Circular Intelligence Applied to Lignocellulosic Biomass Management

M.C. García Vargas[1], J.M. Romero-García[2,3]*, I. Gómez-Cruz[3,4], M. M. Contreras[3,4], E. Castro[3,4]

[1]Department of Industrial Engineering, Technological Institute of Zitácuaro/National Technological Institute of Mexico, Zitácuaro, Michoacán, 61534, Mexico
[2]Department of Chemical Engineering. Universidad de Murcia. Campus de Espinardo s/n, Murcia, 30100, Spain
[3]Institute of Biorefineries Research (I3B); [4]Department of Chemical, Environmental and Materials Engineering. Universidad de Jaén. Campus Las Lagunillas s/n, Jaén, 23071, Spain
Keywords: circular intelligence; circular economy; lignocellulosic biomass management; artificial intelligence; big data analytics; Internet of Things.
*Presenting author email: jrgarcia@ujaen.es

Circular Intelligence as the integration of Artificial Intelligence, Big Data Analytics, and the Internet of Things in operational circular economy models.

A circular economy is commonly described as an economic system in which materials do not become waste and nature is regenerated, keeping products and materials, including complex biological streams such as lignocellulosic biomass, in circulation through maintenance, reuse, refurbishment, remanufacturing, recycling, and composting (Ellen MacArthur Foundation, 2019). International standardization efforts reinforce this systemic view by defining key concepts, principles, and implementation guidance for organizations transitioning from linear to circular models (International Organization for Standardization, 2024a). However, moving from principles to operational performance requires continuous visibility of material flows and fast decision-making across multiple actors.

Circular Intelligence can be positioned as a digital-operational layer that combines Artificial Intelligence (AI), Big Data Analytics, and the Internet of Things (IoT) to close information and control loops in waste management and resource recovery systems. Within the broader “smart circular economy” literature, digital technologies such as IoT, big data, and AI are treated as key enablers that connect circular strategies with analytics capabilities and real-time execution (Kristoffersen et al., 2020). Systematic reviews also highlight how specific digital functions (for example, sensing, tracking, prediction, optimization, and coordination) can support circular economy strategies across the value chain (Liu et al., 2022).

From a control perspective, Circular Intelligence operates through a recurring loop: (1) actions and physical states such as the moisture content, chemical composition, or degradation levels of lignocellulosic biomass generate data, (2) data are integrated and cleaned, (3) models learn patterns and produce forecasts or prescriptions, and (4) decisions are executed, creating the next set of data. This feedback architecture is relevant for constrained environments such as islands, where logistics, capacity limits, and seasonal variability increase the value of adaptive scheduling and material traceability.

Differentiating isolated AI applications from dedicated Circular Intelligence platforms

Distinguishing between isolated AI applications and dedicated Circular Intelligence platforms is essential for research design and implementation planning. Standalone AI solutions typically target a specific process (for example, image classification for sorting or optimization for routing) and may deliver local efficiency gains without ensuring traceability across the full life cycle of materials. In contrast, Circular Intelligence platforms are designed explicitly to support circularity by integrating heterogeneous data, coordinating multiple actors, and tracking materials across life-cycle stages (Kristoffersen et al., 2020; Liu et al., 2022).

Five differentiating attributes are consistently emphasized in the digital circular economy literature (Figure 1):

- Full life-cycle perspective: trace materials from generation through multiple valorization pathways, not only “end-of-life” handling.
- Heterogeneous data integration: consolidate operational, commercial, regulatory, and environmental data into a unified material-flow view.
- Circularity-oriented prediction: forecast not only service demand, but also the availability and quality of secondary materials, particularly critical for the seasonal and heterogeneous supply of lignocellulosic biomass destined for biorefinery processes, for recovery markets.
- Multi-actor coordination: connect generators, operators, recyclers, manufacturers, and authorities through shared data and process rules.
- Explicit circularity metrics: compute closure of material loops, extension of product life, and contributions to circular economy objectives; measurement standards such as ISO 59020 provide guidance for consistent indicators (International Organization for Standardization, 2024b).
- A practical illustration is CoCircular’s 360º advisor, a commercial platform focused on end-to-end waste traceability, compliance documentation, and decision dashboards for recovery and valorization. CoCircular

presents customer cases reporting that non-hazardous waste valorization can exceed 85% when workflows, documentation, and contractor engagement are digitized and monitored (CoCircular, 2024).

