Revista Ciências Administrativas
e-ISSN:2318-0722 Journal of Administrative Sciences
Universidade de Fortaleza

Methodological Proposal for the Transition of Industrial Parks Toward the Circular Economy

Proposta Metodológica para Transição de Parques Industriais Rumo à Economia Circular

Propuesta Metodológica para la Transición de Parques Industriales Hacia la Economía Circular

10.5020/2318-0722.2025.31.e17173

Felipe Moura Oliveira
Assistant Professor I at State University of Piauí..

Luís Matheus Tavares Silva
CNPq Industrial Technological Development Fellow (Level B).

Mônica Cavalcanti Sá de Abreu
CNPq Research Productivity Fellow (Level 1C). Head of the Laboratory for Studies in Competitiveness and Sustainability (LECoS/UFC).

Caroline Rodrigues Vaz
CNPq Research Productivity Fellow (Level 2). Head of the Research Group on Sustainability and Innovation in Renewable Energies (SINERGIA/ UFSC).

Abstract

This study proposes a methodology for initiating the mapping of industrial processes and material flows in industrial parks to support the early stages of the transition toward the Circular Economy (CE). Unlike the Linear Economy (LE), which is based on resource extraction, production, consumption, and disposal, the Circular Economy, when applied to industrial parks, seeks to integrate companies and material flows so that waste and by-products from one activity can be reincorporated as inputs into other production processes. The proposed methodology comprises three stages: (1) identification of the industrial park and the companies operating within it; (2) mapping of inputs, production processes, products, and waste through documentary analysis of Environmental Impact Assessments (EIAs) and Environmental Impact Reports (EIRs), integrated with a scoping review of the scientific literature; and (3) identification of circularity opportunities based on the reuse of waste in manufacturing processes. The Pecém Industrial and Port Complex (CIPP) was selected as the empirical setting of the study. To operationalize the methodology, seven EIA/EIR documents and 125 articles indexed in the Web of Science were analyzed. Its application at the CIPP identified a range of industrial processes, waste streams, and reuse opportunities, including the incorporation of fine particles into precast concrete production, the use of residual gases in the fertilizer industry, and sludge for energy generation. The study contributes a structured and replicable methodology for the initial diagnosis of circularity opportunities in industrial parks, supporting the reduction of environmental impacts and the advancement of more sustainable strategies at the meso-industrial level.

Keywords: circular economy, waste management, methodological proposal.

Resumo

Este estudo tem como objetivo propor uma metodologia para o início do mapeamento de processos industriais e de fluxos materiais em parques industriais, visando subsidiar o início da transição para a Economia Circular em parques industriais. Diferentemente da Economia Linear (EL), baseada na extração, na produção, no consumo e no descarte, a Economia Circular (EC), quando aplicada a parques industriais, busca integrar empresas e fluxos materiais para que resíduos e subprodutos de uma atividade sejam reinseridos como insumos em outros processos produtivos. A metodologia foi estruturada em três etapas: (1) identificação do parque industrial e das empresas nele instaladas; (2) mapeamento de insumos, processos produtivos, produtos e resíduos, por meio da análise documental de Estudos de Impacto Ambiental e Relatórios de Impacto Ambiental, articulada a uma revisão *de escopo da literatura científica; e (3) identificação de oportunidades de circularidade a partir do reaproveitamento de resíduos em processos fabris. O Complexo Industrial e Portuário do Pecém (CIPP) foi adotado como lócus empírico do estudo. Para o mapeamento, foram analisados 7 EIA/RIMA e 125 artigos indexados na Web of Science. A operacionalização da metodologia no CIPP permitiu identificar diferentes processos, resíduos e oportunidades de reaproveitamento, incluindo partículas finas na produção de pré-moldados, gases residuais para a indústria de fertilizantes e lodo para geração de energia. Como contribuição, o estudo oferece uma metodologia estruturada e replicável para o diagnóstico inicial de oportunidades de circularidade em parques industriais, contribuindo para a redução de impactos ambientais e para o avanço de estratégias mais sustentáveis em nível mesoindustrial.*

Palavras-chave: *economia circular, gestão de resíduos, proposta metodológica.*

Resumen

Este estudio tiene como objetivo proponer una metodología para iniciar el mapeo de procesos industriales y flujos de materiales en parques industriales, con el fin de apoyar las primeras etapas de la transición hacia la Economía Circular en estos entornos. A diferencia de la Economía Lineal (EL), basada en la extracción, producción, consumo y eliminación de recursos, la Economía Circular (EC), cuando se aplica a parques industriales, busca integrar empresas y flujos de materiales de modo que los residuos y subproductos de una actividad sean reincorporados como insumos en otros procesos productivos. La metodología se estructuró en tres etapas: (1) identificación del parque industrial y de las empresas instaladas en él; (2) mapeo de insumos, procesos productivos, productos y residuos mediante el análisis documental de Estudios de Impacto Ambiental y Informes de Impacto Ambiental, articulado con una revisión de alcance de la literatura científica; y (3) identificación de oportunidades de circularidad a partir del reaprovechamiento de residuos en procesos industriales. El Complejo Industrial y Portuario de Pecém (CIPP) fue adoptado como ámbito empírico del estudio. Para el mapeo se analizaron siete Estudios e Informes de Impacto Ambiental (EIA/RIMA) y 125 artículos indexados en la base de datos Web of Science. La operacionalización de la metodología en el CIPP permitió identificar diversos procesos, residuos y oportunidades de reaprovechamiento, incluyendo partículas finas para la producción de elementos prefabricados, gases residuales para la industria de fertilizantes y lodo para la generación de energía. Como contribución, el estudio ofrece una metodología estructurada y replicable para el diagnóstico inicial de oportunidades de circularidad en parques industriales, contribuyendo a la reducción de impactos ambientales y al avance de estrategias más sostenibles a nivel mesoindustrial.

