Synergizing Circular Economy and Eco-Industrial Park Concepts: A Literature-Based Exploration for Advancing Inclusive and Sustainable Industrial Development in Indonesia

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Abstract. The adoption of Circular Economy (CE) principles within Indonesia's Eco-Industrial Parks (EIPs) is a strategic pathway toward sustainable industrial development. This paper conducts a literature-based synthesis of these two complementary approaches, explores their relevance to Indonesia's policy and industrial landscape, and recommends further research and pilot experimentation to validate these insights in Indonesian contexts. A key recommendation is the development of a robust policy and regulatory framework aligned with CE principles, including waste hierarchy, extended producer responsibility, and sustainability reporting and create a mechanism to incentivise the industrial parks for adopting the CE approaches. Equally important is the need to build technical and institutional capacity by incorporating CE concepts into education and training, strengthening institutional coordination and targeted capacity-building initiatives can empower stakeholders, particularly SMEs, to adopt and scale CE practices effectively. Innovation and technology transfer are also critical to CE adoption, encouraging R&D in material recovery, waste valorisation, and digital technologies (e.g., IoT and data analytics) which can support the development of locally appropriate solutions. While this research is grounded in literature, its secondary nature highlights the need for empirical studies to validate findings. Future work should include on-the-ground assessments to support Indonesia's transition from linear to circular industrial models.

1 Introduction

The term "triple planetary crisis," introduced by the United Nations Environment (UNEP) in 2022, encompasses three significant interconnected challenges currently confronting

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humanity: climate change, biodiversity loss, and pollution and waste. Each issue has distinct causes and consequences, necessitating comprehensive solutions for a viable future. The underlying link among these crises is unsustainable patterns of production and consumption. Existing development paradigms have not fully addressed these crises, leading to the formulation of sustainable development goals. In alignment with this, Indonesia has implemented policies under the Sustainable Development Goals (SDGs) to realize the 2030 development agenda. Industrial growth is being steered towards sustainability, prioritizing a balance between economic, social, and environmental considerations.

The Circular Economy (CE) concept embodies a revolutionary shift in how societies produce, consume, and manage resources. This shift has gained considerable traction lately as societies confront the issues of unsustainable consumption and resource depletion. In contrast to the traditional linear model of "take, make, dispose," CE aims to establish a closed-loop system where products, materials, and resources are reused, repaired, remanufactured, and recycled to prolong their usefulness and minimize waste. The circular economy (CE) has emerged as a transformative framework to redefine production and consumption by promoting resource efficiency, waste reduction, and system regeneration. Unlike the traditional linear take-make-dispose model, CE emphasizes closed-loop systems where products and materials are used for as long as possible through reuse, remanufacturing, recycling, and design innovations. This innovative approach prioritizes sustainability and environmental conservation and emphasizes economic efficiency, offering a promising trajectory for our future.

Industrial parks have both potentially positive and negative impacts. While they contribute to economic growth and social development, they can also cause adverse environmental and social impacts, including climate change, pollution, resource depletion, labor issues, and negative impacts on communities. Thus, sensitive planning and management are needed to mitigate adverse outcomes and to optimize economic, social, and environmental gains. Interest in industrial parks has grown substantially in recent decades. Grouping firms in defined locations offers potential collaborative and efficiency gains, for instance, by implementing circular economy practices. As developing and emerging economies seek increased industrial output, there is a pressing need to balance economic growth with environmental and social objectives.

Eco-industrial parks (EIPs) represent a paradigm shift towards sustainable industrialization by emphasizing resource efficiency, environmental responsibility, and economic growth. The circular economy is now at the forefront of the competitiveness agenda for various industrial sectors, industrial parks, and firms [1]. A crucial aspect of EIPs is the integration of circular economy principles, which aim to minimize waste and promote the continual use of resources.

Concurrently, the Circular Economy (CE) has gained traction worldwide as a systemic model to decouple economic growth from resource consumption and environmental degradation. The CE promotes reuse, recycling, and regeneration of materials to close the loop on industrial processes, contrasting with the traditional linear model of take-make-dispose. Incorporating CE principles within EIPs can enhance industrial sustainability, improve resource efficiency, and foster innovation.

This paper aims to survey the literature on the integration of CE in EIPs globally and assess the prospects and challenges specific to Indonesia to provide a comprehensive, evidence-based analysis.

2 Materials and methods

2.1 Materials and methods

To explore the development, application, and critique of the circular economy (CE) concept, a comprehensive literature review was conducted using a combination of academic databases and institutional sources.

