A Review of GIS-based Research in Industrial Ecology: Postprint

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Abstract

Industrial ecology suffers from a lack of spatial analysis tools, which limits the support for management efficiency and precision due to the absence of spatial dimension information in research findings. GIS-based research in industrial ecology has emerged as a new direction in the field. To summarize existing research achievements and prospect future research directions, this study employs bibliometric and comparative analysis methods to systematically review the progress of GIS-based industrial ecology research both domestically and internationally, drawing the following conclusions: Current GIS-based industrial ecology research primarily concentrates on three aspects: material metabolism, industrial symbiosis, and Life Cycle Assessment (LCA). The integration of GIS technology into material metabolism research can better reveal spatiotemporal distribution patterns of material flows, providing a novel methodological approach. Leveraging GIS technology, potential industrial symbiosis opportunities can be identified more efficiently, and it can also be applied to the planning and management of eco-industrial parks, including enterprise site selection, spatial layout optimization, and waste recycling and reuse. Coupling GIS with LCA can effectively supplement, improve, and manage conventional data, facilitating exploration of the spatial characteristics of environmental impacts from products, activities, or processes, as well as enabling environmental impact assessments related to land use. Furthermore, research emphases differ between domestic and international studies. In material metabolism research, domestic studies are relatively scarce, having only analyzed material metabolism and stocks of infrastructure at the urban scale, whereas international studies have examined material metabolism of metals such as copper and zinc at both national and urban scales. In industrial symbiosis research, domestic studies focus on eco-industrial parks, while international studies emphasize identifying industrial symbiosis opportunities at the urban scale. In LCA research, domestic studies have developed GIS-based Life Cycle Assessment databases and product material information management systems, while international studies concentrate

on regionalized Life Cycle Assessment, evaluation of land use impact categories, and pollutant tracking; domestic research in this area remains in its infancy. Domestic and international studies share common methodological foundations, all employing GIS spatial analysis methods, buffer analysis methods, and database technologies. In the future, utilizing GIS as a platform to develop comprehensive theoretical and methodological frameworks in industrial ecology oriented toward industrial transformation can provide effective support for sustainable industrial management.

Full Text

Preamble

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A Review of Industrial Ecology Based on GIS

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Abstract

Industrial ecology lacks spatial analysis tools, which limits its ability to provide effective and accurate support for industrial management. GIS-based industrial ecology has emerged as a new research direction in the field. This paper systematically reviews recent progress in GIS-based industrial ecology using bibliometric and comparative analysis methods, focusing on three main aspects: substance metabolism, industrial symbiosis, and life cycle assessment (LCA). The integration of GIS into substance metabolism research better reveals the spatiotemporal distribution patterns of material flows, offering a novel methodological approach. GIS technology can more efficiently identify potential industrial symbiosis opportunities and optimize eco-industrial park planning, including site selection, spatial layout, and waste recycling. When combined with LCA, GIS helps supplement, refine, and manage traditional data, enabling exploration of the spatial characteristics of environmental impacts from production activities and processes, as well as land-use-related impact assessments. However, research emphases differ between domestic and international studies. Domestic research on substance metabolism remains limited, focusing primarily on infrastructure metabolism at the city scale, while international studies examine metals such as copper and zinc at national and urban scales. In industrial symbiosis research, domestic studies concentrate on eco-industrial parks, whereas international research emphasizes identifying symbiosis opportunities at the urban scale. For LCA, domestic research focuses on GIS-based LCA databases and material information management systems, while international research prioritizes regionalized LCA, land-use impact assessment, and pollutant tracking. Despite these differences, both domestic and international studies commonly employ spatial analysis, buffer analysis, and database technologies. Future GIS-based industrial ecology research is expected to provide effective support for industrial sustainability management.

