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Editorial

Industrial sustainability: integrating sustainability principles and the latest industrial revolutions

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The term net-zero is frequently used in the literature; it refers to a situation in which an organization removes emissions using science-based methods and simply neutralizes residual emissions to reach balance in a given period [1]. Net-positive, however, means more than just being neutral. It implies that the complete footprint must be examined in order to demonstrate measurable changes in the environment and/or society when compared to a baseline [2]. Net-zero and net-positive are the two major principles influencing the industrial sustainability paradigm. Industrial sustainability is best understood as a co-evolutionary process shaped by successive Industrial Revolutions (IRs), each of which has fundamentally restructured socio-technical and economic systems. Digitalization, cyber-physical systems, AI (artificial intelligence), and the IOT (internet-of-things), for instance, have enabled new approaches to improve industrial systems and use resources more efficiently. These technologies have facilitated predictive maintenance by monitoring events in real time and making data-driven decisions [3]; this, consequently, has resulted in reduced waste and more environmental efficiency.

However, IR 1.0–3.0's approach to sustainability has been mostly incremental, with a focus on technical advancements for financial sustainability. Conversely, IR 4.0 could better expand its coverage to other sustainability pillars: environment and social. The current shift to IR 5.0 has, however, resulted in a more inclusive and human-centric attitude than previously observed. IR 5.0 emphasizes resilience, human well-being, and ethical governance, moving beyond the narrow operational and financial gain logic of past IRs and embedding sustainability more deeply within socio-technical systems. Thus, this shift is consistent with wider transition theories, which contend that systemic change necessitates not only technological replacement but also industrial transformation, stakeholder participation, and changes in cultural norms. IR 5.0 has radically altered the course of modernization, stressing social equality and human-machine collaboration in order to develop a holistic, sustainable framework. Yet, despite these developments, scientific investigation [4] suggests that prevailing industrial models remain fundamentally linear and extractive, contributing to climate change, biodiversity loss, and systemic social inequalities.

Although focused on reducing environmental harm, the paradigm of industrial sustainability has proven insufficient for tackling cumulative ecological deterioration. Efficiency-driven approaches cannot adequately counteract the long-term consequences of resource depletion and ecological disruption. This recognition has stimulated discussion of an IR 6.0, framed as a regenerative trajectory in which industries and supply chain systems pursue net-positive environmental and social outcomes [5]. This notation of IR 6.0 is viewed as a mechanism for industries and systems to collaborate and achieve net-positive social and environmental outcomes. This is based on systems theory [6,7], which states that complex socio-ecological systems are interconnected and have feedback loops. The proposed path for the IR 6.0 is viewed as a paradigm that prioritizes ecological regeneration. Previously, the IRs were about financial growth and operational optimization, but in IR 6.0, industries continuously limit their harm and also actively seek to restore and enhance ecosystems. In the real world, this means that firms must devise strategies to increase ecosystem services, restore natural resources, and consider planetary boundaries when planning their industrial operations. This is consistent with circular economy debates, which promote restorative processes over producing less. The circular economy is a way of thinking about design and operations that makes the best use of materials and resources by ensuring they last, can be reused, repaired, remanufactured, or recycled [8]. Circular economy allows for either net-zero or net-positive behavior, but neither is guaranteed; however, in the proposed IR 6.0, regenerative systems are place-based, living systems strategies that restore ecosystem function and community well-being through sourcing, operations, and governance, with success judged by net improvements in ecosystem services rather than material loops alone.

Technology that will enable this transition has already begun to emerge via IRs. For instance, AI and machine learning are aiding in the automation of industrial operations as well as the prediction of their environmental impact. This enables one to take action before issues arise. Networking, IOT, and sensor technologies allow continuous monitoring of energy consumption, emissions, and material flow, enabling the transparency required for the construction of a regenerative supply chain [9,10]. Using blockchain technology in circular supply chains makes it simpler to trace items and trust people, allowing individuals to be held accountable across global networks [11,12]. Additionally, digital twin technologies are virtual models that allow you to test sustainability ideas before using them in real life, optimizing resource use and reducing risk [13,14]. In practice, according to research [3,15], adopting AI-powered predictive maintenance in manufacturing has resulted in fewer downtime and resource utilization, demonstrating substantial advantages for sustainability. Blockchain-enabled supply chains in the dairy industry, as Khanna [16] explains, have increased transparency and reduced the likelihood of contamination. They have also increased customer trust in sustainable sourcing. IOT-powered solutions have increased energy efficiency and assisted the building and energy industries in meeting green certification criteria [17].