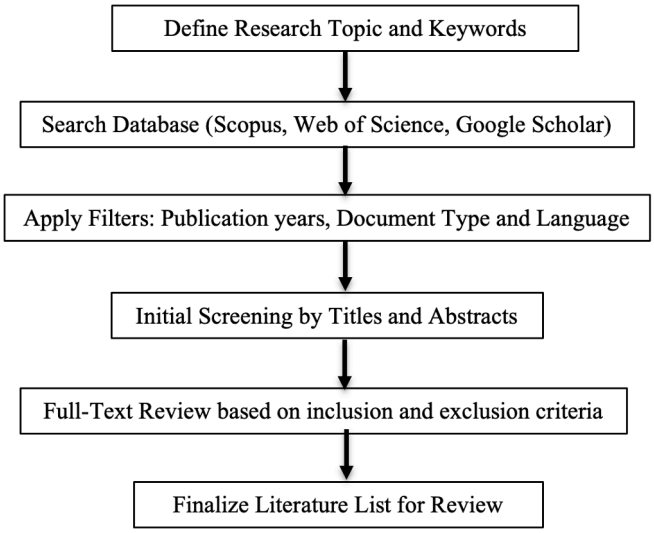

Fig. **1.** Literature review paper selection process

The review focused on peer-reviewed journal articles, foundational books, and key institutional reports related to circular economy theory, implementation strategies, and policy developments.

The literature search was conducted using leading academic databases, including Scopus, Web of Science (WoS), ScienceDirect, and Google Scholar, with supplementary sources and relevant institutional websites such as the World Bank, UNIDO and the Ellen MacArthur Foundation. Search terms were carefully selected and combined using Boolean operators, with keywords including "circular economy," "eco-industrial park," "industrial symbiosis," "sustainable industrial development," "Indonesia," and "developing countries."

Inclusion criteria focused on peer-reviewed journal articles, high-quality institutional reports, and policy papers that addressed relevant topics such as CE–EIP integration, technological enablers, policy frameworks, or case studies within Indonesia or comparable economies.

Exclusion criteria eliminated non-English publications, inaccessible full texts, and unrelated sustainability topics. The screening process included title and abstract reviews

followed by full-text evaluation to ensure thematic relevance and methodological rigor. Quality assurance was maintained by prioritizing articles from Scopus-indexed (Q1 and Q2) journals, cross-checking citation counts, and verifying institutional source credibility.

The final selection of literature comprised scholarly articles, case studies, and policy reports that collectively informed a comprehensive understanding of the synergy between circular economy practices and eco-industrial park development, particularly in the Indonesian context.

2.2 Eco-industrial parks

Eco-industrial parks (EIPs) embody the tenets of industrial ecology and sustainable development by fostering the aggregation of industries to share resources. Eco-Industrial Parks (EIPs) are defined as managed industrial areas that promote cross-industry and community collaboration for common benefits related to economic, social and environmental performance [2]. Other researchers have also defined EIPs as geographically defined industrial clusters where companies collaborate to improve environmental and economic outcomes through resource sharing, industrial symbiosis, and sustainable infrastructure development. Characterized by integrated infrastructure, collaborative governance frameworks, environmental management systems, and mechanisms for stakeholder engagement, EIPs exemplify the principles of industrial synergies and symbiosis and circular resource flows. Industrial symbiosis, as one of the key features of EIPs, was clearly illustrated by Lowe's seminal 2001 study on the Kalundborg Eco-Industrial Park in Denmark, where the byproducts of one industry are utilized as inputs for another, creating closed-loop material flows. This collaboration reduces waste, lowers costs, and improves environmental performance, making EIPs a global best practice for sustainable industrialization.

In recent years, Indonesia has witnessed early-stage efforts to develop EIPs, particularly in industrial hubs such as MM2100 Industrial Town, Batamindo Industrial Park, Karawang International Industrial City, Greenland International Industrial Center, and Kawasan Industri Medan, which have been joined as pilot industrial parks for implementing EIP approaches to transform into Eco Industrial Parks with the support under the Global Eco-Industrial Parks Programme (GEIPP) following the International Framework for Eco-Industrial Parks. However, these initiatives still require a conducive policy and regulatory framework to implement EIP approaches.

Comparative studies underscore that while countries like Denmark, South Korea, and China have advanced EIP systems, Indonesia is still developing its approach to industrial symbiosis and eco-design. For example, Ulsan Industrial Park in South Korea integrates environmental engineering innovations and strong government-industry collaboration, setting benchmarks for resource efficiency and pollution reduction. Similarly, Tianjin EIP in China demonstrates how coordinated policy, infrastructure investment, and technology adoption can drive circularity at scale. Indonesia can learn from these examples but must adapt them to its unique socio-economic and industrial contexts.

The literature identifies several benefits of EIPs, including reduced raw material consumption, lower waste treatment costs, and improved industrial competitiveness. Moreover, environmental benefits such as decreased emissions and improved local air and water quality have been documented. Nevertheless, fully realizing these benefits depends on

overcoming barriers such as a lack of trust among industries, data transparency challenges, and insufficient monitoring mechanisms.

