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Review

Industrial Metabolism: A Multilevel Characterization for Designing Sustainable Manufacturing Systems

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Abstract: The development of industrial manufacturing systems has significant implications for society and the environment, often resulting in substantial waste generation. To address this issue and promote sustainable growth, the concept of industrial metabolism offers a promising approach. Industrial metabolism facilitates the circularity of energy and material flows within the industrial environment, contributing to the establishment of more sustainable manufacturing systems. This paper provides a comprehensive analysis of industrial metabolism, highlighting its analogy with natural systems and categorizing models based on their application at different levels: macro (national or regional), meso (eco-industrial park), and micro (manufacturing plant or line). The analysis emphasizes the importance of considering the trophic network and evaluating the efficiency, cyclicality, toxicity, and resilience of industrial metabolic pathways. The proposed characterization of bioinspired industrial metabolism is positioned within the industrial environment. This positioning facilitates the design of manufacturing systems that emphasize circularity, drawing on frameworks applied at different levels within industrial metabolism.

Keywords: industrial metabolism; biological analogy; circularity design; multilevel organization; sustainable manufacturing system

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1. Introduction

The concept of metabolism has been used to describe the exchanges of matter and energy between nature and society, providing support for criticism of industrialization centered on the exploitation of wage labor in capitalism [1]. In this sense, Marx and Engels considered labor as the regulation of the society-nature metabolism [2]. Marx coined the term "metabolic rift," illustrating how industrialization disrupts the centuries-old metabolism between society and nature, creating a gap [3]. Although the metabolic rift has Marxist connotations, it can contribute to the understanding and guidance of social metabolism [4]. Thus, decoupling in the economy is needed towards an inclusive and circular approach [5].

Industrial Metabolism (IM) is a part of social metabolism [6] and refers to this exchange of matter and energy between human society and nature in a manner analogous to the processes and balance of matter and energy in natural organisms and ecosystems [7]. However, this definition lacks geographic, temporal, and material-type dimensions. To address this issue, the relevant boundaries of the system must be explicitly defined in each study, without relying on the society-nature dichotomy [8]. The researcher needs to establish these boundaries and consider the relationships with other elements [9,10]. From another perspective, the field of ecology aims to consider inclusive natural closed cycles [2]. In this context, the use of the term metabolism as a valid concept at scales beyond the individual organism is embraced by industrial ecology [8]. Thus, this analogy between the metabolism of an individual organism and a larger system (the ecosystem) is well received [11].

IM, in relation to the economy, focuses on the consumption of low-entropy resources and the disposal of high-entropy waste into the biosphere [12]. This approach aims to increase resource efficiency through circularity and the utilization of by-products within industrial systems [13]. Sustainable manufacturing systems seek to minimize exchanges with the environment by enhancing internal material circulation through renewable energy flows [14]. Studies are directed towards environmental improvement through technological, economic, and policy instruments that address social and environmental concerns within the Circular Economy (CE) [15,16]. The biological analogy justifies the importance of this approach, as biological metabolism is characterized by high efficiency in energy transformation, material utilization, and circulation [17]. However, IM exhibits a significant difference, as natural systems demonstrate closed loops and nearly universal material recycling. Understanding these energy and material flows in the economy of a community allows for a systemic perspective that facilitates goal setting and the development of indicators [18–20].

Therefore, this study aims to investigate the following research inquiries: (a) Can analogies be established between IM and natural systems? (b) Can the characterization of IM from the analogy with ecological systems be used as a framework to guide the design of manufacturing systems for resource circularity? (c) Can specific frameworks for IM be identified at different levels?

The main contributions of the presented work can be summarized as follows. Firstly, it establishes analogies between manufacturing systems and natural systems using the concept of metabolism. By drawing parallels between these two domains, a deeper understanding of industrial processes and their relationship to natural systems is achieved. Secondly, the research provides a comprehensive characterization of IM at multiple levels: macro (nation or region), meso (eco-industrial park), and micro (manufacturing plant or line). Approaching from a bioinspired perspective, characterized by observing and imitating functions in living organisms, this multilevel characterization enables the design of manufacturing systems for resource circularity, identifying the most suitable frameworks in IM.

This work is structured as follows. Section 2 describes the methodology used for the conducted review. Section 3 provides a review of the existing analogies between IM and natural systems, along with an analysis of the works that employ IM at different levels (micro, meso, and macro). Section 4 describes the conceptual characterization of IM from a multilevel bioinspired perspective. Finally, the conclusions are drawn in Section 5.

2. Methodology

In this section, among the existing review methodologies, a Status Quo review [21] will be conducted. This corresponds to a critical and constructive analysis of the existing literature in the field of industrial metabolism through its classification and analysis. The most relevant publications are reviewed with the aim of presenting the most current state of research in the field of industrial metabolism by identifying patterns and trends.

The proposed review methodology consists of four steps [22]. Firstly, the research areas, such as industrial, manufacturing, ecology, and sustainability, are defined and delimited to gather relevant material. Subsequently, a descriptive analysis of the formal aspect of the material is conducted. Following this, the collected material is selected based on structural dimensions and related analytical categories. The first three steps of the methodology are elaborated below, with the fourth step, involving material analysis, extensively developed in Section 3.

