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Bridging Human Behaviour and Circularity: The Social Impact of IoT-Based Energy Monitoring in the Textile Industry

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Abstract

The textile industry faces dual pressures to enhance operational efficiency while meeting global circular economy targets. While the Internet of Things (IoT) presents a solution, quantitative impact analyses often lack rigor in data normalisation and fail to account for the human element. This study quantitatively analyses the impact of a real-time IoT energy monitoring system (SEMWOSH) on energy efficiency and estimated carbon footprint, while explicitly investigating the human-centric behavioural mechanisms driving these changes. A 12-month pre-post intervention design was employed in a vocational textile workshop. Energy data were normalized using a Production Factor (PF) index to control for workload. Semi-structured interviews with operators and managers were conducted to explain quantitative trends. Normalized analysis revealed a significant operational efficiency improvement of 1.85% in the post-implementation period. Qualitative findings indicate this improvement was driven by the "Observer Effect," where data transparency triggered self-regulation among operators and proactive decision-making by managers. This study confirms that human-centric IoT systems effectively bridge digitalization with circularity. The novelty of this research lies in isolating the behavioural component of energy efficiency, demonstrating that data visibility alone—without mechanical upgrades—can serve as a catalyst for sustainable manufacturing.

Keywords: circular economy, social impact, energy efficiency, internet of things (IoT), human-centric manufacturing

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1. Introduction

The global textile industry stands at a critical juncture, grappling with the imperative of economic survival and environmental stewardship. As one of the most energy-intensive sectors, it faces mounting pressure to transition towards circular economy principles (Leal Filho et al., 2024). In this context, digital transformation, particularly through the Internet of Things (IoT), has emerged as a promising enabler for optimizing resource usage(Garg & Pancholi, 2023; Sharanya et al., 2024).

However, a significant gap exists in the current body of knowledge. While numerous studies document the technical capabilities of IoT in manufacturing (Leal Filho et al., 2024; Petrillo et al., 2024), there is a scarcity of empirical evidence that rigorously quantifies its impact on energy efficiency while simultaneously accounting for the human dimension. Many existing claims of energy savings lack robust methodologies, often failing to normalize data against production fluctuations. Furthermore, the "human-centric" aspect of Industry 5.0—how real-time data influences the behaviour of shop-floor operators—remains under-investigated (Introna et al., 2024; Sentoso et al., 2023; Skere et al., 2025).

This study aims to bridge this gap by addressing three interconnected objectives: (1) to quantitatively analyze the impact of a real-time IoT energy monitoring system on normalized energy efficiency; (2) to uncover the human-centric mechanisms (behavioural changes) that mediate these efficiency gains; and (3) to evaluate the system's contribution to circularity goals via carbon footprint reduction.

2. Literature Review & Theoretical Framework

2.1. IoT as an Enabler for Circular Economy

The integration of IoT into the textile industry is increasingly viewed as a cornerstone for Circular Economy (CE) transitions. Recent literature highlights IoT's capacity to facilitate real-time monitoring, traceability, and resource optimization (Das, 2023; Ghoreishi & Happonen, 2022). Petrillo et al. (2024) argue that digital transitions in textiles are not merely technical upgrades but are essential for regulatory compliance and sustainability. IoT technologies support CE principles by "dematerializing" energy consumption—reducing the energy input per unit of output—thereby extending the efficient lifecycle of production processes (Nalini et al., 2024; Swami et al., 2024; Turskis & Šniokienė, 2024).

2.2. Human Behaviour and Social Impact in Digitalized Manufacturing

While technical efficiency is well-documented, the social impact of IoT remains a developing field. Sentoso et al. (2023) utilised the UTAUT2 model to show that employee acceptance of digital transformation is heavily influenced by performance expectancy. However, empirical studies linking data visibility to behavioural change in factory settings are limited.

Theoretically, this study draws on the concept of "Eco-Feedback" and the "Observer Effect" (Hawthorne Effect). Literature suggests that when operators are aware their energy consumption is being monitored in real-time, they unconsciously or consciously alter their behaviour to align with perceived "green" norms (Casado-Mansilla et al., 2020; Nabeel et al., 2019; Sehrawat et al., 2025). This aligns with the Industry 5.0 paradigm, which shifts focus from automation replacing humans to technology empowering humans to make smarter decisions (Human-Centricity).

