidate pathways include amino-acid sensing, lipid metabolism, oxidative stress, immune activation and intestinal barrier function. These pathways offer mechanistic insight into why identical diets can produce different responses, but interpretation requires caution: gene expression may be a response to stress or disease rather than a cause of improved performance. Nutrigenomics is therefore most informative when integrated with the diet, microbiome, blood metabolites, phenotype and environment. At present, routine farm decisions are more likely to depend on intake and performance records than on transcriptomic testing. Genotype-by-diet interaction is potentially important when lean-growth potential, appetite and maintenance requirements differ among lines. However, a genomic association does not directly define a practical ration. Translation requires replicated studies showing that a genotype-informed feeding strategy improves outcomes relative to a simpler programme after accounting for testing and management costs. The most useful models may identify broad groups needing different nutrient densities or feeding curves, rather than promise exact requirements for every animal. This staged approach reduces the risk of creating an expensive precision system with little economic value.

16.3 Artificial intelligence: usefulness, not novelty

Machine-learning tools can identify patterns among animal weight, feed intake, environmental data, health events and production outcomes. Their utility depends on the quality and representativeness of the input data, a clear definition of the prediction target and validation on independent farms. A model may accurately predict weight while failing to improve feed cost or welfare. Practical models should therefore be evaluated by decision impact: did the recommendation change feeding, did that change improve the intended outcome, and was the economic value greater than the cost of collecting and processing the data?

For implementation, simple models can be preferable to opaque systems when data are limited. A transparent feeding curve linked to measured weight may be easier to maintain than an algorithm requiring continuous high-quality sensor streams. Where advanced systems are used, they need version control, recalibration, audit trails and a route for staff to report implausible output. Models should indicate when data are missing or outside the training range. No algorithm should autonomously prescribe a clinically consequential intervention without safeguards, particularly when low intake may signal disease or environmental distress.

17. Applied decision examples for pig farms

17.1 When feed conversion worsens unexpectedly

A sudden increase in feed conversion ratio should trigger diagnosis before reformulation. The investigation should first verify the data: feed delivered, feed wastage, weigh scale accuracy, mortality recording, start and final weights, and the duration of the calculation period. Next, review feed batch changes, ingredient moisture, pellet durability, water availability, temperature, ventilation and health events. Mycotoxin exposure, digestive disease, lameness or feeder competition can reduce performance even when the nominal nutrient formula is unchanged. A ration adjustment made before the cause is established can increase cost without resolving the problem.

Once the likely cause is clarified, change one or a small number of variables and define the expected response. If a new ingredient batch is implicated, sample and test it; if heat stress is evident, address the environment and feeding schedule; if intake is restricted by feeder access, correcting hardware may be more effective than increasing nutrient density. Record the action and compare outcomes over a predefined period. This diagnostic sequence makes the feeding system more reproducible and limits unnecessary use of supplements.

17.2 When post-weaning diarrhoea increases

An increase in diarrhoea after weaning may reflect pathogen pressure, lower feed intake, excessive undigested protein, unsuitable fibre characteristics, water problems, hygiene or stress. The first step is veterinary assessment and review of herd history, timing, severity, mortality and relevant diagnostics. In parallel, verify the starter feed formula, ingredient quality, mixing accuracy, feed freshness, water flow and temperature. Nutritional strategies may include more digestible ingredients, balanced amino acids, a suitable fermentable fibre fraction and carefully selected additives, but those measures depend on diagnosis and the existing diet (Han et al., 2024; Tang et al., 2024).

A farm should avoid changing multiple additive products simultaneously because this makes the result difficult to interpret. If an intervention is trialled, define the primary endpoint—for example, clinically defined diarrhoea incidence, average daily gain, mortality or antimicrobial treatment—and record any adverse effects. One successful pen does not establish general efficacy, while one unsuccessful trial may reflect a poor fit between product and cause. Sustained improvement requires attention to sanitation, vaccination where applicable, stocking density, thermal comfort and staff procedures as well as nutrition.

