

Next-Generation Feed Processing Technologies: From Conventional Processing to Nano-Enabled and Biotechnological Nutrient Delivery

Dr. Vaibhav Pandurang Kharade^{1*} and Dr. Vyavahare Pranav Prasad²

^{1,2}MVSc, Animal Nutrition, ICAR- Indian Veterinary Research Institute Bareilly,

Corresponding Author

Dr. Kharade Vaibhav Pandurang

Email: kharadevaibhav999@gmail.com



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ABSTRACT

Feed processing has evolved from basic grinding and mixing toward integrated technologies capable of modifying the physical, chemical and biological properties of feed ingredients. Conventional particle-size reduction, pelleting, thermal conditioning, extrusion and ensiling remain fundamental because they improve handling, reduce segregation and waste, alter starch and protein structures, and can increase nutrient availability. However, increasing feed costs, variable ingredient quality, climate-related storage risks, mycotoxin contamination and the need for higher nutrient-use efficiency are accelerating the adoption of fermentation, enzyme-assisted processing, encapsulation, nano-enabled delivery and digital quality-control systems. This review examines the transition from conventional feed processing to next-generation platforms, with emphasis on how processing can be deliberately designed to control nutrient release, detoxify anti-nutritional factors, protect sensitive bioactives and improve animal responses. Particular attention is given to solid-state fermentation, precision fermentation, exogenous enzymes, microbial bioprocessing, micro- and nanoencapsulation, nano-minerals and rapid non-destructive quality assessment using near-infrared spectroscopy (NIRS) and machine learning. The review also discusses feed safety, mycotoxin mitigation, sustainability, energy and water requirements, and the

translational issues surrounding scale-up and regulatory acceptance. Indian applications are highlighted because crop residues, agro-industrial by-products, variable forage quality and decentralized feeding systems create a strong need for low-cost, robust processing technologies. Recent evidence indicates that fermentation can upgrade underutilized substrates and generate functional metabolites, while modern NIR and AI approaches can shorten quality-assessment time. Nano-enabled delivery may improve stability and targeted availability of selected nutrients, but safety, residue, environmental and dose-response questions remain important. The future of feed technology is therefore not a single processing method but an integrated, data-informed manufacturing system that links ingredient characterization, processing conditions, nutrient delivery, animal response and feed safety.

INTRODUCTION:

Feed processing is no longer viewed simply as a mechanical step between ingredient purchase and feeding. It is increasingly treated as a nutritional engineering process in which particle size, moisture, temperature, shear, residence time, pressure, microbial activity and carrier design can be manipulated to change the fate of nutrients in the digestive tract. Conventional technologies such as grinding, mixing and pelleting remain indispensable, but they are being complemented by bioprocessing and targeted-delivery technologies that can address specific nutritional limitations rather than treating all ingredients in the same way (Abdollahi *et al.*, 2013; Lancheros *et al.*, 2020).

The rationale for this transition is particularly strong in livestock systems where feed ingredients vary widely in chemical composition and physical quality. Cereal grains can differ in starch structure; oilseed meals can contain anti-nutritional factors; crop residues can have high lignification and silica; and agro-industrial by-products may be wet,

unstable or highly variable. Processing can therefore be used to improve utilization, reduce heterogeneity and create more predictable feed matrices. In India, where crop residues and agro-industrial by-products are important components of animal feeding, the value of processing is closely tied to resource efficiency and practical affordability (Sampath *et al.*, 2005; ICAR, 2026).

The current literature also shows a shift from end-product quality alone toward process-to-function relationships. For example, recent pelleting research has quantified how ingredient composition and manufacturing variables interact to determine pellet durability, while systematic reviews indicate that NIRS can provide rapid estimates of crude protein, fibre and moisture when calibration and external validation are adequate (You *et al.*, 2025; Hossain *et al.*, 2024). Fermentation research has expanded beyond preservation toward protein upgrading, reduction of anti-nutritional factors and generation of beneficial microbial metabolites (Katu *et al.*, 2025; Wang *et al.*, 2026).

