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Article

Driving Forces and Strategic Pathways for the Ecological Development of Industrial Chain Clusters

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Abstract: Amid the growing global emphasis on sustainable development and carbon neutrality, the ecological development of industrial chain clusters has emerged as a critical strategic priority for regions and firms. This paper systematically examines the key driving forces propelling the ecological transformation of industrial chain clusters, including the guidance of policy incentives, the diffusion of green and low-carbon technologies, shifts in domestic and international market demand, and the tightening of environmental governance and regulatory standards. Building on this analysis, the study further explores practical and strategic pathways for realizing ecological upgrading, such as the integration of green technologies into production and logistics, the empowerment of clusters through digital tools and data-driven management, the establishment of circular and symbiotic value chains, and the construction of open regional innovation ecosystems that link enterprises, governments, and research institutions. Particular attention is paid to the coordination between policy instruments and market mechanisms, the role of innovation in reducing transition costs, and the importance of collaborative governance within and across clusters. By synthesizing these elements into a coherent analytical framework, the paper seeks to offer actionable insights for policymakers, industry leaders, and cluster coordinators, equipping them with conceptual tools and strategic options to promote high-quality, resilient, and sustainable development of industrial chain clusters under evolving environmental and economic constraints.

Keywords: industrial clusters; sustainable development; green innovation; circular economy; environmental policy; industrial strategy

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1. Introduction

1.1. Research Background and Significance

In recent years, as the global community increasingly prioritizes sustainability and carbon neutrality, industrial development has been undergoing a profound transformation [1]. Traditional industrial clusters, which were once the primary drivers of economic growth, are now facing significant challenges due to resource depletion, environmental degradation, and the limitations of outdated production models [1, 2]. These issues are particularly pronounced in sectors that are energy-intensive and prone to pollution, where the external costs of economic activities are becoming increasingly unsustainable. Against this backdrop, the concept of ecological development has emerged as a promising framework for reimagining industrial clusters. This approach emphasizes the integration of environmental stewardship and social equity into the operational and economic structures of these clusters. By adopting strategies such as circular economy

practices, green supply chain management, and eco-innovation, ecological development not only reduces the environmental footprint of industrial activities but also strengthens the resilience and competitiveness of clusters over the long term. Consequently, exploring pathways for ecological development is both timely and critical for facilitating sustainable industrial transformation in the context of the global green transition.

1.2. Problem Statement

Although awareness of ecological imperatives has been increasing, the practical application of sustainable development within industrial clusters remains uneven and fragmented. While some clusters have adopted green technologies and environmentally friendly practices, these initiatives are often isolated and lack systemic integration. Significant obstacles include the absence of comprehensive strategic planning frameworks, inadequate alignment of policies at both regional and national levels, and insufficient coordination among stakeholders across the value chain. Additionally, variations in environmental regulations and governance mechanisms across different regions further hinder efforts to standardize ecological practices. This inconsistency makes it challenging for clusters to scale up successful pilot programs, resulting in limited progress and missed opportunities for broader transformative change. Addressing these issues requires the development of structured frameworks and actionable strategies that promote ecological upgrading in a holistic and coordinated manner. Such approaches must prioritize collaboration, policy coherence, and the establishment of unified standards to ensure sustainable and scalable outcomes across diverse industrial clusters.

1.3. Research Objectives and Structure

This study aims to explore the primary factors driving the ecological transformation of industrial chain clusters and to develop strategic approaches for their sustainable advancement. By examining both theoretical frameworks and practical applications, the research seeks to uncover how industrial clusters can effectively incorporate environmental considerations into their core operations while simultaneously maintaining or even enhancing their competitive edge. The structure of the paper is designed to provide a comprehensive analysis, beginning with an extensive review of relevant literature and theoretical perspectives. This is followed by a detailed discussion of the research methodology and an in-depth empirical analysis. Subsequent sections are dedicated to interpreting the findings and formulating actionable strategies that can be implemented in real-world scenarios. The study concludes by reflecting on the broader implications of ecological development for industrial clusters and offering recommendations for future research directions to further advance this critical field.

2. Driving Forces for the Ecological Development of Industrial Chain Clusters

2.1. Policy Orientation and Regulatory Pressure

In recent years, national and regional governments have introduced a variety of policy instruments aimed at fostering sustainable development, with a strong focus on achieving carbon peaking and carbon neutrality goals. These high-level policy commitments are supported by an expanding range of regulatory mechanisms, such as environmental taxation, carbon trading systems, mandatory disclosure of environmental information, and the adoption of green certification standards. For industrial chain clusters, these frameworks act not only as compliance mandates but also as strategic indicators, prompting businesses to reassess and transform their production processes. Regulatory pressures necessitate that clusters internalize environmental costs, integrate cleaner technologies, and adopt more sustainable resource utilization practices. Furthermore, clusters that align with these policy directions are more likely to benefit from government incentives, access to preferential financing options, and enhanced reputational standing [3]. This alignment positions them competitively within an increasingly environmentally conscious global market, where green practices are

becoming a critical determinant of long-term success and resilience. By embracing these changes, industrial clusters can ensure their sustainability while contributing to broader ecological and economic objectives.

