



Integrated pig production and biogas from manure: energy, economics and environment

¹O. Călin Safirescu, ^{1,2}Petru Burduhos, ³F. Camelia Oroian

¹ Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania; ² EBBSA International, Niš, Serbia; ³ Faculty of Horticulture and Business for Rural Development, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania. Corresponding author: P. Burduhos, petru.burduhos@usamvcluj.ro

Abstract. Integrated pig production combined with anaerobic digestion (AD) of manure represents a viable strategy to convert agricultural waste into renewable energy and valuable biofertilizer. This study synthesizes recent findings on the energy performance, economic feasibility, and environmental implications of pig-manure-based biogas systems. Methane yields vary significantly depending on operational parameters and co-digestion strategies, with optimized systems achieving substantial improvements in energy output. Economic analyses indicate that profitability is strongly influenced by farm scale, energy valorization pathways, and policy incentives, with digestate utilization playing a key role in revenue generation. Environmentally, AD systems reduce greenhouse gas emissions, improve waste stabilization, and enhance nutrient recycling, although challenges related to ammonia emissions, digestate management, and system optimization remain. Overall, integrated pig-biogas systems can significantly improve farm sustainability when properly designed and managed.

Keywords: pig manure, anaerobic digestion, biogas production, farm sustainability, methane yield, digestate management.

Introduction. Simultaneous pig production and anaerobic digestion (AD) of manure can turn a waste management cost into an energy and fertilizer resource (Bora et al., 2025), while influencing farm profitability and environmental performance.

The aim of this study is to evaluate the integration of pig production with anaerobic digestion systems, focusing on three main dimensions: (i) energy performance and biogas production efficiency, (ii) economic profitability at farm level under different operational scenarios, and (iii) environmental impacts, including greenhouse gas emissions, nutrient recycling, and potential trade-offs. The study seeks to identify the conditions under which integrated systems become sustainable and economically viable.

Energy Performance of PIG-Manure Biogas Systems. AD of pig manure alone typically yields methane in the range 171–249 L CH₄ kg⁻¹ volatile solids (VS), with co-digestion increasing yields substantially (Tian et al., 2023; Correa et al., 2025; Wang et al., 2018). A meta-analysis of 384 case studies reported average methane yield of 171 L kg⁻¹ VS for mono-digestion of animal manure, rising to 249 L kg⁻¹ VS with co-digestion; swine manure in continuous reactors reached 212–322 L kg⁻¹ VS (Tian et al., 2023). Optimized co-digestion of pig manure with rice straw achieved 553.8 mL biogas g⁻¹ VS (Correa et al., 2025), and co-digestion with corn straw gave maximum volumetric biogas production rates of about 2.6 L L⁻¹ d⁻¹ at organic loading rate (OLR) 6 g VS L⁻¹ d⁻¹ (Wang et al., 2018). In a lab study focused on pig manure, the optimal OLR of 1.89 g VS L⁻¹ d⁻¹ produced 438 mL CH₄ g⁻¹ VS (Theansuwan & Laohavanich, 2025). Farm- and country-scale modeling for pig manure at 37 °C and 30-day hydraulic retention showed CH₄ productivities up to 1.03 m³ m⁻³ d⁻¹, equivalent to 42 m³ CH₄ per ton of manure

and ~466 kWh electricity ton⁻¹, with 184 kg CO₂-equivalent avoided per ton (Zhang et al., 2021). Field biodigesters on Ivorian pig farms (1:4 manure:water) produced 16–23 m³ biogas over 56 days per 1600 L unit, giving 2.3–3.3 kWh d⁻¹ at 80–82% CH₄ after upgrading (Bae et al., 2024). At farm scale, a 3500-head pig farm equipped with a photosynthetic upgrading plant achieved net energy production of about 687 kWh d⁻¹ of vehicle-grade biomethane (Putmai et al., 2020), while a medium farm running a biogas-fueled generator showed stable electrical output of 80–120 kW and thermal efficiency up to 11.7% with improved engine control (Zhang et al., 2020). Studies on farm management show that spreading pig batches to stabilize wastewater flow can cut electricity purchases by 36–44%, corresponding to saving about 43,782 m³ biogas per year (~35,834 kWh) compared with conventional all-in/all-out management (N’guessan et al., 2025). Lowering nitrogen content of manure via low-protein pig diets did not reduce specific methane yield; CH₄ concentration remained 60–65% with stable digestion even at OLR 2.15 g COD L⁻¹ d⁻¹ at 20 °C (Ma et al., 2020). Co-digestion with other organic residues (olive pomace, grass silage, crop residues) can more than double or even quintuple methane yields (e.g., from 53 to 283 mL CH₄ g⁻¹ VS for olive pomace when pig manure was added) and generate surplus electricity and heat (about 577 MWh y⁻¹ electricity and 1074 MWh y⁻¹ heat in a full-scale co-digestion plant) (Shih et al., 2021; Palomar et al., 2024; Wang et al., 2018; Tian et al., 2023). These figures indicate that well-designed swine-biogas systems can cover a significant share of on-farm electricity and heat demand and, in some cases, export energy.

