Industrial Ecology

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A Fusion of Material and Energy in Green Supply Chain Context

Springer

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Industrial ecology and circular economy is a peer-reviewed book series that focuses on different disciplinary approaches to waste management, sustainable practices & strategies on different scientific, societal, pyschological, technological, economic, governance, and cultural and political aspects of the ongoing and emerging debate. This primary goal of this series is to offer scientists from different school of thoughts and institutions a platform for scientific analysis and debate.

Undeniably, Industrial ecology is a rapidly growing field that systematically examines local, regional and global materials and energy uses and flows in products, processes, industrial sectors and economies. It focuses on the potential role of industry in reducing environmental burdens throughout the product life cycle from the extraction of raw materials, to the production of goods, to the use of those goods and to the management of the resulting wastes. Industrial ecology is ecological in that it (1) places human activity—industry in the very broadest sense—in the larger context of the biophysical environment from which we obtain resources and into which we place our wastes, and (2) looks to the natural world for models of highly efficient use of resources, energy and byproducts. By selectively applying these models, the environmental performance of industry can be improved. Industrial ecology sees corporate entities as key players in the protection of the environment, particularly where technological innovation is an avenue for environmental improvement. As repositories of technological expertise in our society, corporations provide crucial leverage in attacking environmental problems through product and process design.

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Dedicated to the late Mr. Shahjehan Syed Kareem, visionary founder and President of Instítiute of Business Management, and to my beloved family

Dr. Adeel Shah

Preface

In an interconnected world where goods traverse continents, and production processes span borders, sustainability has become paramount. The intricate dance between industry, environment, and society necessitates a holistic approach—one that transcends traditional silos and embraces a systems perspective. Welcome to the world of Industrial Ecology. A discipline that seeks harmony between human activities and the natural world. This book delves into the heart of industrial processes, supply chains, and their impact on our planet in the era of post-COVID-19. It invites you to explore the intricate relationships that bind production, consumption, waste, and regeneration. As we embark on this journey, we will unravel the threads that weave together industrial systems, ecosystems, and human well-being. From raw material extraction to product design, manufacturing to distribution, and end-of-life disposal to circular economy solutions, each thread contributes to the fabric of our global supply chain and production ecosystem.

The book aims at readers of university students and professionals. The manuscript focuses on educating about the basic principles of industrial ecology and its impact on organizational performance and society. Reading the book allowed the audience to rationalize and select critical first steps to illustrate better strategies. We use quantitative studies and empirically test them to bring meaning to the whole concept of industrial ecology. The book aims to bridge the gap between equivocal and thorough understanding of the subject matter. Besides designing the book to be a stepping stone in the science of industrial ecology, we hope our audience can understand the challenges in the post-COVID-19 era.

The chapters educate the readers to embrace a system's perspective and recognize that every action has repercussions. Thus, it enables an understanding of optimizing resource use, minimizing waste, and creating closed-loop systems wherever possible. We will delve into the life cycle of products, assessing their environmental impact from the cradle to the grave and the hidden costs embedded in our everyday items while educating new sustainable strategies that businesses of the future would implement, like cradle to cradle in developing their product and services. The whole concept of industrial ecology thrives on collaboration between stakeholders and transitional stages. We shed light to educate businesses, policymakers, and communities working together to create regenerative systems. Resilience and adaptability are also important features for businesses; thus, climate change and its impact causing disruptions of the value chain also looms and should be considered for supply chain adaptation and how industrial symbiosis can play an essential role in creating resilience.

Our effort is not to design or produce an academic exercise, but it is a call to action. Whether you are a student, a practitioner, or a concerned citizen, you hold a thread in this intricate tapestry. Let us weave a future where industry and ecology dance in harmony—a future where supply chains nourish rather than deplete.