The literature review is limited to specific considerations. Only articles from peer-reviewed scientific journals, encompassing research and reviews written in English, are included, except for justified exceptions. The review period spans 20 years, from 2003 to 2023, though earlier works were considered if they were relevant to the field. The search was conducted using keywords in relevant databases such as Scopus, ScienceDirect, SpringerLink, Web of Science, and Taylor & Francis. This delimitation resulted in the identification of 1037 articles with the keyword "industrial metabolism." Subsequently, detailed searches were conducted to assign each article to specific categories, providing a map of the weight of concepts, as detailed in Table 1.

Table 1. Number of documents that include key concepts alongside the term industrial metabolism.

Concept		Concept	
Circular economy	423	Inter-/Intra-specific	3
Industrial ecology	894	Eco-industrial park	286
Analogy	48	Resilience	135
Eco-efficiency	258	Ecological network	65
Toxicity	69	Trophic chain	24
Cyclicity/Circularity	124	Metabolic pathway	25
Ecosystem	597	Habitat	66
Symbiosis	319	Keystone species	5

Among all the identified articles, a selection is made of those that align with the stated objectives. Specifically, the focus is on articles aimed at characterizing industrial metabolism through analogy with natural systems.

3. Background of the Literature

In this section, a review is conducted on the main concepts considered in this study. The aim is to identify and establish the analogies between IM and natural systems, as well as analyze the approaches taken at different levels (micro, meso, and macro) to characterize IM from a bioinspired perspective.

3.1. Analogies between Natural Systems and Manufacturing Systems

3.1.1. Biological Analogy of Industrial Metabolism

The term "metabolism" refers to the internal processes of a living organism, which involve the intake of energy-rich, low-entropy materials to sustain its functions and grow [23]. This process also entails the elimination of waste materials, which are degraded and high-entropy substances. Biological organisms and industrial activities exhibit a complete analogy, as both process materials are driven by a flow of exergy and are self-organizing systems within a stable system [24].

The economic system is governed by rules or human components, involving direct and indirect labor as consumers [25]. Unlike natural systems, productive activity is not self-regulating or self-limiting but is stabilized through mechanisms such as price regulation of inputs and demand. The concept of IM can be applied at different levels, such as nations or regions [26], as long as well-defined boundaries exist to monitor the physical flows of materials and energy [24].

In biology, metabolism encompasses anabolic and catabolic reactions in living beings [23,27]. There are parallels between cellular metabolism and the metabolism of a manufacturing cell. Both involve material transport, product assembly (anabolism), and intermediate material storage. Enzymes catalyze biological reactions in cellular metabolism, while manufacturing cells utilize machinery or workstations [28]. The flow of substances within a cell resembles the flow of material in a manufacturing network [29,30].

However, the definition of metabolism can extend beyond the cellular level, encompassing material and energy flows at different functional levels of living systems [8]. Industrial ecology has led to the study of industrial ecosystem metabolism, focusing on the complexity and balance between synthesis and degradation processes, thus expanding the biological analogy [31]. While direct manufacturing (synthesis and anabolism) has seen significant development, reverse manufacturing (degradation or catabolism) is still a pending challenge, presenting an opportunity within the framework of the CE [32].

The analysis of IM seeks to understand the circulation of materials, water, and energy linked to human activity from their initial extraction to their reintegration into global biogeochemical or technical cycles within the technosphere, as a concept analogous with nature [8,33,34]. The following subsections describe each of these analogies and their relationships.

3.1.2. Ecosystem

An ecosystem includes abiotic and biotic components [27]. Each population in an ecosystem has a range of tolerance to environmental variations, which can limit population growth and survival [23], including productive analogies in the industry [35].

The concept of industrial ecosystem emerges from industrial ecology [36] and is used to model and analyze the energy, material, and economic networks of industrial manufacturing ecosystems [10]. In addition to a positive view, these systems present negative and competitive aspects, such as ecosystem-level competition, predation, parasitism, keystone species, resilience, and system destruction. To establish the analogy, it is necessary to analyze the problems of structural complexity, identify limiting factors of industrial ecosystem evolution, strengthen its capacity for adaptation and self-organization [37], and establish its boundaries [33] for design and modeling purposes [38]. Each actor in the ecosystem possesses different attributes, decision-making principles, and purposes, with coherence being the key concept [33], understood as the proportion of actors whose behavior aligns with their principles and objectives in an ecosystem [39].