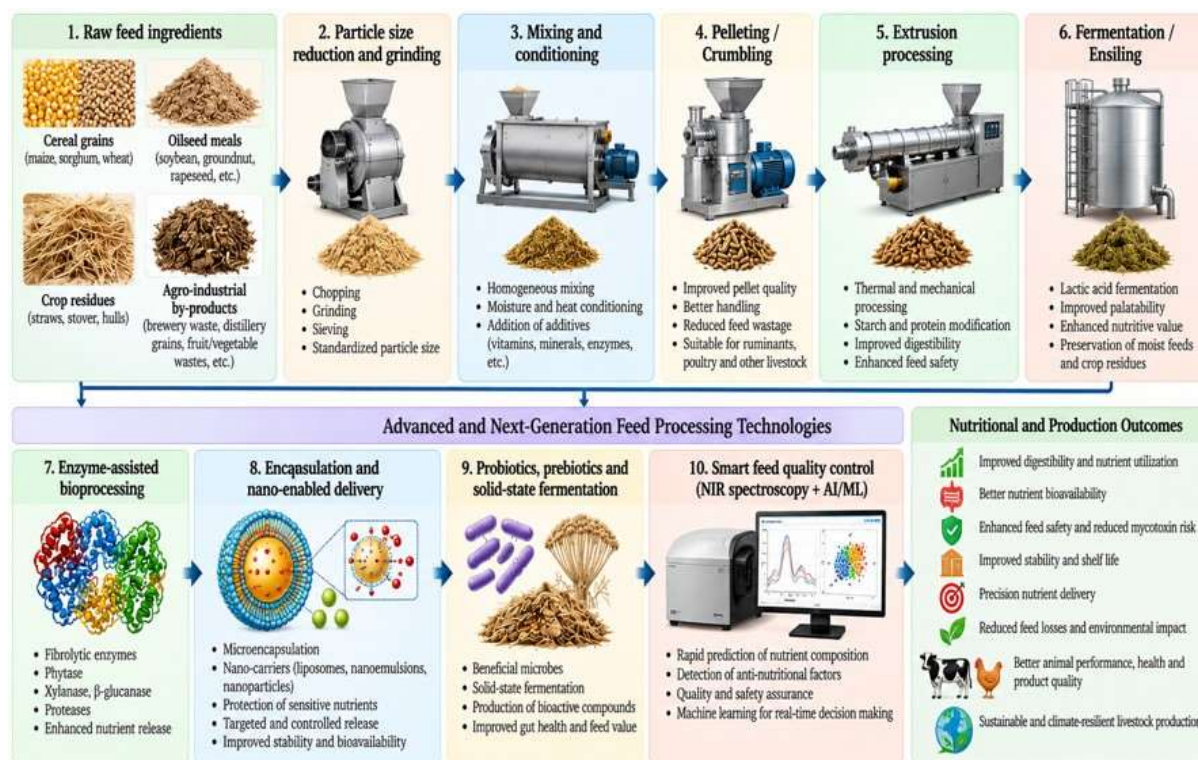


Fig. 1. Conventional and next-generation feed processing continuum, showing progression from raw-ingredient preparation through physical, thermal, fermentation, enzyme-assisted, encapsulation and digital quality-control technologies to improved nutrient utilization, feed safety and animal performance. The framework is synthesized from Abdollahi et al. (2013), Lancheros et al. (2020), Katu et al. (2025), Wang et al. (2026), Hossain et al. (2024) and You et al. (2025).

Figure 1 summarizes the central argument of this review: next-generation feed technology builds upon, rather than replaces, conventional processing. Grinding and pelleting determine the physical platform into which enzymes, fermented ingredients or encapsulated compounds may subsequently be incorporated. Thus, processing design should be considered as a continuum from ingredient preparation to nutrient delivery and quality assurance. This systems view is important when comparing technologies because a method that improves one nutritional trait may adversely affect another if temperature, moisture or residence time is poorly controlled.

1. Feed Processing as Nutritional Engineering

Feed processing changes the matrix in which nutrients exist. Mechanical reduction exposes internal surfaces and can increase accessibility

of starch and protein, whereas hydrothermal processing can gelatinize starch, denature proteins and alter fibre-associated structures. Biological processing adds a further layer because microorganisms and their enzymes can metabolize carbohydrates, proteins and phytochemicals before the feed is consumed. The nutritional consequence is therefore determined by both the initial ingredient and the processing trajectory (Lancheros *et al.*, 2020).

A useful framework is to distinguish four linked objectives: physical optimization, chemical modification, biological transformation and delivery control. Physical optimization includes particle-size standardization, density enhancement and pellet formation. Chemical modification includes gelatinization, denaturation and reduction of some anti-nutritional factors.

Biological transformation includes encapsulation and nano-enabled release. These fermentation and enzymatic hydrolysis. objectives can be combined in a single Delivery control includes coating, manufacturing chain.

Table 1. Major feed-processing technologies and their nutritional engineering functions.*Source/Reference basis: Compiled from Abdollahi et al. (2013), Lancheros et al. (2020), Siddiqui et al. (2022), Katu et al. (2025) and Wang et al. (2026).*

S. No.	Technology	Primary mechanism	Potential nutritional benefit	Major limitation
1	Grinding / particle-size reduction	Mechanical size reduction	Uniformity, accessibility of nutrients, reduced segregation	Too fine particles may increase dust or alter gut/rumen function
2	Mixing and conditioning	Moisture/heat homogenization	Uniform nutrient distribution, improved pelletability	Poor mixing creates batch variability
3	Pelleting	Pressure + steam + die compaction	Handling, reduced waste, altered starch/protein structure	Heat may damage some vitamins/enzymes
4	Extrusion / expansion	Heat + pressure + shear	Starch gelatinization, ANF reduction, ingredient restructuring	High severity can reduce heat-sensitive nutrients
5	Fermentation ensiling /	Microbial metabolism under controlled conditions	Preservation, detoxification, protein/functional metabolite enhancement	Process instability and contamination risk
6	Enzyme-assisted processing	Targeted hydrolysis	Reduction of phytate/fibre/oligosaccharides; improved availability	Enzyme stability and dose optimization required
7	Encapsulation / nano-delivery	Carrier-based protection and release	Stability, controlled release, targeted bioavailability	Safety, regulatory and residue concerns

As shown in Table 1, no processing method is universally superior. The appropriate technology depends on ingredient composition, target species, desired nutrient response, processing severity and economics. The core principle is to optimize the smallest set of changes required to achieve the nutritional objective while protecting feed safety and sensitive nutrients.

2. Conventional Processing: The Foundation of Modern Feed Manufacture

2.1 Grinding and particle-size control

Grinding remains one of the most basic but influential feed-processing operations. Hammer and roller mills modify particle size distribution, surface area and bulk density. In

monogastric diets, moderate particle-size reduction can improve energy and nutrient digestibility, while in ruminants particle size must be considered alongside physically effective fibre because excessive reduction of forage particles can compromise rumination and rumen buffering. Lancheros *et al.* (2020) summarized evidence that particle-size reduction can improve energy digestibility in several cereal and legume ingredients but also emphasized that responses are ingredient- and species-dependent.

Modern feed plants increasingly use particle-size monitoring rather than relying only on fixed grinder settings. This is relevant in India because regionally sourced grains and by-products can vary in hardness, moisture and contamination. Adaptive grinding based on

moisture and ingredient properties can reduce energy use and improve downstream pellet quality, although implementation requires suitable sensors and process control.

2.2 Mixing and conditioning

Mixing determines whether the formulated nutrient concentration is actually delivered consistently to the animal. Micro-ingredients such as trace minerals, enzymes and additives are particularly vulnerable to segregation. Conditioning before pelleting also determines the thermal and moisture history of the feed. Steam conditioning can improve binding and modify starch, but excessive exposure can reduce the activity of heat-sensitive enzymes, probiotics and some vitamins (Abdollahi *et al.*, 2013). Consequently, modern lines increasingly rely on post-pellet addition or protected formulations for sensitive additives.

2.3 Pelleting and pellet quality

Pelleting improves handling, bulk density, transport and intake characteristics and can reduce sorting and feed wastage. The process uses moisture, heat and mechanical pressure to agglomerate particles through a die. Nutritional effects arise from changes in starch and protein structures and from improved physical integrity. However, the magnitude of benefit varies with ingredient composition, pelleting severity and animal species (Abdollahi *et al.*, 2013; Lancheros *et al.*, 2020).

Recent work has moved toward quantitative prediction of pellet quality. You *et al.* (2025) evaluated formulation and manufacturing variables influencing Pellet Durability Index using 29 studies and 280 treatment means. Their results illustrate why pellet quality should be understood as a multivariable process outcome rather than as a property determined by one ingredient alone.