No particular background knowledge is required to read the book; anyone with basic English language skills can easily understand the main crux. We have used the spiral learning technique to impregnate the whole concept of industrial ecology to the book's reader. A few chapters where the empirical study is used to provide logical solid backing would require external online help to understand the analysis and discussions of the results. However, the concepts in each chapter are easily relatable to different industries, thus providing coherence and clear understanding. The book introduces industrial ecology to expose the readers to definitions from known authors, providing history and its relation with United Nations sustainability goals (UN SGDs) and green supply chain while commenting on the post-COVID-19 era. In Chap. 1. Chapter 2 introduces the current practices, methods, and tools used in industrial ecology. Chapter 3 provides an overview and implementation of industrial ecology applications by studying organizations from developing countries' manufacturing and services industries.

Chapter 4 builds an understanding of the importance of the digital supply chain, while case studies from the Pharma and healthcare industry are brought forward for experiential learning in Chaps. 5 and 6. The Reduce, Reuse, and Recycle (3Rs) are explained in Chap. 7, along with understanding organizational intention to use the whole concept as sustainable development by testing a hypothesis in a quantitative study under Chap. 8. Social economic benefits derived from industrial ecology are brought forward in Chap. 9, and the same is discussed with the help of exploratory research conducted in Chap. 10 to understand the actual social, economic benefits derived in the textile industry, which is the most established sector globally with product consumption by people in all seven continents.

Chapter 11 touches on the most important topic under the limelight, climate change and its relation with industrial ecology; a case study is brought forward from a sourcing company looking for sourcing options in future to prepare a supplier selection strategy in the best suited location. Moving forward, Chap. 12 in the book discusses industrial ecology in the food supply chain and makes themes to improve industrial ecology advancements through industrial experts. Finally, the book's closure starts with Chap. 13, which discusses the impact of COVID-19 on industrial ecology. The topic is understood by put forward the case from an automated industry. Finally, Chap. 14 concludes the book by addressing the challenges of industrial ecology in the current manufacturing sector.

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Contents

Abbreviations

A&F	Abercrombie and Fitch
AAB	American Association of Blood Banking
AGVs	Automated Guided Vehicles
AI	Artificial Intelligence
AMRs	Autonomous Mobile Robots
APICS	Association for Supply Chain Management
APIs	Application Programming Interfaces
APS	Advance Planning and Scheduling
AR	Augmented Reality
ASCM	Association for Supply Chain Management
AVE	Average Variance Extracted
BDA	Big Data Analytics
BI	Business Intelligence
BIPOC	Black, Indigenous, and People of Color
BPCS	Business Planning and Control System
BYOB	Bring Your Shopping Bag
C2C	Cradle to Cradle
CAIC	Computer Numerical Control
CAP	College of American Pathologists
CCS	Carbon Capture and Storage
CDMOs	Contract Manufacturing and Development Organizations
CDP	Carbon Disclosure Project
CE	Circular Economy
COVAX	COVID-19 Vaccines Global Access
CPFR	Collaboration Planning, Forecasting, and Restocking
CPS	Cyber-Physical Systems
CRCP	Climate Risk Country Profile
CRM	Customer Relationship Management
CSC	Circular Supply Chain
CSCP	Certified Supply Chain Professional
CSR	Corporate Social Responsibility