Innovations and digitalization of waste and resource exchange are emerging as critical enablers of industrial symbiosis within EIPs. Studies from Indonesia have begun exploring how IoT and blockchain technologies can support transparency and coordination among industries. However, digital adoption remains uneven, with many small and medium enterprises (SMEs) lacking the capacity to engage fully.

Grouping firms in defined locations offers potential collaborative and efficiency gains, for instance, by implementing circular economy practices. As developing and emerging economies seek increased industrial output, there is a pressing need to balance economic growth with environmental and social objectives.

Eco-industrial parks (EIPs) represent a paradigm shift towards sustainable industrialization by emphasizing resource efficiency, environmental responsibility, and economic development. The circular economy is now at the forefront of the competitiveness agenda for various industrial sectors, industrial parks, and firms [2]. Research into industrial parks has mostly focused on eco-industrial parks (EIPs) instead of circular transformation for at least the past two decades. EIPs have been promoted to achieve sustainable industrial development. The circular economy (CE) is receiving increased attention globally as a way of sustainable production and consumption, and increasing resource throughput [3].

The second edition of the international framework for eco-industrial parks, jointly published by UNIDO, World Bank, and GIZ in 2021, provided the 64 benchmarks to assess the performance of industrial parks that can be used for improving their performance in the areas of industrial park management, environmental, social and economic performance. These benchmarks also include, but are not limited to, the aspects of the circular economy approach for transforming industrial parks into eco-industrial parks.

2.3 Circular economy

The circular economy (CE) has recently emerged as a significant topic in sustainability discussions, despite its conceptual roots in the 1970s. This evolving concept faces competition from various interpretations, with many existing models focusing on technocentric solutions while overlooking crucial social, political, and ecological aspects. This opinion paper aims to explore the meanings of cycles and flows in relation to the economy and society, identifying seven key socio-ecological cycles—biogeochemical, ecosystem, resource, power, wealth, knowledge, and care—that are vital for understanding CE and its connection to human and planetary well-being. The paper critiques current CE discourses for inadequately addressing these cycles and proposes the idea of a "circular society" as a framework to tackle the ecological, social, and political implications of transitioning to circularity. It also outlines strategies to operationalize this concept, hoping to enhance the discourse around circularity and promote collaborative solutions for the socio-ecological challenges of the twenty-first century [4].

The concept of a circular economy signifies a departure from the conventional linear model of production and consumption toward a regenerative and restorative approach. Rooted in principles of industrial ecology and sustainable development, the circular economy framework underscores the importance of resource efficiency, waste reduction,

and the reuse, remanufacture, and recycling of materials and products. Prominent advocates such as Walter R. Stahel, known for the "Cradle to Cradle" concept, and Ellen MacArthur, founder of the Ellen MacArthur Foundation, have championed the adoption of circular economy principles to disassociate economic growth from resource depletion and environmental degradation.

The circular economy (CE) has emerged as a transformative framework to redefine production and consumption by promoting resource efficiency, waste reduction, and system regeneration. Unlike the traditional linear take-make-dispose model, CE emphasizes closed-loop systems where products and materials are used for as long as possible through reuse, remanufacturing, recycling, and design innovations.

Material cascading and looping are fundamental CE strategies where residual materials from one process serve as inputs for another, thereby maximizing resource utility and minimizing waste generation [5]. Several studies have demonstrated how CE practices reduce raw material consumption and environmental burdens while promoting economic competitiveness [6]. For example, integrating product life extension strategies through refurbishment and remanufacturing can significantly lower environmental footprints and enhance circularity within industrial clusters.

Incorporating renewable energy and energy efficiency measures is another pillar of CE implementation, reducing carbon intensity and fostering sustainable industrial ecosystems. The shift to CE also requires systemic changes in supply chains and production networks, involving collaboration across multiple stakeholders and sectors to enable circular flows [7]. Furthermore, digital technologies like IoT, AI, and blockchain are increasingly recognized as enablers of CE by improving resource tracking, transparency, and coordination among industrial actors [8].

Despite the increasing adoption of CE principles worldwide, challenges remain in developing economies where infrastructural and technological gaps, regulatory weaknesses, and low awareness impede large-scale implementation. Context-specific studies highlight that CE adoption needs to be sensitive to local economic, social, and environmental realities to be successful. In Indonesia, initial efforts to embed CE in industrial practices show promise but require stronger policy alignment and capacity building.

The literature suggests that CE in industrial parks can deliver substantial environmental benefits, including reduced waste, lower emissions, and improved resource productivity, while driving innovation and job creation. However, realizing these benefits depends on overcoming barriers such as limited technological infrastructure, fragmented regulations, and insufficient stakeholder coordination [9]. Effective CE implementation is thus not only a technical challenge but also an institutional and cultural one.

