A WHITE PAPER ON

INDUSTRIAL ECOLOGY
IN THE INDIAN CONTEXT

Opportunities, Challenges, Policy and Strategic Pathways for Resource Efficiency

PREPARED BY

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JUNE 2026

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Foreword

India's industrial aspiration and its environmental commitments are not mutually exclusive but they are complementary and need to be designed. This conviction is at the core of the present White Paper and is the guiding philosophy of the Centre for Industrial Ecology and Circular Economy (CIECE) that CSIR-NEERI has set up to take forward this agenda at the national level.

The concept of industrial ecology is not new. It has intellectual roots spanning six decades of scientific research on the flows of materials and energy in human societies, and its techniques like material flow analysis, life cycle assessment, industrial symbiosis mapping and substance flow analysis, representing a sophisticated analytical tool with proven policy relevance. What is new is the sense of urgency with which India needs to approach this framework. A country that consumes more than thirteen billion tonnes of materials every year, produces more than sixty million tonnes of municipal solid waste, is experiencing acute water stress in over half its geographic area, and is aiming to double its GDP and become a net-zero country by 2070 simply cannot afford a linear industrial model. Economically and environmentally, it just can't be done.

For more than 60 years, CSIR-NEERI has been the country's leading applied environmental research institute. The creation of CIECE in this institution is a conscious and thoughtful step towards solutions rather than problem diagnosis, solutions based on industrial ecology science, solutions that are adapted to the institutional context of India, and solutions that are scalable for implementation. This White Paper is the most thorough statement of that agenda that our institution has ever made.

The shift to a circular, resource-efficient industrial economy is not an unattainable goal. This White Paper suggests that with the right institutional architecture, the right data infrastructure, and the right policy instruments, it is a national objective that is achievable within this decade.

(Dr. S. Venkata Mohan)

EXECUTIVE SUMMARY

India is at a critical juncture in its industrial and environmental journey. India's resource consumption and waste generation patterns are of global concern, as it is the fifth largest economy in the world, and its manufacturing sector accounts for around 17 per cent of Gross Domestic Product and provides jobs for more than 60 million people. The country's extraction, transformation and waste of materials occurs at a rate and volume that frequently strains the absorptive and regenerative capacity of natural ecosystems. Meanwhile, the economic value of discarded materials, underutilised industrial by-products and underutilised waste streams is a game-changer opportunity that is largely unexploited at the policy and institutional level.

Industrial Ecology (IE) offers precisely the scientific and analytical framework required to navigate this challenge. IE is a mature, interdisciplinary discipline that applies a systems perspective to the flows of materials and energy through industrial and societal systems, drawing on the metaphor of natural ecosystems in which the outputs of one organism become the inputs of another. Its core methods, including Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Industrial Symbiosis (IS) mapping, and Substance Flow Analysis (SFA), provide the empirical and normative architecture for transitioning India from a linear 'take-make-dispose' industrial model to a circular economy grounded in resource efficiency, closed material loops, and design-stage environmental intervention.

The White Paper document provides a detailed national framework for the development of industrial ecology in India. It is based on the scientific literature of the field, the experience of the Centre for Industrial Ecology and Circular Economy (CIECE) at CSIR-NEERI and is tailored to the policy, regulatory and industrial context of India. It is explicitly inspired by international precedents in Denmark, China, European Union and Japan and provides India-specific adaptation strategies that take into account the diversity of the industrial structure, the importance of the informal sector for material recovery and the need for inclusive and equitable growth.

The document is structured to address three interconnected imperatives. First, it builds the scientific and conceptual case for IE as an indispensable framework for India's transition to a circular economy, demonstrating how its methods can address the structural inefficiencies in India's industrial metabolism. Second, it critically analyses the existing policy and regulatory landscape, identifying gaps, overlaps, and opportunities for institutional innovation. Third, it proposes an actionable implementation roadmap, structured across short, medium, and long-term horizons, accompanied by specific policy recommendations targeted at national and state government bodies, regulatory agencies, research institutions, and the private sector.

