Porcine Research

Cereal-based feed systems in swine production: from primary grains to by-product valorisation in a circular bioeconomy

[1]Teodor Rusu, [2]Praveen Pandey

[1] Department of Technical and Soil Sciences, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania; [2] Division of Plant Breeding and Genetic Resource Conservation, CSIR - Central Institute of Medicinal and Aromatic Plants, Lucknow, India. Corresponding author: P. Pandey, pandeypraveen1986@yahoo.com

Abstract. This mini-review examines cereal-based feed systems in swine production, with particular emphasis on the integration of primary grains and agro-industrial by-products within a circular bioeconomy framework. Major cereal grains such as corn, wheat, and rice remain fundamental energy sources in pig nutrition, yet their processing generates substantial co-products that can be effectively valorised. The paper synthesizes current knowledge on the nutritional characteristics of cereal fractions and by-products, including wheat bran, middlings, and distillers dried grains with solubles (DDGS), highlighting their roles in maintaining growth performance and feed efficiency when properly formulated. Additionally, the review explores technological interventions such as enzymatic supplementation and microbial fermentation that enhance nutrient digestibility and reduce anti-nutritional factors. The potential of incorporating food-industry residues, including bakery waste, into swine diets is discussed in the context of reducing agri-food losses and improving resource efficiency. Life cycle assessment (LCA) studies are analyzed to evaluate the environmental implications of feed reformulation strategies, demonstrating that feed production remains the primary contributor to the environmental footprint of pork. The inclusion of alternative feed ingredients and by-products can significantly reduce land use, greenhouse gas emissions, and other environmental impacts. Overall, the integration of cereal by-products into swine feeding systems represents a viable pathway toward more sustainable and resource-efficient livestock production.
Keywords: agro-industrial by-products, cereal grains, circular bioeconomy, DDGS, feed efficiency, fermentation, food waste valorisation, life cycle assessment, sustainability, swine nutrition.

Introduction. Cereal grains and their processing by-products are central to pig feeding and to the environmental footprint of pork. Integrating primary grains, milling co-products and food-industry residues into swine diets links nutrition, feed efficiency, food-waste reduction and life cycle impacts within a circular bioeconomy.

The aim of this study is to critically evaluate the role of cereal-based feed systems in modern swine production, with a focus on the integration of primary grains and their processing by-products within a circular bioeconomy framework. Specifically, the paper seeks to (i) assess the nutritional value and functional limitations of major cereal fractions and co-products used in pig diets, (ii) analyze their effects on feed conversion efficiency and nutrient utilization, (iii) examine the potential of agro-food waste valorisation strategies for reducing resource losses, and (iv) evaluate the environmental impacts of these feeding systems through life cycle assessment approaches. By synthesizing recent scientific evidence, the study aims to identify sustainable feeding strategies that balance animal performance, economic viability, and environmental responsibility.

Utilization of Cereal Fractions and Processing By-Products. Corn, wheat, rice and generally cereals remain core energy sources for domestic animals and human population (Tiwari et al 2011; Pandey & Tiwari 2012; Syafruddin, 2017; Aedin et al., 2019; Guta & Marin, 2020; Pandey et al., 2026), providing high digestible and metabolizable energy,

though their amino acid digestibility and anti-nutritional risks differ (Rosenfelder et al., 2013; McAuliffe et al., 2016; Pan et al., 2017; Stas et al., 2024). Wheat co-products (bran, middlings, shorts, red dog) are increasingly used; they are richer in fiber and protein but reduce diet energy density, requiring careful formulation (Rosenfelder et al., 2013; Stas et al., 2024). Distillers dried grains with solubles (DDGS) from corn and wheat concentrate protein, phosphorus and fiber; corn DDGS tends to have higher digestible and metabolizable energy and amino acid digestibility than other DDGS sources (Widyaratne & Zijlstra, 2007; Rothmund et al., 2026). Bakery meal and other food-industry residues can replace cereals and soybean meal while maintaining pig growth when nutritionally balanced (Melas et al., 2023; Kum et al., 2025). Microbial and solid-state fermentation, including co-fermentation of DDGS with lignocellulosic feedstocks, is promoted to upgrade low-value residues (wheat bran, corn stover, fruit–vegetable discards) into more digestible, protein-enriched feeds (Pan & An, 2020; Fan et al., 2023; Yafetto et al., 2023) (Table 1, Figure 1).

