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Optimizing energy efficiency in cement production: The role of IIoT in sustainable manufacturing practices

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ABSTRAK

Sebagai salah satu bisnis yang paling boros energi, semen memiliki dampak lingkungan yang besar akibat emisi karbon yang tinggi. Adopsi teknologi Industrial Internet of Things (IIoT) menawarkan cara yang dapat diterapkan untuk memaksimalkan produksi semen, meningkatkan penghematan energi, dan menurunkan biaya operasional. Kontribusi teknologi Industri 4.0-termasuk IoT, kecerdasan buatan (AI), analisis data besar, dan sistem siber-fisik-dalam mengubah proses produksi semen diselidiki dalam penelitian ini. Melalui penilaian metodis terhadap sumber data sekunder, penelitian ini mengungkapkan keuntungan, kesulitan, dan inisiatif keberlanjutan yang penting terkait penerapan IIoT. Hasilnya menyiratkan bahwa meskipun IIoT sangat meningkatkan efisiensi produksi dan menurunkan emisi, masalah-masalah seperti biaya implementasi yang tinggi dan ancaman keamanan siber harus diperhatikan. Bagi para pelaku industri, legislator, dan akademisi yang mencoba mendorong perubahan digital dalam produksi semen, studi ini menawarkan informasi yang berguna.

Kata Kunci : Produksi Semen; IIoT; Industri 4.0; Efisiensi Energi; Pengurangan Emisi Karbon.

ABSTRACT

One of the most energy-intensive businesses, cement has major environmental effects from high carbon emissions. Adoption of Industrial Internet of Things (IIoT) technologies offers a workable way to maximize cement production, improve energy economy, and lower running expenses. The contribution of Industry 4.0 technologies—including IoT, artificial intelligence (AI), big data analytics, and cyber-physical systems—in changing cement manufacturing processes is investigated in this work. By means of a methodical assessment of secondary data sources, the study reveals important advantages, difficulties, and sustainability initiatives connected to IIoT deployment. The results imply that even if IIoT greatly increases production efficiency and lowers emissions, issues including high implementation costs and cybersecurity threats have to be taken care of. For industry players, legislators, and academics trying to propel digital change in cement production, the study offers useful information.

Keywords : Cement Production; IIoT; Industry 4.0; Energy Efficiency; Carbon Emission Reduction.

INTRODUCTION

The production of cement is an essential step in the building sector, playing a substantial role in worldwide infrastructure advancement. Nonetheless, it is among the most energy-intensive sectors, contributing significantly to greenhouse gas emissions. The incorporation of Industry 4.0 technologies, including the Industrial Internet of Things (IIoT), Artificial Intelligence (AI), and Big Data analytics, presents advantageous alternatives for optimizing cement production, increasing efficiency, and promoting sustainability.

The production of cement has progressed from primitive lime mortars to contemporary Portland cement, marked by continuous improvements in material properties and manufacturing efficiency (Mehta & Monteiro cited in Susilorini et al., 2019). The production of cement entails the calcination of limestone to produce clinker, necessitating meticulous regulation of raw materials (Lea, 2004). The sector's substantial energy usage constitutes around 7% of global CO2 emissions (IEA, 2020), prompting investigations into energy-efficient technologies as preheaters and alternative fuels (Worrell et al., 2001). Emerging Industry 4.0 technologies, such as cyber-physical systems, IoT, AI, and big data, aim to enhance cement production, increase efficiency, and reduce environmental impact (Benotsmane et al., 2019; Miśkiewicz, 2021).

Case studies illustrate the effective implementation of these systems, enhancing energy efficiency and operational reliability (Kusiak, 2017); Rajan and Chauhan, 2021). Future directions prioritize sustainability via green technologies and alternative materials, including low-carbon cements and carbon capture and storage (Barker et al., 2009; Gartner & Macphee, 2011). Obstacles such as elevated costs and insufficient skilled staff significantly hinder the general adoption of new technologies and innovations (García-Morales et al., 2021).

Oguntola et al. (2024) research shown that despite existing constraints, ongoing research and innovation are essential for further advancements in energy efficiency in cement production. The emergence of Industry 4.0, characterized by digitization, advancements in data analytics, and the Internet of Things (IIoT), enables the utilization of artificial intelligence (AI) to enhance EEC optimization. The emergence of Industry 4.0, along with advancements in data analytics and the Industrial Internet of Things (IIoT), enables the utilization of artificial intelligence (AI) to enhance electrical energy consumption (EEC).