2.3. *The Gap: Empirical Validation in Vocational/SME Contexts*

Despite the proliferation of frameworks linking IoT, behaviour, and circularity (Mahmud et al., 2025), most studies remain theoretical or focused on large-scale automated industries. There is a lack of longitudinal empirical research in Small and Medium Enterprises (SMEs) or vocational settings where automated SCADA systems are absent. This study fills this gap by validating a low-cost, human-centric IoT intervention in a resource-constrained environment (Dubal et al., 2025; Tadja et al., 2025).

3. Research Methodology

3.1. *Research Design*

This study adopted a mixed-methods embedded design. A quasi-experimental quantitative study (pre-post intervention) was employed to measure efficiency changes, while qualitative interviews provided explanatory insights into the human-centric aspects. The study spanned 12 months (January–December 2024).

3.2. *Setting and Participants*

The research was conducted at the textile manufacturing workshop of the Community Academy of Textile Industry and Products, Surakarta, Indonesia. This vocational setting serves as a "controlled microcosm" of the industry, equipped with standard machinery (Roving, Ring Spinning).

- Participants: The user ecosystem consisted of students acting as novice machine operators and instructors acting as managers.
- Justification: While utilizing students limits direct generalizability to veteran industrial workforces, this setting allows for the observation of behavioural formation in "novice operators" without the interference of long-standing entrenched habits, providing a clear baseline for the impact of digital interventions.

3.3. *Intervention: SEMWOSH System*

The intervention involved the implementation of SEMWOSH (Smart Energy Monitoring System for Workshop). This IoT-based platform visualises real-time energy consumption from individual machines, accessible via a dashboard to all users commencing April 1, 2024.

3.4. *Data Collection and Analysis*

1) Quantitative: Monthly energy consumption (kWh) was recorded. To control for workload variations, a Production Factor (PF) index was established.

  - Limitation Note: The PF is a proxy index based on expert estimation by the workshop manager, as automated machine-hour logs were unavailable. While this introduces a degree of subjectivity, it represents the best available methodology for normalising data in SME-like environments.
  - Metric: Energy Efficiency = Total kWh / PF.
  - Analysis: Independent Samples t-test comparing Pre- (Jan-Mar) and Post-Implementation (Apr-Dec) periods.

2) Qualitative: Semi-structured interviews were conducted with operators ($n=5$) and managers ($n=2$) to explore behavioural changes. Data were analysed using thematic analysis.

3.5. Validity of the Normalisation Approach

A key challenge in this study was normalising energy data (kWh) against production output in a facility lacking automated production counters. To address this, we developed a Production Factor (PF) index. While we acknowledge that PF is an expert-based estimation (proxy), it represents the most robust methodological choice available for SME and vocational contexts. To mitigate subjectivity bias, the PF values were cross-verified by two senior workshop managers with over 15 years of experience. This approach aligns with the "frugal innovation" needed for circularity in developing economies, as noted by Jayawickrama et al. (2025).

4. Results

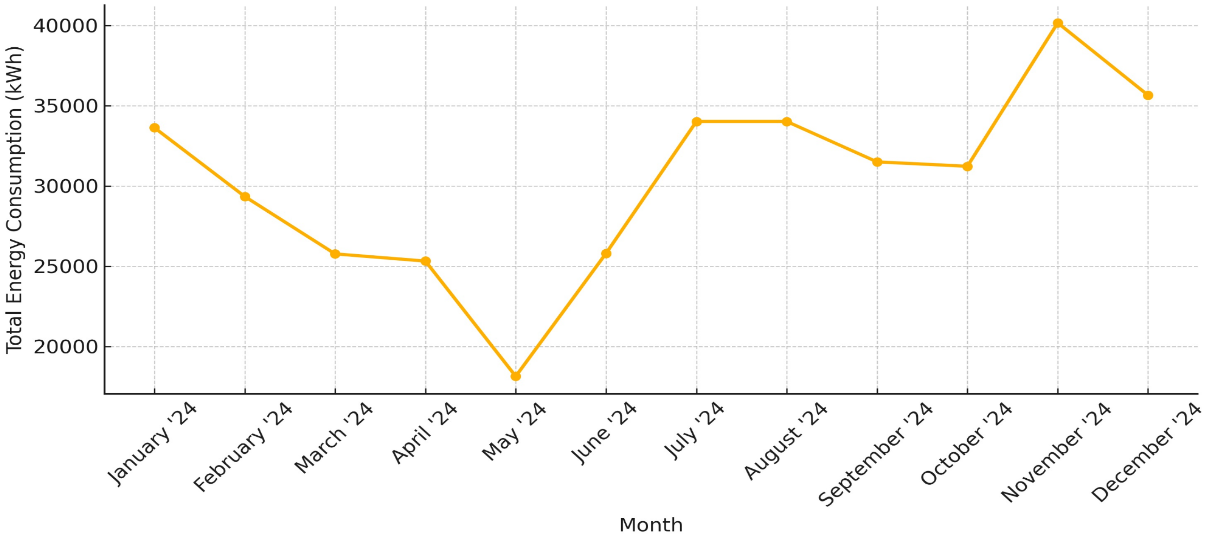
4.1. Total Energy Consumption vs. Normalized Efficiency