3.1.3. Resilience in the Industrial Ecosystem

Resilience is the capacity of a system to recover its original state after changes in input and state variables while maintaining its essential characteristics and functional relationships [40,41]. Resilience is studied in various fields and disciplines, such as ecology, economics, socio-ecological systems, and engineering [42,43]. Studies on resilience in ecological, complex, and engineering systems have been analyzed [44]. Resilience in complex systems refers to the ability of the industrial system to sustain itself in an unstable environment [45]. Although resilience may lead to inefficiency, system capacities, resource reserves, and critical redundancy for resilience may be in opposition to efficiency logics [46]. In economy, resilience is divided into static [47] and dynamic [42], with established indicators for both [25]. In ecological systems, it is used to guide the design and management of industrial ecosystems to increase adaptability [48]. In engineering systems theory, network structure is important for system resilience [49]. Resilience characteristics include redundancy and flexibility; although they may decrease efficiency, they improve sustainability by allowing the system to handle various disturbances [42]. Thus, emerging countries specializing in natural resource supply are vulnerable and unstable, with high rates of economic growth but lower resilience [50].

Resilience at the eco-industrial park (EIP) level is analyzed through various characteristics and indices of the industrial manufacturing ecosystem, such as network topological characteristics, economical aspects, connectivity among network nodes, the number of roles referred to astrophic levels [51,52], and different indicators of network centrality and efficiency [53]. Additionally, metrics are used for sustainability and resilience in infrastructure construction and its interdependence with society [54,55]. Resilience is also analyzed by considering the removal of an important node (a key species from the natural analogy) and studying the trend of network efficiency change based on load and capacity at a node [56].

Resilience in the industrial manufacturing ecosystem is characterized by its topology, diversity, flexibility, stability, robustness, redundancy, and speed, while at the level of manufacturing systems, it is conceptualized in terms of vulnerability, adaptability, absorptive capacity, and recovery capacity [57,58]. CE can help make the industrial manufacturing ecosystem more resilient, following the analogy of natural systems [59].

3.1.4. Trophic Chain

The trophic chain classifies the biotic components of the ecosystem according to the feeding habits of organisms, dividing them into autotrophs and heterotrophs [27].

Autotrophs, known as producers, manufacture nutrients from compounds and energy in the environment, primarily from the sun, while heterotrophs feed on other living organisms. Heterotrophs are further subdivided into herbivores, carnivores, top predators, omnivores, decomposers, and detritivores [23]. In analogy with the industrial ecosystem, they are classified as producers, consumers, and decomposers [60], with a greater accumulation of energy and matter at higher trophic levels [61]. Industrial producers are companies that produce goods, including water and energy, while industrial consumers are companies that consume the goods produced by producers, and industrial decomposers transform waste into eco-compatible resources [62,63]. This imbalance in the technosphere and the importance of CE and vertical integration among companies emerge as relevant topics. In this line, the concept of a trophic chain contributes significantly to the characterization of IM by providing a structured framework to understand the flow of materials and energy within the industrial ecosystem. The trophic chain allows the modeling of each industry, following the biological analogy, as a producer, consumer, or decomposer.

3.1.5. Trophic Network

Organisms can feed on various prey and be preyed upon by multiple predators, situated at different trophic levels [23]. For greater accuracy, a trophic network can be employed, a graph that shows all the feeding interactions among species in an ecosystem. The arrowhead in the network indicates which organism feeds on another. Trophic networks serve two important objectives [36]: analyzing resource flows in ecosystems and dynamic interactions among species. The network allows for the identification of organisms, their trophic level, and their interactions, enabling the analysis of resource flows. In industry, Ecological Network Analysis (ENA) serves as an analogy to trophic networks [64,65].

In modeling and analyzing IM, ENA is used to characterize the metabolism in the network, its processes, and key pathways [66], identifying effective trophic levels and their efficiency [67], as well as industrial symbiosis relationships [68]. Analogous to ecological systems, it is observed that a network with less diversity has negative repercussions in the form of overdependence and reduced resilience to random perturbations [69]. This analogy becomes particularly insightful when examining cross-sector relationships within the value chain. It sheds light on symbiotic, predatory, and parasitic interactions, offering a succinct comparison between the natural trophic network and the intricate dynamics of interconnection within diverse industrial activities.

3.1.6. Metabolic Pathways

The analogy between cellular and manufacturing metabolic pathways emerges at different levels, highlighting the close connection between trophic networks and specific element pathways [70,71]. The analogy of IM refers to physical processes and resource flows between raw materials and energy. Production factors, such as labor and machinery, act as catalytic enzymes in the conversion of inputs into products [72]. Methodologies are employed to handle the complexity of IM, including temporal dynamics and the quantification of energy and material flows, as well as the embodied energy in facilities and maintenance [73].

3.1.7. Key Species

In ecology, it is hypothesized that certain species act as keystones, having a significant effect on other organisms in an ecosystem [27,74]. In industrial manufacturing, a key species can serve as an indicator of ecosystem stability, as its alteration can impact diversity and production [17,75,76]. Key companies in the industrial ecosystem should share value rather than deplete it [77], and within the supply chain context, identifying the key company is essential for maintaining the stability of the industrial system [78]. Identifying key products in industrial manufacturing is also important [79].

ENA is used to evaluate key species in a network based on their contribution to the overall network and biomass [80,81]. The concept of key species also applies to the value chain and supplier network in industrial manufacturing.