Palabras clave: *economía circular, gestión de residuos, propuesta metodológica.*

Introduction

The Linear Economy (LE) is a model of production and consumption based on the sequence of "extract, produce, use, and dispose" (Geissdoerfer et al., 2017). In the context of industrial parks, the linear model is characterized by high water and energy consumption, substantial waste generation, and the absence of Industrial Symbiosis (IS) mechanisms, such as intercompany resource reuse and the valorization of waste as substitute inputs in new production processes (Nguyen & Le, 2025; The World Bank, 2021). In contrast, the Circular Economy (CE) has emerged as an approach capable of mitigating environmental impacts and promoting sustainability across multiple sectors of the global economy (MacArthur, 2013). CE encourages the reuse of materials that would otherwise be discarded while reducing the amount of energy dissipated into the environment. Simultaneously, it reduces waste generation and diverts waste from landfills, incinerators, and other inappropriate disposal sites, thereby extending the service life of these facilities (Geng et al., 2019).

Implementing CE in industrial parks requires the participation of all organizations operating within the park in decision-making processes, as well as the integration of different supply chains to reduce environmental and social impacts and promote the sustainable production and consumption of material resources (Abreu et al., 2020; Ceglia et al., 2017). More broadly, this entails regulating and facilitating interactions among industrial park stakeholders, thereby creating an ecosystem that synchronizes and optimizes all activities (Asgari & Asgari, 2021).

Within the Brazilian regulatory context, the National Circular Economy Plan (PNEC, 2025–2034) incorporates IS, defining it as "a system that enables circular resource flows by bringing together traditionally separate organizations within a collective approach to share input and output flows and optimize their value networks" (Ministério do Desenvolvimento, Indústria, Comércio e Serviços [MDIC], 2025, p. 14). Accordingly, IS constitutes the primary mechanism through which CE is introduced into industrial parks. Parida et al. (2019) argue that establishing such a circular ecosystem enables market differentiation and competitive leadership by reducing costs while improving social, financial, and environmental performance for customers and consumers.

Despite its potential, several barriers hinder the transition of industrial parks toward CE. These include a lack of initiative to exchange information on production processes and generated waste (Abreu et al., 2020; Kirchherr et al., 2018), insufficient knowledge of opportunities for reusing industrial by-products (Bacudio et al., 2016; Sellitto et al., 2021), and limited collaboration and trust among companies, often coupled with a narrow focus on achieving economies of scale (Zhang et al., 2019). Furthermore, Brazil currently lacks legislation requiring industrial parks to adopt circular models. Nevertheless, this does not imply an absence of regulatory pressure. Decree No. 12,082/2024 established the National Circular Economy Strategy to promote the transition from a linear production model to CE. In addition, PNEC provides for the development of targets, standards, indicators, and the National Industrial Symbiosis Program (MDIC, 2025; Decree No. 12,082/2024).

Although Prieto-Sandoval et al. (2021), Rodríguez-Borges (2024), and Verkic et al. (2026) have reported advances in IS and CE through the development of frameworks, conceptual models, and implementation roadmaps, an operational gap remains at the industrial park level because of the absence of a methodological pathway to guide this transition. In this regard, Krzeminski et al. (2026) demonstrated that IS implementation typically begins with mapping the current situation, followed by identifying synergies, assessing feasibility, and selecting opportunities.

Although several methods have been employed to support the transition toward CE, important limitations remain. Material Flow Analysis (MFA), for example, facilitates the quantification of resource inputs, outputs, and stocks but depends on consistent datasets and extensive data collection. Moreover, it has difficulty capturing the dynamic complexity of industrial systems, which may make its application costly and constrain it because of confidentiality concerns and limited access to information (Patricio et al., 2022; Munonye, 2025). Similarly, Life Cycle Assessment (LCA) is better suited to comparing previously defined circularity scenarios than to structuring initial diagnostic assessments. In addition, it is characterized by considerable methodological variability and limited comparability across studies (Patricio et al., 2022; Vahidzadeh et al., 2025). Consequently, transition-readiness assessment tools can help evaluate the conditions necessary for resource exchanges among companies but do not, by themselves, address the challenge of mapping industrial processes and waste streams within industrial complexes (Agudo et al., 2022).

Ramírez-Rodríguez et al. (2024) argue that the transition toward CE should not rely on a single method but rather on methodological combinations tailored to the different phases of identification, assessment, implementation, and monitoring. In light of this gap, the present study addresses the following research question: How can a methodology based on documentary evidence and the scientific literature be structured to map industrial processes and material flows in industrial parks and identify IS opportunities that support the transition toward CE? Accordingly, this study aims to propose a methodology for initiating the mapping of industrial processes and material flows in industrial parks to support the early stages of the transition toward CE.