Table 1

Energy performance metrics for pig-manure biogas systems:
key energy outputs from pig-manure biogas systems and co-digestion

<i>System / Parameter</i>	<i>Typical performance values</i>	<i>References</i>
Mono-digestion, animal manure	171 L CH ₄ kg ⁻¹ VS	Tian et al., 2023
Co-digestion, continuous swine AD	212–322 L CH ₄ kg ⁻¹ VS	Tian et al., 2023
Optimized pig manure AD (lab)	438 mL CH ₄ g ⁻¹ VS at OLR 1.89 g VS L ⁻¹ d ⁻¹	Theansuwan & Laohavanich, 2025
Pig manure + rice straw	553.8 mL biogas g ⁻¹ VS	Correa et al., 2025
Farm modeling (scraper manure)	42 m ³ CH ₄ ton ⁻¹ ; ~466 kWh ton ⁻¹ ; 184 kg CO ₂ -eq ton ⁻¹ avoided	Zhang et al., 2021
Medium farm generator	80–120 kW electrical; ~11.7% peak thermal efficiency	Zhang et al., 2020
3500-head farm, photosynthetic upgrading	~687 kWh d ⁻¹ net energy; annual profit 30,348 €	Putmai et al., 2020
Farm management optimization	43,782 m ³ biogas y ⁻¹ (35,834 kWh) saved vs. conventional	N’guessan et al., 2025.

Economic Profitability and Farm-Level Integration. Economic analyses indicate that integrating AD with pig production can be profitable, but profitability thresholds depend on herd size, by-product valorization and local energy prices. A Brazilian lab-scale and techno-economic study found that, when revenues included biofertilizer sales, a swine-biogas system became economically viable from around 1,300 pigs, with biofertilizer contributing roughly 72% of total revenue; if only electricity was sold, viability required about 10,468 pigs, yielding 14.69 kW electrical capacity (Ning et al., 2019). For Taiwanese small farms, adding a rapid-build AD module into the existing 3-stage wastewater treatment system yielded average biogas production of 46.4 m³ d⁻¹ and electricity income of about 6091 USD per year, while significantly lowering pollution charges and externalities (Myers et al., 2023). A life-cycle techno-economic study of centralized co-digestion of swine manure with corn stover in Iowa showed that small, distributed digesters were not competitive with natural gas at prevailing prices, but centralized large-scale plants with grid injection could become competitive when

benefiting from low-carbon fuel standard and renewable fuel standard credits (Parodi et al., 2021). Photosynthetic upgrading of pig-farm biogas with microalgae showed relatively low capital and operating costs compared with conventional upgrading, and in a 3500-head farm delivered 687 kWh d⁻¹ net energy and an estimated annual profit of 30,348 €, demonstrating that advanced upgrading integrated in pig units can support vehicle-fuel production at modest scale (Putmai et al., 2020). On-farm electrical self-consumption models and improved swine-batch management lowered purchased electricity costs by 36–44% without new capital investment in digesters, mainly by avoiding long lag phases and smoothing biogas output (N'guessan et al., 2025). A biogas-to-electricity system on a medium swine farm showed a breakeven period of ~15.8 months under base assumptions, remaining economically viable under ±20% variation in biogas yield and ±10% fluctuations in electricity price, indicating robust payback for well-sized plants (Zhang et al., 2020). Country-specific modeling in Korea suggested that manure from pig-fattening operations treated by scraper systems can produce up to 141–184 kg CO₂-equivalent emission reduction per ton of manure, together with 276–466 kWh electricity per ton, highlighting significant climate and energy value per unit of pig output (Zhang et al., 2021). Overall, profitability is markedly enhanced when digestate is commercialized as fertilizer, when co-substrates increase methane yields, and when policies reward low-carbon gas; smaller farms may require cooperative or centralized models to reach economic scale (Ning et al., 2019; Myers et al., 2023; Parodi et al., 2021; N'guessan et al., 2025; Putmai et al., 2020; Zhang et al., 2020; Zhang et al., 2021; Tian et al., 2023).