3.1.8. Industrial Habitat

The industrial habitat consists of a specific area with infrastructure and specific resources [82]. The following analogy can be made between natural habitat [27] and industrial habitat based on their components [60]: the soil or territory, water, air, and unlimited solar energy in the natural habitat correspond to the area, air, water supply and sewage, and energy network (different types of energy used, usually limited), respectively. However, the industrial habitat also includes information systems (telecommunications) and transportation (roads, railways, and airports), which do not have a direct analogy in the natural habitat. Although the transfer of information is observed in natural ecosystems and not in habitat [23].

3.1.9. Symbiosis at Eco-Industrial Park Level

The primary means of establishing the industrial habitat, drawing from a biological analogy, is through the implementation of EIP. Industrial symbiosis is a key approach wherein companies collaborate for the exchange of resources, yielding economic, environmental, and social benefits [83,84]. This includes the exchange of materials, energy, water, by-products, and information [85,86]. Industrial symbiosis studies are based on IM and analyze exchanges within a network of industries. The types of industrial symbiosis are classified according to the typology of EIP, as they are the most obvious examples of industrial symbiosis [87,88].

Based on the key species theory from the science of ecology, EIPs are divided into categories based on the presence of a single central company or multiple dominant companies [89], and the relationships among their members are classified into dependence, equality, and hierarchy [90,91]. According to their location, EIPs can be co-located near industries, which reduces costs and risks and optimizes environmental and economic benefits [89], or virtual, with the exchange of by-products and wastes separated by long distances [92]. In terms of formation and origin, EIPs can be promoted by government entities (planned parks) [93] or arise from private initiative (self-organized) [83]. Other approaches to parks include integrated sectors [91], which involve companies from different industrial sectors; specific-sector parks [94,95], with one or more central companies from the same sector and related enterprises; and reuse and recycling parks [92], focused on resource recovery. In terms of complexity, parks are divided into new and existing, with newly planned parks being built from scratch with the goal of connecting companies through shared infrastructure and facilities to reduce environmental impact [66]. Another classification of approaches to industrial symbiosis is based on the dynamics of symbiosis [96].

3.2. Levels of Industrial Metabolism

3.2.1. Micro Level: Industrial Plant

At the micro level, there are studies that analyze the metabolic flows of carbon at the manufacturing plant level [97–99], addressing the analysis of processes that compose the metabolic pathway and evaluating the system from an efficiency perspective. At this same level, based on Material Flow Analysis (MFA), company models are established to physically describe IM and the use of natural resources for different materials [100,101]. Another approach to manufacturing plant-level metabolism is through Energy Flow Analysis (EFA) and MFA [70], with the aim of improving flows while considering their effectiveness. At the industrial population level for the coal industry, there are models linked to metabolism and symbiotic relationships [102], as well as the establishment of pathways and their contextualization in the decarbonization-linked territory [103]. In the iron and steel industry, there are models based on IM through EFA [104], where the processes specific to this type of industry are identified, and energy flows are characterized for each activity [105]. Along this line, the IM of pathways is quantified using MFA to comparatively investigate energy efficiency, material efficiency, and emission intensity at the company level [106].

3.2.2. Meso Level: Eco-Industrial Park

EIPs are organized as industrial ecosystems that conserve natural and economic resources, reduce production costs, and provide opportunities to gain benefits through the use and sale of waste materials [62,107]. These EIPs are communities of manufacturing and service companies that seek to improve their economic, environmental, and resource performance through collaboration and the pursuit of collective benefits [108]. In this context, it is essential for companies to be able to self-regulate their behavior and self-organize effectively to facilitate self-regulation and information flows [109].

It is important to distinguish the terms industrial symbiosis, eco-industrial network, and EIP, as although they are sometimes used interchangeably, they differ in the scale of analysis, objectives, actors involved, and implementation [110]. The study of metabolism in EIPs aims to create a consortium of companies to strengthen synergies and support decision-making [111]. EIPs act as innovation platforms for environmental management and promote a systemic approach to the system rather than a point-specific treatment of environmental issues [112]. Methodologies are proposed that identify material and energy flows, define collective strategies, and compare scenarios through multi-criteria analysis [113]. In CE, hybrid frameworks are used to assess the benefits of EIPs with multi-criteria approaches based on indices configured using the Delphi method, considering economic, social, and environmental criteria, especially toxicity related to emissions per unit of value added [114]. Likewise, the use of Life Cycle Assessment (LCA) and product value chain assessment within the context of EIPs [115,116].

In the field of EIPs, IM is used to model the processes and metabolic pathways of elements such as chlorine, copper, sulfur, among others [117]. For chlorine, the Substance Flow Analysis (SFA) method is employed to analyze its metabolic pattern and identify the main metabolic pathways in chemical EIPs [9]. Indicators such as resource efficiency, yield rate, conversion rate, and emission factor are established to assess chlorine metabolism in EIPs [115]. In the case of copper, Sankey diagrams are used, and indices such as resource utilization efficiency, production efficiency, and system loss rate are proposed to quantify and evaluate copper metabolism in EIPs [118]. Regarding sulfur, SFA and ENA are employed to analyze the delivery processes, transformation, and internal characteristics of sulfur IM in EIPs [66]. SFA and LCA are also applied to identify impacts and material and energy flows related to sulfur [119].

