

Integrated Anaerobic Digestion and Composting for Energy and Material Recovery from Dairy Waste in Arid Climates: A Case Study from Qatar

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Introduction

The rapid growth of the dairy industry has resulted in the generation of large volumes of organic waste, including wastewater, whey, and sludge (Aamir Shahzad et al., 2025). In arid and hot regions such as Qatar, the management of these waste streams presents significant environmental and operational challenges due to limited land availability, water scarcity, and high ambient temperatures (Naeem et al., 2024). Conventional waste disposal practices, such as landfilling and uncontrolled discharge, contribute to greenhouse gas (GHG) emissions, eutrophication, and soil degradation (Kurniawan et al., 2024). Anaerobic digestion (AD) is a well-established biological process for treating high-strength organic waste while producing renewable energy in the form of biogas. However, the digestate generated from AD requires further stabilization before safe reuse (Duan et al., 2025). Composting offers an effective post-treatment option to convert digestate into nutrient-rich biofertilizer. Integrating AD and composting provides a closed-loop waste management strategy that enhances both energy and material recovery (Cucina, 2023). This study presents an integrated anaerobic digestion and composting (IADC) framework tailored to dairy waste management in arid climates, with Qatar as a representative case. The proposed approach aligns with Qatar National Vision 2030 and the United Nations Sustainable Development Goals (SDGs 6, 7, 12, and 13) by reducing environmental impacts while promoting circular economy practices (Figure. 1).

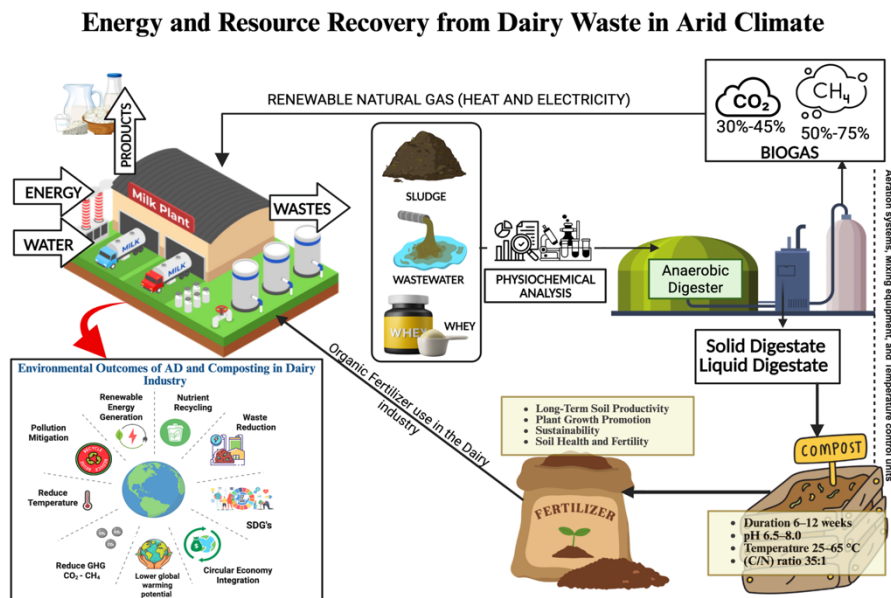


Figure 1. Graphical abstract of Anaerobic digestion and composting of Dairy waste.

Materials and Methods

Dairy wastewater, whey, and sludge were selected as the main waste streams due to their high organic content. Anaerobic digestion performance was evaluated based on literature data suitable for arid climates, considering pH (6.8–7.5), C/N ratio (20–30), and hydraulic retention time (20–30 days).

The solid digestate obtained from AD was treated through aerobic composting under controlled conditions, including moisture content of 50–60%, thermophilic temperatures (50–60 °C), and a composting duration of 45–60 days. The integrated system was assessed for energy recovery, nutrient recycling, and environmental benefits.