17.3 When a local ingredient appears cheaper

Before introducing a new low-cost ingredient, evaluate its dry matter, usable energy, digestible amino-acid pattern, fibre, fat stability, antinutritional factors, contaminant risks and supply variability. The ingredient should be compared on a nutrient-delivered basis rather than cost per bag. A lower purchase price can be offset by reduced feed intake, poorer digestibility, pellet problems, extra testing, higher feed conversion or increased spoilage. A controlled inclusion trial with a reference diet can determine whether an ingredient works in the target production system, but the diet needs to remain nutritionally balanced so that the ingredient is not blamed for unrelated deficiencies.

A staged adoption pathway is prudent: collect ingredient samples from multiple batches; formulate a conservative test diet; confirm palatability and feed manufacturing performance; run a monitored pilot; and only then expand inclusion. Safety screening is essential for variable by-products, and all use must comply with applicable feed and food-safety rules. For smallholder farms, a reliable shared supply chain and extension support may matter more than the theoretical nutritional value of a novel ingredient. This decision framework supports innovation without transferring unmanaged risk to animals or consumers.

18. Synthesis: a practical research-to-farm roadmap

The evidence supports an order of operations. First, ensure clean water, healthy housing, reliable feed mixing, ingredient quality and stage-appropriate diet formulation. Second, collect a small set of consistent indicators such as body weight, feed intake, feed conversion, mortality, faecal outcomes and feed cost. Third, identify the main bottleneck before choosing an intervention. Fourth, test feed additives, alternative ingredients or digital tools against a baseline with explicit endpoints. Fifth, document the response and revise the programme only when the evidence supports the change. This sequence prevents an emerging technology from distracting from basic management failures.

For Indian research and extension, priorities include region-specific composition matrices for cereals, oilseed meals and by-products; affordable testing for moisture and mycotoxins; robust feeding recommendations for backyard systems; sow lifetime performance; and field validation of digital systems across climates and breeds. Open reporting of diet composition, uncertainty and cost-benefit results would improve transfer between universities, feed manufacturers and farmers. A sustainable swine feeding programme should be judged not by the number of additives or sensors installed but by animal health, efficient growth, responsible nutrient use and practical affordability.

Table 7. Nutritional decision indicators across swine production stages

Stage / group	Priority data	Potential decision	Caution
Nursery piglets	Feed intake, faecal consistency, water access, early weight gain	Review diet palatability, digestibility, feeder access and health	Diarrhoea is multifactorial; nutrition does not replace diagnosis
Grower–finisher	Weight trajectory, pen feed intake, FCR, diet composition	Adjust phase / blend to weight and lean-growth objectives	Use consistent mortality and feed-disappearance accounting
Gestating sow	Body condition, parity, backfat where available, feed access	Adjust gestation curve and fibre supply	Avoid both overconditioning and excessive restriction
Lactating sow	Daily intake, water flow, litter growth, sow weight change	Investigate low intake and balance energy/amino acids	Check disease, farrowing, heat and feeder function

Interpretation: this table is a decision-support framework; confirm relevance to the species, production system and local evidence before application.

Table 8. Feed-resource screening matrix for Indian pig systems

Resource group	Possible nutritional role	Key screening requirement	Main risk to manage
Cereal grains / broken grains	Energy supply	Moisture, energy and mycotoxin screening	Fungal contamination and batch variation
Oilseed meals / cakes	Protein and amino acids	Digestible amino-acid quality and processing history	Heat damage, rancidity or antinutritional factors
Rice bran and cereal by-products	Energy, fibre and variable protein	Stability, fibre, fat and nutrient variation	Rancidity and high variability
Agro-industrial residues	Potential circular feed ingredient	Origin, composition, contaminants, legal suitability	Uncontrolled residues or unsafe processing
Mineral / vitamin premixes	Micro-nutrient balancing	Premix identity, inclusion accuracy and storage	Overlapping supplementation and mixing errors