Table 1

Illustrative cereal by-products and circular feed roles

By-product/ residue	*Main nutritional features/issues*	*Role in circular systems and constraints*	*References*
Corn DDGS	High CP, fiber, P; high DE/ME, good AA digestibility	Displaces grain; limits: fiber, PUFA, carcass and FCR effects	Widyaratne & Zijlstra, 2007; Wu et al., 2016; Pan & An, 2020; Wang et al., 2025; Rothmund et al., 2026
Wheat bran and middlings	Higher fiber, moderate CP, NSP enrichment	Valorises flour-milling streams; may depress energy without enzymes	Rosenfelder et al., 2013; Aderibigbe et al., 2024; Stas et al., 2024
Bakery meal	Mixed cereal/fat/sugar residues	20% inclusion reduced land use and toxicity impacts	Melas et al., 2023
Mixed agro-food wastes (bran, peels, hulls)	Low initial value, anti-nutritional factors	Fermentation upgrades protein, digestibility, safety	Fan et al., 2023; Malenica et al., 2023; Nath et al., 2023; Yafetto et al., 2023

Feed Conversion Efficiency and Nutrient Utilization. Cereal choice and processing strongly influence growth and feed conversion. Corn-, wheat- and sorghum-based diets can support similar average daily gain, but sorghum may reduce protein digestibility and increase nitrogen excretion unless inclusion is limited or protease is added (McAuliffe et al., 2016; Pan et al., 2017). In grow-finish pigs, high DDGS or wheat middlings levels can slightly reduce early growth and carcass yield, though overall gain:feed can be maintained when diets are formulated on a net energy basis (Widyaratne & Zijlstra, 2007; Wu et al., 2016). Enzyme complexes targeting non-starch polysaccharides in wheat-, barley- and middlings-rich diets improve digestibility of dry matter, energy and fiber, enhancing gain:feed without major microbiome disruption (Rosenfelder et al., 2013; Aderibigbe et al., 2024). Systematic databases of DDGS energy and amino acid digestibility improve predictability in diet formulation, helping to maintain performance when conventional cereals are partially displaced (Pan & An, 2020; Wang et al., 2025; Rothmund et al., 2026).

Reduction of Agri-Food Losses and Waste Through Feed. Valorising agro-industrial and food-system by-products as animal feed is highlighted as a key strategy to reduce food waste, conserve resources and close nutrient loops (Fan et al., 2023; Malenica et al., 2023; Nath et al., 2023; Yafetto et al., 2023). Bakery by-products converted to meal and incorporated into pig diets directly divert human food-chain waste from disposal (Melas et al., 2023). Reviews of food-waste-to-feed systems emphasize that biofuel co-products (DDGS), oilseed meals, cereal brans, fruit and vegetable discards and crop residues can be upgraded by bioprocessing (fermentation, enzymatic treatments) to improve protein quality, fiber utilization and phosphorus digestibility, while lowering mycotoxins and other anti-nutritional factors (Pan & An, 2020; Fan et al., 2023; Nath et al., 2023; Yafetto et al., 2023). These practices support EU-style circular-economy and green-biorefinery concepts by transforming low-value streams into nutritious, lower-cost feeds for pigs and other livestock (Fan et al., 2023; Malenica et al., 2023).