In relation to carbon and nitrogen metabolism, SFA methods are used to establish IM models at the level of industrial parks, considering metabolic networks [120,121]. Likewise, phosphorus metabolism is analyzed at the EIP level through the use of SFA and the construction of metabolic networks, analyzing the metabolic structure and dynamics to improve water use efficiency and reduce water pollution [122].

There are two main methods for quantitatively analyzing the IM of industrial systems [123]: MFA [124] and SFA [125,126]. Both methods quantify flows and resources in the industrial ecosystem. MFA examines the complete life cycle of a material, but obtaining sufficient data to quantify material flows is challenging [127]. However, SFA traces the pathways of elements in each metabolic process, allowing the specification of flows, stocks, and efficiency. The use of MFA was not found in the reviewed literature, making SFA an important tool for studying the metabolism of specific elements at the meso level, such as copper [118], sulfur [66], or nitrogen [120].

3.2.3. Macro Level: Region

In the analysis of studies on regional IM, the impact of human activity on natural phosphorus cycles is found, which has led to serious environmental problems such as water eutrophication [128,129]. In this context, IM models have been proposed to analyze the metabolic pathways of this element at a regional level, which consider extraction, manufacturing, consumption, waste management, as well as imports, exports, and the biosphere [130,131]. To trace these metabolic pathways and analyze environmental pollutants, the SFA approach is used [132]. Additionally, in the context of chlorine, the MFA is employed to achieve a circular system in a specific region [133]. Regarding the evaluation of IM, studies have compared different input–output models, revealing differences based on residential consumption management, service sectors, waste recycling, and price assumptions [134].

At the national level, MFA is widely used [135–140]. This method allows the evaluation of the metabolic transition of regions over a specific period of time while also enabling the observation of metabolic patterns in a specific area [141,142]. In the same vein, other studies expand the scope of the flow accounting approach at the regional level to allow for future decision-making in the management domain [143]. However, it is noted that one of the fundamental aspects lacking in these methods, and many of the previously mentioned studies, is the incorporation of the dynamic aspect. Other approaches establish metabolic models at the national level based on socio-economic models and MFA, where the model is evaluated in economic and environmental terms [138,139]. Alternative approaches employ IM in the analysis and quantification of recycling cycles at the national level [144]. However, one of the main drawbacks of these models is their static nature. Therefore, some authors employ system dynamics to incorporate it into the regional IM model [145].

At the global level, analyses of phosphorus flows and their environmental impacts have been conducted [146]. They use the SFA and a metabolic pathway model to study these flows. They identify impacts such as mineral reserve conservation, soil erosion, fertility degradation, animal waste management, the use of wastewater and detergents, and eutrophication. Other studies propose a macro-model of phosphorus IM based on the CE [147]. SFA and economic, resource use efficiency, and eco-efficiency indicators are considered. In this line, other research develops an IM model that integrates the economic perspective and industrial ecology, based on MFA, input–output analysis, and LCA to model fixed capital stocks within a common framework [148], and others are based on emergy analysis [149].

Regarding the different approaches for quantifying metabolism, Daniels and Moore provide a comparison of various methods. They compare methods and techniques such as MFA, input–output analysis, SFA, ecological footprint analysis, environmental space, material intensity per unit of service, LCA, process sustainability index, and MFA [150]. Among them, MFA stands out as the most suitable for quantifying metabolism at both the micro and macro levels [150]. However, suitability depends on the objective, system boundaries, and its incorporation into a framework that allows for evaluating the goodness of the system. In addition, Sankey diagrams are identified as a useful tool for visualizing IM [151].

Regarding eco-efficiency [152], IM seeks to combine the prudent use of natural resources with economic efficiency to reduce their consumption [153,154]. It is considered a practical and suitable tool for measuring progress toward sustainable development [155]. Some authors define three indices of eco-efficiency for specific cases: resource use efficiency, energy efficiency, and environmental efficiency [156].

Within IM, the main drivers of unsustainable resource use are identified in different sectors [157]. These drivers include the categories of informational behavior, policy and regulatory framework, socio-economic, technological, and infrastructure. Some research delves into the analysis and characterization of endosomatic and exosomatic metabolism [158], linked to complex systems theory [159]. These studies propose controlling the import of advanced products and technology, as well as regulating product export [160], using thermoeconomics [161], and exosomatic metabolism indicators [162]. For endosomatic societal metabolism, the aim is to reduce primary industries, develop industries with high production efficiency, and scale up recycling industries [163].