Initial observation of total energy consumption showed high volatility, driven by fluctuating production schedules. Analyzing total kWh alone would yield inconclusive results regarding the system's impact. However, after normalising the data using the Production Factor (PF), a clear trend emerged. As shown in Table 1, the mean Energy Efficiency improved from 39.44 kWh/PF in the pre-implementation phase to 38.71 kWh/PF in the post-implementation phase. This represents a statistically significant operational efficiency improvement of 1.85%. The data demonstrates a downward trend in energy intensity even during months of high production volume.

4.2. Impact on Carbon Footprint

This efficiency gain directly contributes to circularity goals. Based on the average emission factor for Indonesia's electricity grid*, the 1.85% improvement translates to an estimated reduction of approximately 472 kg of CO2e per month. (Note: Calculation assumes a static grid emission factor of ~0.85 kg CO2e/kWh. Variations in the regional grid mix throughout the year are not accounted for.)

Figure 1. Trend of Total Monthly Energy Consumption During the Study Period.



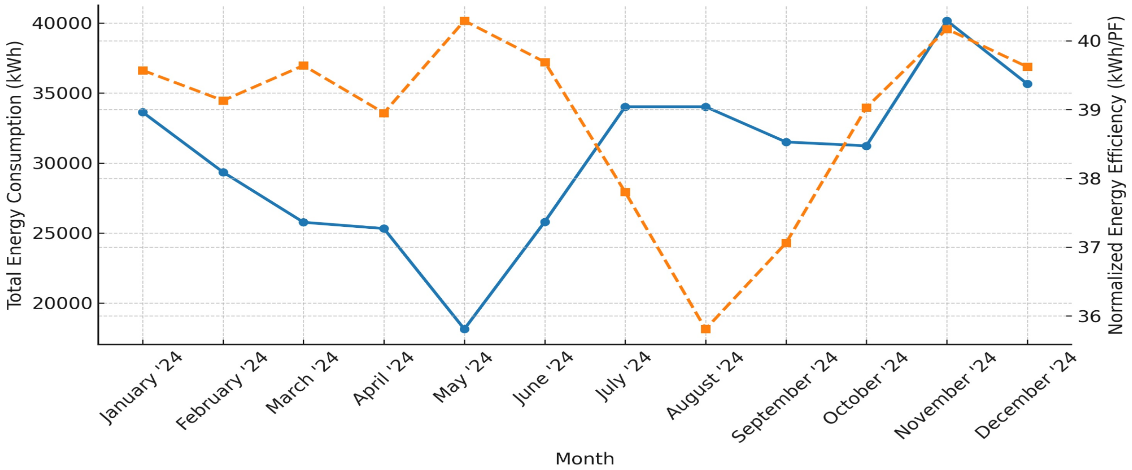
Source: Author's elaboration

Table 1. Normalised Energy Consumption and Efficiency

Month (2024)	Status	Consumption (kWh)	PF (Index)	Efficiency (kWh/PF)
January	PRE	33,632	850	39.57
February	PRE	29,344	750	39.13
March	PRE	25,764	650	39.64
April	POST	25,316	650	38.95
May	POST	18,132	450	40.29
June	POST	25,799	650	39.69
July	POST	34,019	900	37.80
August	POST	34,019	950	35.81
September	POST	31,500	850	37.06
October	POST	31,226	800	39.03
November	POST	40,166	1000	40.17
December	POST	35,654	900	39.62

Source: Author's elaboration

Figure 2. Comparison of Trends in Total Energy Consumption vs. Normalized Energy Efficiency.