3. Thermal Processing: Pelleting, Extrusion and Expansion

3.1 Effects on starch

Thermal processing can alter starch granule integrity, gelatinization and subsequent susceptibility to digestive enzymes. Extrusion combines elevated temperature, moisture, pressure and shear, producing rapid structural transitions when material exits the die. The nutritional consequence is highly dependent on the starting cereal, moisture content and process severity. Reviews of extrusion chemistry emphasize that changes in starch order, swelling and molecular degradation can substantially modify digestibility (Jiao *et al.*, 2024).

For animal feeds, the desired degree of starch modification is not always the maximum possible gelatinization. Excessive processing may create unwanted stickiness, increased energy cost or nutrient losses, whereas insufficient treatment may leave the target anti-nutritional factors or structural barriers intact. Thus, process optimization should be outcome-based: the target might be improved digestible energy, controlled starch release, better pellet integrity or reduced anti-nutritional activity.

3.2 Effects on protein and amino acids

Heating can denature proteins and inactivate some proteinaceous anti-nutritional factors, which may improve access to proteolytic enzymes. On the other hand, excessive heat can promote Maillard reactions and reduce reactive lysine, thereby lowering amino acid availability. Extrusion studies in cereals such as barley, wheat, sorghum and broken rice have shown that available energy and amino acid digestibility can change after processing, supporting the need to evaluate nutritional consequences alongside physical quality (Zhang *et al.*, 2024).

3.3 Species-specific opportunities

In poultry, pelleting is widely used because it can improve feed handling and often supports efficient intake. In aquaculture, extrusion provides floating or slow-sinking feeds with controlled water stability. In ruminants, processing is more selective because the physical structure of the ration interacts with rumen fermentation and chewing activity. India therefore needs processing strategies tailored to production systems rather than direct transfer of equipment settings from intensive pig or poultry industries.

Table 2. Key variables controlling the nutritional and physical outcomes of thermal feed processing. *Source/Reference basis: Abdollahi et al. (2013), Lancheros et al. (2020), Jiao et al. (2024), You et al. (2025).*

S. No.	Processing factor	Primary effect	Potential advantage	Potential risk
1	Moisture	Affects heat transfer, plasticization and pellet binding	Optimum moisture improves conditioning and reduces fines	Too much moisture raises drying requirement
2	Temperature	Controls gelatinization, denaturation and microbial reduction	Can increase starch accessibility and improve safety	Excessive heat may reduce enzyme/vitamin activity
3	Pressure / shear	Determines structural disruption	Supports extrusion and expansion	High severity may increase energy demand
4	Residence time	Sets cumulative thermal exposure	Important for uniform processing	Long exposure may increase nutrient damage
5	Ingredient composition	Starch, fibre, protein and fat affect processing	Can be used to formulate for target pellet properties	Batch-to-batch variation reduces predictability
6	Particle size	Changes surface area and die throughput	Improves uniformity and binding when optimized	Extremely fine fractions may create dust and flow problems

Table 2 reinforces the need for process control. The same ingredient can respond differently when moisture, temperature or residence time changes. Feed manufacturing should therefore specify critical process limits and verify the final nutritional outcome rather than relying solely on equipment settings.

4. Non-Thermal and Emerging Physical Technologies

Non-thermal processing is receiving attention because it can reduce microbial loads or alter

material properties while limiting the cumulative heat burden imposed on sensitive feed components. Technologies such as pulsed electric fields, cold plasma, irradiation and high-pressure systems are much more established in food processing than in animal-feed manufacturing, but their principles are relevant to future feed applications, particularly for decontamination and preservation (Yaya-González *et al.*, 2025; Sikdar and Ghosh, 2026).

4.1 Cold plasma and oxidative decontamination

Cold plasma can generate reactive species capable of damaging microbial cells and, under optimized conditions, degrading selected contaminants. Its attraction for feed lies in the possibility of surface decontamination without the high temperatures used in conventional roasting or heat sanitation. However, plasma chemistry may also oxidize sensitive lipids, change sensory properties or produce secondary reaction products; therefore, animal-feed applications require matrix-specific validation.

4.2 Pulsed electric fields and related approaches

Pulsed electric fields (PEF) use short high-voltage pulses to permeabilize biological membranes. In feed systems, potential applications include microbial control, modification of plant tissues and facilitation of extraction or subsequent fermentation. Evidence from food processing shows that PEF can operate at comparatively low thermal loads, but cost, throughput and uniform treatment remain barriers for large-scale feed plants (Pandiselvam *et al.*, 2025).

4.3 Practical place in animal feed

The most realistic near-term role of non-thermal technologies may be as targeted interventions for high-value ingredients,

contaminated lots or sensitive functional products rather than universal processing steps. A processing line may combine sorting and cleaning with a selective decontamination stage, followed by conventional pelleting. Such hybrid systems are more likely to be economically justified than attempting to replace all heat-based processing.

For Indian conditions, a key consideration is decentralization. Small and medium feed units may not be able to adopt capital-intensive non-thermal equipment immediately. Demonstration projects should therefore compare energy use, throughput, reduction of contamination, nutritional preservation and cost per kilogram of safe feed, rather than technology novelty alone.

5. Fermentation as a Biotechnological Feed-Processing Platform

Fermentation represents a major transition from processing feed ingredients mechanically to biologically transforming them. Microorganisms can consume soluble carbohydrates, hydrolyze polymers, synthesize biomass and produce organic acids, enzymes and other metabolites. The result can be a feed ingredient with altered protein concentration, reduced anti-nutritional factors, improved palatability or enhanced functional properties. Recent reviews have emphasized fermentation for upgrading agricultural residues and low-grade protein ingredients, while the 2026 literature increasingly discusses precision control and process optimization (He and Cui, 2025; Zhang *et al.*, 2026).

5.1 Solid-state fermentation

Solid-state fermentation (SSF) is attractive for feed ingredients with relatively low free water because microbial growth occurs on a moist solid substrate with limited water movement. Agricultural by-products such as bran, oilseed meals and fibrous residues can serve as substrates. Microbial enzymes may hydrolyze

fibre, phytate or other anti-nutritional components while microbial biomass contributes protein and functional metabolites. Indian work has previously demonstrated the feasibility of SSF biomass in buffalo feeding and in vitro rumen studies, showing the relevance of this approach to crop-residue-based systems (Patel *et al.*, 2020; Sherasia *et al.*, 2016).