The proposed methodology provides a practical tool for planning the transition of industrial parks toward CE through IS by enabling the identification of waste, by-products, resources, and potential interorganizational connections based on documentary and scientific evidence. From an academic perspective, this study contributes to the growing body of research on CE at the meso level by proposing a replicable procedure for identifying preliminary IS opportunities in industrial parks, where the concentration of industrial activities and diversity of material flows coexist with limited information transparency and weak interorganizational coordination. By using publicly available and standardized documents as its analytical basis, the proposed method enables an initial diagnostic assessment without requiring prior collaboration among stakeholders. From a managerial perspective, the methodology supports material-flow mapping, the prioritization of collaborative initiatives, and the early-stage planning of actions aimed at promoting circularity.

This article is organized as follows: (a) the Introduction presents the study background and research context; (b) the Methodology describes the proposed steps for supporting the transition of industrial parks toward CE; (c) the Results Analysis presents the application of the proposed methodology to an industrial park and identifies potential circularity opportunities; (d) the Discussion develops the proposed methodological framework and examines its implications; and (e) the Conclusions summarize the study's main contributions and limitations.

Methodology

This study proposes that the transition of industrial parks toward CE should begin by identifying the companies operating within them. This step is essential because material exchanges among colocated companies foster a circular ecosystem through resource circulation (Wen & Meng, 2015). The next step involves mapping inputs, manufacturing processes, products, and waste streams (Pereira et al., 2023; Yu et al., 2015). For this purpose, the methodology recommends collecting and conducting a documentary analysis of Environmental Impact Assessments (EIAs) and Environmental Impact Reports (EIRs), where available, for the companies operating within the industrial complex, together with a scoping review of the scientific literature on their core manufacturing processes and potential CE applications for their waste streams.

Within the environmental licensing framework, an EIA is the technical instrument used to identify, predict, and assess the potential environmental impacts arising from the implementation and operation of a given project, thereby providing the analytical basis for evaluating its environmental feasibility (Secretaria do Desenvolvimento Sustentável do Paraná, 2025). Complementarily, an EIR presents the main findings of the EIA in a concise, objective, and accessible manner, making the information understandable to the public and promoting transparency and public participation in decision-making (Instituto Água e Terra, 2025). Together, EIAs and EIRs play a central role in bridging technical assessment, institutional oversight, and social legitimacy within environmental licensing processes.

EIAs and EIRs are therefore valuable resources for this process because they provide empirical information on installed operations and manufacturing processes, as well as on the products and waste generated by facilities classified by environmental legislation and the relevant authorities as having high pollution potential (Rocha et al., 2023; Oliveira et al., 2024). The scoping review is also important because it explores the principal concepts related to the topic and synthesizes and organizes the available evidence into information suitable for analysis (Mattos et al., 2023; Kastner et al., 2012; Mays et al., 2005; Thomas & Harden, 2008). Together, these sources make it possible to identify inputs, manufacturing processes, products, and potential opportunities for reusing waste commonly generated within the industrial complex.

Methodological Stages

The Pecém Industrial and Port Complex (CIPP) was selected for the application of the proposed methodology because it aims to promote industrial development in the state of Ceará by integrating port and industrial activities (Abreu et al., 2020). The CIPP is a joint venture between the Governo do Estado do Ceará and the Port of Rotterdam and is located in the municipalities of São Gonçalo do Amarante and Caucaia (Complexo do Pecém, 2023). Companies operating within the CIPP produce cement, steel products, precast concrete components, animal feed, fertilizers, ceramic products, wind turbine blades, and electricity through coal combustion (Complexo do Pecém, 2023).

Between February and April 2023, seven EIA/EIR documents were collected and analyzed through online searches and two visits to the Superintendência Estadual do Meio Ambiente (SEMACE-CE). These comprised three EIA/EIRs from cement companies, two from steel companies, and two from thermoelectric power plants. Scientific articles were subsequently retrieved from the Web of Science database in September 2023. Data collection and analysis were guided by the Preferred Reporting Items for Systematic Reviews (PRISMA) checklist (Liberati et al., 2009).

The literature review included studies published up to 2023, corresponding to the period in which the research data were collected. This cutoff was established to ensure consistency between the literature analyzed and the empirical period in which the study was operationalized, thereby reflecting the state of knowledge available at that time. Following retrieval, the articles underwent screening, application of the inclusion and exclusion criteria, and in-depth analysis, a process that required time to systematize the findings. Furthermore, integrating the selected studies with the data obtained from the EIA/EIRs provided sufficient theoretical and empirical depth to identify the IS opportunities discussed in this study.

The scoping review comprised the following steps: (1) identification of the search strings; (2) establishment of the study inclusion and exclusion criteria; (3) definition of the information to be extracted from the relevant studies, including study categorization; (4) interpretation of the findings; and (5) presentation of the review through a synthesis of the evidence (Munn et al., 2018; Pham et al., 2014; Tricco et al., 2016).

The search strategy included three components: (1) industrial sector; (2) CE; and (3) LCA. The first component defined the industrial sector of interest, the second identified potential CE applications within that sector, and the third focused on the inputs, processes, products, and waste generated. This search retrieved 125 scientific articles. The search strings are presented in Table 1.