2.4 Circular economy in developing economies

Incorporating circular economy principles into eco-industrial parks presents collaborative avenues to propel sustainability objectives and spur innovation across industries. Eco-industrial parks can function as dynamic arenas for experimenting with and implementing circular economy strategies and establishing closed-loop systems.

Implementing circular economy principles in developing economies presents unique challenges and opportunities that differ significantly from those in developed countries [10]. These countries often face infrastructural constraints, including limited waste management

systems, inadequate recycling facilities, and inconsistent energy supplies, which complicate the transition to circular industrial models. Furthermore, regulatory frameworks tend to be less stringent or poorly enforced, reducing incentives for industries to adopt sustainable practices and circular approaches [11]. This regulatory fragmentation also creates barriers to investment in CE technologies and infrastructure, hindering progress.

Low awareness and knowledge about CE among business leaders, policymakers, and the general public are additional critical obstacles in developing economies like Indonesia [12]. This lack of understanding often results in limited demand for circular products and services, as well as insufficient pressure on industries to innovate toward CE models. Nonetheless, targeted capacity building and education programs have shown promise in raising awareness and fostering cultural shifts toward sustainability. Governments' active roles in promoting CE principles through incentives and pilot projects are crucial to stimulate adoption and demonstrate tangible benefits.

Localized studies highlight that CE strategies must be adapted to fit local contexts, respecting economic realities, social norms, and existing industrial capacities [13]. For instance, in Indonesia, informal sectors play a significant role in waste collection and recycling, which offers opportunities to integrate these actors into formal circular systems, enhancing inclusivity and effectiveness. Moreover, the diverse industrial landscape in Indonesia, spanning small-scale manufacturers to heavy industries, requires differentiated CE approaches tailored to specific sectors and scales.

Despite these challenges, several developing economies have demonstrated successful CE initiatives, particularly within eco-industrial parks, by leveraging government-industry-academia partnerships [14]. Such experiences offer valuable lessons for Indonesia, emphasizing the importance of strong institutional frameworks and cross-sectoral collaboration.

Economic incentives are vital for CE uptake, especially in resource-constrained environments where short-term financial returns dominate business decisions. Subsidies, tax breaks, and preferential financing for CE-aligned technologies encourage industries to invest in cleaner production methods and circular material flows. Moreover, establishing CE-friendly infrastructure such as material recovery facilities and digital platforms for resource exchange enhances feasibility and scalability.

Technological adoption is another crucial enabler but is often limited by capital shortages and technology transfer barriers in developing countries [15]. Innovative solutions that are cost-effective and context-specific, such as low-tech recycling methods or modular industrial symbiosis schemes, have shown potential to overcome these hurdles. Digital tools supporting transparency and traceability further strengthen the operationalization of CE in industrial parks.

Social acceptance and cultural adaptation also play decisive roles in CE success. Behavioral changes toward waste segregation, reuse, and responsible consumption require continuous engagement and education campaigns. Engaging local communities, workers, and SMEs ensures that CE benefits are broadly shared and sustainable over time.

Aligning CE efforts with national development goals and international commitments such as the SDGs provides additional momentum and resources for implementation. Indonesia's commitment to climate action and sustainable growth creates a favorable policy backdrop for integrating CE into industrial policy frameworks, including within EIPs.

However, continuous monitoring and adaptive governance mechanisms are necessary to navigate the evolving challenges and maximize impact.

Mechanisms such as material exchange networks, industrial symbiosis platforms, and joint research endeavours facilitate the exchange of expertise, resources, and exemplary approaches among stakeholders within eco-industrial parks. Empirical investigations into the environmental, economic, and social ramifications of circular initiatives within these parks reveal favourable outcomes, including reductions in waste, financial savings, job generation, and community advancement. Technical factors are related to the availability of technologies that facilitate resource optimization, remanufacturing, and regeneration of by-products. Ulla A. Saari et al. (2024) have shown how companies benefit from a set of capabilities for CE innovation that support their CE implementation and result in product/service innovations.

Nikolaos Nikolakis et al. (2024) discussed an extended eco-efficiency indicator using the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) and linking them to product quality, process performance, and availability, the while extended eco-efficiency indicator targets single processes; by combining all processes of a manufacturing system, the extended indicator can be calculated on a system level, providing insights into both the environmental and value performance.

Marinella Tsakalova et al. (2024) discussed a methodology for assessing bio-based circular value chains focused on innovative bio-based solutions. The circularity value of waste generated within the industrial park was evaluated to assess the economic value addition of the industrial park within a circular economic framework.