CTP	Conformance to Plan
CTRP	Conformance to Release Plan
CTS	Conformance to Supply
DC	Distribution Center
D-EMRP	Domestic Manufacturing Enterprise Resource Planning
EIP	Eco-Industrial Parks
EOQ	Economic Order Quantity
EPA	Environmental Protection Agency
EQAS	External Quality Assurance System
ERP	Enterprise Resource Planning
ESG	Economic, Social, and Governance
ETAs	Estimated Time of Arrival
ETP	Effluent Treatment Plant
EUETS	European Union Emissions Trading System
Evs	Electric Vehicle
FDA	Food and Drug Administration
FEA	Finite Element Analysis
FSC	Forest Stewardship Council
GBG	Green Banking Guidelines
GDP	Gross Domestic Product
GHG	Green House Gas
GMP	Good Manufacturing Practices
GOP	Government of Pakistan
GPN	Green Purchasing Network
GPP	Green Public Procurement
GPS	Global Positioning System
GRI	Global Reporting Initiative
GSCM	Green Supply Chain Management
GTFS	Green Technology Financing Scheme
HEIs	Higher Education Institutions
HR	Human Resource
HYVs	High Yielding Varieties
ICT	Information and Communication Technologies
IE	Industrial Ecology
ILO	International Labor Organization
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPOs	Initial Public Offerings
IPS	Indoor Positioning Systems
IR 4.0	Industrial Revolution 4.0
IS	Industrial Symbiosis
ISBT	International Society of Blood Transfusion
ISRI	Institute of Scrap Recycling Industry
IT	Information Technology
ITA	International Trade Administration

JIT	Just in Time
KPIs	Key Performance Indications
LCA	Life Cycle Assessment
LCM	Life Cycle Management
LEED	Leadership in Energy and Environmental Design
MENGO	Malaysian Environmental NGOs
MES	Manufacturing Execution System
MFA	Material Flow Analysis
MIT	Massachusetts Institute of Technology
ML	Machine Learning
MPMA	Malaysian Plastics Manufactures Association
MSC	Marine Stewardship Council
MS-DOS	Microsoft Disk Operating System
NGO	Non-Profit Organizations
OEE	Overall Equipment Effectiveness
OEKO-TEX	Textiles Testing for Harmful Substances
OEMs	Original Equipment Manufacturers
ORION	On-Board Integrated Optimization and Navigation
PC	Personal Computer
PDA	Personal Digital Assistant
PEPA's	Pakistan-Environmental-Protection-Act 1997
PET	Polyethylene Terephthalate
PI	Pharmaceutical Industry
PLS	Partial Least Square
PLS-SEM	Partial Least Square Structural Equation Modeling
PPEs	Personal Protective Equipments
PPP	Profit People and Plant
PV	Photovoltaic System
QR Code	Quick Response Code
R&D	Research and Development
RFID	Radio Frequency Identification
RFQs	Request of Quotations
RH	Relative Humidity
RLNG	Regasified Liquefied Natural Gas
ROHS	Restriction of Hazardous Substance
ROI	Return on Investment
SAC	Public Private Partnership
SAFE	Coffee and Farmer Equity
SAP	Systems, Applications, and Products in Data Processing
SBP	The State Bank of Pakistan
SBTI	Science-Based Target Initiative
SC	Supply Chain
SCM	Supply Chain Management
SCS	Supply Chain Sustainability
SDGs	Sustainable Development Goals

SFI	Star Fades International
SME	Small and Medium Size Firms
SMS	Short Message Service
SOPs	Standard Operating Procedures
SSCF	Sustainable Supply Chain Foundation
SSCM	Sustainable Supply Chain Management
TBL	Triple Bottom Line
TIF	Thalassemia International Federation
TMS	Transportation Management System
UKM	Universiti Kebangsaan Malaysia
UN SDG	United Nations Sustainable Development Goals
UN	United Nations
UNEP	United Nations Environment Program
UNIDO	United Nations Industrial Development Organization
UNISDR	United Nations Office of Disaster Risk Reduction
USGBC	United States Green Building Council
VF	Vanity Fair Mills
VIF	Variance Inflation Factor
VMI	Venders Managed Inventory
VOC	Volatile Organic Compound
WEEE	Waste Electrical and Electronic Equipment
WFG	World Federation of Hemophilia
WHO	World Health Organization
WWF	World Wildlife Fund

Chapter 1
Introduction to Industrial Ecology

The 21st Century's most significant threat to planet Earth is humanity's industrial revolution, which caused drastic climate change that affects current and future generations. Besides humankind, other branches of bio-organisms are at risk of extinction, too. Recently, policymakers have been captivated by the potential ramifications of climate change and other environmental concerns on economies and communities, owing to the indisputable significance of these matters. Due to regulations and consumer awareness, organizations are increasingly pressured to do business sustainably. There is an emphasis on sustainability and the necessity to better the flow of material and energy in the industrial ecosystem to meet the economic, social, and legal concerns of all stakeholders (investors, customers, policymakers, and the general public). Many organizations are ignorant of industrial ecology to achieve sustainability and desire to increase profits at the cost of the environment, which has specifically caused global warming and changes in biodiversity.