5.2 Lactic fermentation and ensiling

Lactic acid fermentation is fundamental to silage preservation. More controlled microbial inoculation can improve acidification, reduce undesirable fermentation and stabilize dry matter. For perishable green fodders and agro-industrial by-products, fermentation therefore functions both as a preservation technology and as a means of converting a seasonally available material into a storable feed. Wang *et al.* (2026) emphasized preservation and nutritional upgrading as complementary objectives of modern feed fermentation.

5.3 Fermentation of low-value ingredients

Fermentation is particularly valuable for ingredients restricted by fibre, protein quality or anti-nutritional factors. A 2025 review on low-grade poultry ingredients summarized evidence that fermentation can improve nutrient quality of alternative protein and by-product feeds, while an Indian Journal of Animal Nutrition study reported that fermentation conditions changed the nutritional composition of rice and wheat bran (Katu *et al.*, 2025; Debi *et al.*, 2025). These observations support the concept of “process-designed ingredients” in which the starting substrate and the microbial transformation are treated as one nutritional product.

6. Enzyme-Assisted and Microbial Bioprocessing

Exogenous enzymes offer a highly targeted form of feed processing. Unlike bulk thermal

treatment, enzymes can be selected for specific substrates: phytase hydrolyzes phytate; xylanases act on arabinoxylans; beta-glucanases reduce viscous cell-wall fractions; proteases hydrolyze proteins; and cellulases or hemicellulases can assist fibre breakdown. Enzyme use can be implemented before feeding, during ingredient processing or as a post-pellet inclusion when thermal stability is limited.

6.1 Enzyme synergy and substrate specificity

The greatest opportunity lies in matching enzyme combinations with ingredient composition. A multi-enzyme blend may be effective in wheat-based poultry diets because xylanase can reduce arabinoxylan-related viscosity and release nutrients trapped within cell walls, whereas a high-phytate ingredient may benefit from phytase. In fibrous ruminant feeds, cellulolytic enzymes may improve access to structural carbohydrates. However, responses are influenced by dose, pH, temperature, ingredient structure and the animal's endogenous digestion.

6.2 Microbial enzymes for feed safety

Biotechnology is increasingly relevant to mycotoxin control because selected microorganisms and enzymes can bind or biotransform toxins into less toxic compounds. Recent reviews emphasize enzyme discovery, microbial degradation and enzyme immobilization as important directions for sustainable detoxification (Zhu *et al.*, 2019; Makowska *et al.*, 2025). Because mycotoxins can be relatively heat-stable, relying only on conventional thermal processing is not sufficient for all contamination scenarios.

6.3 Precision fermentation

Precision fermentation extends conventional feed fermentation by using selected microorganisms, defined media and controlled

bioreactor conditions to generate specific products such as microbial protein, enzymes, vitamins or organic acids. The technology can decouple feed value from the original agricultural composition and may eventually support production of high-value feed ingredients with predictable composition. The current research challenge is to move from laboratory success to stable, economical, feed-grade production with regulatory traceability (Zhang *et al.*, 2026).

Table 3. Enzyme and microbial bioprocessing targets in next-generation feed technology.

Source/Reference basis: Lancheros *et al.* (2020), Zhu *et al.* (2019), Katu *et al.* (2025), Makowska *et al.* (2025), Zhang *et al.* (2026).

S. No.	Biotechnological agent	Target	Main processing/feeding role	Expected nutritional outcome
1	Phytase	Phytate	Releases P and bound minerals; lowers phytate effects	Mineral availability
2	Xylanase	Arabinoxylans	Reduces viscosity and releases entrapped nutrients	Energy and nutrient utilization
3	β -glucanase	β -glucans	Reduces viscosity and improves digesta flow	Digestibility
4	Protease	Protein/proteinaceous ANFs	Improves protein hydrolysis and may reduce inhibitors	Amino acid utilization
5	Cellulase / hemicellulose	Cellulose/ hemicellulose	Enhances fibre hydrolysis	Fibre utilization
6	Mycotoxin-degrading enzymes	Specific mycotoxins	Biotransformation into less toxic compounds	Feed safety

7. Encapsulation and Controlled Nutrient Delivery

Encapsulation changes the question from “How much nutrient is present in the feed?” to “How much active nutrient reaches the intended site in an active form?” Microencapsulation and nanoencapsulation can protect vitamins, essential oils, minerals, enzymes and other bioactives from heat, oxidation, moisture or premature interaction with other feed components. Siddiqui *et al.* (2022) reviewed a wide range of nanocarriers and emphasized improved protection, absorption and potential targeted delivery in animal feeding.

7.1 Microencapsulation

Microencapsulation typically uses a coating matrix such as starch derivatives, proteins, lipids or polysaccharides. The resulting particles can be designed to release the core material during storage, mixing or digestion. For feed manufacturers, this can improve uniformity and reduce losses of volatile or oxidation-sensitive compounds. It can also permit post-pellet addition of products that would otherwise be damaged by thermal processing.

7.2 Targeted release in ruminants

Ruminants provide a particularly interesting delivery problem because the rumen is both a digestive chamber and a microbial fermentation ecosystem. Some nutrients or bioactives may need protection from ruminal degradation to reach the small intestine, whereas other compounds should act directly within the rumen. Encapsulation offers the possibility of designing release profiles that respond to pH, enzymes or degradation conditions. This is conceptually aligned with precision nutrition, although practical validation of release kinetics under real rumen conditions remains essential.

7.3 Functional feed additives

Essential oils, polyphenols, probiotics, postbiotics and sensitive vitamins can benefit from protection during storage and processing. The objective is not necessarily to maximize absorption but to maintain a reproducible dose at the site where the biological response is expected. Such thinking may also reduce the required inclusion rate for some bioactives, although this should be demonstrated experimentally rather than assumed from particle size alone.

A central engineering challenge is “process compatibility.” An encapsulated nutrient must survive mixing, conditioning and pellet

formation while maintaining its intended release profile after ingestion. Therefore, carrier selection should be evaluated together with the complete manufacturing line, not in isolation.