Circular manufacturing systems in developing countries and economies in transition have the potential to intertwine economic, environmental, and social elements in a way that fundamentally reshapes the fabric of society. Central to this vision is the design phase of products, which prioritizes their entire lifecycle and focuses on qualities like durability and modularity. This shift can open the door for many skilled job opportunities, from design engineers specializing in sustainable materials to technicians trained in product repair and remanufacture, heralding a resurgence of craftsmanship and localized industries.

3 Results and discussion

3.1 Opportunities for the circular economy in indonesian industrial parks

Indonesia is Southeast Asia's largest economy and has experienced rapid industrial growth over recent decades, contributing significantly to GDP and employment. However, this growth has also led to environmental challenges such as increased pollution, waste accumulation, and natural resource depletion, raising sustainability concerns. Eco-Industrial Parks (EIPs) have emerged as an innovative approach to mitigate such impacts by promoting cooperation among industries to share resources, minimize waste, and reduce emissions through industrial symbiosis. These parks represent an opportunity for Indonesia to align industrial expansion with environmental, social, and economic resilience as outlined in the International Framework for Eco-Industrial Parks.

Indonesia's unique industrial landscape offers fertile ground for the integration of circular economy principles within eco-industrial parks (EIPs). Recent studies emphasize that Indonesia's industrial parks, especially on Java and Sumatra islands, host a diverse mix

of industries, which facilitates the potential for industrial symbiosis and resource sharing. Proximity between industries in these parks supports waste exchange and collaborative energy use, key components of CE strategies. The Indonesian government's "Green Industrial Park" policy further incentivizes sustainability, focusing on pollution reduction and resource efficiency. Moreover, the country's commitment to international climate agreements exerts external pressure to adopt greener industrial models, creating a supportive environment for CE adoption.

Technological advancements in renewable energy and digital monitoring have enhanced opportunities for optimizing resource use in Indonesian EIPs. Indonesia's abundant renewable resources also contribute to CE potential and the availability of biomass and solar energy allows industries to transition to cleaner inputs, reducing reliance on fossil fuels. This energy transition aligns with global CE strategies focusing on renewable integration to decarbonize industrial clusters. Collaborative platforms facilitated by government and industry associations enhance knowledge exchange and collective problem-solving, which are critical for scaling CE practices.

Financial mechanisms, including green financing and subsidies for circular technologies, are increasingly accessible, encouraging investment in EIPs' circular infrastructure. The Indonesian government is piloting circular economy roadmaps at provincial levels, integrating EIPs as flagship initiatives for sustainable industrialization. These strategic efforts are complemented by active participation from academia and NGOs, enriching the innovation ecosystem needed for CE success. Together, these elements create a multifaceted opportunity framework for CE integration within Indonesian EIPs.

A study on the circular economy in Indonesia was conducted by the Ministry of National Development Planning/National Development Planning Agency (BAPPENAS) in 2021 in a study entitled "Summary for Policymakers of Economic, Social, and Environmental Benefits of Circular Economy in Indonesia", containing identification of circular economy practices that have been implemented in Indonesia, especially in 5 (five) priority industrial sectors namely food and beverages, construction, electronics, textiles, and plastics. These five industry sectors were selected in 2019 because they contribute 1/3 of Indonesia's Gross Domestic Product (GDP) and employ more than 43 million people. A circular approach can generate meaningful economic, environmental, and social benefits by 2030 when compared to a "business as usual" scenario.

In 2022, the Ministry of National Development Planning/National Development Planning Agency (BAPPENAS) launched a study entitled "The Future Is Circular: Real Steps of Circular Economy Initiatives in Indonesia," which contained the stories of 36 (thirty-six) initiators from various economic sectors and various actors (government, business actors, and NGOs) who implemented circular economy models in Indonesia.

While there are promising advantages to incorporating circular economy principles into EIPs, numerous obstacles impede their widespread adoption and implementation. These hurdles encompass regulatory restrictions, technological constraints, financial barriers, and a lack of awareness or incentives among stakeholders. Nevertheless, emerging trends like digitalization, servitization, and product-as-a-service models offer fresh avenues to surmount these challenges and expedite the shift towards a circular economy. Collaborative governance frameworks, policy incentives, capacity-building endeavors, and strategies for engaging stakeholders are imperative for surmounting barriers and realizing the complete potential of circular economy practices within EIPs.

A crucial aspect of Eco-Industrial Parks is the integration of circular economy principles, which aim to minimize waste and promote the continual use of resources. This research proposal outlines a comprehensive study to understand and implement strategies to enhance circular economy practices within EIPs.