1.1 Introduction

IE has been the focus of the past few years, but a lot is still to be researched in the context of economics (Yu & Zhang, 2021) and resilience (Kendall & Spang, 2020). Recently, there has been considerable focus on climate change and other environmental concerns, which policymakers find intriguing due to the potential ramifications for economies and populations. Organizations are under more and more pressure to do business sustainably in both developed and developing economies. For organizations to be sustainable, Industrial Ecology (IE) can significantly help businesses by preventing wastages that impact the environment, thus preventing or slowing climate change (Awan, 2022) and reversing all the ill effects. The existing literature provides many definitions of IE, and an important one is brought forward

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by Jelinski et al. (1992) to suggest that it is a new manufacturing concept that efficiently supplies material for achieving sustainability. The nebulous explanations and definitions of the subject make it difficult to differentiate between IE and sustainability (Hicks, 2022). To better understand the concept of IE, Table 1.1 illustrates a set of definitions by different authors over the past years.

In pursuit of understanding, we can divide IE into three phases;

1. It investigates how the parts and pieces of industrial and natural systems interact.
2. To introduce fundamental ideas as practical approaches for material and energy flows for industrial metabolism.
3. Providing policy to create a roadmap for sustainable development.

The IE is coupled with sustainable supply chain methodologies to improve performance. The efforts for IE to achieve sustainability in recorded history started in the 18th Century in a German company for the continuity of their business related to woods and forests. Sustainability deviates from the noun "sustenance," which means "which one retains." As mentioned earlier, the term sustainability was used for the first time in the 18th Century by German Hans Carl von Carlowitz in his book Silvicultura Economic (Spindler, 2013). According to Schmithüsen (2013), the sustainability concept was first developed in central Europe to conserve forestry. In the 1330s, it was mentioned in common law for Germany that woodcutting should be moderate and should not impact the perpetuity of this industry. This was done through different principles, like trees with fruits should not be cut, and forests near the villages and towns should be there to provide shade to the people and animals. Trees will be planted and should be protected from the al grazing to sustain themselves. In France, this term was used in the Ordonnance de Brunoy, which was related to waterways and forests.

Table 1.1 Definitions of industrial ecology

Authors	Definitions
Frosch and Gallopoulos, (1989)	'Transformation of conventional production activities of value-adding raw material to produce finished goods and discard waste, to an integrated production ecosystem: an industrial ecosystem similar to biological ecosystems'
Graedel (1996)	'A systematic study to understand the collaboration of human activities and the environment. In the context of industrial application, industrial ecology pursues improving the flow and consumption of virgin material to produce a final product and dispose of waste during the process'
Korhonen (2000)	'Commonly defined as management of material in manufacturing, also focusing on flow material and energy extracted by the enterprise and co-partners. It also focuses on the waste and emissions produced during the process and its environmental impact
Allenby (2006)	'A multifaceted discourse that pursues to comprehend evolving behavior of human and natural systems and its complications'
Vujanović et al. (2022)	'An organic industrial system which imitates a biological system'

Further, historical evidence is brought forward that, in 1346, King Philippe V made a law that the owners of rivers and forests would make arrangements for the waterways and forests to be sustained in perpetuity. A book entitled Sylva: A Discourse of Forest Trees and the Propagation of Timber in His Majesty's Dominions was published by John Evelyn in 1664 and presented to the King, the royal society, and the general public in Britain. This was reprinted many times in the 17th Century to encourage the planting of trees (Schmithüsen, 2013). Spindler (2013) suggests that the book published by the Royal Society in 1664 was on the conservation, growing, and use of wood in perpetuity. The book advises enterprises to cut the forest to the extent they can regrow through planned forestation projects to sustain this industry; in the true sense, it related to the understanding of sustainability, which means that resources are used to satisfy current needs in such a way that future needs can be met without any compromise.