Source: Author's elaboration

4.3. Qualitative Findings: Thematic analysis confirmed that the 1.85% efficiency gain was not accidental.

- Theme 1: Behavioural Nudging. Operators reported that the dashboard acted as a "digital nudge." One operator stated: "Seeing the red graph makes me feel responsible."
- Theme 2: Data-Driven Maintenance. Managers used the data to identify "energy hog" machines, shifting maintenance from reactive to predictive.

5. Discussion

5.1. Interpreting the Efficiency Gains: The Power of Behavioural Change

The study observed a 1.85% improvement in normalized energy efficiency. While numerically modest, this figure is statistically significant and theoretically profound. Unlike efficiency gains derived from installing newer, expensive machinery (CapEx), this gain is purely behavioural and managerial.

This confirms the "Observer Effect" theorized in behavioural science (Sehrawat et al., 2025). The visibility of data transformed energy from an abstract cost into a tangible metric, empowering operators to engage in "micro-sustainability" actions (e.g., shutting down idling machines immediately).

5.2. Implications for Circularity and Social Impact

These findings offer empirical support for the frameworks proposed by (Hassan et al., 2025), linking digital tools to circular transitions. By reducing energy intensity through human behaviour, the SEMWOSH system fosters a culture of "Resource

Stewardship." This demonstrates that the social impact of IoT goes beyond convenience; it cultivates a workforce that is actively engaged in the circular economy loops.

6. Conclusion

This research demonstrates that bridging human behaviour with digital monitoring is a viable pathway to sustainability. By methodologically isolating the human factor through data normalisation, we proved that IoT transparency can drive a 1.85% efficiency gain without mechanical upgrades. Future research should test this model in larger commercial facilities to validate scalability.

References

Casado-Mansilla, D., Irizar-Arrieta, A., Solabarrieta-Roman, M., Manterola-Lasa, A., Kamara-Esteban, O., Tsolakis, A. C., Krinidis, S., Tzovaras, D., Borges, C. E., & Lopez-de-Ipina, D. (2020). Lasting and Spillover Effects of Ambient Eco-Feedback in the Office-based Workplace. *2020 5th International Conference on Smart and Sustainable Technologies (SpliTech)*, 1–6. https://doi.org/10.23919/SpliTech49282.2020.9243717

Das, M. C. (2023). Characterization of pineapple leaf fiber, areca fiber and egg shell powder reinforced phenolic resin composites and finding optimal parameters for sustainable machining. *Materials Today: Proceedings*, (Query date: 2025-02-24 12:28:54). https://doi.org/10.1016/j.matpr.2023.04.023

Dubal, S., Gupta, U., Jha, S., Musale, P., & Sajwan, P. (2025). Human-Centric Design in IIoT Solutions. In B. K. Mishra, G. Dhiman, H. Kasturiwale, S. Alegavi, & K. Yadav, *Industrial Internet of Things for Responsible Technology* (1st ed., pp. 77–100). CRC Press. https://doi.org/10.1201/9781003587903-7

Garg, S., & Pancholi, N. (2023). IoT-Driven Sustainable Development and Future Trends in Industries: In S. Lamba Sahdev, C. Krishnan, & A. Hassan (Eds.), *Advances in Environmental Engineering and Green Technologies* (pp. 1–11). IGI Global. https://doi.org/10.4018/978-1-6684-9979-5.ch001

Ghoreishi, M., & Happonen, A. (2022). The Case of Fabric and Textile Industry: The Emerging Role of Digitalization, Internet-of-Things and Industry 4.0 for Circularity. In X.-S. Yang, S. Sherratt, N. Dey, & A. Joshi (Eds.), *Proceedings of Sixth International Congress on Information and Communication Technology* (Vol. 216, pp. 189–200). Springer Singapore. https://doi.org/10.1007/978-981-16-1781-2_18

Hassan, R., Acerbi, F., Rosa, P., & Terzi, S. (2025). The role of digital technologies in the circular transition of the textile sector. *The Journal of The Textile Institute*, *116*(12), 2860–2873. https://doi.org/10.1080/00405000.2024.2414162