8. Nano-Enabled Feed Technology

Nanotechnology introduces materials with dimensions and surface characteristics that differ from their bulk counterparts. In animal nutrition, research has focused on nano-minerals such as zinc, copper and selenium and on nanocarriers for bioactive compounds. Potential advantages include greater surface area, altered dissolution behavior and the possibility of lower inclusion rates. However, “nano” does not automatically mean “more effective”; biological performance depends on particle size, shape, surface chemistry, dose, aggregation and the receiving animal.

Indian studies provide useful examples. Work published in the Indian Journal of Animal Nutrition has evaluated nano-copper and nano-zinc in dairy calves, Sahiwal heifers and Barbari goats. In one Sahiwal-heifer study, nano-copper supplementation produced similar general performance while copper absorption was higher in nano-copper groups, suggesting that lower inclusion rates may merit investigation when bioavailability is demonstrably improved (Kumar *et al.*, 2022; Indian Journal of Animal Nutrition, 2024). A separate study in young calves compared nano-Cu and nano-Zn supplementation and assessed growth and nutrient utilization (Kumar *et al.*, 2024).

Nano-zinc also illustrates the need for careful dose-response interpretation. A 2025 review described ZnO nanoparticles as a promising feed additive but highlighted physicochemical characteristics and safety considerations. Indian experiments in goats and transition-period Sahiwal cows demonstrate that nano-minerals are already moving from conceptual

research toward species-specific nutritional trials, although long-term residue and environmental evaluations remain limited (Singh *et al.*, 2024; Nandanwar *et al.*, 2022; Wang *et al.*, 2025).

Figure 2 depicts the intended logic of nano-enabled nutrient delivery. The central pathway

is protection → controlled release → improved availability → host response, while safety and regulatory evaluation run in parallel. This parallel is essential because biological performance cannot be separated from the dose, exposure route and fate of the nanomaterial.

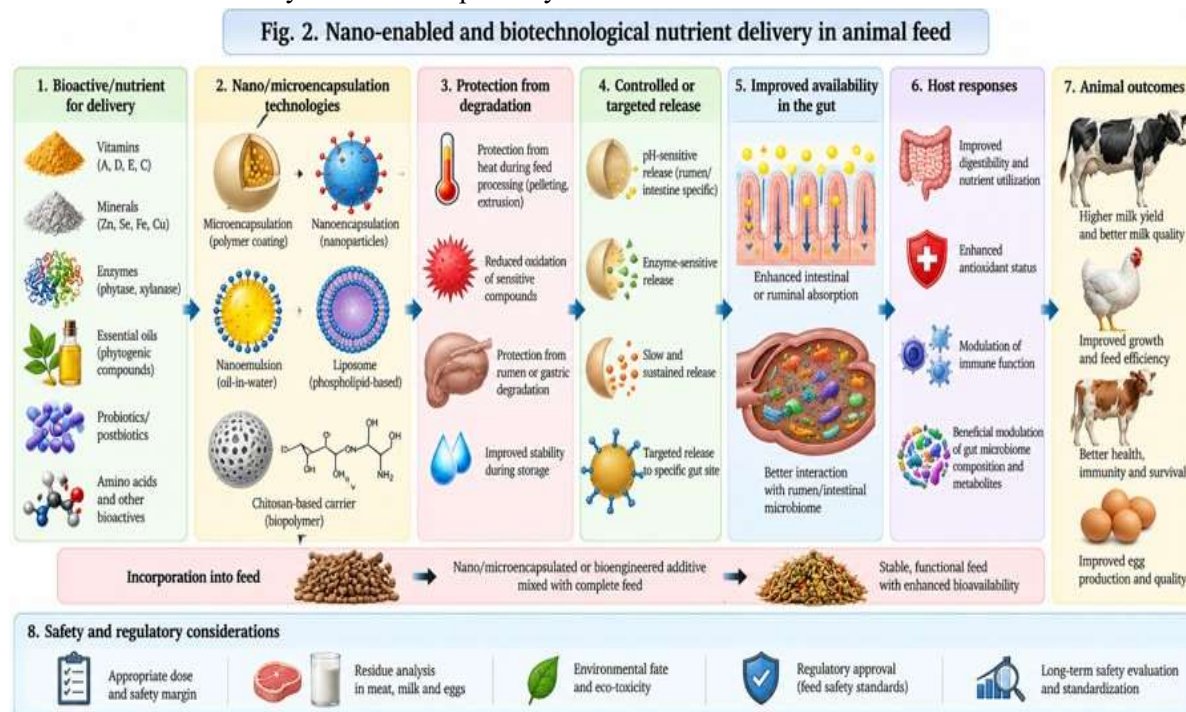


Fig. 2. Nano-enabled and biotechnological nutrient delivery pathway, from functional nutrient selection and nano/microencapsulation to controlled release, intestinal or ruminal availability, animal response and safety evaluation. The conceptual model is based on Siddiqui *et al.* (2022), Wang *et al.* (2025) and Indian studies summarized in the Indian Journal of Animal Nutrition (2022-2024).

9. Feed Safety and Mycotoxin Management through Processing

Feed safety is a core function of processing technology. Contaminants can enter feeds before harvest, during drying, transport or storage, and some contaminants persist despite conventional processing. Mycotoxins are particularly important because heat stability, heterogeneous distribution and multiple-toxin exposure complicate control. Recent reviews continue to identify aflatoxins, fumonisins, ochratoxin A, zearalenone and trichothecenes as major feed risks, while emerging

mycotoxins are receiving increasing attention (Food Bioscience, 2025; Food Control, 2026).

9.1 Physical and thermal approaches

Cleaning, sorting and removal of contaminated kernels remain fundamental because they can prevent contaminated material from entering the feed stream. Thermal treatment may reduce some microbial risks but is not uniformly effective against all mycotoxins. Consequently, process design should combine prevention, ingredient screening, segregation and, where necessary, targeted detoxification

rather than rely on a single decontamination step (Aldana *et al.*, 2014).

9.2 Biological detoxification

Microbial adsorption or biotransformation is attractive because it may generate fewer undesirable residues than some chemical treatments. Current biotechnology research explores specialized bacteria, yeasts and enzymes, as well as immobilized enzyme systems that can improve stability and reuse. Recent reviews in 2025-2026 emphasize biological and combined approaches as promising routes toward greener feed safety systems (Makowska *et al.*, 2025; Sikdar and Ghosh, 2026).

Table 4. Feed-processing and biotechnological options for mycotoxin risk management.