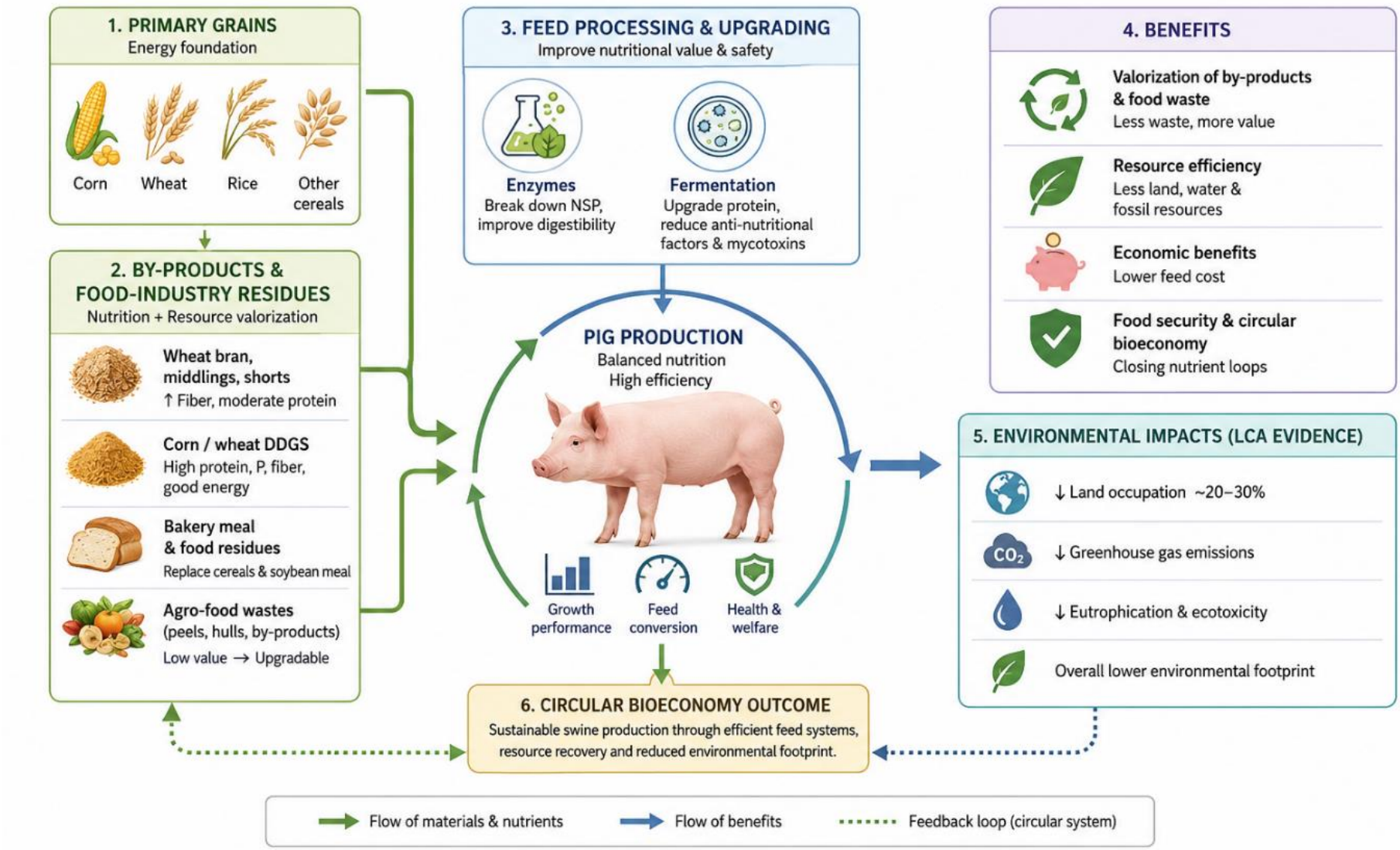

Figure 1. Cereal-based feed system in swine production, from primary grains to by-product valorisation in a circular bioeconomy.

LCA-Based Evaluation of Cereal-Based and By-Product Feed Systems. Life cycle assessment shows feed production as the dominant environmental hotspot in pig systems, often contributing 60-70% of impacts per kg of live weight or product (McAuliffe et al., 2016; Santos et al., 2025; Treml et al., 2025). Reformulating feeds toward alternative ingredients and by-products (e.g. bakery by-product, peas) can reduce environmental burdens, especially land occupation and climate change potential, while sometimes also reducing feed cost (Melas et al., 2023; Kum et al., 2025). In a Greek case study, including 20% bakery meal in pig diets decreased land occupation by about 30% and reduced marine eutrophication, freshwater ecotoxicity and human carcinogenic toxicity by 20-25%, mainly through lower wheat and soybean cultivation (Melas et al., 2023). Multi-objective LCA optimisation of pig feeds found bakery by-products could lower environmental impacts by up to 9% and peas could cut costs by up to 28%, illustrating trade-offs and synergies among impact categories and economics (Kum et al., 2025). Broader reviews of pig-production LCAs underline that improving feed efficiency, lowering crude-protein levels, and using more sustainable ingredients are key levers for reducing greenhouse-gas emissions, eutrophication and toxicity, particularly when combined with improved manure management and bioenergy recovery (McAuliffe et al., 2016; Sun et al., 2024; Santos et al., 2025; Treml et al., 2025).

