

Unveiling Heterogeneity in Circular Economy Strategies: An LLM-Based Clustering Approach to Environmental and Economic Performance

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Abstract

Although the Circular Economy (CE) is gaining momentum as a corporate objective, the relationship between strategic disclosures and actual environmental and financial performance remains complex and insufficiently explored. This study investigates how distinct CE strategies, identified through textual narratives in integrated reports, impact corporate waste generation and cost structures (specifically Cost of Goods Sold [COGS] and SG&A expenses). Using a dataset of major Japanese companies listed in the Nikkei 225 from 2018 to 2025, we employed large language models (LLMs) to extract CE-related narratives. By applying text embedding techniques and unsupervised clustering algorithms (UMAP and HDBSCAN), we identified three stable strategic groups that reflect underlying industry characteristics: process industries, assembly industries, and construction/infrastructure. Subsequent analysis using linear support vector regression (SVR) revealed significant heterogeneity in performance outcomes across strategic groups. First, regarding environmental performance, strategic groups associated with process and construction industries exhibited higher waste intensity compared to the baseline. This suggests that extensive CE disclosures in high-burden sectors are often driven by legitimacy concerns rather than by immediate performance outcomes. Second, regarding economic performance, the study revealed a clear divergence in cost structures. While a trade-off between waste reduction and production costs (COGS) was observed in the baseline, the assembly industry group achieved "eco-efficiency," where waste reduction significantly correlated with cost reduction, thus supporting the Porter Hypothesis. Furthermore, all identified CE strategy groups exhibited structurally lower SG&A expenses and successfully decoupled management costs from fluctuations in cost management. These findings imply that coherent

CE narratives serve not only as environmental disclosures but also as signals of superior management quality and governance capability. The study contributes to the literature by quantifying the linkage between textual disclosures and performance outcomes and by demonstrating that the economic viability of CE strategies is path-dependent on industry characteristics.

Keywords

Circular Economy Strategy; large language models (LLMs); Text Clustering; Environmental Performance; Cost Structure; Eco-efficiency

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Biographies

Hirotsugu Kitada is an Associate Professor of Accounting at Hosei University in Tokyo, Japan. His research primarily explores how management accounting systems can support corporate sustainability and the transition toward circular economy (CE) business models. He has published academic work on cost behavior, ESG disclosure, and sustainability-oriented control systems. His recent projects focus on the financial implications of CE, including the development of frameworks for mapping cost and revenue structures and evaluating circular strategies from a financial perspective. He is actively engaged in international sustainability standard-setting initiatives, including contributions to the development of the Global Circularity Protocol (GCP), in collaboration with organizations such as ISO/TC323 and the World Business Council for Sustainable Development (WBCSD). He also utilizes emerging AI technologies, particularly large language models, to conduct scoping reviews and analyze narrative disclosures in integrated and sustainability reports.

Hitoshi Iyatomi is a Professor in the Department of Applied Informatics at Hosei University. He received the B.E., M.E., and Ph.D. (Eng.) degrees from Keio University, Japan, in 1998, 2000, and 2004, respectively, and a second Ph.D. degree in medical science from Tokyo Women's Medical University in 2011. From 2000 to 2004, he was a Technical Consultant at Hewlett-Packard Japan. In 2004, he joined Hosei University as a Research Associate. From 2016 to 2017, he was a Visiting Scholar at Johns Hopkins University. He has authored or coauthored more than 170 peer-reviewed journal articles and conference papers in machine learning-based research areas, including computer vision, medical engineering, natural language processing, and generative AI.

Shigesada Takagi is a Deputy General Manager of Sustainability Consulting Division at Mizuho Research & Technologies, Ltd in Tokyo, Japan. Since 2002, he has been engaged in policy support and policy research support for government agencies on sound material-cycle society and circular economy (CE), and consulting for private companies. In addition to the CE, he currently oversees consulting on bioeconomy, impact assessment, and integrated sustainable assessment. In consulting for private companies on CE, he focuses on supporting the transition to CE, and supports sustainable resource procurement and conversion to CE-type business models.