Environmental Impacts, Disadvantages and Co-Benefits. From an environmental standpoint, coupling pig production with AD significantly changes the pollution profile compared with direct manure application or composting. A life cycle assessment for Ireland found that mono-digestion of pig manure followed by land application of digestate cut direct greenhouse gas (GHG) emissions by 48% (190 t CO₂-eq) compared with direct land spreading, while co-digestion of manure with grass silage increased total energy recovery by 226% (additional 1592 MWh) and showed better performance in 9 of 11 environmental impact categories (Palomar et al., 2024). In this case, nitrogen available for plants in digestate (41.8%) was slightly lower than in raw manure (43.2%) due to increased ammonia losses after AD, and land area requirements for digestate application were governed mainly by phosphorus limits (Palomar et al., 2024). At pig farms in Côte d'Ivoire, on-farm digesters reduced chemical oxygen demand, biochemical oxygen demand, organic acids and total nitrogen in slurry, while achieving near-complete removal of pathogens such as *Escherichia coli*, *Enterococcus* and *Salmonella*; spore-forming *Bacillus* and *Clostridium* were reduced by 3.1–5.8 log₁₀ but not fully eliminated (Bae et al., 2024). In Taiwan, retrofitting an AD module into swine wastewater treatment reduced the farm's carbon footprint by 22.6% and emissions of methane by 51.8%, sulfur oxides by 92.6%, nitrogen oxides by 74.2%, carbon monoxide by 54.7%, nitrous oxide by 28.6%, suspended particulates by 95.4% and non-methane volatile organic compounds by 80%; damage impacts to human health, ecosystem quality and resource scarcity were reduced by 82%, 59% and 87% respectively (Myers et al., 2023). Farm-level management models that stabilize AD loading reduce periods of excess biogas flaring, cutting avoidable GHG emissions by roughly 9441–11,902 m³ CO₂-equivalent per year for the scenarios tested (N'guessan et al., 2025). At national level, modeling of pig-manure AD scenarios showed emission reductions of 85–184 kg CO₂-eq per ton of manure, depending on management type, alongside significant renewable electricity generation (Zhang et al., 2021). However, some disadvantages and environmental trade-offs are evident. Digestate typically contains high levels of mineral nitrogen and phosphorus; in Ireland, digestate application area was constrained mainly by soil phosphorus saturation, implying substantial land requirements and transport distances, especially under strict environmental regulations (Palomar et al., 2024). Increased ammonia emissions during and after AD can raise local air-pollution and indirect N₂O formation unless controlled; studies on composting of pig manure show that poor management can lose 27.5% of total nitrogen (mostly as NH₃ and N₂O) and 48.7% of

total carbon (mainly as CO₂), and that N-rich feedstocks elevate NH₃ and GHG losses (De Castro E Silva et al., 2021; Liu et al., 2023). Composting meta-analyses highlight that mis-managed composting emits large amounts of N₂O (the dominant GHG from composting, contributing about 74% of GHG impact) (De Castro E Silva et al., 2021). For AD-based systems, similar issues arise if digestate storage and spreading are not optimized. Co-digestion and co-treatment strategies create additional nutrient-use opportunities but also risks. For example, using black soldier fly larvae on pig manure stores about 25% of manure nitrogen and 14% of its energy into larval biomass, but increases CO₂ emissions (247 vs. 148 g kg⁻¹ manure DM) and ammonia emissions (7 vs. 4.5 g NH₃-N kg⁻¹) during treatment, while methane emissions remained approximately 1.3 g kg⁻¹ DM in both treatments (Duan et al., 2019). Composting optimization strategies such as adding biochar, bean dregs, zeolite or wood vinegar can significantly cut nitrogen loss (up to 24–28%) and reduce NH₃, N₂O and CH₄ emissions by 30–80%, indicating that integrating AD with improved solid-fraction composting could further reduce the environmental footprint of swine systems (Hickmann et al., 2024; Liu et al., 2023; Yang et al., 2019). Another challenge is energy required for heating digesters in temperate or cold climates. Reactor-scale analysis showed that low OLR and low solids content increase water and energy consumption and produce more diluted digestate, while high OLR reduces reactor volume and capital cost but can risk instability over long runs; biogas boilers were the most favorable heating option under moderate OLR, with combined heat and power (CHP) becoming more attractive at higher OLR (Theansuwan & Laohavanich, 2025). Finally, large centralized biogas systems can entail substantial transport of manure and co-substrates, with associated costs and emissions, unless sited carefully; centralized systems using pig manure and corn stover were economically attractive only under strong policy incentives and required significant corn-stover harvest areas (up to 1116 ha for the largest configuration) and land for digestate application (about 1576 ha) (Parodi et al., 2021; Palomar et al., 2024; Myers et al., 2023; Liu et al., 2023; De Castro E Silva et al., 2021; Yang et al., 2019; Duan et al., 2019; Theansuwan & Laohavanich, 2025).