India's Domestic Material Consumption (DMC) in 2020 was around 13.4 billion tonnes (DMC per capita increased by 0.18 tonnes, from 1.92 in year 2011-12 to 2.10 in year 2020-21), which is one of the highest in absolute terms in the world, but significantly lower than the material productivity of Organisation for Economic Co-operation and Development (OECD) countries, suggesting that there is a systemic inefficiency rather than absolute scarcity. The informal recycling industry, which recycles most of India's post-consumer waste, is a public health risk and an institutional opportunity due to the occupational hazards and environmental contamination it causes. Theoretically, more than 50 million tonnes of waste can be diverted from landfill each year through industrial symbiosis networks, but they are still largely underdeveloped, with institutional inertia, data gaps and a lack of platforms to facilitate them.

It is recommended that a National Industrial Ecology Mission should be set up under the Prime Minister's Science, Technology and Innovation Advisory Council, development of sector specific material flow accounts should be made mandatory, reform and extension of Extended Producer Responsibility (EPR) frameworks, and strategic positioning of CIECE, NEERI as the national anchor institution for IE research, training and policy advisory. These recommendations, when implemented in a phased and coordinated manner, can make a significant contribution to India's climate commitments, its Sustainable Development Goal (SDG) targets and its ambition to become a global leader in sustainable industrial development by 2035.

List of Abbreviations

Abbreviation	Full Form
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
bio-CCUS	Bio-Carbon Capture, Utilisation and Storage
BIS	Bureau of Indian Standards
BOD	Biochemical Oxygen Demand
BRICS	Brazil, Russia, India, China, South Africa
C&D	Construction and Demolition Waste
CBAM	Carbon Border Adjustment Mechanism
CE	Circular Economy
CIECE	Centre for Industrial Ecology and Circular Economy
CPCB	Central Pollution Control Board
CPWD	Central Public Works Department
CSIR-NEERI	Council of Scientific and Industrial Research – National Environmental Engineering Research Institute
CWC	Central Water Commission
DMC	Domestic Material Consumption
EIP	Eco-Industrial Park
EoL-RR	End-of-Life Recycling Rate
EPR	Extended Producer Responsibility
ESG	Environmental, Social and Governance
EU	European Union
EW-MFA	Economy-wide Material Flow Analysis

Abbreviation	Full Form
G20	Group of Twenty
G7	Group of Seven
GDP	Gross Domestic Product
GIDC	Gujarat Industrial Development Corporation
IE	Industrial Ecology
IEA	International Energy Agency
IPAT	Impact = Population x Affluence x Technology (equation)
IS	Industrial Symbiosis
ISIE	International Society for Industrial Ecology
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MFA	Material Flow Analysis
MIDC	Maharashtra Industrial Development Corporation
MIPS	Material Input per Service unit
MoEFCC	Ministry of Environment, Forest and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MoSPI	Ministry of Statistics and Programme Implementation
MSME	Micro, Small and Medium Enterprise
MSW	Municipal Solid Waste
NDC	Nationally Determined Contribution

Abbreviation	Full Form
NIEIS	National Industrial Ecology Information System
NIEM	National Industrial Ecology Mission
NISP	National Industrial Symbiosis Programme (United Kingdom)
NITI Aayog	National Institution for Transforming India Aayog
NREP	National Resource Efficiency Policy
NWDA	National Water Development Agency
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
ORC	Organic Rankine Cycle
PCPIR	Petroleum, Chemical and Petrochemical Investment Region
PM	Prime Minister (as in PM Gati Shakti National Master Plan)
PMAY	Pradhan Mantri Awas Yojana
PRO	Producer Responsibility Organisation
PTB	Physical Trade Balance
SDG	Sustainable Development Goal
SEEA	System of Environmental-Economic Accounting
SEEA-MFA	System of Environmental-Economic Accounting – Material Flow Accounts
SFA	Substance Flow Analysis
TDS	Total Dissolved Solids
TMR	Total Material Requirement
TNPCB	Tamil Nadu Pollution Control Board
UNEP	United Nations Environment Programme

TABLE OF CONTENTS

1. INTRODUCTION

1.1 The Global Industrial Ecology Movement: A Historical Perspective

The formal intellectual history of industrial ecology as a named discipline is conventionally traced to the 1989 publication by Robert Frosch and Nicholas Gallopoulos in Scientific American, entitled 'Strategies for Manufacturing,' in which the authors proposed a reconceptualisation of the industrial system as an industrial ecosystem in which consumption of energy and materials is optimised, waste generation is minimised, and the effluents of one process serve as the feedstocks of another (Frosch and Gallopoulos, 1989). This biological metaphor, simple in formulation yet analytically transformative in consequence, catalysed an extraordinary efflorescence of interdisciplinary scholarship spanning thermodynamics, ecology, economics, engineering, and the social sciences.