However, IE became popular research (Frosch & Gallopoulos, 1989). The concept has been evolving since the 20th Century; according to Erkman (2001), in the 1950s, there was a concept named "end of pipe," which was to clean or treat your waste at the end of the process. Though a good step, it is not sufficient for the current global issues due to the existence of industries in the ecosystem. To overcome the problem, IE tries to resolve the issues of humans and the environment to minimize ill actions on the ecosystem and to control industrial global problems.

The environmental hazards caused by the Industrial Revolution are global. To correct the trajectory of growth and industrial development (United Nations, 2023) has proposed seventeen sustainable development goals that need to be achieved by all signatory nations. In developed countries, laws are stringent and are correctly implemented, unlike in developing countries.

1.2 History of Industrial Ecology

Industry ecology (IE) is a pragmatic approach to sustainability. An investigation into the correlation between physical surroundings and living organisms is called ecology. IE is the set of tools, perspectives, and principles taken from the concept of ecology, and it analyses the industrial impact on the people surrounding it and the environment. IE gives the perspective of process optimization. Initial work was done only on the material flow of the system, but currently, only energy flow is also being focused on (Lowenthal & Kastenberg, 1998).

According to Erkman (2001), industrial ecology was initially considered an oxymoron, which means industry and ecology were considered as there is no relationship between them. These are proposed to each other like bittersweet is an oxymoron. In the 1950s, a concept named "end of pipe" was developed after awareness of environmental pollution caused by the industry. According to this concept, companies started treating their waste streams to reduce or control the pollution caused by their processes. This was the start of realizing that the industrial process impacts the environment and the surrounding biosphere. Industrial ecology refers to all human activities at manufacturing sites, hotels, and other service industries. Industrial Ecology is an effort to address the question, "How can the concept of sustainable development be made operational in an economically feasible way" (Erkman, 2001). IE emerged after it was evident that the end-of-pipe concept is inadequate to solve the environmental problem and will be expensive in the long run. There are three perspectives regarding IE on which more or less all researchers agree and are as follows:

A. It encompasses a thorough, methodical, and cohesive examination of the interconnections among every element of the industrial economy and the biosphere in which it operates.
B. It correlates with the biophysical foundation of human activities.
C. It examines technological dynamics, specifically the evolution of clusters of critical technologies over an extended period. It is an essential component in facilitating the shift from the present unsustainable industrial system to a sustainable industrial ecosystem in the future.

IE looks at the industrial system with complete focus. It does not only talk about pollution and environmental issues but also the technology economy and other issues involved in managing a business. It talks about the optimum usage of scarce resources. Different authors frequently used The term Industrial ecology after the 1970s literature. This expression resurfaced at the beginning of the 1990s, initially in a group of industrial engineers connected with the National Academy of Engineering in the US. There was a practice to write on a particular topic every September. In 1989, the special issue on which they wrote was "Managing Planet Earth." In this issue, Robert Frosch and Nicholas Gallopoulos, engineers at General Motors, wrote on "Strategies for manufacturing." This focus was on the idea that production systems can be designed that may have less impact on the environment than the current processes; this led them to the term industrial ecosystem. They thought the human population was growing exponentially; conversely, the natural resources were depleted due to high consumption. So, the process should be designed so that the products to be sold and used should be maximum, and waste should be minimized. In 1994, White introduced the idea that, as in IE, we study the flow of energy and material in the industrial sector, and this should also involve the impact of consumer activities (Allenby & Richards, 1994). The International Society for Industrial Ecology was established in the early 21st Century (2001), and the Journal of Industrial Ecology (MIT Press) was established in 1997.