Table 1

Search strings used in the scoping review

Industrial activity	Search string	Results
Cement industry	“Cement industry” AND “circular economy” AND “Life Cycle Assessment”	11
Steel industry	“Steel industry” AND “circular economy” AND “Life Cycle Assessment”	12
Animal feed	“Animal feed” AND “circular economy” AND “Life Cycle Assessment”	19
Wind turbine blades	“wind blade” AND “circular economy” AND “Life Cycle Assessment”	1
Thermoelectric power generation	“steam thermal power plant” OR “coal-fired” OR “thermal power plant” AND “circular economy” AND “Life Cycle Assessment”	4
Precast concrete	“Precast concrete” OR “prefabricated concrete” AND “circular economy” AND “Life Cycle Assessment”	7
Fertilizers	“fertilizer*” AND “circular economy” AND “Life Cycle Assessment”	71
Ceramics	“Potter*” OR Ceramic* AND “circular economy” AND “Life Cycle Assessment”	20

Source: Prepared by the authors (2025).

The inclusion and exclusion criteria presented in Table 2 were applied.

Table 2

Inclusion and exclusion criteria for articles in the scoping review

Criterion	Question
Inclusion	Does the article directly address the relationship between CE principles and the LCA methodology?
	Does the article explore the application of LCA to assess CE concepts within the specified industrial sectors?
	Does the article focus on one of the following industrial sectors: • Cement production, • Steel production, • Animal feed, • Wind turbine blade manufacturing, • Gas-fired or coal-fired thermoelectric power generation, • Prefabricated or precast concrete, • Fertilizer production, • or Ceramics and pottery?
	Does the article provide a clear description of the LCA methodology, including data sources, system boundaries, and assumptions?
	Does the article address or explore CE principles, strategies, or practices within the specified industrial sectors? Examples include product design for longevity or reuse, recycling and material recovery, resource efficiency and waste reduction, remanufacturing or refurbishment, Extended Producer Responsibility (EPR), and circular supply chains.
Exclusion	Is the article unrelated to the intersection between CE and LCA?
	Is the article not a peer-reviewed publication, such as an editorial, opinion article, or news item?
	Was the article not published in English?
	Does the article focus on industries outside the industrial sectors included within the scope of the review?
	Is the article inconsistent with the EIA/EIR documentation of the companies operating within the industrial complex under study?
	Does the article exhibit substantial or unbalanced bias that compromises impartiality and objectivity?
	Does the article fail to provide substantial or relevant information on the intersection between CE and LCA, even if it meets other criteria?
	Is the article unavailable through open access or otherwise not reasonably accessible to the review team?

Source: Prepared by the authors (2025).

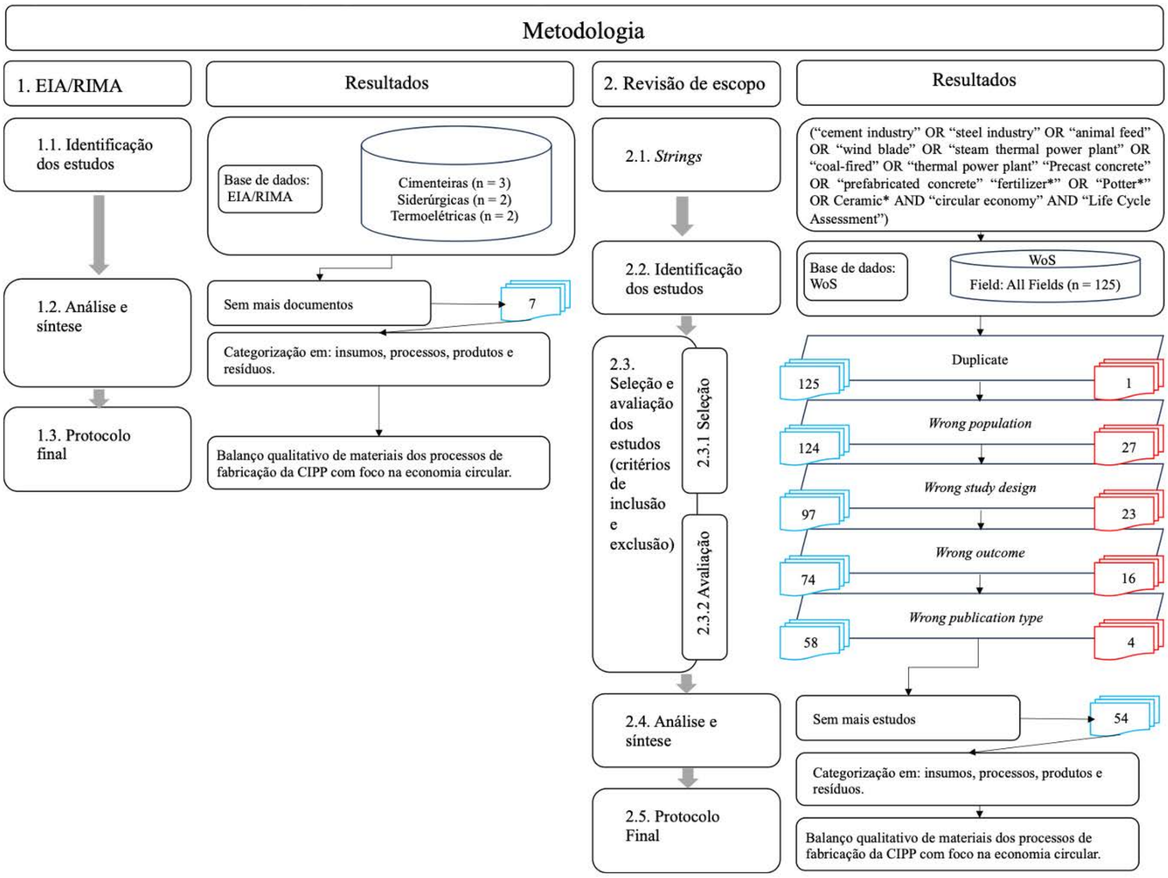
The initial screening of articles for the scoping review was conducted by three reviewers with expertise in the subject. All had academic backgrounds, had completed stricto sensu graduate programs, and had experience teaching in higher education. Before screening began, all reviewers were given access to the EIA/EIRs of the companies operating within the CIPP, which served as reference documents to guide study selection.