Results and Discussion

The integration of anaerobic digestion and composting significantly enhances resource recovery from dairy waste streams. Anaerobic digestion effectively reduces the organic load of wastewater, whey, and sludge while producing biogas that can be utilized for heat and electricity generation within dairy facilities. Reported methane

yields for dairy waste range from 0.35 to 0.45 m³ CH₄/kg volatile solids, demonstrating strong potential for renewable energy production in arid climates (Cárdenas et al., 2021). Composting of the AD digestate improves the stability of organic matter and increases the availability of essential nutrients such as nitrogen, phosphorus, and potassium. The resulting compost can be safely applied as a biofertilizer, reducing dependence on chemical fertilizers and supporting sustainable agricultural practices (Dincă et al., 2024).

Table 1. Conceptual integration of AD and composting studies about dairy waste management in Arid regions.

Category	Key Findings	Reference
Biogas yield optimization	Co-digestion of whey and sludge improves methane yield by 15-40 % vs single-substrate digestion.	Ghanimeh et al., 2025
Digestate valorization	Composting the digestate stabilizes organic matter and enhances N-P-K availability.	María, 2024
Circular-economy integration	AD with composting aligns with SDGs 6,7,12 and 13, reducing GHGs and closing loops.	Li et al., 2025
Climate-adapted operations	High temperature and low moisture in arid climates require insulated control during composting.	Singh et al., 2022;

In arid regions, compost application also enhances soil water retention and structure, which is critical for agricultural productivity. From an environmental perspective, the integrated system reduces GHG emissions by diverting organic waste from landfilling and offsetting fossil fuel use through biogas utilization (Ansar et al., 2025). The closed-loop IADC framework supports a transition from a linear “take–make–dispose” model to a circular economy by converting waste into valuable energy and material products (Figure. 2).

Despite these advantages, challenges remain, including process optimization under high temperatures, digestate handling, and the need for supportive policies and market pathways for biogas and compost. Addressing these challenges through pilot-scale implementation and techno-economic analysis is essential for large-scale adoption in Qatar and similar arid regions (Sher et al., 2024).

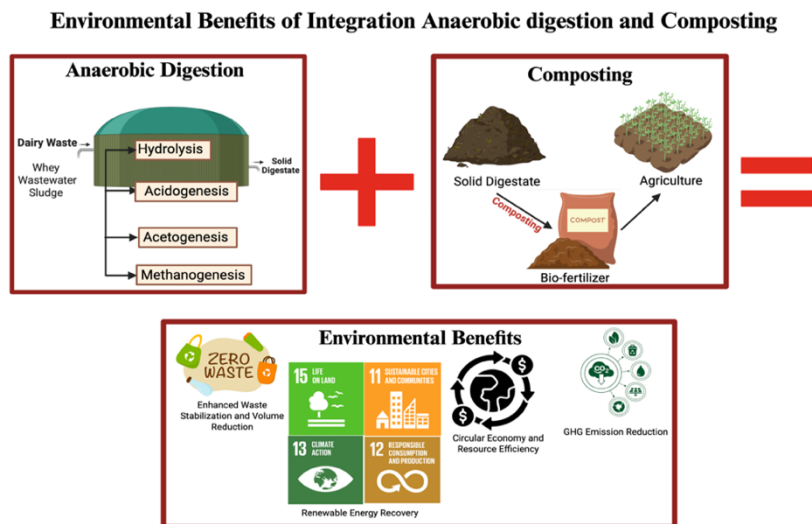


Figure 2. Environmental Benefits of Integrated system (AD-composting).

Conclusion

This study demonstrates that integrating anaerobic digestion and composting provides an effective and sustainable solution for dairy waste management in arid climates. The proposed IADC framework enables simultaneous energy recovery and nutrient recycling, reduces environmental impacts, and supports circular economy objectives. In the context of Qatar, this approach aligns with national sustainability strategies and offers a viable pathway to reduce GHG emissions while enhancing resource efficiency. Future work should focus on pilot-scale validation, life-cycle assessment, and economic feasibility to support practical implementation.