Conclusions. Cereal-based feed systems remain a cornerstone of swine production, yet their sustainability increasingly depends on the efficient utilization of by-products and residues generated along the agri-food chain. The incorporation of cereal processing co-products such as DDGS, wheat bran, and food-industry residues can partially replace conventional feed ingredients without compromising animal performance, provided that diets are precisely formulated to account for variability in nutrient composition and digestibility. Advances in feed processing technologies, including enzyme supplementation and microbial fermentation, further enhance the nutritional value of low-quality biomass and mitigate anti-nutritional constraints.

From an environmental perspective, feed production constitutes the dominant hotspot in pig production systems, making feed reformulation a critical lever for reducing overall impacts. Evidence from life cycle assessment studies indicates that substituting conventional cereals with alternative ingredients and by-products can significantly lower land use, greenhouse gas emissions, and ecotoxicity indicators, while also contributing to cost efficiency. Moreover, the valorisation of agro-industrial and food-system wastes as animal feed aligns with circular bioeconomy principles by closing nutrient loops and minimizing waste streams.

Finally, the transition toward more sustainable swine production systems requires an integrated approach that combines nutritional optimization, technological innovation, and environmental assessment. Cereal by-product valorisation represents a key strategy in this transition, offering tangible benefits for both production efficiency and ecological sustainability.

Acknowledgements. OpenAI ChatGPT-5.3 - https://openai.com - was used for plate editing. An AI-powered search engine for research - https://consensus.app – Consensus NLP, Inc – was used to summarize data in a table.

Authors Contributions. TR wrote the manuscript; PP read and revised the manuscript.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This research received no external funding.

References

Aderibigbe, A. S., Park, C. S., Johnson, T., Velayudhan, D. E., Vinyeta, E., & Adeola, O. (2024). Efficacy of a novel multi-enzyme feed additive on growth performance, nutrient digestibility, and gut microbiome of weanling pigs fed corn–wheat or wheat–barley-based diet. *Journal of Animal Science, 102*, skae064.

Aedin, C., Mircea, V., & Marin, D. I. (2019). Research regarding the influence of soil tillage and fertilization on corn hybrids (*Zea mays* L.) grown in Osmancea area, Constanta County, Romania. *AAB Bioflux, 11*(2), 109-119.

Fan, W., Sun, X., Cui, G., Li, Q., Xu, Y., Wang, L., Li, X., Hu, B., & Chi, Z. (2023). A strategy of co-fermentation of distillers dried grains with solubles (DDGS) and lignocellulosic feedstocks as swine feed. *Critical Reviews in Biotechnology*, *43*(2), 212-226.

Guta, B. A., & Marin, D. I. (2020). Grain yield and yield components on an assortment of winter wheat (*Triticum aestivum* L.) genotypes cultivated under conditions of A.R.D.S. Teleorman. *AAB Bioflux, 12*(2), 45-51.

Kum, S. W., Voccia, D., Grimm, M., Froldi, F., Suciu, N. A., & Lamastra, L. (2025). Reducing the environmental impacts of pig production through feed reformulation: a multi-objective life cycle assessment optimisation approach. *Sustainability, 17*(18), 8509.

Malenica, D., Kass, M., & Bhat, R. (2023). Sustainable management and valorization of agri-food industrial wastes and by-products as animal feed: for ruminants, non-ruminants and as poultry feed. *Sustainability, 15*(1), 117.

McAuliffe, G. A., Chapman, D. V., & Sage, C. L. (2016). A thematic review of life cycle assessment (LCA) applied to pig production. *Environmental Impact Assessment Review, 56*, 12-22.

Melas, L., Batsioula, M., Malamakis, A., Patsios, S. I., Geroliolios, D., Alexandropoulos, E., Skoutida, S., Karkanias, C., Dedousi, A., Kritsa, M. Z., Sossidou, E. N., & Banias, G. F. (2023). Circular bioeconomy practices in the Greek pig sector: the environmental performance of bakery meal as pig feed ingredient. *Sustainability, 15*(15), 11688.

Nath, P. C., Ojha, A., Debnath, S., Sharma, M., Nayak, P. K., Sridhar, K., & Inbaraj, B. S. (2023). Valorization of food waste as animal feed: a step towards sustainable food waste management and circular bioeconomy. *Animals, 13*(8), 1366.

Pan, L., & An, D. (2020). Comparative energy and nitrogen excretion from growing pigs fed on corn, sorghum and wheat-based diets. *Animal Feed Science and Technology, 264*, 114477.