Although these solutions are promising, the majority are not yet established, and the question of how to apply regenerative solutions to supply chain networks and industry systems has yet to be resolved. Technology opportunities exist, to some extent, and are emerging, but existing barriers make it difficult for systems to best make use of them or apply them to larger-scale purposes. According to literature [18–20], practical barriers remain impediments to technology integration. Besides, current governance systems should also be upgraded; legislative uncertainty around data privacy, regulations, and the incorporation of ethics discussions has hampered progress. Still, adaptable systems, cross-industry partnerships, and supporting legislative frameworks that fully encourage regenerative innovation while maintaining inclusivity and equality are required.

The papers in this Special Issue on Industrial Sustainability, "Industrial Sustainability: Integrating Sustainability Principles and the Latest Industrial Revolutions", give insights into how IRs and their connected technologies may be connected to a sustainability movement, as well as shortcomings that future IR6.0 must address. Investigations should focus on the operationalization of regenerative systems, as well as the development of clear and strict metrics for net-zero, net-positive, circularity, and regeneration. To guarantee that industrial sustainability is understood as covering not only technical optimization but also systemic regeneration, interdisciplinary techniques must be used to incorporate concepts from engineering, environmental science, and social sciences. In the past, IRs were judged on two criteria: new technology and economic productivity. In today's dynamic environment, however, it is critical to come up with a fresh development concept. IR6.0 needs to aim to transform industrial systems from their extractive development focuses to sources of social and environmental well-being. Thus, in this Special Issue, as Figure 1 maps, we define circularity as the tool to achieve goals, reducing harms to net-zero as the baseline, creating more environmental benefit than harm, placing net-positive as a forward direction, and introducing regenerating supply chains and systems as the final destination and our main mission. These positions contribute to the connection between technological decisions, governance goals, and methods of measuring performance with ecological results in specific locations. Past IRs, with their technology and human-centered triumphs, have already laid the groundwork for the regeneration transformation. The goal is to build on these foundations to develop a total regenerative model. This ensures that industries can contribute to making things more efficient and competitive while also helping to restore ecosystems and society's ability to recover.

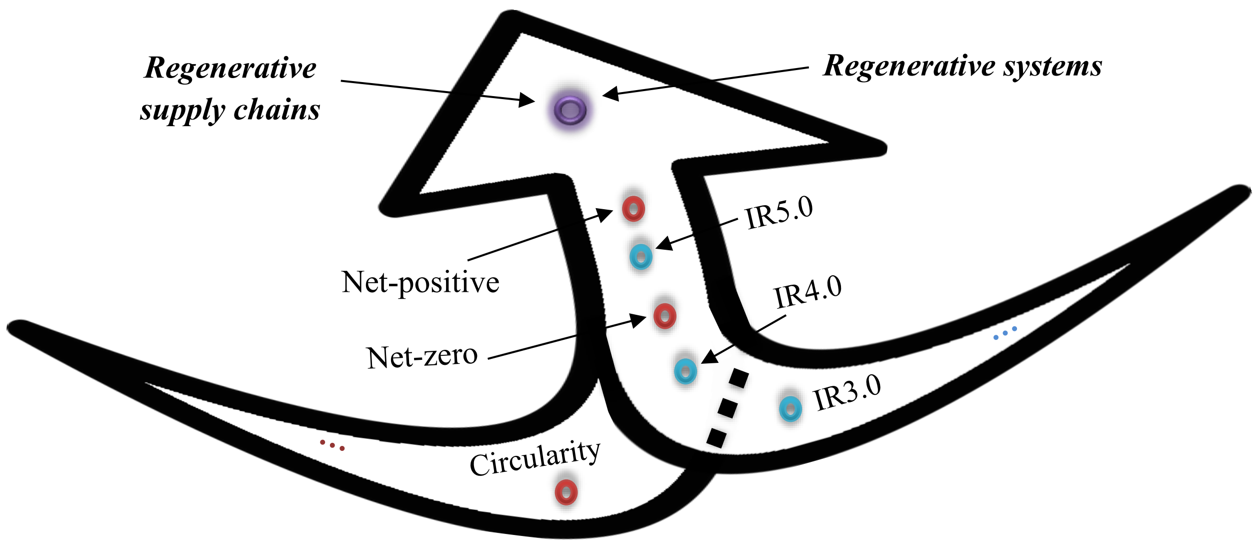

Figure 1. Proposed industrial sustainability direction.

Use of AI tools declaration

I would like to acknowledge the use of AI to assist in the initial drafting of this paper. The ideas and core arguments presented are my own, and I have edited and validated all content to ensure accuracy and coherence.

Conflict of interest

I have no conflict of interest to report for this article.

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