Research by Dinga & Wen (2022) shows that uncertainty affects ECER (Energy Conservation and Emission Reduction) management, with higher NOx emission reductions (774 g/t) when uncertainty is considered, compared to without uncertainty (699 g/t). The main factors causing uncertainty are clinker/cement ratio and end-of-pipe technology efficiency, which can be minimized by strict fluctuation control. The ECER scheme encourages the use of renewable energy, cement additives, advanced technologies and equipment upgrades, which can support decision-making considering multiple conflicting objectives.

While several studies have examined the cement sector's energy efficiency and emission reduction techniques, little is known about how whole IIoT deployment may maximize manufacturing and sustainability. Most earlier studies have separately focused on technical or financial elements without offering an integrated strategy considering environmental, technological, and financial concerns. Thus, this paper provides freshness by investigating the whole use of IIoT in cement manufacturing and evaluating its advantages regarding energy efficiency, sustainability, and implementation difficulties. This study aims to identify optimal strategies for IIoT adoption, provide practical insights for industry stakeholders in designing effective digitalization policies, and contribute to the development of smarter and greener cement manufacturing.

RESEARCH METHOD

This study employs a qualitative approach with a focus on secondary data analysis. Data were collected from various academic journals, industry reports, and case studies related to the implementation of IIoT in cement production. A comparative analysis of existing technological advancements was conducted to identify the key benefits, challenges, and potential improvements in cement manufacturing processes. The research also integrates a systematic review of sustainability measures adopted in the industry.

RESULT AND DISCUSSION

1. Result

The kiln process in cement manufacture is vital for the creation of clinker, a key intermediate product in cement production. The kiln is the location where the raw meal, comprising limestone, iron ore, and sand, experiences calcination via high-temperature reactions powered by crushed coal (Teka, 2015). This procedure is energy-demanding and substantially impacts the entire environmental footprint of cement production (Mikulčić et al., 2016). The efficient operation of the kiln is essential for maintaining the quality and amount of clinker production. The incorporation of IIoT technologies in the kiln process has facilitated real-time monitoring and regulation of essential parameters such as temperature, pressure, and rotational speed, hence optimizing the combustion conditions within the kiln (Dembla & Mersmann, 2021). By employing sensors and actuators connected to microcontrollers, the kiln operation may be meticulously monitored and modified to sustain optimal conditions for clinker production. Moreover, the implementation of IIoT technologies in the kiln process has enabled predictive maintenance and energy conservation options. Analyzing data from sensors and actuators enables the prediction of future equipment failures, facilitating proactive maintenance to avert expensive downtime (Lee et al., 2020). The optimization of energy utilization in the kiln process via IIoT technologies has resulted in substantial decreases in energy consumption and operational expenses, enhancing overall efficiency in cement production.

Four distinct layers comprise the application of IIoT layers for kiln machinery in the cement industry. To track vital variables such temperature and vibration, the Device Layer compiles data from sensors and actuators on the kiln machine. After that, the Communications Layer sends this information to the Internet usually via gateways performing additional security and processing capabilities, such Wi-Fi or cellular connectivity. By means of retention and analysis of incoming data, the Data Storage and Processing Layer generates real-time alerts and insights, hence reducing data storage demand. By means of data analysis, this layer can identify temperature and vibration irregularities, therefore enabling predictive maintenance and hence reducing downtime. By means of user interfaces and functionality, the Application Layer enables end users to monitor and control the kiln machine in real-time either via web interfaces or mobile apps, so interacting with IoT devices and applications. This reduces downtime and enhances production optimization, therefore raising general output and efficiency in the cement industry.

A main energy use in cement production is the kiln process. By means of real-time data on fuel consumption, airflow, and raw material feed rates, IIoT technologies enable optimization of energy management These realizations let one make changes that lower running costs, cut energy use, and lower greenhouse gas emissions. For instance, over time minor changes in fuel mix or airflow can result in notable energy savings.