Introna, V., Santolamazza, A., & Cesarotti, V. (2024). Integrating Industry 4.0 and 5.0 Innovations for Enhanced Energy Management Systems. *Energies*, *17*(5), 1222. https://doi.org/10.3390/en17051222

Leal Filho, W., Dinis, M. A. P., Liakh, O., Paço, A., Dennis, K., Shollo, F., & Sidsaph, H. (2024). Reducing the carbon footprint of the textile sector: An overview of impacts and solutions. *Textile Research Journal*, *94*(15–16), 1798–1814. https://doi.org/10.1177/00405175241236971

Mahmud, Md. Z. A., Rabbi, S. M. F., Islam, Md. D., & Hossain, N. (2025). Synthesis and applications of natural fiber-reinforced epoxy composites: A comprehensive review. *SPE Polymers*, *6*(1), e10161. https://doi.org/10.1002/pls2.10161

Nabeel, M., Ali, B., & Hamdan, A. (2019). REAL-TIME FEEDBACK ON CONSUMER'S BEHAVIOR: LITERATURE REVIEW. *International Journal of Energy Economics and Policy*, *9*(5), 489–493. https://doi.org/10.32479/ijeep.8353

Nalini, M., Varadharajan, D., Natarajan, N., & Umasankar, Y. (2024). IOT-Based Advanced Energy Management in Smart Factories. In S. Sagar, T. Poongodi, R. K. Dhanaraj, & S. Padmanaban (Eds.), *Cyber Physical Energy Systems* (1st ed., pp. 183–216). Wiley. https://doi.org/10.1002/9781394173006.ch6

Petrillo, A., Rehman, M., & Baffo, I. (2024). Digital and Sustainable Transition in Textile Industry through Internet of Things Technologies: A Pakistani Case Study. *Applied Sciences*, *14*(13), 5380. https://doi.org/10.3390/app14135380

Sehrawat, M., Nandwani, A., Rohila, M., & Jain, A. (2025). Redefining Consumer Behaviour in a Circular Economy: Strategies for Sustainable Living. In M. Mokdad (Ed.), *Social System Reforms to Achieve Global Sustainability* (pp. 391–420). IGI Global. https://doi.org/10.4018/979-8-3373-1280-4.ch013

Sentoso, T., Kusrini, K., & Hanafi, H. (2023). The effectiveness of using RFID and IoT in digital transformation processes in garment companies using the UTAUT model2. *Gema Wiralodra*, *14*(2), 697–709. https://doi.org/10.31943/gw.v14i2.511

Sharanya, C., Radhakrishnan, P., Nirmalsingh, N., Ashwin Kumar, D. R., Cloudin, S., & Robinson Joel, M. (2024). IoT-Driven Innovations for Sustainable Resource Use and Waste Reduction: In E. Ozen, A. Singh, S. Taneja, R. Rajaram, & J. P. Davim (Eds.), *Advances in E-Business Research* (pp. 307–328). IGI Global. https://doi.org/10.4018/979-8-3693-9699-5.ch013

Skėrė, S., Bastida-Molina, P., Skėrys, P., & Molina-Palomares, P. (2025). Empowering Industry 5.0: A Multicriteria Framework for Energy Sustainability in Industrial Companies. *Applied Sciences*, *15*(16), 9170. https://doi.org/10.3390/app15169170

Swami, S., Suthar, S., Srinivasan, S. M., Joshi, A., Pandey, N., & Yamsani, N. (2024). Integrating Circular Economy and IoT For Sustainable Resource Management. *2023 International Conference on Smart Devices (ICSD)*, 1–5. https://doi.org/10.1109/ICSD60021.2024.10751410

Tadja, D. D., Lehyani, F., Zouari, A., Bassetto, S.-J., Tollenaere, M., & Wong, T. (2025). *Leveraging Internet of Things to Enhance Skill Acquisition in Lean Manufacturing Practices: An Experimental Study*. In Review. https://doi.org/10.21203/rs.3.rs-7322105/v1

Turskis, Z., & Šniokienė, V. (2024). IoT-Driven Transformation of Circular Economy Efficiency: An Overview. *Mathematical and Computational Applications*, *29*(4), 49. https://doi.org/10.3390/mca29040049