Chapter 11
Integration of Industry 4.0 in Green Supply Chain Management: A Comprehensive Review and Future Directions

Mirna Ibrahim
Ain Shams University, Egypt

ABSTRACT

The global manufacturing landscape is undergoing two key transformations that intersect in important ways, the digitization of operations through Industry 4.0 technologies and the push toward more sustainable systems via the implementation of green supply chain management (GSCM) strategies. Industry 4.0 technologies like the internet of things, big data analytics, and blockchain are transforming production and SC operations with embedded sensors, automation, and transparency. This digital transformation intersects with the sustainability agenda by enabling enhanced environmental monitoring, resource efficiency, closed-loop flows, and SC coordination. This chapter reviews the literature on how these Industry 4.0 technologies can enable more sustainable and GSCM practices. Specifically, it examines the drivers, practices, and performance outcomes associated with implementing green SCs in the context of Industry 4.0. The chapter concludes with a discussion of future research directions at the intersection of Industry 4.0 and GSCM.

1. INTRODUCTION

The disruptions triggered by COVID-19 and geopolitical conflicts have emphasized the urgency of building resilient and sustainable supply chains (SCs) through contemporary technologies and management practices (Fu et al., 2022). Particularly for emerging economies, gaining competitiveness and continuity depends on how well they can embrace the digital transformation wave initiated as Industry 4.0 and integrate sustainable protocols within traditional operations (Ivanov et al., 2021). Industry 4.0 technologies like the Internet of Things (IoT), and BDA equip SC partners to make data-centric decisions,

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ensure visibility, and achieve agility through connecting physical objects, machines, and inventory via the Internet (Naseem and Yang, 2021). On the other hand, green supply chain management (GSCM) offers the advantage of eco-efficiency by addressing environmental issues in SC processes, from green design manufacturing to delivery (Zhu and Sarkis, 2004). While previous studies have analyzed these concepts individually, research on their integration is scarce, especially on how digitalization powers sustainability across SCs (Taghipour, et al., 2022b; Taghipour, 2021).

Industry 4.0, also known as, the fourth industrial revolution, is transforming supply chain management (SCM) through new technologies. Industry 4.0 refers to the ongoing transformation of manufacturing and SC processes via cyber-physical systems and smart, connected technologies (Ghobakhloo, 2018). Industry 4.0 denotes the ongoing digitization of products, assets, and processes via cyber-physical systems and hyperconnectivity across every node and link in modern value production and distribution networks. Networked sensors feed continuous real-time data from production equipment and assets into analytic dashboards, while machine learning algorithms leverage this river of data to spot patterns, predict outcomes, and automatically optimize processes (Zhong et al., 2016).

Major digital innovations driving this change include IoT, artificial intelligence (AI), big data analytics (BDA), cloud computing (CC), and Blockchain (BC) (de Sousa Jabbour et al., 2018). These technologies provide unprecedented visibility, data sharing, automation, and decentralization across product life cycles and global supply networks. As such, researchers suggest Industry 4.0 holds promise for enabling more sustainable production and consumption via GSCM (Kusiak, 2018; Li et al., 2020). The "smart" manufacturing environments allow gathering rich data from networked sensors, gaining actionable intelligence through analytics, and enabling adaptable, flexible automation towards batch size one production. Sophisticated simulation of operational environments in digital twins (DT) allows virtual testing of new production scenarios to evaluate sustainability impacts before deployment. BC architectures promise to bring unprecedented transparency, security, and coordination capability to decentralized manufacturing ecosystems and circular SCs.

GSCM integrates environmental thinking into SC practices across product design, material sourcing, manufacturing, distribution, usage, and end-of-life management (Sony, 2019). Adopting GSCM practices like green purchasing, green manufacturing, and closed-loop recycling can enhance firms' environmental and economic performance (Zhu et al., 2007). In parallel, rising ecological pressures call for sustainable value chains through the adoption of GSCM practices. GSCM often begins internally with environmental management programs and eco-efficiency drives before expanding outward to coordinate green purchasing, green marketing, investment recovery through closed-loop recycling, and reverse logistics considerations between SC partners (Taghipour et al., 2020).

GSCM has arisen as a key strategy for enterprises to reduce the environmental burdens of their upstream and downstream value chain activities (Dubey et al., 2020). GSCM expands the focus from internal programs like ISO 14000 adoption and pollution prevention to managing environmental performance through green coordination of inbound logistics, suppliers, product recovery networks, and customers. Key programs span green purchasing agreements that specify materials attributes, product eco-design targeting life cycle impacts, investment in closed-loop reverse logistics capabilities to reuse components and recapture embedded value at product end-of-life, as well as the marketing of corporate eco-commitments like carbon neutrality to stakeholders (Ying-Liu et al., 2012).

Motivations for GSCM include growing ecological pressures and resource constraints, rising energy and compliance costs, preemptive Circular Economy legislation banning product disposal in landfills, and corporate social responsibility demands from activist investors and conscientious consumers, es-