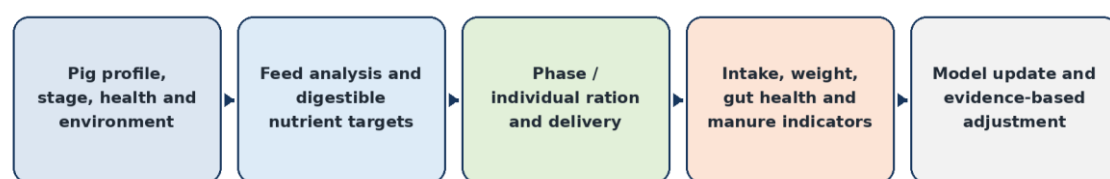
Interpretation: this table is a decision-support framework; confirm relevance to the species, production system and local evidence before application.

Table 9. Evaluation metrics for a precision-feeding pilot

Domain	Minimum indicators	Suggested comparison	Interpretation
Production	Average daily gain, final weight, FCR	Baseline batch or matched pen	Report mortality and feed wastage consistently
Animal health	Diarrhoea, medication, mortality, lameness	Defined case criteria over the same period	Changes may reflect management or pathogen pressure
Economics	Feed cost/kg gain, labour and equipment cost	Total cost of ownership	Include maintenance, training and downtime
Environment	Dietary N/P supply; manure nutrient indicators where feasible	Nutrient input-output comparison	Do not infer emissions from feed conversion alone
Data quality	Missing records, calibration and alerts acted upon	Predefined acceptable thresholds	A model with poor input quality cannot be trusted

Interpretation: this table is a decision-support framework; confirm relevance to the species, production system and local evidence before application.

Integrated precision swine nutrition



Links production-stage formulation with gut-health monitoring and nutrient-use efficiency.

Interpretation: use species-specific data, verify the response and adapt the plan to local conditions.

Table 10. Emerging research tools and their decision value

Tool / data stream	Question addressed	Readiness and caution
Metagenomics / metabolomics	Which microbial functions and metabolites respond to diet?	Research tool; requires host-outcome validation
Individual intake sensors	How much does each pig consume?	Useful where calibration and animal identification are reliable

Tool / data stream	Question addressed	Readiness and caution
Nutrient models / AI	Can diet be adjusted to daily need?	External validation and uncertainty reporting are essential
NIR / rapid feed testing	Does ingredient composition vary between batches?	Requires local calibration against laboratory reference data
Longitudinal health records	Does a diet change alter morbidity or medication?	Case definitions and complete records are needed

Interpretation: choose indicators before implementing the intervention and review outcomes alongside safety, welfare and economics.

Table 11. Farm-level response protocol for common feeding problems

Signal	First checks	Nutrition response after diagnosis	How to evaluate
Unexpected poor growth	Scales, feed wastage, water, illness, ventilation	Recheck nutrient supply and feed quality	ADG, FCR, mortality and cost
More post-weaning diarrhoea	Veterinary assessment, hygiene, water, pathogen history	Review digestibility, protein, fibre and diet transition	Defined incidence, growth and treatments
Ration cost rises	Ingredient price, nutrient analysis, supply variability	Reformulate on digestible nutrient cost	Cost/kg gain and consistency
Uneven market weights	Sorting, competition, feed access, weight data	Consider phase separation or feeding adjustment	Weight variation and days to market

Interpretation: choose indicators before implementing the intervention and review outcomes alongside safety, welfare and economics.