The first reviewer held a degree in Civil Engineering and postgraduate training in Environmental Engineering and screened articles related to the cement, steel, wind turbine blade, thermoelectric power generation, precast concrete, and ceramics sectors, evaluating a total of 55 articles. The second reviewer, who held a degree in Environmental Engineering, contributed to the selection of studies on animal feed, wind turbine blades, thermoelectric power generation, precast concrete, and fertilizers, evaluating 102 articles. The third reviewer held a degree in Economics and postgraduate training in Operations Research and screened studies related to the cement, steel, ceramics, animal feed, and fertilizer sectors, evaluating 114 articles. Following screening, 54 articles met the eligibility criteria and were retained for full-text review and data extraction.

Screening was conducted using Rayyan, a free web-based platform designed to support systematic literature reviews. Blind mode was enabled so that each reviewer could access only their own screening decisions. The number of studies included as the basis for this research is presented in Figure 1.

Figure 1

Protocol for the proposed methodology



Source: Prepared by the authors (2025).

Following expert review, the scoping review retained only the articles that met the predefined inclusion and exclusion criteria for each specific study area. The final sample comprised one article on wind blades, three articles on thermal power plants, four articles on precast concrete, three articles on the cement industry, four articles on the steel industry, 14 articles on animal feed, 11 articles on the ceramics industry, and 14 articles on fertilizers, resulting in a total of 54 articles.

Results of the Application

The proposed methodology is replicable and can be adapted to different industrial parks. In this study, its empirical application was limited to the industries currently operating within the CIPP. Because not all companies within the complex had EIA/RIMA available, the methodology was designed as a complementary approach, integrating documentary evidence with findings from the scientific literature. Consequently, its primary contribution lies in its applicability to different industrial contexts, provided that sufficient information is available to support an initial diagnosis of material flows and the identification of opportunities for CE.

This study systematized 54 articles identified through the scoping review together with seven EIA/RIMA. Based on these sources, the information required to initiate the transition of industrial parks toward CE was extracted, including inputs, manufacturing processes, products, and generated waste. Table 3 presents the industries' linear business models, describing the inputs used by each company, their manufacturing processes, products, and waste streams. Some of these waste streams can be incorporated as inputs into other industrial processes within the complex, thereby increasing circularity in the CIPP. Such practices may provide numerous organizational benefits, including reduced environmental impacts and extended material lifecycles (Ghisellini et al., 2016).

Slag is a by-product of metal smelting and steel production consisting of non-metallic materials and impurities separated from molten metal during the melting process (Uddin et al., 2023; Ren et al., 2017; Perathoner et al., 2021). Because it is rich in silica and alumina, two key constituents of cement, it can be used as a partial or complete replacement for clinker, the principal component of cement (Perathoner et al., 2021). Slag may also be incorporated into concrete production, improving compressive strength, abrasion resistance, and durability. In addition, it can be used in asphalt production and other construction materials (Pinto & Diemer, 2020). Another waste stream generated within the CIPP is fly ash from thermal power plants. Owing to its high silica and alumina content, fly ash enhances cement resistance to abrasion and cracking, thereby increasing its durability and mechanical performance (Batuecas et al., 2021; Uddin et al., 2023). Likewise, solid waste generated during the production of wind turbine blades, cement, and concrete can be incorporated into cement manufacturing after mechanical crushing (Batuecas et al., 2021).

During fertilizer production, anaerobic treatment generates sludge rich in methane, which can be converted into biogas for energy production. The subsequent combustion of biogas produces ash that can be used in cement and precast concrete manufacturing (Rufí-Salís et al., 2020). The Strategic Water Resources Action Plan of the State of Ceará provides for the operation of a reclaimed water treatment plant to supply the CIPP. This facility will be supplied with urban wastewater collected from the Metropolitan Region of Fortaleza (Secretariat of Water Resources of the State of Ceará, 2018). Consequently, sludge is also produced during wastewater treatment. This material can be recovered for fertilizer production through struvite crystallization using three established technologies: (1) REM-NUT®, an ion-exchange process that recovers phosphorus as struvite from secondary-treated effluent by adding Mg^{2+} to satisfy stoichiometric requirements; (2) Ostara®, which employs a dedicated reactor together with Mg^{2+} and NH_4^+ to precipitate struvite from digestate; and (3) AirPrex®, which introduces Mg^{2+} as magnesium chloride before the material enters an AirLift reactor, where intensive aeration through CO_2 stripping raises the pH and promotes struvite crystallization (Rufí-Salís et al., 2020).

