Proceedings of the 11th North American International Conference on Industrial Engineering and Operations Management, Milwaukee, Wisconsin, USA, June 9-11, 2026

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA11.20260386
Published: June 9, 2026

From Drain to Energy: A Carbon-Aware Algorithmic Framework for Expired Milk Reverse Logistics

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Abstract

The United States generates over 80 million tons of food waste annually, with expired dairy among the highest-impact yet least-recovered retail categories. Expired milk is routinely disposed through municipal sewers, generating approximately 150 kg CO_2 per tonne through biochemical oxygen demand treatment and fugitive methane, while destroying its biogas energy recovery potential through anaerobic digestion. This paper presents a carbon-aware multi-objective routing framework that routes expired milk to its highest-value end use, selecting dynamically among anaerobic digestion for biogas recovery, composting, and sewer disposal based on full lifecycle net CO_2. The framework integrates a Haversine distance calculator, facility acceptance model, constrained net CO_2 optimizer, and greedy sequential assignment algorithm enforcing AD capacity constraints in real time. Validated through a 30-day simulation across five real retail locations in Hammond-Chicago and three processing facilities, the framework routes 12,120 kg of expired milk across 150 daily records. Results demonstrate a 45.4% reduction in net lifecycle CO_2 versus the sewer baseline, recovery of 1,296 kWh biogas energy, 98% diversion from sewer, and zero AD overload events, validated using Lean Six Sigma DMAIC. A comparator analysis against cost-only and transport-CO_2-only routing confirms that only the lifecycle objective produces improvement. A sensitivity analysis across six parameters confirms the directional result is stable across all tested ranges, with reduction ranging from 23% to 82% under transport emission factor variation and remaining constant under AD capacity and instability day variation. This research contributes the first carbon-aware routing framework linking retail perishable reverse logistics with AD biological capacity constraints through a net lifecycle CO_2 objective function, with limitations and future extensions explicitly identified.

Keywords
Expired Milk, Anaerobic Digestion, Carbon-Aware Reverse Logistics, Multi-Objective Optimization, Lean Six Sigma DMAIC

Biographies

Jayank Maanas Ranganadham is a Master of Science student in Engineering Technology at Purdue University Northwest, Hammond, Indiana. His research interests center on carbon-aware supply chain optimization, circular economy frameworks for perishable goods, and optimization-based reverse logistics systems. He has presented research at Purdue University Northwest's Days of Discovery and Technology Day events. This paper represents the first phase of a multi-stage research program on expired perishable goods routing and biogas energy recovery.

Sesha Raghavendra Srinivas Subnivis is originally from India and is currently pursuing his doctoral degree in Mechatronics at Purdue University Northwest. He earned his Bachelor of Technology degree in Mechanical Engineering from Jawaharlal Nehru Technological University Kakinada, Andhra Pradesh, India, and his Master of Technology degree in Mechatronics from Jawaharlal Nehru Technological University Hyderabad, Telangana, India. His academic background spans mechanical systems, mechatronics, automation, control systems, and applied engineering technologies. His research interests include artificial intelligence, supply chain analysis, automation, robotics, smart manufacturing, programmable logic controllers, the Internet of Things, and programming. He is particularly interested in integrating intelligent technologies with industrial automation systems to improve efficiency, reliability, and decision-making in interdisciplinary areas connecting mechanical engineering, electronics, computer programming, and intelligent automation.

Lakshman Mapa, Ph.D. is a faculty member in the Department of Technology, Leadership and Innovation at Purdue University Northwest. His research spans manufacturing systems engineering, nanofluid applications in energy systems, Lean Six Sigma process improvement methodologies, and sustainable engineering technology. He supervises graduate research in supply chain optimization, advanced manufacturing, and applied engineering systems.

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