References:

- Aamir Shahzad, H. M., Asim, Z., Elkahout, Z. I., Mahmoud, K. A., Almomani, F., & Rasool, K. (2025). Integrated bioprocess for single-cell protein production: Converting waste-derived biogas into sustainable feed protein. *Energy Conversion and Management*, *X*, 26, 101036. <https://doi.org/10.1016/j.ecmx.2025.101036>
- Ansar, A., Du, J., Javed, Q., Adnan, M., & Javaid, I. (2025). Biodegradable Waste in Compost Production: A Review of Its Economic Potential. *Nitrogen*, *6*(2), 24. <https://doi.org/10.3390/nitrogen6020024>
- Cárdenas, A., Ammon, C., Schumacher, B., Stinner, W., Herrmann, C., Schneider, M., Weinrich, S., Fischer, P., Amon, T., & Amon, B. (2021). Methane emissions from the storage of liquid dairy manure: Influences of season, temperature and storage duration. *Waste Management*, *121*, 393-402. <https://doi.org/10.1016/j.wasman.2020.12.026>
- Cucina, M. (2023). Integrating anaerobic digestion and composting to boost energy and material recovery from organic wastes in the Circular Economy framework in Europe: A review. *Bioresource Technology Reports*, *24*, 101642. <https://doi.org/10.1016/j.biteb.2023.101642>
- Dincă, M., Ferdeş, M., Zăbavă, B., Ionescu, M., Moiceanu, G., & Paraschiv, G. (2024). Effective Valorization of Anaerobic Digestate—A Sustainable Approach to Circular Economy. *Applied Sciences*, *15*(16), 8939. <https://doi.org/10.3390/app15168939>
- Ghanimeh, S., et al. (2025). Assessing anaerobic digestion benefits in Qatar using livestock manure. *Bioresource Technology Reports*, *28*, 104216. <https://doi.org/10.1016/j.biteb.2025.104216>
- Kurniawan, T. A., Hassan, G. K., Al-Hazmi, H. E., Othman, M. H. D., Goh, H. H., Aziz, F., Anouzla, A., Ali, I., Khan, M. I., Khan, M. M. H., & Maqinia, J. (2024). WITHDRAWN: Landfill mining: A step forward to reducing CH₄ emissions and enhancing CO₂ sequestration from landfill. *Journal of Hazardous Materials Advances*, 100512. <https://doi.org/10.1016/j.hazadv.2024.100512>
- Li, Z., Fan, T. W., Lun, M. S., Li, Q., Hong, Q., Chen, H., Ma, L., & Yu, J. (2025). Study on implementation of anaerobic digestion and composting technologies for kitchen waste management: A case study in Macau. *Heliyon*, *11*(10), e42778. <https://doi.org/10.1016/j.heliyon.2025.e42778>
- María, A. (2024). A Review on Anaerobic Digestate as a Biofertilizer: Characteristics, Production, and Environmental Impacts from a Life Cycle Assessment Perspective. *Applied Sciences*, *15*(15), 8635. <https://doi.org/10.3390/app15158635>
- Naeem, K., Aloui, S., Zghibi, A., Mazzoni, A., Triki, C., & Elomri, A. (2024). A system dynamics approach to management of water resources in Qatar. *Sustainable Production and Consumption*, *46*, 733-753. <https://doi.org/10.1016/j.spc.2024.03.024>
- Sher, F., Smječanin, N., Hrnjić, H., Karadža, A., Omanović, R., Šehović, E., & Sulejmanović, J. (2024). Emerging technologies for biogas production: A critical review on recent progress, challenges and future perspectives. *Process Safety and Environmental Protection*, *188*, 834-859. <https://doi.org/10.1016/j.psep.2024.05.138>
- Singh, R., Hans, M., Kumar, S., & Yadav, Y. K. (2022). Thermophilic Anaerobic Digestion: An Advancement towards Enhanced Biogas Production from Lignocellulosic Biomass. *Sustainability*, *15*(3), 1859. <https://doi.org/10.3390/su15031859>