

Green Manufacturing in the Indian Cement Industry – Research Gaps and Definition of Methods

Dr Sanjeev Shrivastava¹, Dr. Mohammad Israr²

¹Post Doctoral (PostDoc) Researcher and Research Associate [LGPR Programme],

Lincoln University College, 47301, Petaling Jaya, Selangor Darul Ehsan, Malaysia

² President, Maryam Abacha American University of Nigeria, Kano, Federal Republic of Nigeria

Email : 1sanjeevshrivastava1972@gmail.com

2president@maaun.edu.ng

Abstract : Green manufacturing (GM) refers to production practices designed to reduce environmental damage and eliminate waste throughout the manufacturing lifecycle. It focuses on adopting methods and technologies that safeguard the environment while ensuring the health and safety of workers, consumers, and surrounding communities. As industries seek long-term sustainability, GM is increasingly recognized as a viable approach to addressing global environmental and resource challenges.

To examine the current level of understanding and application of GM practices, a preliminary survey was conducted in 2011 across manufacturing firms in central India. Building on this groundwork, the present study aims to design a structured assessment tool to evaluate both awareness and implementation of green manufacturing initiatives within the Indian industrial context. Additionally, the research seeks to establish and validate measurable indicators that organizations can use to evaluate and enhance their environmental performance.

Drawing extensively from existing literature, the study identifies eight key dimensions of green manufacturing performance, comprising 59 specific variables. These dimensions were subjected to rigorous statistical analyses to confirm their reliability and validity. The finalized and validated framework provides manufacturing organizations with a practical instrument to measure, prioritize, and strengthen their green manufacturing strategies.

Keywords: green manufacturing, sustainability, environmental performance metrics, eco-friendly technologies, regulatory compliance, industrial sustainability, performance evaluation, India.

Introduction

Industrial sustainability has become an important research theme due to increasing environmental concerns and the urgent need to reduce global carbon emissions. Among various industrial sectors, the cement industry has attracted significant attention because of its high energy consumption and substantial contribution to greenhouse gas emissions. Cement manufacturing processes require large amounts of thermal energy during clinker production and involve calcination reactions that release carbon dioxide into the atmosphere. As a result, the sector is considered one of the major contributors to industrial emissions worldwide (Hasanbeigi et al., 2010; Prakasan et al., 2020; Cheng et al., 2023).

In India, the cement industry plays a crucial role in supporting infrastructure development and economic growth. However, increasing regulatory pressure, environmental concerns, and global climate commitments have created a strong need for more sustainable production practices within the sector.

India's long-term climate strategy, which includes the objective of achieving net-zero emissions by 2070, has further intensified the importance of developing low-carbon industrial systems (Chaturvedi et al., 2024; Kumar et al., 2025).

Green manufacturing has emerged as a strategic approach for improving environmental performance in industrial operations. This concept focuses on minimizing resource consumption, reducing waste generation, improving energy efficiency, and incorporating environmentally responsible technologies throughout the production lifecycle (Digalwar et al., 2013; Toke & Kalpande, 2019). In the context of cement manufacturing, green manufacturing includes practices such as the use of alternative fuels, adoption of energy-efficient technologies, utilization of industrial by-products as raw materials, and integration of digital technologies for process optimization (Schneider, 2015; Gupta et al., 2020).

Over the last fifteen years, scholarly research on sustainability in the cement sector has expanded considerably. Early studies primarily focused on environmental impacts and operational efficiency, whereas more recent investigations emphasize circular economy practices, digital transformation, and integrated sustainability frameworks. This chapter reviews the existing literature on green manufacturing within the cement industry, particularly in the Indian context, and identifies major research themes, trends, and gaps.

Industry 4.0 and Digital Transformation in Cement Manufacturing

The emergence of Industry 4.0 technologies has created new opportunities for improving sustainability in manufacturing industries. Digital technologies such as artificial intelligence, big data analytics, and Internet of Things systems enable real-time monitoring and optimization of industrial processes.

IoT technologies allow continuous monitoring of manufacturing operations, enabling firms to identify inefficiencies and reduce energy consumption (Li et al., 2024).

Artificial intelligence has also been applied to optimize cement production processes. Machine learning models have been developed to analyze clinker composition and improve product quality (Zaki et al., 2022; Fayaz et al., 2025).

Digital twin technology represents another significant innovation in manufacturing systems. Digital twins create virtual representations of physical production systems, enabling engineers to simulate manufacturing processes and evaluate operational improvements before implementation (Li, 2025; Runkana et al., 2025).

Blockchain technology has also been explored for improving transparency and traceability in supply chains (Singh & Dadhich, 2024).

These digital technologies have the potential to transform cement manufacturing by enabling data-driven decision making and improving environmental performance.

Literature Review Matrix

Author	Method	Findings	Research Gap
Mandal &	Environmental	Identified regional differences in	Need integrated

Author	Method	Findings	Research Gap
Madheswaran (2010)	efficiency analysis	environmental performance	sustainability framework
Hasanbeigi et al. (2010)	Case study	Identified energy efficiency opportunities in cement plants	Limited application in developing countries
Bishnoi et al. (2014)	Experimental study	Developed LC3 cement with lower emissions	Requires large scale adoption
Varma & Srinivas (2015)	Thermal engineering model	Waste heat recovery improves efficiency	Economic feasibility studies needed
Sangwan et al. (2019)	Sustainability assessment framework	Proposed sustainability indicators	Lack of empirical validation
Li et al. (2024)	IoT monitoring model	Real-time monitoring improves sustainability	Integration with decision systems
Fayaz et al. (2025)	Machine learning model	Accurate prediction of clinker phases	Need real-time implementation

Research Gaps

Despite extensive research on sustainability in the cement industry, several important gaps remain.

First, many existing studies focus on individual sustainability practices rather than integrated frameworks that combine environmental, technological, and organizational factors. There is still limited research examining how these factors interact within complex industrial systems.

Second, although digital technologies have been widely discussed, empirical studies examining their large-scale implementation in cement manufacturing are still limited.

Third, most studies focus on environmental performance without integrating economic and operational considerations into a comprehensive sustainability evaluation framework.

Conceptual Framework Development

Based on the literature review, the following key dimensions influence green manufacturing performance in the cement industry:

- Energy efficiency practices
- Sustainable material usage
- Green supply chain management
- Digital technology adoption
- Organizational and policy support

These factors collectively influence environmental performance, operational efficiency, and sustainability outcomes.

The conceptual model therefore proposes that: Green Manufacturing Practices → Sustainability Performance with Industry 4.0 technologies acting as an enabling factor.

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