Source/Reference basis: Zhu *et al.* (2019), Shekhar *et al.* (2025), Food Bioscience (2025), Food Control (2026).

S. No	Approach	Mechanism	Strength	Important limitation
1	Ingredient sorting / cleaning	Physical removal	Simple and low chemical burden	Depends on uneven toxin distribution and contamination severity
2	Thermal processing	Heat-driven reduction/ inactivation	Integrated into pelleting/ extrusion	Not effective against all toxins; may affect nutrients
3	Adsorbents	Binding in gastrointestinal tract or feed	Can reduce bioavailability of selected toxins	Binding may be toxin-specific and non-selective
4	Microbial detoxification	Adsorption or biotransformation	Potentially selective and eco-friendly	Requires strain/process stability and validation
5	Enzymatic detoxification	Specific biochemical transformation	High target specificity possible	Cost, stability and regulatory requirements
6	Emerging technologies	Plasma, irradiation, HPP etc.	Potential targeted decontamination	Scale-up, cost and safety assessment needed

As summarized in Table 4, the best practical strategy is usually layered. Rapid screening and ingredient segregation should precede processing, and the chosen treatment should be verified for both toxin reduction and preservation of nutritional value.

9.3 Combined and emerging mycotoxin-control systems

The most promising feed-safety strategies increasingly combine complementary

mechanisms. A realistic manufacturing chain may use ingredient cleaning and segregation to reduce the initial contamination load, rapid screening to identify suspect batches, a physical or thermal treatment to lower selected hazards, and a biological detoxification step when a specific mycotoxin remains problematic. This layered approach is consistent with recent literature emphasizing that no single method reliably addresses all toxin types and all feed matrices. Future systems may also combine microbial enzymes with immobilized carriers or emerging physical treatments, provided nutritional quality and toxicological safety are preserved (Shekhar *et al.*, 2025; Sikdar and Ghosh, 2026).

10. Digital Feed Quality Control: NIRS, Sensors and Machine Learning

One of the most important next-generation developments is the conversion of feed quality control from slow laboratory testing to rapid in-line or at-line measurement. Near-infrared spectroscopy (NIRS) has attracted particular attention because it is rapid and largely non-destructive. A 2024 systematic review identified 718 publications and evaluated 54 studies in depth, concluding that NIRS can estimate parameters such as crude protein, fibre and moisture in livestock diets when calibration and validation are appropriately designed (Hossain *et al.*, 2024).

10.1 From NIRS to hyperspectral sensing

NIRS measures molecular information through spectral signatures dominated by overtone and combination bands. Machine-learning models can translate spectral patterns into predictions of chemical composition, but performance depends strongly on reference-data quality. Matrix differences, moisture, particle size, instrument transfer and spectral drift can reduce prediction robustness. Current research on NIR and hyperspectral imaging

increasingly emphasizes external validation, transfer learning and process monitoring rather than simply maximizing calibration R^2 (Xiao *et al.*, 2025; NIR-ML review, 2026).

10.2 AI-assisted manufacturing

Artificial intelligence can potentially link ingredient measurements with grinder settings, conditioning variables, pellet quality and final nutrient composition. The result is a closed-loop manufacturing system in which process variables are continuously adjusted to keep output within defined specifications. Such systems could be especially valuable where ingredient composition changes rapidly, as occurs with by-products or variable seasonal raw materials.

10.3 Process analytical technology and digital twins

The next step beyond stand-alone NIRS is process analytical technology, in which incoming-ingredient data and real-time equipment signals are combined to predict and control the final product. A digital-twin concept can represent the feed line virtually and estimate the effect of changes in moisture, ingredient composition, screw speed, conditioning temperature or die pressure. The 2026 animal-nutrition literature places AI and big-data systems within a broader precision-feeding framework; the same logic can be applied to feed manufacture, provided process data are standardized and model outputs are validated against laboratory measurements (Devi *et al.*, 2026).

Table 5. Digital technologies enabling data-driven feed manufacturing.
Source/Reference basis: Hossain et al. (2024), Xiao et al. (2025), Devi et al. (2026).

S. No.	Technology	Core capability	Example feed application	Future role
1	NIRS	Rapid composition prediction	Moisture, CP, fibre, selected quality attributes	Fast screening and formulation
2	Hyperspectral imaging	Spatial + spectral	Heterogeneity, defects and	Sorting and authentication

		information	some safety indicators	n
3	Process sensors	Temperature, moisture, pressure, torque	Real-time process state	Process control
4	Machine learning	Nonlinear pattern recognition	Quality prediction from multivariable data	Predictive control
5	AI decision support	Links formulation, process and outcome data	Dynamic setting optimization	Precision manufacturing

Table 5 shows why digitalization belongs within feed technology rather than outside it. A modern feed mill can be imagined as a sequence of sensing, processing and feedback operations. The key challenge is not the availability of algorithms but the creation of reliable, standardized datasets connecting raw-material variability, process conditions and biological outcomes.

11. Indian Context: From Crop Residues to Smart Feed Manufacturing

India offers a distinctive setting for next-generation feed technology because of the wide diversity of feed resources and production systems. Crop residues such as wheat and rice straw, sorghum and millet residues, sugarcane tops and other by-products are abundant but often limited by low protein, high fibre, silica or poor digestibility. Agro-industrial by-products from oilseed processing, breweries, distilleries and food processing can provide valuable nutrients but may be unstable or variable. Processing therefore offers a route to convert heterogeneous resources into more standardized ingredients.

11.1 Complete feed blocks and densification

Indian research has demonstrated complete feed blocks and straw-based densified rations as practical methods of combining roughages and concentrates into transportable, uniform units. Studies with rice- and wheat-straw-based complete feed blocks in calves and crossbred cattle illustrate the feasibility of this

approach, although animal responses depend on formulation and feeding system (Singh *et al.*, 2016; Sahib *et al.*, 2020). Such technologies can reduce labour associated with mixing separate components and may improve ration consistency for smallholders.

11.2 Fermentation and local by-products

Indian fermentation research also provides a strong translational base. Solid-state fermented biomass has been studied in lactating buffaloes, and more recent Indian Journal of Animal Nutrition papers have evaluated fermented rice and wheat bran and fermented rapeseed meal. These studies indicate that fermentation conditions themselves are nutritional variables: time, substrate moisture and environmental conditions can alter the final composition and biological activity of the product (Patel *et al.*, 2020; Debi *et al.*, 2025; Vasavi *et al.*, 2025).