Keywords: industrial ecology; geographic information system; material metabolism; industrial symbiosis; LCA

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1. Bibliometric Analysis

The research objects of industrial ecology include industrial systems, waste, and industrial services. At the macro level, industrial ecology employs material flow analysis to study the metabolic processes of production systems. At the meso level, it examines industrial symbiosis phenomena, while at the micro level, it focuses on product ecological design and life cycle management [1]. Against this background, we conducted literature searches in the Web of Science Core Collection and China National Knowledge Infrastructure (CNKI) using the following search terms: ("industrial ecology" OR "industrial symbiosis" OR "Eco-industrial park" OR "material metabolism" OR "LCA") AND ("geographic information system" OR "GIS"). The retrieved literature was reviewed and categorized into three major groups: substance metabolism at the macro level, industrial symbiosis at the meso level, and life cycle assessment at the micro level.

Overall, research on GIS-based industrial ecology has been increasing, but a systematic review of its development trajectory and trends has been lacking. This paper provides a comprehensive review and comparative analysis of domestic and international literature, systematically examining progress in GIS-based industrial ecology across these three research domains and identifying future research directions.

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2. Research Progress

2.1 GIS-Based Substance Metabolism Research in Production Systems

Industrial ecology aims to optimize material and energy flows in socio-economic systems. At the macro level, it emphasizes the metabolic processes of production systems, using material flow analysis (MFA) to quantitatively characterize these processes [6]. MFA involves systematic analysis of material flows and stocks within specific spatiotemporal boundaries [7], enabling tracking of material inputs, outputs, and waste generation throughout entire processes. This facilitates regulation of material flows between economic systems and the ecological environment to improve resource efficiency and reduce environmental impacts [8]. While widely used in substance metabolism research, traditional MFA has limitations in reflecting spatial characteristics and variations. Current studies rely heavily on socio-economic statistical data, focusing on temporal evolution while lacking analysis of spatial patterns in material metabolism. Statistical data also suffer from incompleteness, limited validity, and poor comparability across countries [9], resulting in policy recommendations with weak geographical specificity.

GIS can compensate for these spatial representation deficiencies in traditional MFA methods, enabling more systematic investigation of material metabolism in both temporal and spatial dimensions. At the 2015 International Society for Industrial Ecology conference, Laurent Georgeault proposed a GIS-based computational system that systematically describes construction material inputs and outputs and assesses urban mining potential [5].

Table 1 summarizes domestic and international research on GIS-based substance metabolism. International studies dominate this field, with domestic research still in its infancy and concentrated at the urban scale. Studies analyze material stocks of specific systems, such as copper and zinc at various spatial scales in Australia, and temporal changes in urban building and infrastructure material stocks.

2.2 GIS-Based Industrial Symbiosis Research

Chertow defined industrial symbiosis as a collaborative approach where traditionally separate industries cluster together to exchange materials, water, and by-products, creating competitive advantages [20-21]. As an innovative pathway for waste resource utilization and a strategic tool for green growth and resource efficiency, industrial symbiosis has gained increasing attention, with related policies becoming integral to economic and environmental strategies. The EU Waste Framework Directive recommends industrial symbiosis as a method for achieving resource efficiency, presenting national industrial symbiosis programs as exemplary cases [22].

Analyzing industrial symbiosis relationships is a systematic endeavor involving corporate spatial location data, raw material and waste types/quantities, site selection for new enterprises, and planning of waste treatment facilities. GIS, with its powerful spatial data processing capabilities, can provide effective support for urban industrial symbiosis management by analyzing specific regional conditions.

2.2.1 Industrial Symbiosis Opportunity Identification Matthew identified the primary challenges in implementing industrial symbiosis as recognizing symbiosis opportunities and encouraging stakeholder engagement [23]. GIS serves as a tool to identify potential symbiotic relationships by analyzing existing material and energy flows, thereby reducing environmental impacts. Research methods primarily involve analyzing regional contexts, industrial layouts, by-product recycling, infrastructure sharing, and spatial organization to uncover potential synergies. GIS' s robust spatial data analysis and mapping capabilities make analytical processes and results more visual while serving as a decision-support tool.

International research on GIS-based industrial symbiosis opportunity identification is well-established, while domestic research remains nascent. At the 2015 International Conference on Industrial Ecology, Guillaume presented research using GIS to identify and spatially analyze industrial symbiosis relationships in the Geneva region. **Table 2** summarizes relevant studies, which employ spatial analysis, buffer analysis, and database technologies to identify water reuse opportunities, optimal material exchange patterns, and potential industrial partnerships.