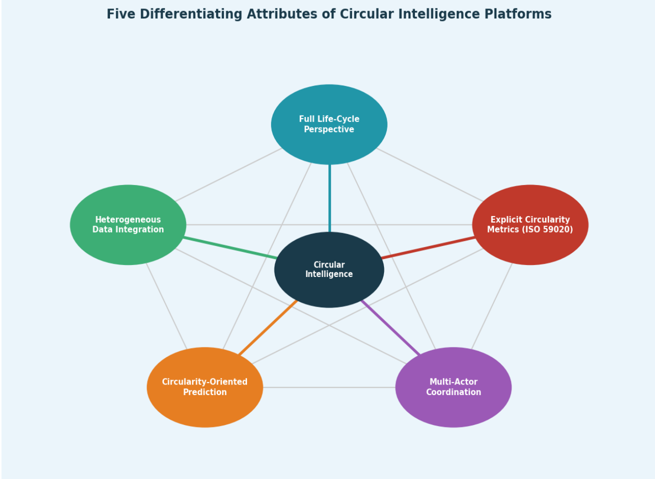

Figure 1. Five differentiating attributes of Circular Intelligence platforms.

Conclusion

Circular Intelligence provides an operational approach to make circular bioeconomy goals measurable and actionable in solid waste systems. By integrating IoT sensing, big data analytics, and AI into closed-loop decision cycles, organizations can reduce collection and processing waste and increase recovery. This enables the high-value valorization of lignocellulosic residues through advanced biorefineries into bio-based economy loops and document compliance and environmental outcomes in near real time. The highest value is reached when isolated optimizations are elevated into platform-based coordination and standard-aligned measurement.

Acknowledgements

I.G.-C. thanks the grant DGP_POST_2024_00733 from the Andalusian Government. The authors thank the project PID2023-149614OB-C21, funded by the "Ministerio de Ciencia, Innovación y Universidades" MICIN/AEI/10.13039/501100011033 and by FEDER, UE, and the project M.1.B.A TA_000701 funded by the "Programa Operativo FEDER Andalucía 2021-2027" (BOJA nº 248, de 29 de diciembre de 2023). The project from the "Instituto de Estudios Giennenses" (research projects in the area of knowledge of Natural Sciences and Technology in accordance with the provisions of the Call Bases BOP No. 42, dated 29 February 2024) is also appreciated. Thanks to the "Chemical and Environmental Engineering" Research Group (IQUIMA) at the Universidad de Jaén.

References

AMP Robotics. (2020, December 10). AMP Robotics extends AI capabilities to packaging and chemical recycling. https://ampsortation.com/articles/efforts-showcase-opportunity-for-ai-and-industry-c

CoCircular. (2024). Waste management – CoCircular. https://cocircular.es/en/

Ellen MacArthur Foundation. (2019, September 16). The circular economy in detail. https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive

Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., Hamza, E. H., Rooney, D. W., & Yap, P.-S. (2023). Artificial intelligence for waste management in smart cities: a review. Environmental Chemistry Letters, 1–31. https://doi.org/10.1007/s10311-023-01604-3

Gupta, S., Chen, H., Hazen, B. T., Kaur, S., & Santibañez Gonzalez, E. D. R. (2019). Circular economy and big data analytics: A stakeholder perspective. Technological Forecasting and Social Change, 144, 466–474. https://doi.org/10.1016/j.techfore.2018.06.030

International Organization for Standardization. (2024a). ISO 59004:2024 Circular economy — Vocabulary, principles and guidance for implementation. https://www.iso.org/standard/80648.html

International Organization for Standardization. (2024b). ISO 59020:2024 Circular economy — Measuring and assessing circularity performance. https://www.iso.org/standard/80650.html

Kristoffersen, E., Blomsma, F., Mikalef, P., & Li, J. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. Journal of Business Research, 120, 241–261. https://doi.org/10.1016/j.jbusres.2020.07.044

Liu, Q., Hofmann Trevisan, A., Yang, M., & Mascarenhas, J. (2022). A framework of digital technologies for the circular economy: Digital functions and mechanisms. Business Strategy and the Environment, 31(5), 2171–2192. https://doi.org/10.1002/bse.3015