4. Bioinspired Characterization of Industrial Metabolism

IM is characterized from a biomimetic perspective, emphasizing trophic network analysis. This analysis enables evaluating and managing metabolic pathways for cyclicality, efficiency, toxicity, and resilience, derived from knowledge of the food chain, key products, and companies. The cyclicality of resources through the industrial manufacturing system is achieved through the establishment of metabolic pathways. First, resource cycles are classified based on whether the nutrients belong to biological or technical cycles. Secondly, these metabolic pathways are divided into two main processes: anabolism (or synthesis) and catabolism (or degradation). Finally, both processes will determine the structure of the metabolic pathways, differentiating them as convergent or divergent. The efficiency of metabolism aims to maximize the use of resources and is highly dependent on the associated production process that transforms the resource. From an energy perspective, CE aims to work towards energy use based on renewable sources, made possible by the reduced energy requirements of a restorative CE [164]. A more integrated system allows for a reduction in the use of fossil fuels and an increase in the performance of by-products, which, once their cascade processes are completed, enhance their energy value in decomposition processes and reintegrate into biogeochemical cycles. Viewing the industrial manufacturing system as a living organism, toxicity within the metabolism is influenced by substance properties, dose, and the incorporation of toxic chemicals into products or manufacturing processes through various pathways. This significantly influences their toxicological consequences and pathway predominance. The toxicity perspective encompasses SFA, LCA for human and ecotoxicity, substance analysis from Cradle to Cradle (C2C) [13], and bioinspired/biomimetic design. This underscores the critical need to use toxicity indicators for a thorough assessment and mitigation of the environmental impacts associated with substances [165]. Likewise, the resilience of industrial metabolism refers to its ability to withstand, adapt, and recover from disturbances and changes in the environment.

Figure 1 structures the features of IM based on the review conducted. It establishes relationships that enable modeling IM in a generic manner, allowing for the customization of various aspects depending on the level of observation considered for modeling. Thus, two fundamental aspects of modeling emerge: the habitat and trophic networks. These aspects facilitate the modeling and characterization of industries, their specific relationships, and the features of material pathways (technical and biological nutrients) in terms of cyclicality, efficiency, and toxicity. Additionally, they contribute to understanding the resilience of the industrial network. This characterization is in line with and contributes to the development of the four fundamental objectives of CE [166]: (a) as a regenerative and restorative economic framework; (b) decoupling economic growth from environmental degradation; and (c) seeking to preserve economic, social, and environmental value while (d) contributing to the resilience of the system.

Based on the conducted research, a series of requirements are identified as innovation opportunities that should be incorporated into IM, enabling this approach to be feasible and implementable in sustainable manufacturing systems:

1. *Integration of biomimetic approaches*: Nature-inspired strategies for efficient and sustainable industrial systems.
2. *Industrial trophic network analysis*: Optimizing material and energy flows in the industrial supply chain.
3. *CE focus*: Minimizing waste and maximizing resource value throughout the product life cycle.
4. *Efficiency and cyclicality of processes*: Enhancing resource consumption and material reuse in manufacturing.
5. *Toxicity management*: Safeguarding human health and the environment through sustainable material choices.
6. *Territorial contextualization*: Contextual adaptation; tailoring strategies to local conditions for resource optimization and impact reduction.

7. *Continuous evaluation and monitoring*: Monitoring performance to drive improvement in environmental, social, and economic aspects.