2.2.2 Eco-Industrial Park Planning Research Eco-industrial parks represent a concrete manifestation of industrial symbiosis, where enterprises cluster within a specific area to form by-product exchange networks driven by economic benefits or emission reduction targets. With rapid development of eco-industrial parks, a common challenge has emerged: despite planning schemes, there is insufficient technical support for implementation. Enterprise site selection in industrial parks represents a critical investment decision requiring GIS-based spatial data analysis for rational planning.

At the 2015 annual conference of the Chinese Geographical Society, Qian Yu proposed an eco-industrial park planning approach supported by GIS technology, emphasizing environmental benefits and optimized spatial layout [35]. **Table 3** details domestic research on GIS-based eco-industrial parks, covering decision support systems, spatial database construction, site selection algorithms, and recycling network optimization. These studies integrate material, technology, and environmental information to facilitate industrial symbiosis matching, though they face limitations such as long development cycles, update difficulties, and high specialization requirements.

2.2.3 Solid Waste Management Research Waste represents misplaced resources, and waste valorization has become a global trend in waste management. Industrial symbiosis systems can incorporate solid waste to achieve zero-emission goals through material exchange [19]. Research has investigated whether waste recycling, remanufacturing, and treatment enterprises can bridge product manufacturing and waste streams. Geographic information systems, with functions such as environmental mapping, statistical analysis, and spatial interpolation, have been widely applied in solid waste management planning.

International researchers have conducted studies at regional and urban scales, using GIS to analyze waste characteristics and recycling potential. Domestic research in this area remains limited. **Table 4** summarizes international studies on GIS-based waste valorization, including models for waste characterization analysis, transportation efficiency improvement, and environmental failure mode analysis to identify new waste reuse pathways.

2.3 GIS-Based Life Cycle Assessment Research

Life Cycle Assessment (LCA) evaluates the environmental impacts of products, processes, or activities throughout their entire life cycle from cradle to grave. A prominent limitation of traditional LCA is the lack of temporal and spatial elements, as well as economic and social equity factors [52]. GIS can store observation data with specific locations, compensating for these limitations and providing more comprehensive and accurate data for LCA research.

At the 2014 European Biomass Conference, Garofalo integrated crop simulation models with GIS-LCA to analyze energy requirements and greenhouse gas emissions from cereal straw energy conversion, obtaining precise spatial distributions of environmental impacts at the regional scale [53]. At the 2015 International Conference on Informatics for Environmental Protection, Mastracci et al. developed a GIS-based LCA framework for urban building stocks in Luxembourg, assessing environmental impacts at the urban scale from a life cycle perspective [54].

Current LCA research lacks regionalized characterization factors, land-use impact assessment, and evaluation of environmental impacts' spatial characteristics. International research has focused on these aspects, while domestic research concentrates on database construction and spatial characterization of environmental impacts. **Table 5** summarizes GIS-based LCA studies, including site-dependent life cycle analysis, pollutant flow mapping, regionalized LCA methodology, and land-use impact assessment for desertification and biodiversity.

3. Comparison of Domestic and International Research

Domestic and international research differ in starting time, content, and methods, though both show increasing trends in recent years. International research began earlier, with the first relevant paper appearing in 2000, while domestic research started later. **Figure 3** illustrates the annual variation in publication numbers.

In terms of research scale, domestic studies focus on the urban and eco-industrial park scales, while international research covers national, urban, and regional scales. Regarding research content, domestic studies emphasize eco-industrial park planning, with limited research on industrial symbiosis opportunity identification. International research has extensively explored material metabolism of metals, symbiosis opportunity identification, and regionalized LCA. **Table 6** provides a detailed comparison.

Methodologically, both domestic and international studies commonly employ spatial analysis, buffer analysis, and database technologies for collecting and managing regional data. However, limitations persist: domestic research suffers from single-focus studies, lack of comprehensive material flow analysis, and insufficient urban-scale industrial symbiosis and waste management research. International research faces challenges in data availability, information sharing, and corporate participation enthusiasm.