In the study "The Future Is Circular: Real Steps for Circular Economy Initiatives in Indonesia" by the Ministry of National Development Planning/National Development Planning Agency (BAPPENAS) in 2022, the circular economy principles focus on reducing the consumption of resources and materials in the production chain summarized in the 9R framework. The 9R framework consists of 10 circular economy principles and is divided into three major parts, namely (1) making and using products smarter, (2) extending product life, and (3) benefiting from materials (Ministry of National Development Planning/Bappenas, et al. 2022). Ten circularity principles or strategies can exist to reduce the consumption of natural resources and materials and minimize waste production. The strategies are priority according to their level of circularity, where more circularity equals more environmental benefits.

The literature suggests that CE in industrial parks can deliver substantial environmental benefits, including reduced waste, lower emissions, and improved resource productivity while driving innovation, technology transfer, and job creation. However, realizing these benefits depends on overcoming barriers such as limited technological infrastructure, fragmented regulations, and insufficient stakeholder coordination.

3.2 Barriers to circular economy implementation

Despite the increasing adoption of CE principles worldwide, challenges remain in developing economies where infrastructural and technological gaps, regulatory weaknesses, and low awareness impede large-scale implementation. Fragmented regulatory frameworks pose one of the most critical challenges, with inconsistencies among environmental, industrial, and economic policies limiting coherent CE development. Context-specific studies highlight that CE adoption needs to be sensitive to local economic, social, and environmental realities to be successful. In Indonesia, initial efforts to embed CE in industrial practices show promise but require stronger policy alignment and capacity building. Moreover, the lack of standardized metrics and monitoring systems for circularity undermines efforts to track progress and incentivize continuous improvement.

Technological limitations are also pronounced in Indonesian industrial contexts. Many EIPs lack access to advanced CE-enabling technologies such as real-time resource monitoring, automated waste sorting, or efficient material recovery systems. The high capital costs of these technologies discourage adoption, particularly among small and medium enterprises (SMEs) that dominate many industrial parks. Additionally, insufficient technical expertise and human capital constrain operational capacity to implement and maintain CE processes effectively.

Cultural factors and business mindsets centered on short-term profits present another barrier to CE adoption. Informal sectors, while vital to recycling, are often marginalized in formal CE frameworks, limiting potential synergies. Many industrial actors remain skeptical about the economic viability of circular models or prioritize immediate cost savings over long-term sustainability benefits. There is also limited awareness of circular economy principles outside major urban centers, hampering inclusive engagement.

In addition, infrastructural gaps such as unreliable energy supplies, inadequate logistics, and insufficient waste management infrastructure complicate circular system implementation. The absence of strong public-private partnerships and cross-sectoral collaboration hinders holistic solutions and scaling. Overcoming these barriers requires integrated strategies that simultaneously address technical, regulatory, and infrastructural challenges.

3.3 Comparative analysis with global models

Global experience with CE in eco-industrial parks offers valuable lessons for Indonesia's pathway to circularity. The principles of circular economy are in line with the performance requirements in the Eco-Industrial Park (EIP). The approach in the EIP performance indicators can enhance the circular economy in industrial parks, such as in the areas of energy (development of new and renewable energy and energy efficiency), water (water consumption, wastewater treatment, efficiency, reuse, and recycling), waste and materials (waste/byproducts are reused and recycled and resource conservation including industrial symbiotic networks in the park).

The interaction between industry and the environment is increasingly important as growing environmental pressures impact industrial performance. Eco-industrial parks aim to transform traditional industrial systems into ecosystems through shared infrastructure, resource efficiency, and industrial symbiosis—where one company's waste becomes another's input. Applying these circular economy principles at both the industrial park and city levels promotes zero-waste systems and fosters integration between socio-economic and ecological systems.

Eco-industrial parks (EIPs) can be evaluated based on their integration of circular economy technologies using a new metric called the specialization index. The index is calculated through four key technologies: waste treatment, industrial symbiosis, water resource efficiency, and renewable energy. A correlation analysis across 15 regions in 2021 found that a balance of demand and supply had been reached only for waste treatment technologies, while industrial symbiosis remained at an average level. The development of markets for water efficiency and renewable energy technologies in 2021 indicates the need for EIPs to implement a full range of circular economy technologies to achieve sustainable development goals.

Saha et al. (2022) mentioned the issues of waste management in Russian cities and highlighted that adopting circular economy principles offers a promising solution by introducing a five-stage methodology for developing EIPs and applying it to create a model for the Voronezh Region, aiming to address local environmental, economic, and social challenges. Given Russia's high waste disposal rate, implementing such models nationwide could significantly enhance resource efficiency and support sustainable development goals. Eco-Industrial Parks (EIPs), which promote industrial symbiosis through shared resources and energy exchange, represent a key infrastructure for supporting this transition.

Eco-industrial parks can reduce natural resource consumption and environmental pollution by promoting circular economic development, improving ecological conditions, and enhancing sustainable development in economic zones. However, evaluating these parks' ecological and economic efficiency faces challenges, such as comparability of analysis objects and unification of dimensions. These issues can be addressed using emergy analysis, which gathers data on industrial parks' natural, geographical, social, and economic

aspects. Zhao et al. (2019) used emergy ternary diagrams to assess the sustainability of the Shenyang Economic and Technological Development Zone, providing a scientific approach to planning and evaluating eco-economic efficiency in industrial agglomeration areas.