The intellectual precursors of IE, however, reach further back into the twentieth century. Abel Wolman's 1965 essay on 'The Metabolism of Cities' introduced the concept of urban metabolism, treating cities as systems that consume resources and generate wastes in patterns amenable to quantitative analysis (Wolman, 1965). Kenneth Boulding's 1966 essay on 'The Economics of Spaceship Earth' argued presciently for a closed-loop economy that recycles rather than discards, and Barry Commoner's 1971 work 'The Closing Circle' identified the systemic nature of environmental degradation as rooted in industrial design choices rather than individual behaviour (Boulding, 1966; Commoner, 1971). These foundational contributions established the conceptual ground upon which IE's formal institutionalisation would later be built.

The discipline institutionalized quickly after the landmark National Academy of Sciences workshop in 1991. In 1997, the Journal of Industrial Ecology was created at Yale University, and in 2001, the International Society for Industrial Ecology (ISIE) was established, with more than a thousand members in fifty countries. The IS network in Kalundborg, Denmark, which was documented systematically in the 1990s, was the most cited empirical example of IS in practice, and was the inspiration for government-supported programmes in the United Kingdom (National Industrial Symbiosis Programme, NISP), China (Circular Economy Demonstration Parks), South Korea and the United States (Jacobsen, 2006). In 2013, the Ellen MacArthur Foundation published 'Towards the Circular Economy', which introduced IE concepts into the business and policy agendas, and was incorporated into the European Union's Circular Economy Action Plans of 2015 and 2020. In the Indian context, the Ministry of Environment and Forests (MoEF) undertook among the earliest institutional interventions by establishing waste exchange banks, a structured brokerage mechanisms designed to systematically match industrial waste generators with prospective by-product users, operationalizing the principle of resource valorisation within the domestic industrial landscape well before the term "industrial symbiosis" entered mainstream policy discourse. Concurrently, the establishment of the National Cleaner Production Centre (NCPC) under the joint UNIDO-UNEP Cleaner Production Programme in the mid-1990s institutionalized cleaner production as a policy-driven imperative, providing structured technical assistance for improving resource efficiency in energy, water, and materials across key industrial sectors and clusters.

1.2 Industrial Ecology and the Circular Economy: A Necessary Distinction

Industrial ecology is a conceptual progenitor of the circular economy, and an institutional offspring. The circular economy discourse provides a new language for concepts that have been around for a longer time in IE, but the two are not the same (Van Ewijk et al., 2023). Industrial ecology is a science with well-defined methods, indicators that are grounded in empirical evidence, and a long history of critical academic research. The circular economy is a policy and business approach that builds on the insights of IE, but also includes elements of economic strategy, design innovation and social entrepreneurship that are outside of IE's disciplinary scope.

This is an analytical distinction of significance for India. Policy actors who use the circular economy terminology without understanding the science of IE may create policies that are symbolically desirable but scientifically unsound, or policies that result in short-term gains on recycling rates but do not lower overall resource use. The ISIE has pointed out that circular economy strategies that lower the cost of products can paradoxically increase consumption enough to negate environmental benefits, which it calls the circular economy rebound (Zink and Geyer, 2017). Rigorous IE analysis, including full material flow accounting, life cycle impact assessment and systems modelling, can differentiate between interventions that actually enhance environmental performance and those that simply move the burden from one place to another or from one time to another or from one impact category to another.