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4. Conclusions

Through systematic review, analysis, and comparison of GIS-based industrial ecology research, this paper draws the following conclusions:

1. Integrating GIS into substance metabolism research better demonstrates spatiotemporal distribution patterns, providing a new methodological approach. Current research primarily employs bottom-up methods; future studies should incorporate top-down approaches to improve data completeness. Most research focuses on resource metabolism, with limited studies addressing waste from a metabolic perspective—representing a promising future direction.

2. GIS can efficiently identify industrial symbiosis opportunities and optimize eco-industrial park planning, site selection, spatial layout, and waste recycling. To facilitate rapid opportunity identification, China should prioritize building information-sharing platforms, drawing on international experience and combining spatial analysis with buffer analysis methods.

3. Coupling GIS with LCA effectively supplements and manages traditional data, helping explore spatial characteristics of environmental impacts from products, activities, and processes, as well as land-use-related impact assessments. Introducing spatial attributes into LCA makes research data

more comprehensive and results more regionally targeted. Regionalized LCA research is particularly necessary for countries like China with vast geographical and economic disparities.

4. As a spatial analysis tool in industrial ecology, GIS-based research integrating material metabolism, industrial symbiosis, and life cycle assessment will provide effective support for industrial sustainability management. Using GIS as a platform to develop comprehensive theoretical and methodological approaches for industrial transformation represents an important new research direction.

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Figures

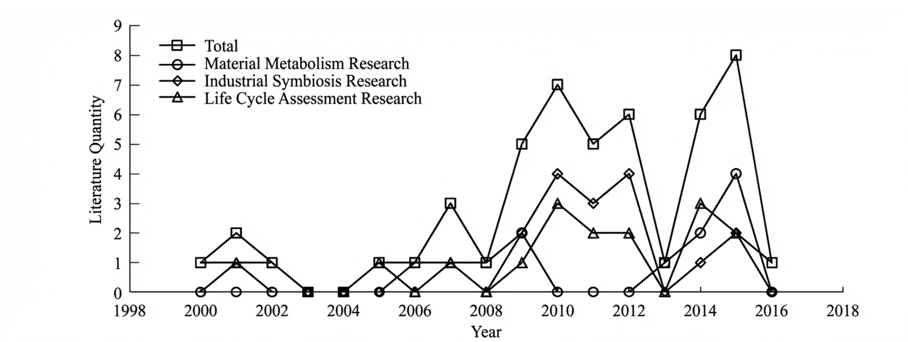

Figure 1: Figure 1

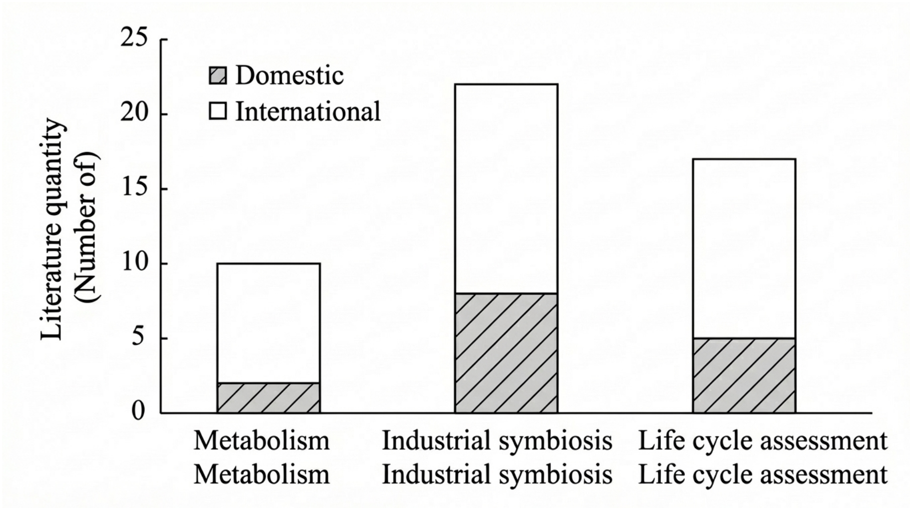

Figure 2: Figure 2

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