Conclusions. The integration of pig production with anaerobic digestion offers a robust pathway for transforming manure from an environmental liability into a valuable resource. Energy performance can be significantly enhanced through co-digestion and process optimization, enabling partial or full energy self-sufficiency at farm level. Economic viability depends largely on system scale, energy valorization routes, and the effective use of digestate as fertilizer, with larger or cooperative systems showing greater competitiveness. From an environmental perspective, AD reduces greenhouse gas emissions, improves sanitation, and supports circular nutrient flows, although careful management of digestate and emissions is essential to avoid secondary pollution. Overall, integrated pig-biogas systems represent a key component of sustainable livestock production, particularly when supported by appropriate technological design and policy frameworks.

Acknowledgement. OpenAI ChatGPT-5.3 - <https://openai.com> - was used for plate editing. The plate is the authors' design.

Authors Contributions. OCS wrote the manuscript; PB and FCO read and revised the manuscript.

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

Data Availability. Not applicable.

Funding. This research received no external funding.

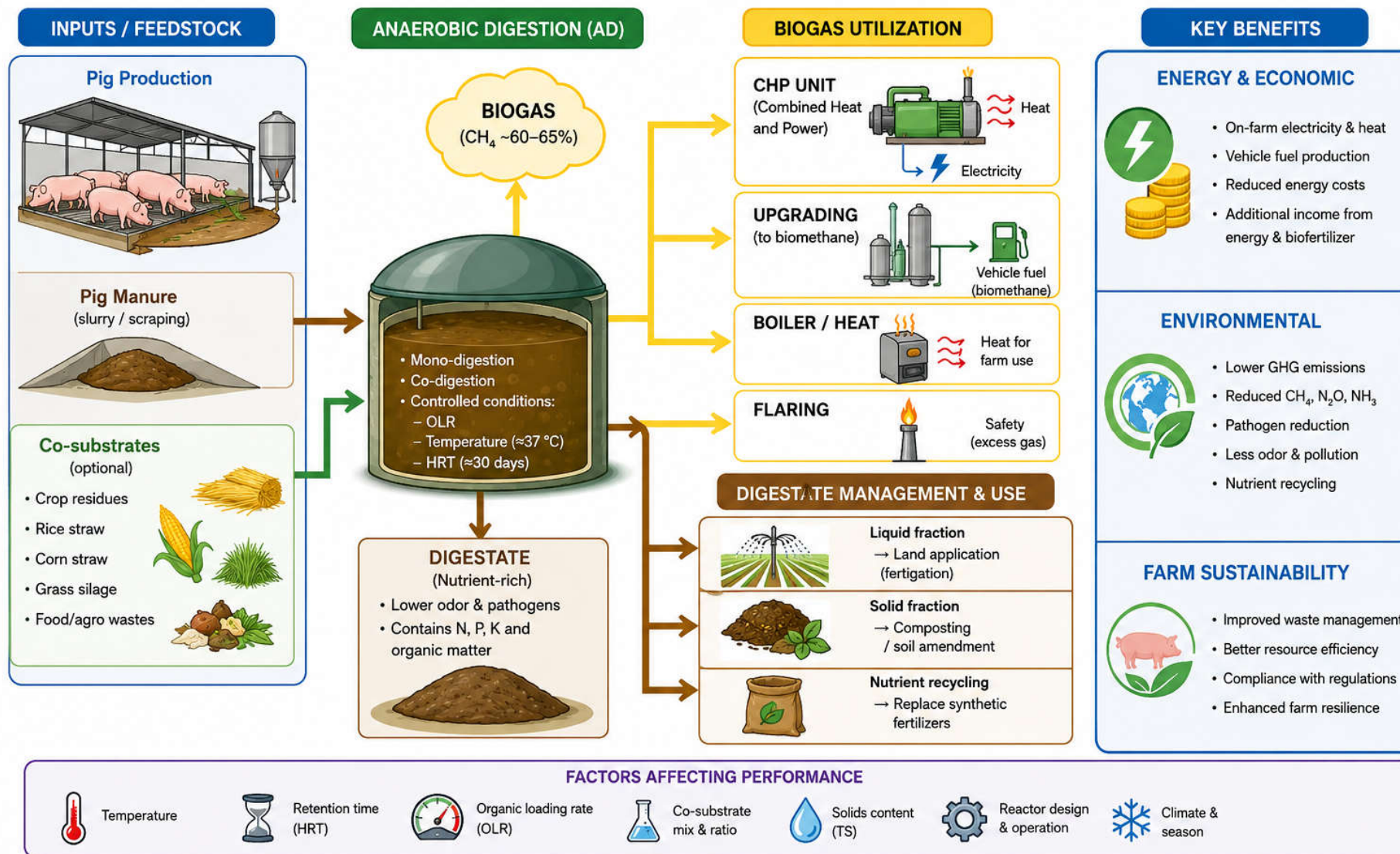


Figure 1. Integrated pig production and biogas system: schematic overview of inputs, processes, outputs, and key benefits.

References

- Bae, I., Park, S., Shin, J., Triolo, J. M., & Shin, S. G. (2024). Country-specific modeling of methane production and emission reduction utilizing pig manure. *Energies*, *18*, 95.
- Bora, F. D., Rusu, T., Popescu, M., Petrescu-Mag, I. V., Păsărin, B., Oroian, I. G. (2025). Swine manure as a feedstock for soil surrogate substrate production. *Porcine Research*, *15*(1), 22-28.
- Correa, S., Llamas, M., Passos, F., Zahedi, S., Espinosa, J. M., Feroso, F., & Ferrer, I. (2025). Enhancing methane yield and microbial resilience in olive pomace anaerobic digestion via co-digestion with pig manure. *Biotechnology for Biofuels and Bioproducts*, *18*, 114.
- De Castro E Silva, H. L., Barros, R., Filho, G. L. T., Lora, E. S. S., Santos, A. H. M., Santos, I. D. F. D., De Oliveira Boton, M. C. C., Pedreira, J. R., & Flauzino, B. K. (2021). Lab-scale and economic analysis of biogas production from swine manure. *Renewable Energy* *186*, 350-365.
- Duan, N., Zhang, D., Lin, C., Zhang, Y., Zhao, L., Liu, H., & Liu, Z. (2019). Effect of organic loading rate on anaerobic digestion of pig manure: Methane production, mass flow, reactor scale and heating scenarios. *Journal of Environmental Management*, *231*, 646-652.