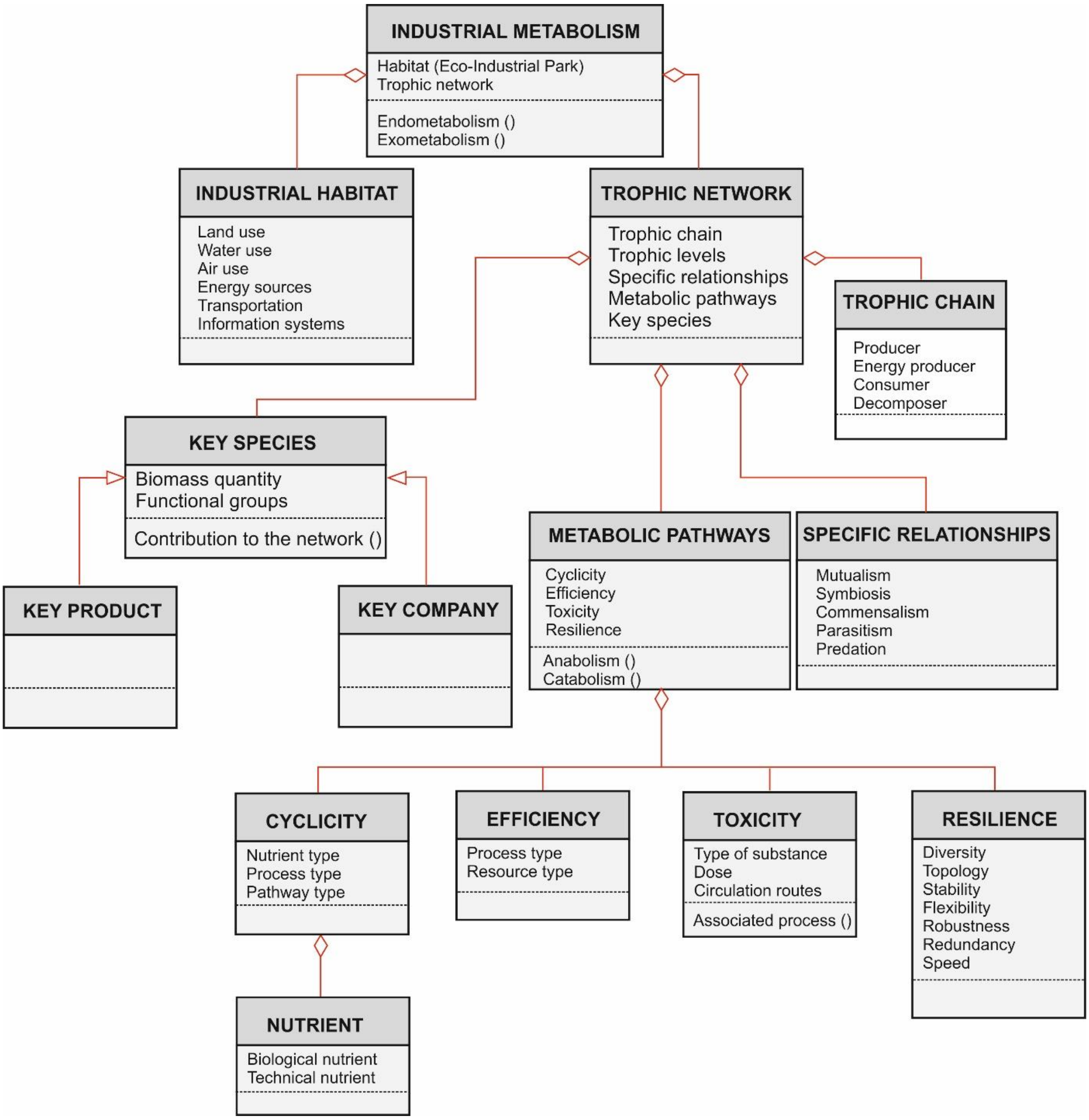

Figure 1. Bioinspired characterization of Industrial Metabolism.

Incorporating these requirements, at both the physical and virtual levels, and innovation opportunities into IM for CE will contribute to the transition towards more sustainable, efficient, and resilient manufacturing systems that promote resource conservation and sustainable development.

The approach to IM from a biomimetic perspective, inspired by natural ecosystems, allows for the structured development of CE for IM based on an operational approach at micro, meso, and macro levels. Figure 2 aims to illustrate, by way of example, how the characterized approaches to IM can be structured at different levels. In this context, the most suitable frameworks for the circularity of manufacturing systems at various levels are identified (Figure 2), as analyzed in previous studies [167]. The following describes each of these three levels and identifies some of the aspects that contribute to IM:

- *Micro Level*: At the micro level, the focus is on the manufacturing company itself, aiming to improve eco-efficiency through clean production practices and frameworks aligned with the product metabolism and manufacturing process in the context of a CE. The company seeks to optimize resource utilization, minimize waste generation, and enhance environmental performance within its own operations.
- *Meso Level*: Industrial ecology at the meso level fosters collaborative networks between companies and communities to optimize resource use, enhance energy and water management, and create symbiotic relationships based on the industrial food chain. This approach promotes sustainability, resilience, and reduced environmental impacts within the industrial ecosystem.
- *Macro Level*: The macro level aims to restructure regional or national industrial systems for circularity, efficiency, and sustainability. It involves analyzing import/export flows, identifying externalities in other economies, and implementing policies, regulatory frameworks, and strategic planning to support the transition to a circular economy, considering economic, social, and environmental factors.