IE is an emerging concept that deals with environmentally sound manufacturing and material and energy consumption. This is due to the limited resources available, and wastes should be in a quantity that the environment can bear without affecting future needs (Van Berkel et al., 1997). In 2006, according to Allenby (2006), IE was a system-based approach that was a multidisciplinary concept to understand the human-natural system interaction.

Industrial metabolism was established in 1988 and is a fundamental concept in IE. It relates to the impact of human activity on the environment and the utilization of natural resources. IS, or Industrial Symbiosis is the lifeblood of the IE discipline. Its inception can be traced back to biological principles and the established symbiotic relationships observed in nature, wherein two or more inconsequential classes of living organisms exchange substances, energy, or data for the benefit of all (Saavedra et al., 2018).

Four challenges in the IE framework need to be addressed.

1. Systematic use of waste and by-products of the process
2. Minimize the loss caused by the dispersion of fertilizers and pesticides
3. Reduce the material flow in the process and increase the efficiency
4. Reduce or avoid the use of hydrocarbon fuels in the system

Coastal cities have more population than non-coastal cities. This is because these provide the gateway to other countries and act as nodes in the international supply chain. Most industries exist in these cities, and urbanization near these plants is meant to provide job opportunities. Plants near the ports are primarily refineries, chemical plants, coal processing facilities, and renewable energy sources. These industrial hubs produce 25% of the world's primary production. So, implementing IE in these cities is more critical as these industrial areas have most of the material and energy and produce most of the waste (Cerceau et al., 2014).

The industrial revolution has increased pollution, and the cost of disposal through incineration disposals in landfills is too much and involves natural resources, so it is not entirely sustainable. Industrial ecology states that one industry's waste should be used by another, which will own the utilization of natural resources and eliminate the cost of disposing of the trash. Eco-industrial parks (EIP) have been developed to work on this phenomenon and reduce waste generation. EIP is an actual practical approach to the application of industrial ecology. The most well-known is in Denmark Kalundborg. This concept was built in the 1960s but was not developed with it then. Now, a benchmark for all over the world to compare the EIPs. This included refineries, pharmaceutical companies, and power plants. Another idea in the name of the environmentally balanced industrial complex uses similar industries that can use each other's wastes and raw materials, which saves the storage and transportation of waste/raw material, which also requires natural resources.

Previously, there was an approach called "cradle to grave," which meant that every material produced had a limited life and was disposed of as waste. Companies are working on "built-in obsolescence," meaning they design their products so they must waste some time selling a new version to the same customer. Then McDonough and Braungart proposed a concept named "cradle to cradle," which states that products should be patterned to allow their material to be reused infinitely. That is a sustainable approach. The product flow based on the cradle-to-cradle approach is shown in Fig. 1.1 for easy understanding.

Industrial ecology somewhat talks about the cyclic flow of materials, not the linear approach like cradle to grave. In 2001 the International Society for Industrial Ecology was established at Yale University. In 2018, this society was registered as a nonprofit organization in the Netherlands. They started the Journal of Industrial Ecology. In

Fig. 1.1 Cradle to cradle approach (McDonough & Braungart, 2010)

2003, the first Ph.D. was offered in industrial ecology, and then after two years, it was taught in the master's program as well (ISIE, 2022).

1.3 The Intriguing World of Industrial Ecology

IE is a subfield of sustainable research that evaluates the stages of service and product production from the standpoint of the natural world, intending to imitate a natural system through resource conservation and reuse. Industrial ecology is relatively new and challenging for engineers, scientists, and policymakers. Frosch and Gallo Poulos' 1989 Scientific American article "Strategies for Manufacturing" gave rise to the contemporary discipline of IE, also known as the "science of sustainability." On the other hand, historical allusions to IE extend back to the early 1970s. Industrial ecology is interdisciplinary, making offering a clear and widely acknowledged description challenging.