2.2. Technological Advancement and Digitalization

Technological innovation plays a crucial role in driving the ecological transformation of industrial clusters. Advanced technologies such as artificial intelligence, the Internet of Things, and blockchain are revolutionizing operational frameworks by enabling more accurate and adaptive environmental management. For example, IoT devices facilitate real-time monitoring of energy usage and emissions across various points in the industrial chain, providing actionable insights for optimization. Artificial intelligence enhances production efficiency by minimizing waste and improving energy utilization through intelligent process adjustments. Meanwhile, blockchain technology ensures transparent and secure tracking of environmental data, fostering greater accountability and trust among stakeholders [4, 5]. These advancements not only aid in meeting environmental standards but also create opportunities for innovation, improved operational performance, and sustainable value generation. As digitalization becomes increasingly embedded in industrial practices, it establishes a robust technical foundation for transitioning from traditional, resource-intensive systems to circular and regenerative models that align with ecological sustainability principles. This integration underscores the transformative potential of technology in achieving long-term environmental and economic goals.

2.3. Market Demand and Green Consumerism

Market dynamics are increasingly shaped by the growing prominence of green consumerism, which reflects heightened awareness of environmental challenges and a stronger preference for sustainable goods and services. This trend is particularly evident in developed economies and among younger generations, who are demanding greater transparency regarding the environmental impact of production processes. These consumers are often willing to pay higher prices for products that are eco-labeled or have a reduced carbon footprint. Such shifts in consumer behavior place significant pressure on companies within industrial clusters to adapt their product designs, sourcing methods, and supply chain operations to align with these evolving expectations. Companies that fail to respond effectively risk losing market share, damaging their reputations, and diminishing their competitive edge. On the other hand, businesses that proactively adopt green practices can seize new market opportunities, foster stronger brand loyalty, and integrate more effectively into global value chains that prioritize sustainability. In this context, market demand serves as an active and transformative force, driving the ecological evolution of industrial development and encouraging widespread adoption of sustainable practices.

3. Strategic Principles for Ecological Transformation

3.1. System Thinking and Whole-Chain Coordination

Achieving ecological development within industrial clusters necessitates a fundamental shift from fragmented management practices to a comprehensive systems-thinking approach. This involves perceiving the entire industrial chain as an interconnected and cohesive system rather than as isolated segments. From the extraction and processing of raw materials to manufacturing, logistics, consumption, and post-consumer disposal, every phase and participant within the chain must be integrated into a unified ecological framework. A systems-thinking perspective underscores the intricate interdependencies among various stages of the value chain and highlights the importance of coordinated actions to optimize resource flows, minimize waste, and eliminate inefficiencies. Effective whole-chain coordination requires the establishment of robust communication channels, the facilitation of seamless information sharing, and the

alignment of strategic objectives across the upstream supply network, core manufacturing processes, downstream distribution channels, and even among end consumers. By harmonizing efforts and fostering collaboration at every stage of the chain, industrial clusters can achieve substantial environmental benefits and operational efficiencies that surpass what individual entities can accomplish independently. This holistic approach not only enhances the resilience of the system but also enables continuous improvements in sustainability. Furthermore, it equips the industrial ecosystem to adapt to emerging ecological challenges, ensuring its long-term viability and fostering environmentally responsible growth.

3.2. Stakeholder Integration and Platform Governance

The scale and complexity of ecological transformation in industrial clusters necessitate the active participation of a diverse array of stakeholders. These stakeholders encompass government agencies that establish policy frameworks and enforce regulations, enterprises that spearhead innovation and invest in environmentally friendly technologies, research institutions that contribute technical expertise and data analysis, and financial institutions that provide funding and strategies for mitigating risks. Effectively integrating the perspectives and capabilities of these stakeholders into a cohesive governance framework is critical for advancing ecological development. Digital platforms, particularly those utilizing industrial internet technologies, serve as pivotal tools in this process. Acting as centralized hubs, these platforms facilitate the exchange of data, monitor ecological performance, disseminate policies, and coordinate stakeholder activities [6]. By offering real-time access to ecological indicators, these platforms enhance transparency, foster trust among participants, and enable adaptive decision-making in response to evolving conditions. Additionally, they promote long-term sustainability by making governance processes more inclusive and participatory. Through the strategic use of these platforms, industrial clusters can harness the collective strengths of all stakeholders, achieving scalable and sustainable ecological development. This collaborative approach ensures that ecological objectives are met efficiently while addressing the multifaceted challenges inherent in industrial transformation.