- Hickmann, F. M. W., Salahshournia, B., Andretta, I., Letourneau-Montminy, M., & Rajagopal, R. (2024). Impact of lowering nitrogen content in pig manure through low crude protein diets on anaerobic digestion process stability, biogas yields, and digestate composition. *The Science of the Total Environment*, *953*, 175957.
- Liu, Y., Tang, R., Li, L., Zheng, G., Wang, J., Wang, G., Bao, Z., Yin, Z., Li, G., & Yuan, J. (2023). A global meta-analysis of greenhouse gas emissions and carbon and nitrogen losses during livestock manure composting: Influencing factors and mitigation strategies. *The Science of the Total Environment*, *885*, 163900.
- Ma, G., Ndegwa, P., Harrison, J. H., & Chen, Y. (2020). Methane yields during anaerobic co-digestion of animal manure with other feedstocks: A meta-analysis. *Science of the Total Environment*, *728*, 138224.
- Myers, G. M., Andersen, D., Martens, B. J., & Raman, D. R. (2023). Cost assessment of centralizing swine manure and corn stover co-digestion systems. *Energies*, *16*(11), 4315.
- N'guessan, A. R., Bi, Y. C. T., Yapo, E. G. A. S., Koffi, A. R. H., Yebouet, F. O., Campitelli, A., Aka, B., & Djeni, N. T. (2025). Enhanced biogas production and pathogen reduction from pig manure through anaerobic digestion: a sustainable approach for urban waste management in Abidjan, Côte d'Ivoire. *Clean Technologies*, *7*(4), 89.
- Ning, J., Zhou, M., Pan, X., Li, C., Lv, N., Wang, T., Cai, G., Wang, R., Li, J., & Zhu, G. (2019). Simultaneous biogas and biogas slurry production from co-digestion of pig manure and corn straw: Performance optimization and microbial community shift. *Bioresour. Technol.*, *282*, 37-47.
- Palomar, C. R., Álvaro, A. G., Muñoz, R., Reparaz, C., Ortega, M. F., & De Godos, I. (2024). Pre-commercial demonstration of a photosynthetic upgrading plant: investment and operating cost analysis. *Processes*, *12*(12), 2794.
- Parodi, A., Gerrits, W., Van Loon, J. V., De Boer, I. D., Aarnink, A., & Van Zanten, H. V. (2021). Black soldier fly reared on pig manure: Bioconversion efficiencies, nutrients in the residual material, greenhouse gas and ammonia emissions. *Waste Management*, *126*, 674-683.
- Putmai, N., Jarunglumert, T., Prommuak, C., Pavasant, P., & Flood, A. (2020). Economic analysis of swine farm management for the enhancement of biogas production and energy efficiency. *Waste and Biomass Valorization*, *11*, 5635-5645.
- Shih, M.-F., Lay, C., Lin, C.-Y., & Chang, S.-H. (2021). Exploring the environmental and economic potential for biogas production from swine manure wastewater by life cycle assessment. *Clean Technologies and Environmental Policy*, *25*, 451-464.
- Theansuwan, W., & Laohavanich, J. (2025). Development of a Biogas-Based Power Generation System for Swine Farms: Performance and Economic Evaluation. *Energies*, *18*, 6482.