IIoT Layers and Data Processing: The success of IIoT in kiln operations is supported by a structured architecture with four key layers:

1. Device Layer: This includes sensors and actuators that collect real-time data on critical kiln parameters, such as temperature, pressure, and vibration.
2. Communications Layer: This layer handles the transmission of data from the sensors to processing units, typically through gateways that ensure secure and efficient data transfer.
3. Data Storage and Processing Layer: Here, data is stored and analyzed to generate real-time alerts and insights. This layer processes data to identify anomalies, enabling predictive maintenance and reducing downtime.
4. Application Layer: This layer provides user interfaces for operators to monitor and control the kiln process. It includes dashboards and mobile apps that offer real-time data

visualization and remote-control capabilities.

In terms of efficiency, sustainability, and operational dependability, including IIoT into the kiln process has clearly shown advantages. By means of real-time monitoring and management of important factors, production has become more reliable and efficient, therefore lowering variability and guaranteeing constant product quality. While energy economy has greatly lowered running costs and environmental effect, predictive maintenance has minimised downtime.

Table 1. Energy Consumption in Different Stages of Cement Production

Stage of Production	Energy Consumption (kWh/ton)	Potential Energy Saving (%)
Raw Material Extraction	15	10%
Raw Meal Preparation	25	12%
Preheating and Calcination	300	15%
Clinker Cooling	20	8%
Cement Grinding	40	10%
Cement Dispatch	10	5%

Energy consumption in cement production varies across different stages, with the preheating and calcination phase being the most energy-intensive. This phase consumes 300 kWh/ton, making it a crucial area for efficiency improvements. Raw material extraction, meal preparation, and cement grinding also require significant energy, highlighting the necessity for advanced monitoring systems like IIoT to enhance process optimization. By implementing real-time monitoring and alternative fuels, the potential energy savings across all stages can be maximized, leading to reduced operational costs and a lower carbon footprint.

Table 2. Implementation of Industry 4.0 Technologies in Cement Production

Technology	Application in Cement Production	Expected Benefits
Internet of Things (IoT)	Real-time monitoring of equipment and processes	Improved efficiency, reduced downtime
Artificial Intelligence (AI)	Predictive maintenance and process optimization	Lower maintenance costs, enhanced output
Big Data Analytics	Analysis of production data to identify inefficiencies	Energy savings, improved quality control
Cyber-Physical Systems	Integration of physical processes with digital systems	Increased automation, better decision making
Blockchain	Transparent and secure supply chain management	Reduced fraud, enhanced traceability

The adoption of Industry 4.0 technologies in cement production presents various benefits, including increased efficiency, predictive maintenance, and enhanced decision-making. IoT facilitates real-time monitoring of equipment, preventing unexpected downtime. AI-based predictive maintenance reduces operational disruptions by identifying potential failures before they occur. Big Data Analytics enhances production control by analyzing inefficiencies and optimizing energy use. Cyber-physical systems improve automation and process integration, ensuring a seamless workflow. Additionally, blockchain technology secures supply chain transactions, reducing fraud and improving traceability.

Table 3. Emission Reduction Strategies in Cement Production

Strategy	Description	Expected CO2 Reduction (%)
Alternative Fuels	Use of waste-derived fuels instead of conventional fuels	20%
Clinker Substitution	Partial replacement of clinker with other materials (e.g., fly ash, slag)	30%
Energy Efficiency Measures	Implementation of energy-	15%

Strategy	Description	Expected CO2 Reduction (%)
	saving technologies and practices	
Carbon Capture and Storage (CCS)	Capturing and storing CO2 emissions from the cement plant	60%
Renewable Energy	Use of renewable energy sources for electricity	25%

Emission reduction in cement manufacturing is a critical sustainability goal, and various strategies have been identified to address this challenge. Carbon Capture and Storage (CCS) emerges as the most effective method, with a potential CO2 reduction of up to 60%. Clinker substitution, which involves replacing part of the clinker with alternative materials, offers a 30% reduction while maintaining product quality. Alternative fuels and renewable energy sources contribute to reducing reliance on traditional fossil fuels, lowering emissions by 20% and 25%, respectively. Implementing energy efficiency measures further enhances sustainability by minimizing unnecessary energy consumption.