Fine particles are waste generated by ceramic and precast concrete production processes and constitute a type of air pollutant comprising solid or liquid particles with an aerodynamic diameter smaller than 2.5 micrometers (PM2.5) or 10 micrometers (PM10). These particles can be inhaled and may even enter the bloodstream, causing a range of health problems, including respiratory and cardiovascular diseases and cancer (Settembre-Blundo et al., 2019). Fine particles can be incorporated into concrete or asphalt production processes, provided that they undergo chemical treatment to eliminate their toxicity (Perathoner et al., 2021).

All cement, steel, precast concrete, and thermoelectric power companies were found to emit greenhouse gases with similar emission profiles, namely CO_2, CO, CH_4, NO_x, N_2O, SO_2, HF, and HCl. These gases can be used to produce fertilizers through the following steps: (1) a catalytic conversion process in which atmospheric nitrogen (N_2) is converted into nitrous oxide (N_2O) (Sen & Bakshi, 2023); and (2) a reaction between nitrous oxide and hydrogen (H_2), resulting in the formation of ammonia (NH_3) (Mohammed et al., 2018). The ammonia produced plays an essential role in manufacturing nitrogen fertilizers, such as urea, ammonium nitrate, and ammonium sulfate (Aleisa et al., 2021). It is important to note that the most widely used ammonia production process is the Haber–Bosch method, which requires high pressure and temperature (Humphreys et al., 2021).

Table 3

Systematization of the identified inputs, processes, products, and wastes

Industry	Inputs	Manufacturing Processes	Product	Wastes	References
Cement Plant	Limestone, clay, iron ore, gypsum, sand, and coal ash.	Grinding, mixing, burning, clinker grinding.	Cement, clinker.	Greenhouse gases (CO_2, CO, CH_4, NO^x, N_2O, and SO_2), volatile organic compounds (VOCs), fine particles (PM 2,5 and PM 10) and heavy metals (As, Cr, Hg, and Ni).	Uddin et al. (2023); Batuecas et al. (2021); Perathoner et al. (2021); Apodi (2019); Votorantim (2014); Polimix (2016).
Steel Mill	Steel scrap, iron ore, coke, coal, and limestone.	Melting, refining, and rolling.	Steel.	Slag, dust, gases, and wastewater.	Broadbent (2016); Pinto and Diemer (2020); Minunno et al. (2020); Li et al. (2022); Dong et al. (2016); ArcellorMittal (2017); Gerdau (2012).
Animal Nutrition	Protein, water, food waste, and grains.	Mixing, granulation, packaging.	Feed.	Production waste, composting co-products, CH_4, N_2O, and VOCs.	Campos et al. (2020); Jagtap et al. (2021); Viana et al. (2023); Laso et al. (2018); Teigiserova et al. (2022); Petit et al. (2020); Ojha et al. (2020); Oldfield et al. (2017); San Martin et al. (2021); Albizzati et al. (2021a, 2021b); Owsianiak et al. (2022); Sanchez Matos et al. (2021); Suckling et al. (2021).
Wind Blade	Carbon fiber, fiberglass, and epoxy.	Manufacturing, molding, and assembly.	Wind blades.	Material scraps and manufacturing waste.	Ghosh et al. (2022).
Thermal Power Plant	Coal, gas, biomass, water, O2, organic, inorganic, and inert waste to produce biogas, red mud, and slag (aluminum and carbide).	Combustion, electricity generation.	Energy.	Ash, wastewater, gases (CO_2, SO_2, NO_x, CO e CH_4), heavy metals (Zn, As, Cd, Cr, Hg, Ni, Pb, and V), and non-methane volatile organic compounds (NMVOC).	Asif et al. (2022); Rathore and Sarmah (2020); Ren et al. (2017); MPX (2001); Termolux (2008).
Precast	Concrete, steel, wood, cement, and aggregates (sand, gravel, and crushed stone), water, solid particles (fly ash), cement, water, sand, superplasticizer, and construction and demolition waste (CDW).	Molding, curing, finishing.	Precast products.	Greenhouse gases (CO_2, CO, CH_4, NOx, N_2O, and SO_2) volatile organic compounds (VOCs), fine particles (PM 2,5 and PM 10), and heavy metals (As, Cr, Hg e Ni).	Zhang et al. (2023); Yu et al. (2024); Zhao et al. (2020); Moreno-Juez et al. (2020).