- Tian, P., Gong, B., Bi, K., Liu, Y., J., Wang, X., Ouyang, Z., & Cui, X. (2023). Anaerobic co-digestion of pig manure and rice straw: optimization of process parameters for enhancing biogas production and system stability. *International Journal of Environmental Research and Public Health*, 20(1), 804.
- Wang, Q., Awasthi, M., Ren, X., Zhao, J., Li, R., Wang, Z., Wang, M., Chen, H., & Zhang, Z. (2018). Combining biochar, zeolite and wood vinegar for composting of pig manure: The effect on greenhouse gas emission and nitrogen conservation. *Waste Management*, 74, 221-230.
- Yang, Y., Awasthi, M. K., Du, W., Ren, X., Lei, T., & Lv, J. (2019). Compost supplementation with nitrogen loss and greenhouse gas emissions during pig manure composting. *Bioresource Technology*, 297, 122435.
- Zhang, Y., Jiang, Y., Wang, S., Wang, Z., Liu, Y., Hu, Z.-H., & Zhan, X. (2020). Environmental sustainability assessment of pig manure mono- and co-digestion and dynamic land application of the digestate. *Renewable and Sustainable Energy Reviews*, 137, 110476.
- Zhang, Z., Liu, D., Qiao, Y., Li, S., Chen, Y., & Hu, C. (2021). Mitigation of carbon and nitrogen losses during pig manure composting: A meta-analysis. *The Science of the total Environment*, 783, 147103.

Received: 18 May 2026. Accepted: 07 June 2026. Published online: 07 June 2026.

Authors:

Ovidiu Călin Safirescu (OCS), Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: calin.safirescu@usamvcluj.ro

Petru Burduhos (PB), Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: petru.burduhos@usamvcluj.ro

Firuța Camelia Oroian (FCO), Faculty of Horticulture and Business for Rural Development, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: camelia.oroian@usamvcluj.ro

This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

How to cite this article:

Safirescu O. C., Burduhos P., Oroian F. C., 2026 Integrated pig production and biogas from manure: energy, economics and environment. *Porcine Research* 16(1):57-63.