3.3. Value Co-Creation and Circular Economy Logic

One of the fundamental principles of ecological industrial development is the shift from a traditional linear production model, characterized by the extraction, consumption, and disposal of resources, to a circular economy framework. In this circular model, value is derived not only from the use of finite resources but also from innovative processes that emphasize reusing, recycling, remanufacturing, and extending the lifecycle of products. This approach significantly reduces the environmental footprint of production and consumption while simultaneously fostering opportunities for innovation and economic growth. Within a circular economy, value co-creation is achieved through the collaborative efforts of suppliers, manufacturers, consumers, and service providers [2, 7]. These stakeholders work together to design and implement systems that enhance resource efficiency, minimize waste, and mitigate environmental harm. For example, products can be engineered for easy disassembly and reuse, enabling the development of closed-loop supply chains where materials are continuously recycled. Additionally, waste streams can be repurposed as raw materials for other industries, creating a symbiotic relationship between different sectors. Such initiatives not only promote environmental sustainability but also pave the way for new business models that align profitability with ecological responsibility. By adopting circular economy principles, industrial clusters can contribute to environmental conservation while driving economic development, thereby reinforcing the interconnectedness of industrial progress and ecological stewardship.

4. Strategic Pathways to Achieve Ecological Cluster Development

4.1. Green Supply Chain and Low-Carbon Upgrading

To facilitate ecological transformation, industrial clusters must integrate sustainability principles across their entire supply chain operations [8, 9]. This begins with the implementation of green procurement standards that emphasize the use of environmentally friendly raw materials, suppliers adhering to sustainable practices, and products meeting rigorous ecological benchmarks. Establishing comprehensive carbon accounting systems at both the firm and cluster levels allows for precise tracking of emissions throughout the supply chain, providing a foundation for informed decision-making and continuous improvement. Encouraging supplier participation in eco-labeling initiatives and third-party environmental certifications further enhances transparency and strengthens market credibility. Beyond procurement, downstream processes such as logistics and packaging require optimization to align with sustainability goals. Transitioning to low-carbon transportation modes, consolidating deliveries to minimize fuel consumption, and redesigning packaging to ensure it is recyclable, biodegradable, or reusable are critical steps. These collective measures not only reduce the environmental impact of the cluster but also enhance its competitive edge in a global market increasingly driven by sustainability considerations. By embedding these practices, industrial clusters can achieve a balance between ecological responsibility and economic growth, fostering long-term resilience and innovation.

4.2. Digital Empowerment and Smart Infrastructure

The integration of advanced digital technologies plays a pivotal role in creating intelligent, responsive, and resource-efficient industrial clusters. Digital twin systems, which serve as virtual replicas of physical industrial processes, facilitate real-time monitoring, predictive analytics, and scenario simulation [10]. These capabilities enable proactive management of energy consumption, emissions, and equipment performance, fostering operational efficiency and sustainability. The development of carbon-neutral industrial parks, featuring smart infrastructure such as energy-efficient buildings, renewable energy systems, and green mobility solutions, establishes a benchmark for sustainable industrial practices. Furthermore, smart energy grids leveraging AI and IoT technologies can dynamically optimize energy supply and demand within the cluster, reducing dependency on fossil fuels and mitigating peak energy loads. Real-time environmental monitoring platforms enhance these efforts by providing instantaneous data on pollution levels, water usage, and waste generation. This enables swift interventions and supports the formulation of evidence-based policies. Digital empowerment not only enhances the operational capabilities of industrial clusters but also promotes ecological transparency and strengthens accountability among stakeholders, ensuring a sustainable and efficient industrial ecosystem.

4.3. Regional Innovation Ecosystems and Talent Linkages

The long-term success of ecological industrial transformation is heavily reliant on the robustness of the surrounding regional innovation ecosystem. This encompasses the establishment of green technology incubators and innovation hubs designed to support the development and commercialization of sustainable technologies. Collaborative R&D efforts between universities, research institutions, and enterprises play a pivotal role in fostering cross-sector partnerships, which in turn accelerate the dissemination of eco-innovations within industrial clusters. Talent serves as a cornerstone of this ecosystem. Platforms that facilitate the mobility of professionals across firms and regions ensure the optimal allocation of expertise in areas such as environmental engineering, green finance, and digital sustainability. At the policy level, governments must adopt strategic measures to attract, nurture, and retain a workforce equipped with green skills. These measures may include providing educational incentives, implementing specialized training programs, and creating structured career development pathways. By maintaining a

consistent influx of skilled talent and fostering innovative capabilities, industrial clusters can effectively address ecological challenges while sustaining their competitive edge in the transition to a low-carbon economy.