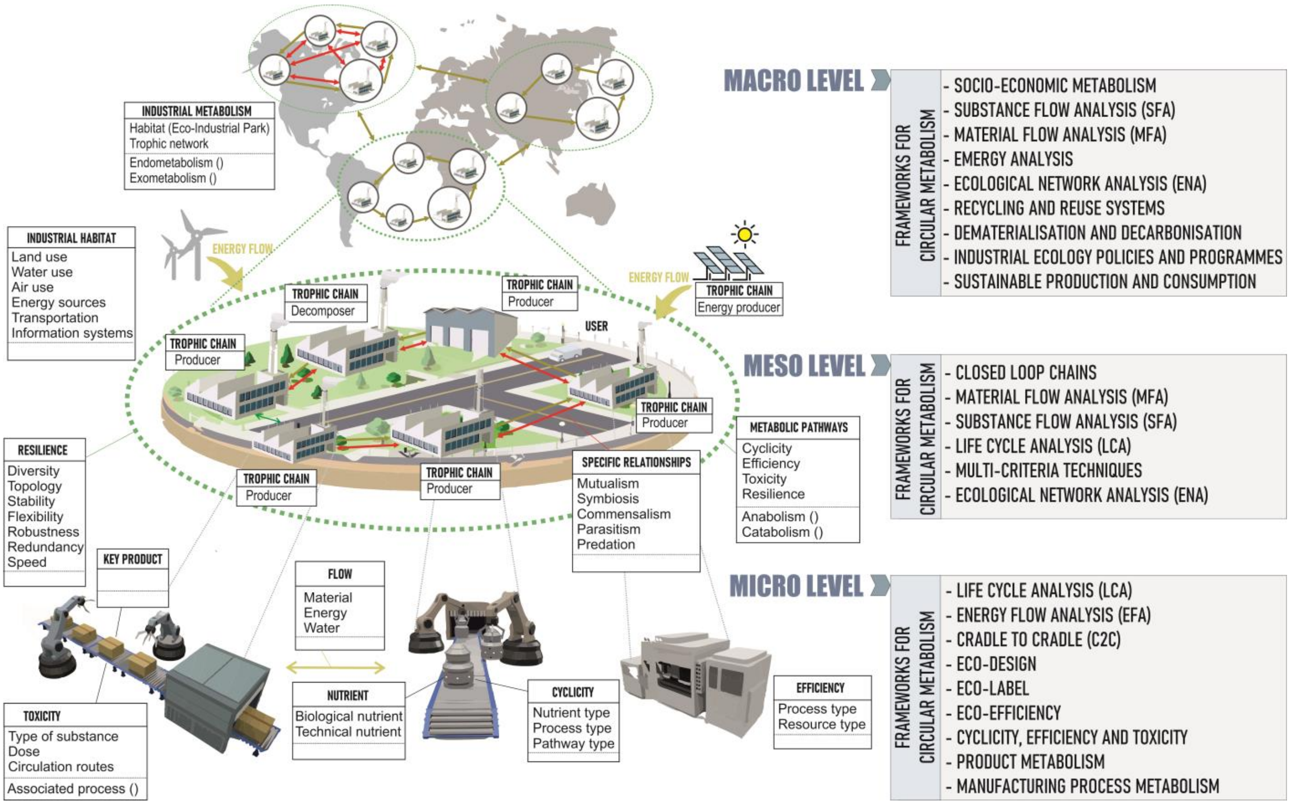

Figure 2. Multilevel characterization of industrial metabolism for design for circularity in manufacturing systems.

The IM approach addresses the micro, meso, and macro levels, promoting a holistic transformation towards circular and sustainable manufacturing systems.

5. Conclusions

The analysis provides an updated understanding of the IM concept and its applications in manufacturing system modeling. Studies focus on different observation levels (micro, meso, and macro), employing approaches such as the establishment of metabolic pathways at the micro and meso levels and material balance analysis at the macro level. The methods employed highlight the use of SFA for specific elements and MFA for global or aggregated analysis, with a lack of studies integrating the triple environmental, social, and economic perspective. The research emphasizes that each level of IM observation has its own characteristics and study approaches, and together they provide a more comprehensive understanding of IM and its implications. The combination of these levels can contribute to the design of more effective strategies and policies to promote sustainability and efficiency in the industrial realm. Furthermore, the suggested design approach plays a crucial role in fostering the conception and modeling of bioinspired manufacturing systems, deeply anchored in the IM concept. This framework facilitates a unified perspective across diverse levels of approximation, contingent upon specific cases, all under an integrated vision. It not only identifies pertinent natural analogies crucial for designing manufacturing systems but also serves as a unifying structure that consolidates the study domain of IM. This is particularly noteworthy as, historically, the study of IM has often been approached in a fragmented manner, focusing on specific levels and characteristics.

Furthermore, it has been identified that the common methodology for modeling and metabolic analysis of an EIP consists of the following: (1) establishing and defining the system/model boundaries; (2) identifying and grouping types of industries based on interspecies relationships criteria; (3) determining their position in the supply chain; (4) relationship with the process of the analyzed element; (5) identifying and quantifying inputs and outputs of each entity in the system; (6) employing a methodology for quantifying flows; and (7) choosing indicators for assessing the determined metabolism and subsequent decision-making.

In terms of model evaluation, five environmental sustainability indicators integrating industrial ecology principles for circular metabolism have been identified. These indicators mainly consider the following: (1) resource renewability; (2) emission toxicity; (3) input of used materials; (4) product recoverability at the end of use; and (5) process efficiency.

The analyzed contributions focus on the IM of specific substances, delineating their metabolic pathways in the system. Most publications concentrate on the environmental dimension, with some economic considerations. Categorization and evaluation of cyclicality and efficiency are emphasized, while studies addressing toxicity are less common. There is a significant lack of publications that comprehensively integrate the environmental, economic, and social dimensions, using recognized methods to evaluate different parameters.

Regarding the limits of the analogy, the concept of IM is applicable to manufacturing systems and companies, with the company serving as the economic analogy of a living organism. Although interesting differences exist, such as companies producing products or services and their ability to quickly change products or businesses, organisms are highly specialized and require long periods of evolution to alter their behavior.

For future research, exploring successful analogies between industrial metabolism and natural systems in manufacturing practices could offer practical insights. Additionally, investigating challenges and opportunities in applying metabolic concepts to industrial ecosystems, considering human-made complexities and social factors, is a promising area for further study.

Finally, IM presents opportunities for innovation through connectivity, integration, adaptation, and management, with the aim of mitigating and reversing the metabolic rift caused by linear manufacturing systems. For future work, the establishment of a control layer to guide metabolic pathways towards greater efficiency, safety, and circularity of flows is highlighted.

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