Conclusions

Precision swine nutrition is best understood as the integration of accurate formulation, stage-specific feeding, gut-health management and reliable measurement. Functional additives can be useful when they address a defined limitation, but they cannot compensate for poor ingredient quality, inadequate water, weak biosecurity or inappropriate nutrient supply. For Indian systems, the immediate opportunities are likely to come from ingredient testing, digestible amino-acid formulation, sensible phase feeding, better records and locally validated decision tools. Automation should be adopted when it improves a measurable decision and its benefits exceed the costs. A sustainable programme balances animal performance, welfare, food safety, farm economics and nutrient losses.

References

- Andretta, I., Pomar, C., Rivest, J., et al. (2020). Improvement of feed and nutrient efficiency in pig production through precision feeding. *Animal Feed Science and Technology*, 268, 114611. <https://doi.org/10.1016/j.anifeedsci.2020.114611>
- Gardiner, G.E., Metzler-Zebeli, B.U., & Lawlor, P.G. (2020). Impact of intestinal microbiota on growth and feed efficiency in pigs: A review. *Microorganisms*, 8(12), 1886. <https://doi.org/10.3390/microorganisms8121886>
- Han, X., Hu, X., Jin, W., & Liu, G. (2024). Dietary nutrition, intestinal microbiota dysbiosis and post-weaning diarrhea in piglets. *Animal Nutrition*, 17, 188–207. <https://doi.org/10.1016/j.aninu.2023.12.010>
- Hu, R., Li, S., Diao, H., Huang, C., Yan, J., Wei, X., Zhou, M., He, P., & Wang, T. (2023). The interaction between dietary fiber and gut microbiota, and its effect on pig intestinal health. *Frontiers in Immunology*, 14, 1095740. <https://doi.org/10.3389/fimmu.2023.1095740>
- Jha, R., & Berrocoso, J.D. (2015). Review: Dietary fiber utilization and its effects on physiological functions and gut health of swine. *Animal*, 9(9), 1441–1452. <https://doi.org/10.1017/S1751731115000919>
- Madesh, M., Yan, J., Gao, J., Hu, P., Kim, I.H., Liu, H.-Y., Ennab, W., Jha, R., & Cai, D. (2025). Phytochemicals in swine nutrition and their effects on growth performance, nutrient utilization, gut health, and meat quality: A review. *Stress Biology*, 5, 11. <https://doi.org/10.1007/s44154-024-00209-2>
- Montagne, L., Pluske, J.R., & Hampson, D.J. (2003). A review of interactions between dietary fibre and the intestinal mucosa, and their consequences on digestive health in young non-ruminant animals. *Animal Feed Science and Technology*, 108, 95–117. [https://doi.org/10.1016/S0377-8401\(03\)00163-1](https://doi.org/10.1016/S0377-8401(03)00163-1)

- National Research Council (NRC). (2012). *Nutrient Requirements of Swine: Eleventh Revised Edition*. National Academies Press, Washington, DC. <https://doi.org/10.17226/13298>
- Pandey, S.P., Kim, E.S., Cho, J.H., Song, M.S., Doo, H., Kim, S., Keum, G.B., et al. (2023). Swine gut microbiome associated with non-digestible carbohydrate utilization. *Frontiers in Veterinary Science*, 10, 1231072. <https://doi.org/10.3389/fvets.2023.1231072>
- Pluske, J.R., Turpin, D.L., & Kim, J.-C. (2018). Gastrointestinal tract (gut) health in the young pig. *Animal Nutrition*, 4(2), 187–196. <https://doi.org/10.1016/j.aninu.2017.12.004>
- Pomar, C., & Remus, A. (2019). Precision pig feeding: A breakthrough toward sustainability. *Animal Frontiers*, 9(2), 52–59. <https://doi.org/10.1093/af/vfz006>
- Tang, Q., Lan, T., Zhou, C., Gao, J., Wu, L., Wei, H., et al. (2024). Nutrition strategies to control post-weaning diarrhea of piglets: From the perspective of feeds. *Animal Nutrition*, 17, 297–311. <https://doi.org/10.1016/j.aninu.2024.03.006>