5. Policy Recommendations and Strategic Actions

5.1. Aligning Fiscal Incentives with Green Targets

To drive the large-scale ecological transformation of industrial clusters, it is essential for public policy to strategically align fiscal tools with environmental objectives. Governments at all levels should establish a results-oriented incentive framework that directly ties tax reductions, subsidies, and preferential financing terms to measurable environmental performance and green innovation achievements. For instance, businesses that achieve significant emissions reductions, obtain recognized green certifications, or invest in eco-friendly technologies can benefit from tiered tax relief or streamlined access to financing. Such financial support encourages enterprises to prioritize sustainable practices and allocate resources toward long-term ecological solutions [11, 12]. Beyond traditional incentives, green finance instruments play a pivotal role in mobilizing private capital to support sustainable development. This includes expanding Environmental, Social, and Governance (ESG) investment funds, issuing green bonds to finance infrastructure upgrades and the adoption of sustainable technologies, and developing dynamic carbon trading systems that reward emissions reductions and promote low-carbon behaviors. By integrating environmental criteria into fiscal policies and financial markets, governments can effectively guide industrial clusters toward creating enduring ecological value while maintaining economic growth and competitiveness. Additionally, fostering collaboration between public and private sectors can further amplify the impact of these initiatives, ensuring that sustainability becomes a core driver of industrial transformation.

5.2. Creating Evaluation Standards and Green KPIs

The establishment of standardized environmental evaluation frameworks is vital for ensuring effective ecological governance and accountability. The absence of unified metrics often results in fragmented implementation and challenges in comparing progress across various clusters and regions. To address this issue, Green Key Performance Indicators (KPIs) should be developed to provide a consistent basis for tracking performance, enforcing regulations, and guiding strategic planning [11, 13]. Examples of such KPIs include energy efficiency, carbon emissions per unit of output, water reuse rates, and material circularity ratios. These indicators should be customized to suit specific industries while being harmonized across regions to enable comprehensive analysis and equitable policy application. Digital platforms can play a crucial role in visualizing real-time ecological data, offering valuable insights for enterprises and regulators to monitor progress and make informed decisions. Integrating these green KPIs into corporate reporting requirements, investment evaluation criteria, and policy reward systems can empower industrial clusters to assess their sustainability performance, pinpoint areas for improvement, and adjust strategies based on evidence. Ultimately, standardized evaluation systems serve as the cornerstone of ecological accountability, fostering continuous progress toward achieving sustainability goals and promoting long-term environmental stewardship.

5.3. Fostering Cluster Synergies and Inter-Cluster Collaboration

The ecological transformation of industrial clusters relies heavily on fostering cooperation within a broader regional and inter-cluster framework. By dismantling administrative and industrial barriers, clusters can effectively pool resources, share technological advancements, and coordinate investments in green infrastructure, thereby amplifying the collective impact of their sustainability efforts. One particularly effective approach is industrial symbiosis, which involves repurposing the waste or by-products

of one enterprise or cluster as raw materials or energy inputs for another. This strategy not only reduces resource consumption and minimizes emissions but also creates innovative value chains and business models rooted in circular economy principles. For instance, a chemical processing cluster could provide steam to a nearby agricultural processing facility, while construction material manufacturers might reuse mining residues from another cluster. Furthermore, inter-cluster innovation networks, joint research initiatives, and talent exchange programs can accelerate the dissemination of green technologies and foster collaborative solutions to complex ecological challenges [14, 15]. As regional coordination mechanisms evolve, they can lay the groundwork for sustainable economic zones characterized by low-carbon resilience, industrial efficiency, and environmental harmony. These zones serve as a model for amplifying the benefits of ecological transformation and achieving long-term sustainability goals.

6. Conclusion

The ecological transformation of industrial chain clusters represents both an urgent sustainability requirement and a strategic opportunity to enhance future competitiveness. As industries face growing pressure from policy frameworks, technological advancements, and shifting market expectations, it becomes increasingly crucial for industrial clusters to adopt comprehensive, cooperative, and innovation-driven approaches to development. To achieve this transformation, clusters must focus on constructing intelligent, eco-friendly infrastructure, strengthening stakeholder collaboration platforms, and integrating green value creation models into their business strategies. These steps will enable clusters to transition toward a growth paradigm that is not only more resilient but also aligned with the principles of sustainability. Furthermore, the adoption of advanced technologies, such as artificial intelligence and data analytics, can significantly enhance the efficiency and adaptability of these clusters, ensuring they remain competitive in a rapidly evolving global market. Effective and coordinated policy support, combined with robust regional innovation ecosystems, will play a pivotal role in scaling these changes across industries. This will ensure that the transition toward ecological sustainability is not only successful but also sustained over the long term, fostering a future where industrial clusters contribute meaningfully to environmental preservation and economic stability.

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