11.3 Nano-minerals in Indian livestock research

Indian studies on nano-minerals are another bridge between advanced technology and local animal-production questions. Work in Sahiwal heifers, calves, Barbari goats and transition-period cattle demonstrates the feasibility of testing nano-Cu and nano-Zn in regionally relevant breeds. However, widespread adoption should wait for stronger evidence on optimal doses, long-term mineral balance, product residues and environmental fate.

Table 6. Indian feed resources and the most relevant next-generation processing opportunities.

Source/Reference basis: Sampath *et al.* (2005), ICAR reports, Singh *et al.* (2016), Patel *et al.* (2020), Debi *et al.* (2025), Indian Journal of Animal Nutrition (2024-2025), Siddiqui *et al.* (2022).

S. No.	Indian feed resource product /	Main challenge	Applicable processing technology	Potential value
1	Crop residues (rice/ wheat straw)	High fibre, variable silica	Chopping, densification, urea treatment, fermentation	Higher accessibility and storage efficiency
2	Oilseed meals	Good protein but variable ANFs	Heat treatment, fermentation, enzyme use	Improved protein utilization
3	Rice/ wheat bran	Energy-rich, variable	Stabilization, fermentation,	Improved storage and

		stability	pelleting	functional value
4	Agro-industrial by-products	Variable moisture and composition	Drying, fermentation, extrusion, blending	Resource recovery and standardization
5	Green fodders / silage crops	Seasonal availability	Ensiling and inoculation	Year-round feed availability
6	Nano-mineral premixes	High surface area formulations	Controlled dosing and protected inclusion	Potentially improved bioavailability
7	Functional phytochemicals	Volatile/ oxidizable bioactives	Micro/ nanoencapsulation	Improved stability and delivery

12. Sustainability, Circular Feed Systems and Climate Considerations

The environmental value of feed processing depends on whether the nutritional benefit exceeds the energy, water and material requirements of the process. A process that increases nutrient digestibility may reduce feed use per unit of animal product, but this benefit must be balanced against electricity and heat consumption. Fermentation can require less intensive thermal energy than some chemical treatments but may involve water, controlled environments and drying. Therefore, technology selection should use life-cycle thinking instead of evaluating processing only by laboratory digestibility.

12.1 Circular bioeconomy

Fermentation and other bioprocesses can support circular feed systems by upgrading agricultural wastes and food-processing side streams into feed ingredients. The 2025 review by He and Cui describes microbial conversion of organic residues into protein-rich biomass, while the 2026 feed-fermentation literature emphasizes waste valorization, functional metabolite generation and resource efficiency. Such systems are particularly relevant to India because feed and food production are physically interlinked through crop residues and agro-industrial by-products.

12.2 Climate-resilient feed manufacturing

Climate variability can alter moisture, storage stability, fungal growth and raw-material availability. Processing can help buffer some of this variability through drying, ensiling,

densification and rapid quality measurement. For example, a portable NIRS system could support rapid screening of incoming feedstocks, while fermentation or densification could stabilize materials available only seasonally. Climate resilience therefore begins before the animal consumes the feed: it is partly a property of the feed-manufacturing system.

12.3 Energy-aware processing

Future feed plants should track energy per tonne, water per tonne, processing yield, nutrient retention and emissions alongside pellet durability or product throughput. The best process may be a hybrid one: minimal grinding, targeted conditioning, efficient pelleting, post-pellet protected additives and digital quality checks. For decentralized Indian production, modular processing units powered partly by renewable energy could improve resilience, although techno-economic validation is still required.

13. Integrating Technologies: Toward Process-Driven Precision Nutrition

The most important future trend is convergence. Grinding, pelleting, extrusion, fermentation, encapsulation, NIRS and AI should not be viewed as separate technologies competing for adoption. They can form a hierarchy in which each process solves a specific problem. Ingredient variability can be identified by rapid analysis; particle size can be adjusted; thermal severity can be optimized; fermentation can be used on difficult substrates; sensitive additives can be encapsulated; and final feed quality can be continuously monitored.

13.1 A proposed integrated manufacturing chain

A practical next-generation workflow for Indian feed systems can be represented as: (1) raw-material screening; (2) rapid compositional analysis; (3) ingredient-specific

grinding; (4) formula correction; (5) conditioning and pelleting/extrusion; (6) fermentation or enzyme processing of selected streams; (7) post-processing addition of heat-sensitive or encapsulated additives; (8) final NIRS/chemical quality verification; and (9) tracking of animal response. The concept turns feed manufacture into a feedback-controlled nutritional process.

13.2 Linking feed matrix with biological target

A strong research question is therefore not “Does processing improve digestibility?” but “Which processing conditions produce the desired nutrient delivery profile for a specific animal and production stage?” This approach aligns feed technology with precision nutrition. In poultry, it may involve controlling starch availability and pellet quality. In ruminants, it may involve protecting selected proteins or additives while preserving physically effective fibre. In aquaculture, it may involve water stability and nutrient retention. The same processing technology can therefore have different optimal settings by species.

13.3 Need for multi-criteria evaluation

Future studies should measure at least four classes of outcomes: physical quality, chemical/nutritional quality, biological response and environmental/economic performance. Reporting only body-weight gain or digestibility is insufficient for emerging technologies. For nano-enabled systems, safety and residues must be included. For fermentation, microbial stability and batch reproducibility should be evaluated. For AI-based quality control, external validation and model transfer across instruments are essential.

14. Major Research Gaps and Future Directions

Despite rapid technological development, several barriers limit translation from

laboratory studies to commercial feed manufacture.

- Process standardization: fermentation, encapsulation and nano-formulations frequently vary in substrate, carrier, particle characteristics, dose and process conditions, making studies difficult to compare.
- Biological validation: improved physical or chemical properties must be connected to digestibility, metabolism, animal health and productive response under practical feeding conditions.
- Scale-up and economics: pilot-scale success does not guarantee industrial feasibility. Energy demand, equipment depreciation, throughput and product recovery need systematic assessment.
- Safety and regulation: nano-materials and novel bioprocessed ingredients require clear specifications for particle properties, residues, environmental fate and dose margins.
- Data interoperability: NIRS, process sensors, formulation systems and animal-response datasets need standardized reference measurements before AI models can be transferred across feed mills.
- Indian adaptation: locally available feed resources, decentralized manufacturing, infrastructure constraints and breed-specific responses require India-specific validation rather than direct extrapolation from intensive systems elsewhere.