The biological comparison, the application of systems views, the importance of technological progress, the involvement of businesses, eco-efficiency and dematerialization, and forward-looking research and practice are some of the fundamental components that define this phenomenon, i.e., Industrial Ecology. There are several analytical techniques and resources available for each of these sub-topics. The most significant characteristics and costs of the fundamental elements—particularly those that are pertinent to bio-degradable and sustainable energy—are covered in the subject (Hariyani & Mishra, 2021).

IE is the study of the systemic interactions that occur between the environment, economy, and society. The approach underscores the utilization of technology to

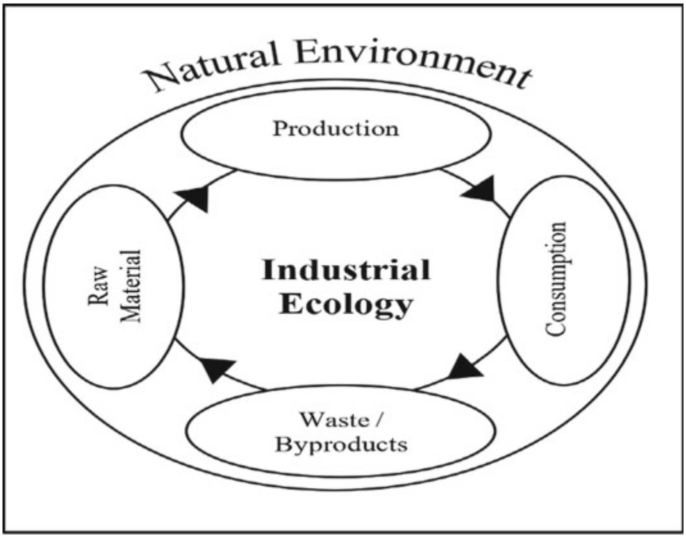

Fig. 1.2 The basic concept of industrial ecology (Celik, 2013)

lessen adverse environmental impacts and find the right balance between ecological stewardship and human advancement while recognizing the significance of socioeconomic factors in pursuing these objectives. The examination of industrial ecology often involves the assessment of resource utilization, recycling, and exchange with the environment (via extraction and emissions) (Al-Thani & Al-Ansari, 2021). These assessments focus on various scales and levels, encompassing municipalities, eco-industrial zones, nations, and the worldwide economy. Originating from the notion that ecosystems and economic systems (including production processes) are comparable is the term "industrial ecology." Industrial ecology incorporates many ecological concepts, including but not limited to the cycles of matter and energy, highly adaptable systems, and environmental networks (Fig. 1.2) (Bruel et al., 2019).

Industrial ecology has advanced since its inception thanks to the creation of databases, more complex mathematical modeling, cooperation between natural, physical, and social scientists, and the expansion of theory independently and in conversation with other related subjects. Meanwhile, industrial ecology significantly impacts environmental management and policy, offering insights on various topics, including climate change, biodiversity loss, water, and more. Despite its young, breadth, and interdisciplinary nature, industrial ecology may claim several subfields within its purview.

1.4 Importance of Industrial Ecology

IE results from cleaner manufacturing, eco-industrial parks, and life cycle analysis. Given the ongoing economic, cultural, and technical progress, IE represents a deliberate and logical approach humanity can adopt to achieve and sustain sustainability. The concept advocates for the collaborative evaluation of an industrial ecosystem alongside its adjacent systems instead of its isolated assessment. The objective is to maximize the efficiency of the entire materials cycle, encompassing raw materials, finished goods, components, finished products, obsolete products, and final disposal. It is imperative to optimize resources, energy, and capital, among other factors (Baumann & Lindkvist, 2022).