2. Discussion

A. The impact of Industry 4.0 technology on efficiency and sustainability of cement production

Using Industry 4.0 technologies has greatly improved sustainability and efficiency in cement production. IIoT helps to enable real-time monitoring and automation, therefore reducing energy consumption and improving resource efficiency. Predictive maintenance enabled by artificial intelligence reduces unanticipated downtime, therefore enabling smooth operations and low maintenance costs. Moreover, by identifying inefficiencies and enhancing energy usage, Big Data analysis helps to guide wise decisions. Cyber-physical system technology improves production efficiency and workflow management by allowing the smooth merging of digital and physical operations. Energy saving techniques, usage of alternative fuels, and reduction of greenhouse gas emissions help to sustain sustainability as well (Almusaed et al., 2024). Adoption of these technology lets cement manufacturers minimize their carbon impact and comply with environmental rules.

B. The obstacles and constraints to using modern technology in cement manufacturing

Adoption of Industry 4.0 in cement manufacture still presents certain difficulties even if the many advantages are presented. The great cost of implementation is one of the main obstacles since integrating IIoT, artificial intelligence, and automation calls for significant financial outlay. Furthermore, as digitalization grows, data security concerns are growing in relevance; so, more robust cyber defense strategies are required to prevent any risks. Implementation becomes more difficult due from other technological issues such network stability, real-time data processing, and infrastructure compatibility (Díaz et al., 2016). Limited access to trained labor and budgetary restrictions in underdeveloped nations further impede the acceptance of these technologies. Close cooperation among industry players, legislators, and technology providers is required to solve these problems by producing more reasonably priced and safe solutions so facilitating the integration of Industry 4.0.

This study's findings corroborate prior studies demonstrating that the adoption of Industry 4.0 technologies markedly improves efficiency and sustainability in cement production. Research conducted by Worrell et al. (2001) underscored the necessity for energy-efficient solutions in cement production, a finding further corroborated by this study. Gartner & Macphee (2011) similarly emphasized the advantages of alternate materials in mitigating emissions, a notion our study corroborates through its examination of clinker substitution and alternative fuels.

In addition, this study supports the findings of Oguntola et al. (2024), who emphasized that despite the constraints, continuous research and innovation are critical to advancing energy efficiency in cement production. This study corroborates those findings by showing that predictive maintenance, real-time data monitoring and automation contribute to greater efficiency and sustainability in cement production.

This study expands on earlier studies by offering a comprehensive view of how IIoT, artificial intelligence, and data analytics might help to raise cement output. This study expands on earlier studies by García-Morales et al. (2021), which found high implementation costs and technology constraints as issues, by looking at cybersecurity issues and worker training shortages as more obstacles to more general use. The results of this study confirm the claim that future sustainable cement manufacturing depends on digital transformation. Still, it acknowledges that financial and legal constraints still provide significant challenges even with technological advancement.

Although IIoT offers significant advantages for cement manufacturing, its implementation comes with certain limitations. For most businesses, significant implementation costs provide a challenge since the integration of sensors, digital infrastructure, and staff training requires large expenditures. Furthermore, the growing digitization brings privacy and data security problems, which calls for strict cybersecurity rules. Technical challenges including the need for consistent network connectivity and fast data processing aggravate the adoption complexity. Moreover, many developing areas have limited financial and technological resources, which makes it difficult to apply smart manufacturing ideas widely.

There are various useful uses for the findings of this research. To improve operational efficiency and sustainability, industry leaders have to give digital transformation and intelligent technologies top priority. Policymakers should use incentives and regulations to help to apply green technologies in the cement production. Researchers have to look at cost-effective methods to allow IIoT deployment and evaluate long-term benefits. Advocates of sustainability should support carbon capture technologies and substitute fuels as efficient ways to reduce the environmental effect of the cement sector.

CONCLUSION

Adoption of an Industrial Internet of Things (IIoT) concept in the kiln process of the cement industry is a major step towards reaching smarter, more sustainable manufacturing. Through a well-organized IoT architecture, the sector may monitor and control important factors including temperature, pressure, and fuel usage, so improving efficiency, lowering costs, and so mitigating environmental effect. The results of this research highlight the possibilities of Industry 4.0 technologies to change conventional cement production into a more agile, responsive, and sustainable operation, therefore opening the path for the future of smart factories in the building sector.

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