Fertilizers	Nitrogen, calcium, silicon, phosphorus, potassium, struvite, organic materials, herbicide, ammonia, treated wastewater, phosphate, magnesium, NH_4NO_3, $(NH_4)2HPO_4$, struvite, sludge, manure, municipal solid waste (MSW), lignocellulosic waste, phosphogypsum, and compost.	Mixing, granulation, gasification, and purification.	Fertilizers.	Purged sludge and ash.	Colley et al. (2021); Pagliaro et al. (2022); Rufí-Salís et al. (2020); Møller et al. (2023); Cobo et al. (2019); Taifouris and Martin (2018); Aleisa et al. (2021); Li et al. (2022); Mohammed et al. (2018); Sen and Bakshi (2023); Pajura et al., (2023); Antonetti et al. (2017).
Ceramics	Clay, feldspar, sand, water, and calcium carbonate.	Molding, drying, firing, and glazing.	Ceramic products.	Production waste (breakage) and pollutant gases (CO_2, NO_x, SO_2, HF, and HCl).	López-García et al. (2021); Silvestri et al. (2021); Bianchi et al. (2023); Barbosa et al. (2022); Barraco et al. (2023); Cangussu et al. (2023); Zygmuntowicz et al. (2021); Dino et al. (2020); Simão et al. (2022); Gaibor et al. (2023); Settembre-Blundo et al. (2019).

Source: Prepared by the authors (2025).

In the fertilizer industry, CH_4 can also be used to produce nitrogen fertilizers (Colley et al., 2021; Li et al., 2022). CO_2, in turn, can be used in the production of phosphate fertilizers, such as single superphosphate and triple superphosphate (Cobo et al., 2019). The recovery and reuse of residual gases are important aspects of efficiency and sustainability in the fertilizer industry, contributing to resource optimization and reduced environmental impacts (Colley et al., 2021).

These residual gases may also be used in animal feed production (Teigiserova et al., 2022). Methane generated through the anaerobic digestion of organic matter, such as animal manure, can, for example, be used directly in animal feed production (Laso et al., 2018). Similarly, CO_2 and NH_3 can also be used in this process through fermentation (Laso et al., 2018). The use of residual gases in animal feed production therefore represents a technological challenge for the industrial complex, as careful attention must be given to the required techniques (Ojha et al., 2020).

Based on the literature, precast concrete and cement companies generate volatile organic compounds (VOCs) as waste streams. VOCs are non-metallic air pollutants and generally comprise organic chemical compounds with low boiling points and high vapor pressures, meaning that they can readily evaporate and become gases in the atmosphere (Yu et al., 2024). Many VOCs are harmful to human health and the environment and are frequently emitted by industrial processes, chemical products, solvents, fuels, and other sources. However, the articles did not specify these compounds or identify opportunities for circularity among the companies operating within the industrial complex. Therefore, disposal at an industrial landfill is recommended for these waste streams.

Similarly, the literature indicates that cement, thermoelectric power, and precast concrete companies generate heavy metals as waste, including As, Cr, Hg, Ni, Zn, Pb, and V. The literature provide no consolidated evidence supporting circular applications for these elements; therefore, their disposal at an industrial landfill is also recommended. According to Zhang et al. (2023), if improperly discarded, these elements can contaminate water, soil, and air, affect the entire biosphere, and pose a threat to human health.

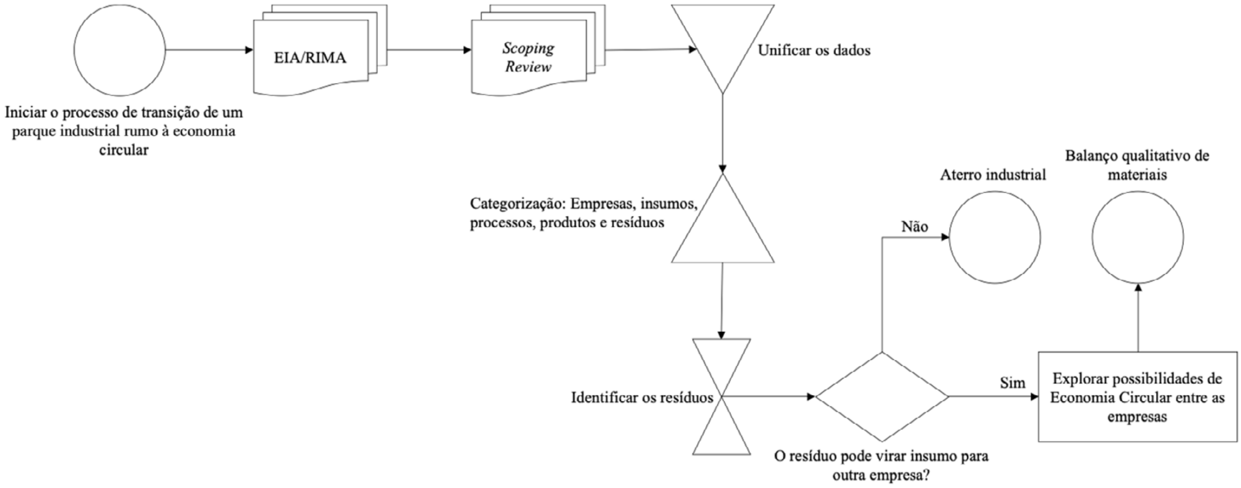
Development of the Methodological Framework and Next Steps for the Transition of Industrial Parks Toward CE

To develop a qualitative material balance for the CIPP with a focus on circularity, the need arose to propose a methodology for initiating the mapping of industrial processes and material flows in industrial parks to support the early stages of the transition toward CE. In this study, the proposed methodology combines the analysis of EIA/EIR documentation with a scoping review. This approach examined the procedures used to understand and improve the operations of companies within an industrial complex, promoting environmental and societal well-being while creating opportunities for new business development.