Scientific planning, effective implementation, and stable operation are critical for the sustainable development of economic zones in China. Chen, Xu, & Li, (2009) emphasize the importance of developing a structured roadmap for the circular economy in eco-industrial parks. Their approach utilizes knowledge engineering technology to construct development roadmaps that facilitate the transition to circular economy practices. This method supports eco-industrial park managers in generating mid- to long-term regional development plans and enables dynamic management, thereby enhancing operational standards and park efficiency, ultimately promoting the sustainability of eco-industrial parks.

The global spotlight is increasingly focused on the concept of the circular economy (CE) to address the challenges posed by continual production and consumption growth while also enhancing resource efficiency. China's Tianjin EIP, demonstrates the impact of clear policy directives combined with government funding and incentives (Xu & Feng, 2023). Strong institutional support enabled rapid adoption of industrial symbiosis and resource sharing, significantly reducing waste and emissions. The collaborative model involved academia, industry, and local government working closely to innovate and implement CE solutions.

Similarly, Kalundborg, Denmark, pioneered the concept of industrial symbiosis by facilitating resource exchanges that improve both environmental and economic performance. Its success is attributed to informal networks and trust built over decades, showing the importance of relationship-building in CE. Ulsan, South Korea, integrates advanced environmental engineering and green innovation in a heavy industrial cluster, highlighting the role of technology and state-led initiatives in enabling CE..

Digital transformation is increasingly leveraged in global EIPs to enhance transparency and optimize circular flows, an area where Indonesia could make significant advances. Financing mechanisms including green bonds and public-private partnerships also feature prominently in successful cases and can be adapted to local market conditions.

The global cases illustrate the necessity of comprehensive frameworks combining policy, technology, financing, and stakeholder engagement. Indonesia can adapt these models by considering its unique social, economic, and institutional context. For instance, while informal recycling sectors are integral in Indonesia, they are less prominent in these global examples, signaling the need for tailored inclusive policies. Moreover, the strong government-industry-academia partnerships exemplified abroad should be fostered domestically to accelerate learning and innovation.

4 Recommendations

The successful integration of circular economy (CE) principles into Indonesia's Eco-Industrial Parks (EIPs) requires a multi-faceted approach combining policy, capacity building, regulation, and innovation. This section outlines practical recommendations grounded in the latest literature to accelerate CE adoption in Indonesian EIPs.

4.1 Build technical and institutional capacity

Building robust technical and institutional capacity is essential for operationalizing CE within Indonesian EIPs. Numerous researchers highlight the need for specialized training programs to equip EIP managers, engineers, and policymakers with practical CE knowledge and skills. Capacity building initiatives should emphasize systems thinking, lifecycle assessment, and industrial symbiosis design principles. Universities and vocational institutions must incorporate CE-related curricula, fostering a future workforce capable of managing circular processes. Collaboration with international CE experts and participation in global knowledge networks enable technology transfer and innovation diffusion. Strengthening institutional frameworks, such as environmental agencies and industry associations, enhances policy enforcement and stakeholder coordination. Pilot projects and demonstration sites within EIPs provide practical training grounds, enabling learning through experience. Digital platforms can support continuous learning and information exchange across stakeholders. Funding mechanisms should also support capacity-building activities, particularly for SMEs, which often lack resources to invest in CE adoption. Building human and institutional capacities lays the groundwork for sustainable and scalable CE practices in Indonesian industrial clusters.

4.2 Strengthen the policy and regulatory framework

An effective and conducive policy and regulatory framework underpins the transition to the circular economy in EIPs by ensuring compliance and driving systemic change. Recent literature emphasizes that Indonesia's current environmental standards often do not fully accommodate CE principles, creating gaps that limit impact. Developing CE-compatible regulations—covering waste hierarchy, product stewardship, and extended producer responsibility—is vital to incentivize circular practices. Transparent and mandatory sustainability reporting can enhance accountability and provide data necessary for monitoring CE progress. Cross-sectoral regulatory coherence is necessary to avoid conflicting mandates and streamline CE implementation. Capacity building for regulators is also critical to equip them with tools and knowledge for effective oversight. Public consultation and stakeholder engagement during regulatory formulation promote legitimacy and practicability. Indonesia can also draw from international best practices, such as the EU's Circular Economy Action Plan, adapting key elements to local context.