Pan, L., Shang, Q. H., Wu, Y., Ma X. K., Long, S. F., Liu, L., Li, D. F., & Piao, X. S. (2017). Concentration of digestible and metabolizable energy, standardized ileal digestibility, and growth performance of pigs fed diets containing sorghum produced in the United States or corn produced in China. *Journal of Animal Science, 95*(11), 4880-4892.

Pandey, P., & Tiwari, D. K. (2012). Modern techniques and agronomic packages for hybrid rice cultivation in India. *Advances in Agriculture and Botanics, 4*(1), 17-21.

Pandey, P., Petrescu-Mag, I. V., & Banatean-Dunea I. (2026). Rice–fish co-culture systems: yield, production, advantages and limitations. *AACL Bioflux, 19*(3), 1068-1083.

Rosenfelder, P., Eklund, M., & Mosenthin, R. (2013). Nutritive value of wheat and wheat by-products in pig nutrition: a review. *Animal Feed Science and Technology, 185*(3-4), 107-125.

Rothmund, V. L., Kiefer, C., Ton, A. P. S., Sbardella, M., de Paula, V. R. C., Cirino, L. C., Lima, I. C., Leda, A. L. B., de Moura, M. M., Pissinatti, N. S., da Silva, J. F., de Freitas, L. W., & Corassa, A. (2026). Nutritional composition and digestibility of corn ethanol coproducts in swine feed: a systematic literature review. *Animals, 16*(4), 560.

Santos, L., Ferreira, M., Domingos, I., Oliveira, V., Rodrigues, C., Ferreira, A., & Ferreira, J. (2025). Life cycle assessment of pig production in Central Portugal: environmental impacts and sustainability challenges. *Sustainability, 17*(2), 426.

Stas, E. B., DeRouchey, J. M., Goodband, R. D., Tokach, M. D., Woodworth, J. C., & Gebhardt, J. T. (2024). Nutritional guide to feeding wheat and wheat co-products to swine: a review. *Translational Animal Science, 8*, txae106.

Sun, X., Dou, Z., Shurson, G. C., & Hu, B. (2024). Bioprocessing to upcycle agro-industrial and food wastes into high-nutritional value animal feed for sustainable food and agriculture systems. *Resources, Conservation and Recycling, 201*, 107325.
Syafruddin, (2017). Maize-soybean intercropping in double row plant spacing. *AAB Bioflux, 9*(1), 21-33.
Tiwari, D. K., Pandey, P., Tripathi, S., Giri, S. P., & Dwivedi, J. L. (2011). Studies on genetic variability for yield components in rice (*Oryza sativa* L.). *AAB Bioflux, 3*(1), 76-81.
Treml, N., Rudi, A., & Schultmann, F. (2025). Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany. *Journal of Cleaner Production, 503*, 145408.
Wang, C., Huang, X., Liu, X., Wang, R., Li, J., Meng, Q., & Shan, A. (2025). Strategies for efficient utilization of corn distillers dried grains with solubles in diets of pigs: a review. *Animals, 15*(12), 1727.
Widyaratne, G. P., & Zijlstra, R. T. (2007). Nutritional value of wheat and corn distiller's dried grain with solubles: digestibility and digestible contents of energy, amino acids and phosphorus, nutrient excretion and growth performance of grower-finisher pigs. *Canadian Journal of Animal Science, 87*, 103-114.
Wu, F., Johnston, L. J., Urriola, P. E., Hilbrands, A. M., & Shurson, G. C. (2016). Effects of feeding diets containing distillers' dried grains with solubles and wheat middlings with equal predicted dietary net energy on growth performance and carcass composition of growing-finishing pigs. *Journal of Animal Science, 94*(1), 144-154.
Yafetto, L., Odamtten, G. T., & Wiafe-Kwagyan, M. (2023). Valorization of agro-industrial wastes into animal feed through microbial fermentation: a review of the global and Ghanaian case. *Heliyon, 9*(4), e14814.

Received: 22 April 2026. Accepted: 20 May 2026. Published online: 11 June 2026.
Authors:
Teodor Rusu (TR), Department of Technical and Soil Sciences, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: teodor.rusu@usamvcluj.ro
Praveen Pandey (PP), Division of Plant Breeding and Genetic Resource Conservation, CSIR - Central Institute of Medicinal and Aromatic Plants, Lucknow-226015, India, e-mail: pandeypraveen1986@yahoo.com

How to cite this article:
Rusu T., Pandey P., 2026 Cereal-based feed systems in swine production: from primary grains to by-product valorisation in a circular bioeconomy. Porcine Research 16(1):69-74.