Figure 2 presents the proposed methodological framework for reproducing the initial steps required to identify CE opportunities among companies operating within an industrial complex. LCA plays a key role in understanding material exchanges because it establishes the system boundaries of the production processes under investigation while identifying their main components — inputs, manufacturing processes, products, and waste streams — as well as their associated environmental impacts.

Figure 2

Proposed methodological framework



Source: Prepared from data collected in this study (2025).

To replicate the proposed methodology, the relevance of CE to the industrial complex under investigation should first be established. Subsequently, the following steps should be undertaken:

1) Select the industrial complex in which the transition toward CE will begin and identify the companies operating within it;
2) Collect the EIA/EIR documentation for the companies operating in the selected industrial complex, as these documents guide the study selection process and improve the quality of the evidence retrieved during the scoping review;
3) Conduct a scoping review to map and synthesize the current state of scientific knowledge on manufacturing processes relevant to the industrial complex under investigation;
4) Categorize the information extracted from both the scientific literature and the EIA/EIR documentation, including the companies involved, inputs, manufacturing processes, products, and waste streams;
5) Identify opportunities to recover waste generated by one company as inputs for other companies operating within the industrial complex;
6) Integrate the findings from the previous steps into a visual synthesis using a table organized according to the predefined categories.

These sequential steps provide a comprehensive and holistic view of the proposed methodology. In summary, the methodology not only identifies opportunities to improve operational efficiency but also maps practical strategies for promoting CE through material exchanges among companies and strengthening circularity within the industrial complex using secondary sources of information.

Figure 2 illustrates that the proposed methodology was specifically designed to address the barriers that hinder the transition of industrial parks toward CE. The use of EIA/EIR documentation reduces dependence on voluntary information sharing in environments characterized by limited transparency among companies, as described by Abreu et al. (2020) and Kirchherr et al. (2018). Complementarily, the incorporation of a scoping review expands the capacity to identify opportunities for by-product recovery by linking the material flows identified within the industrial park to technical alternatives reported in the literature (Bacudio et al., 2016; Sellitto et al., 2021). Furthermore, the integration and categorization of data address the fragmentation that often prevents the identification of connections among manufacturing processes, inputs, products, and waste streams. In this context, assessing the potential conversion of waste into production inputs anticipates, at the analytical level, interorganizational collaboration that would otherwise be constrained by limited trust and cooperation among companies, as argued by Zhang et al. (2019). Consequently, the proposed methodology overcomes the interdependence between information sharing and preexisting trust by enabling an initial diagnostic assessment without requiring established collaborative relationships from the outset. In doing so, it identifies material flows and establishes the informational foundation from which the transition toward CE can begin.

Final Considerations

Overall, this study achieved its objective by proposing a methodology for mapping industrial processes and material flows in industrial parks to support the early stages of the transition toward CE. By integrating the analysis of EIA/EIR documentation with a scoping review of the scientific literature, the proposed methodology identified material flows and preliminary opportunities for circularity among the industrial activities operating within the complex.

The principal contribution of this study lies in providing a replicable methodological procedure that can be applied in contexts where interorganizational collaboration remains limited and primary data are not readily available. Accordingly, the proposed methodology should not be viewed as the transition itself but rather as an essential initial diagnostic stage that supports its implementation by assisting public and private decision-makers in identifying IS opportunities and planning circularity strategies at the meso level.

A limitation of the proposed methodology is its dependence on the availability of environmental documentation in either digital or physical format. This is particularly relevant because not all industrial activities require EIA/EIR documentation, as environmental licensing may instead rely on simplified environmental studies or, depending on the characteristics of the project and the decision of the environmental authority, may not require such documentation. Consequently, the findings reflect the information that was effectively available at the time of data collection. Nevertheless, incorporating additional environmental documentation could broaden the methodological evidence base and further enhance the initial mapping of material flows, waste streams, and circularity opportunities within industrial parks.

Future research should apply the proposed methodology to other industrial contexts in order to assess its replicability and support studies aimed at further investigating, validating, and quantifying circularity opportunities. The opportunities identified through the proposed method require subsequent investigations to determine their feasibility under specific industrial conditions and, where appropriate, to quantify the associated material flows, benefits, and implementation constraints. Such research would not only strengthen the analytical robustness of the methodology but also consolidate its usefulness as a foundation for investigating the transition of different industrial systems toward CE.

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How to cite:

Oliveira, F. M., Silva, L. M. T., de Abreu, M. C. S., & Vaz, C. R. (2025). Methodological Proposal for the Transition of Industrial Parks Toward the Circular Economy. *Revista Ciências Administrativas*, *31*, 1-17. https://doi.org/10.5020/2318-0722.2025.31.e17173

Correspondence address:

Felipe Moura Oliveira
E-mail: felipeoliveira@uespi.urc.br

Luís Matheus Tavares Silva
E-mail: luismatheusts@gmail.com

Mônica Cavalcanti Sá de Abreu
E-mail: mabreu@ufc.br

Caroline Rodrigues Vaz
E-mail: caroline.vaz@ufsc.br

Received on: *01/16/2025.*
Accepted on: *02/21/2025.*