14.1 Priority research themes for India

For Indian Animal Nutrition, several areas are especially suitable for interdisciplinary projects: fermentation of rice/wheat straw and oilseed by-products; enzyme-assisted upgrading of low-quality roughages; complete

feed block optimization; nano-mineral dose-response studies in indigenous cattle and buffaloes; encapsulation of phytogetic compounds for heat-stressed livestock; NIRS prediction of Indian feed-resource variability; and AI-assisted optimization of feed processing conditions. These topics can combine laboratory feed analysis with animal trials and techno-economic assessment.

14.2 From “technology adoption” to “technology matching”

The future question is not whether a technology is advanced, but whether it is correctly matched to a defined nutritional bottleneck. Where the primary problem is dust or segregation, pelleting may be sufficient. Where the problem is an anti-nutritional factor, enzyme treatment or fermentation may be more appropriate. Where the problem is instability of a bioactive, encapsulation may provide the missing function. Where ingredient variability is the main challenge, rapid NIRS and process control may have greater value than additional processing severity. This technology-matching approach can make innovation more economical and scientifically defensible.

15. Technology Readiness and Validation Framework for Feed Processing

Technology readiness in feed processing should be assessed across the entire pathway from raw material to animal response. A feed process may be technically feasible at laboratory scale but still fail to reach practical deployment because of inconsistent raw materials, throughput limitations, heat damage, energy demand or insufficient quality-control infrastructure. Accordingly, validation should proceed through sequential levels: bench characterization, controlled pilot processing, repeatability testing, animal feeding trials, economic analysis and, finally, field-scale demonstration. This sequence is particularly

relevant to fermentation, nano-enabled delivery and AI-based process control, where laboratory protocols can be highly sensitive to conditions that are difficult to reproduce in commercial plants.

Table 7. A staged validation framework for translating next-generation feed technologies from laboratory studies to commercial use.

Source/Reference basis: Synthesized from Lancheros et al. (2020), Siddiqui et al. (2022), Hossain et al. (2024), You et al. (2025), Zhang et al. (2026) and Wang et al. (2026).

S. No.	Validation stage	Main question	Key measurements	Decision criterion
1	Laboratory proof-of-concept	Ingredient and process response	Chemical composition, particle size, enzyme activity, microbial stability	Analytical reproducibility
2	Pilot-scale processing	Repeatability at practical throughput	Yield, energy use, moisture, pellet quality, bioactive retention	Batch-to-batch consistency
3	Nutritional validation	Animal response	Digestibility, nutrient retention, feed intake, performance	Biological efficacy
4	Safety validation	Risk characterization	Mycotoxins, residues, microbial safety, nanomaterial fate	Safety margin
5	Economic validation	Cost-effectiveness	Capital cost, energy, labour, cost/kg feed, value of nutrient improvement	Economic feasibility
6	Field validation	System-level deployment	Variable ingredients, climate, operator effects, farm outcomes	Robustness and scalability

Table 7 emphasizes that biological performance is only one component of technology validation. An encapsulated phytogenic may show improved stability in a laboratory assay but still lose its protective function during pelleting. Similarly, an NIRS calibration may achieve strong internal accuracy but fail when the instrument is moved to a different feed mill. A staged validation framework allows these weaknesses to be identified before full deployment.

16. Research Design Priorities for Indian Feed Technology

Indian research can gain substantially from standardized, multi-location experiments that

retain realistic feed-resource variability. Studies should record the origin, moisture, particle-size distribution, chemical composition and previous processing history of every ingredient. Fermentation experiments should report inoculum identity, substrate moisture, temperature, pH, fermentation time and post-fermentation drying conditions. Nano-enabled studies should report particle size distribution, morphology, surface characteristics, elemental composition, aggregation behaviour and actual delivered dose. Digital quality-control studies should report the reference analytical method, calibration population, external validation set and model-transfer performance.

A second priority is to connect processing variables with biological endpoints. Instead of reporting only final pellet durability or crude protein content, studies should determine whether the processed feed changes starch disappearance, amino acid digestibility, fibre degradation, rumen fermentation, gut microbial composition, oxidative status or animal productivity. For functional and fermented feeds, metabolomics and targeted microbial analysis may help identify why two products with similar proximate composition produce different biological responses.

A third priority is techno-economic and environmental accounting. Energy consumed during grinding, steam conditioning, extrusion and drying should be reported alongside product recovery and nutrient retention. For circular-feed technologies, investigators should also quantify how much waste substrate is diverted from disposal and whether the resulting feed reduces purchased protein or mineral inputs. These measurements can reveal when a processing technology creates a genuine systems benefit rather than merely shifting resource use from one stage to another.

CONCLUSION

Feed processing is entering a phase in which mechanical, thermal, biological and digital technologies are increasingly integrated. Grinding, conditioning, pelleting and extrusion remain the foundation because they determine the physical structure of feeds and influence nutrient availability. Fermentation and enzyme-assisted processing add the ability to transform difficult substrates and reduce selected anti-nutritional factors. Encapsulation and nano-enabled systems introduce a delivery dimension in which nutrients and bioactives can be protected and released more deliberately. NIRS, sensors and machine learning provide the analytical and control layer needed to operate these processes with greater precision.

The strongest opportunity for India lies in combining these technologies with the country's diverse feed-resource base. Crop residues, oilseed meals, cereal by-products, green fodders and agro-industrial streams need processing strategies designed around their specific limitations. The objective should be to convert variable and underutilized resources into nutritionally consistent, safe and biologically functional feeds. Indian studies on complete feed blocks, fermentation and nano-minerals demonstrate that the foundations already exist, but commercial translation requires stronger standardization, multi-location validation, economic analysis and safety evaluation.

Next-generation feed technology should therefore be viewed as a continuum: characterize the ingredient, modify its structure, improve its nutritional availability, protect or target sensitive components, verify quality rapidly and connect the manufactured feed with animal outcomes. Such an integrated model offers a practical route toward precision nutrition, circular feed systems and more efficient livestock production. The future feed

mill may consequently function less as a simple mixing-and-pelleting plant and more as a data-informed nutrient-delivery platform in which processing conditions are selected according to the biological function required from the feed.

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