Understanding how industrial systems—such as a factory, eco-region, or national or international economy—interact with the biosphere is the goal of industrial ecology. An "ecosystem" built on resources and infrastructural capital rather than on natural capital, similar to how different components of industrial systems interact with one another, may be seen through the lens of natural ecosystems (Sun & Wang, 2021). It encourages sustainable design by capitalizing on the notion that waste does not exist in natural systems. Finding ways to reduce modern consumerism's ecological impact economically is crucial to developing sustainable solutions that protect future generations' resources (Sullivan et al., 2018).

One of Natural Capitalism's four goals is to protect industrial ecology. The other three are to save energy and materials and to rethink how linked international trade markets carefully and product stewardship interactions work as a service economy. This method stops people from buying things morally because they don't know what's happening far away (Singh & Basak, 2018). It also suggests a political economy that puts much value on natural capital and needs more educational capital to build and run each industrial ecosystem.

IE also studies societal concerns and how they relate to environmental and technological systems. Through this holistic viewpoint, IE acknowledges that different components cannot be regarded in isolation and that solving issues requires understanding the linkages between these systems (Belaud et al., 2019). Modifications made to one component of a more extensive system frequently spread to affect changes made to a different component. Therefore, you can only comprehend an issue if you consider its components in light of the total. Based on this concept, IE adopts a systematic thinking perspective when examining environmental challenges (Bahers et al., 2020).

As we already said, industrial ecology is an idea about the environment created by academics to help businesses better manage the environment. Industrial ecology tries to make environmental sustainability and industrial operations work together so that neither hurts the other. The cradle-to-cradle idea says that this method should be used to create manufacturing processes that reduce waste and harmful substances in materials. The "cradle-to-cradle" idea can be seen as building on the "industrial ecology" idea. L. W. Jelinski says that IE is "a new way of designing goods and processes for industry and using environmentally friendly ways to make things."

This concept says an industrial system should work with other systems instead of by itself (Lybæk et al., 2021).

1.5 Industrial Ecology and UN SDGs

The international community accepted the Sustainable Development Goals (SDGs), which address global difficulties in education, health, economic security, social equity and justice, and environmental concerns, in September 2015. The SDGs, which are a component of a larger 2030 Agenda that builds on the Millennium Development Goals established in 2000, were raised by the UN as a model for sustainable development on a worldwide scale. The Sustainable Development Goals (SDGs) entered force on January 1, 2016. Although they are not legally enforceable, they provide a way for nations to organize to reduce poverty, combat climate change, and ensure fair livelihoods for all individuals.

According to Rweyendela (2022), the 2030 Agenda proposes 169 targets for global transformation by 2030 in addition to 17 SDGs. Assuring sustainable utilization and production patterns is a requirement of the 12th SDG (United Nations 2023). Under this goal, the following targets are set: 12.2 (efficient use and sustainable management of natural resources), 12.3 (halving per capita global food waste at the consumer and retail levels and reducing food losses along supply chains), 12.4 (environmentally sound management of all wastes and chemicals throughout their life cycle), and 12.5 (reducing waste generation through prevention, reduction, recycling, and reusing). We must substantially reduce our environmental impact to meet them by rethinking how we produce and consume goods and resources to increase resource efficiency and decrease waste. Although significant efforts are being made to persuade governments to support the SDGs, and many are showing enthusiasm for doing so, application gaps still exist, and many countries are still figuring out their implementation strategies.

1.5.1 Five-Node Resource Nexus Approach

According to many experts, land should be included in a resource nexus approach because of its numerous vital environmental roles. Soil and other natural resource formation, as well as the production, management, and purification of water and the provision of resources for livelihood and development, all depend on the land.

Figures 1.3 show how land functions as an input into all other categories and how it is vitally linked to water. Land must be considered while defining appropriate nexus approaches for implementation purposes in SDGs 2 (Zero Hunger), 7 (Affordable and clean energy), 11 (Sustainable cities and communities), 13 (Climate action), and 15 (Life on land). Regarding land and food, functioning landscapes that offer water-based ecosystem services for agricultural output are crucial to the sustainability of food systems. The food system is necessary for achieving SDG 2, as it requires input