4.3 Innovation and technology transfer

Innovation and technology transfer are catalysts for advancing circular economy practices in Indonesian eco-industrial parks. Numerous studies reveal that localized innovation is required to develop CE solutions adapted to Indonesia's specific industrial and environmental conditions. Supporting research and development (R&D) in areas such as waste valorization, material recovery, and renewable energy integration enhances the viability of circular operations. Facilitating partnerships between universities, research institutes, and industry accelerates innovation cycles and practical application. Technology transfer from international CE leaders enables access to proven tools and methodologies, overcoming local capability gaps. Government grants, innovation funds, and public-private partnerships serve as effective financial mechanisms to promote CE-related technology adoption. Digital technologies—including IoT, blockchain, and data analytics—play an increasing role in resource tracking, process optimization, and transparency. Platforms for

knowledge exchange, such as EIP forums and CE networks, support the diffusion of innovations across industrial clusters. Importantly, policies must incentivize incremental and breakthrough innovations while encouraging sustainable business models. Encouraging local entrepreneurship in circular solutions further strengthens economic resilience and job creation. Fostering innovation and technology transfer will support Indonesia's industrial parks with the tools needed for a circular transformation.

4.4 Assessment of the preparedness of industrial parks for CE adoption

Industrial parks are hubs of concentrated economic activity and resource consumption, making them ideal settings for implementing circular practices such as resource efficiency, waste valorization, and industrial symbiosis. However, the shift from linear to circular models requires not only infrastructural readiness but also alignment in policy, governance, stakeholder engagement, and technological capabilities. Without a comprehensive assessment, attempts at CE adoption may face barriers such as misaligned incentives, lack of awareness, or insufficient data on material flows. Preparedness assessments help identify gaps in regulatory frameworks, institutional capacity, and inter-firm collaboration—factors that are critical to enabling eco-industrial development. Such evaluations can also inform tailored policy interventions and investment strategies to support the CE transition in different industrial contexts. A structured readiness assessment is not merely diagnostic but foundational to the long-term success and scalability of circular economy models within industrial parks.

5 Conclusion

The integration of circular economy (CE) principles into Indonesia's eco-industrial parks (EIPs) is a pivotal strategy to drive sustainable industrial development in the country. As the literature reveals, Indonesia's rapid industrial growth presents opportunities and challenges in embedding circularity within existing industrial frameworks. Studies emphasize that while CE is gaining traction among Indonesian stakeholders, practical implementation remains constrained by regulatory gaps and limited institutional capacity.

Industrial symbiosis, a core component of EIPs, is integral to CE and can substantially reduce resource consumption when effectively managed. Learning from global success stories, such as China's Tianjin EIP, demonstrates the value of clear policy frameworks and multi-sector collaboration in overcoming implementation barriers. Indonesia's unique socio-economic conditions necessitate customized CE strategies for local industrial diversity and infrastructure.

Moreover, recent research suggests that increasing awareness and education about CE among industrial actors leads to higher adoption rates and improved sustainability outcomes, and embedding CE principles into corporate social responsibility initiatives fosters stronger stakeholder engagement. Another critical factor is the role of technology and investment in CE-enabling technologies, including waste-to-energy and material recycling, which is essential for the transition.

Policy coherence is also crucial, and harmonized regulations align economic incentives with environmental objectives, reduce business confusion, and facilitate compliance. Collaboration across government, industry, and academia remains foundational to sustaining momentum and fostering innovation and knowledge exchange.

This research has certain limitations as it relied solely on a literature review with a limited scope, depth, and availability of existing published research on circular economy implementation in industrial parks, particularly within the Indonesian context; hence, the secondary nature of the data means that real-time, site-specific conditions, stakeholder perspectives, and practical challenges may not be fully captured or reflected. Additionally, the dynamic and evolving nature of policies, technologies, and industrial practices may also mean that some recent developments or localized initiatives remain undocumented or underrepresented. Consequently, the findings and conclusions drawn are more conceptual and theoretical, with limited empirical validation, underscoring the need for future primary research to validate, expand, and contextualize these insights.

Building upon the literature-based findings, future research should focus on developing comprehensive recommendations for effective policy interventions and technological innovations that can facilitate the adoption of circular economy in the industrial parks for their transformation into eco-industrial parks. An assessment should be undertaken to assess the preparedness of the industrial parks in Indonesia to adopt CE approaches, particularly in terms of infrastructure readiness, stakeholder engagement, and alignment with sustainability goals aiming to provide targeted guidance and strategic recommendations for industrial parks to transform into eco-industrial parks (EIPs), ensuring they are equipped to implement CE principles effectively.

In conclusion, while challenges remain, a strategic, well-coordinated approach, assessing the preparedness of the industrial parks to embrace CE in their transformation to Eco-Industrial Parks, removing barriers, drawing on international best practices, and adapting to Indonesia's unique context can benefit not only the environment but also improve social and economic performance to make industrial parks more resilient and sustainable.

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