1.3 India's Transition Imperative: Resource Stress, Growth Ambitions, and the Need for a New Paradigm

The path of development that India has taken makes it imperative to adopt an IE-based industrial strategy. India is expected to double its GDP in the next decade, add 200 million urbanites by

2031, grow its infrastructure at an unprecedented pace and achieve the Paris Agreement's climate targets of reducing the emissions intensity of GDP by 45 per cent by 2030 from 2005 levels (Government of India NDC, 2022). These goals are interdependent and sometimes conflicting in a linear industrial model, but are reconcilable in an IE model that separates economic production from material consumption.

The quantitative aspects of the resource problem in India are alarming. The country's total annual material consumption is around 13.4 billion tonnes, of which the main categories are biomass, construction minerals, fossil fuels and metal ores (UNEP, 2016; Eurostat, 2018). Material productivity (GDP per tonne of material consumed) is around ¼ to ⅓ of the OECD average, due to structural inefficiencies in supply chains, design for disposability, limited secondary materials markets and the lack of industrial symbiosis networks at scale (World Bank, 2013). The environmental impacts of this inefficiency, such as groundwater pollution due to uncontrolled industrial leachate, particulate pollution due to uncontrolled waste burning, heavy metal pollution in agricultural soils, and urban ecosystem degradation, cost more than 5.7 per cent of GDP per year (Mani et al., 2018).

The need for a paradigm shift is not only environmental, but also economic, strategic and developmental. A shift to IE-informed industrial practice can help simultaneously lower the environmental footprint of India's growth, enhance competitiveness of its exports in markets that are becoming more carbon border adjusted and environmental product declaration-driven, lower supply chain vulnerability by building domestic secondary materials markets, and generate green jobs in the circular economy sector. This document is based on the belief that IE is the most scientifically sound and institutionally sound vehicle to make this transition.

2. SCIENTIFIC AND CONCEPTUAL FRAMEWORK

2.1 Systems’ Thinking and Material Flow Analysis

Industrial ecology differs from traditional environmental management in that it takes a systems approach; the unit of analysis is not the individual facility or pollutant, but the integrated industrial-ecological system in which materials and energy flow, transform and accumulate. This systems approach requires accounting systems that can monitor material and energy flows from the factory to the global economy and from annual snapshots to multi-decadal stock dynamics.

This systemic perspective is operationalised through Material Flow Analysis (MFA), which offers the accounting framework. MFA is based on the principle of conservation of mass and systematically quantifies the extraction, import, transformation, consumption, recycling and disposal of materials in a defined system over a defined time horizon (Brunner and Rechberger, 2004). The national level MFA generates a set of economy-wide MFA indicators required by the Eurostat's MFA methodology, such as Domestic Material Consumption (DMC), Material Input per Service unit (MIPS), and End-of-Life Recycling Rate (EoL-RR). MFA shows at the sector level where inefficiencies, accumulation and losses occur, which creates the resource productivity landscape of individual sectors. Urban metabolism analysis, which is the application of MFA principles to city-scale systems, can be used at the city level to guide infrastructure planning, waste system design and urban mining opportunities.

A more specific version of MFA is called Substance Flow Analysis (SFA) which tracks the flow of specific chemical elements or compounds through the industrial-ecological system, identifying where the substance is released into the environment, where it accumulates in soils and sediments, and where it can be recovered technically. SFA has been found to be especially useful for critical raw materials, toxic heavy metals and persistent organic pollutants, which are qualitatively different in terms of their challenges for circular economy strategy (van der Voet et al., 2019). A key principle of IE is that the 'societal metabolism' (the entire flow of raw resources through society to useful goods and services and then back to wastes and emissions) has predictable thermodynamic constraints: mass and energy are conserved, but entropy means that perfect circularity is thermodynamically impossible (Cullen, 2017; Ayres, 1989).

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is an internationally agreed upon standard (ISO 14040:2006 and ISO 14044:2006/A1:2017/A2:2020) that quantifies the environmental impacts of products, processes and services throughout their entire life cycle, from raw material extraction to manufacturing, distribution, use and end-of-life management. The four phases of LCA (goal and scope definition, LCI compilation, LCIA, and interpretation) allow for a rigorous comparative analysis of alternative product systems and circular economy strategies.

One of the key roles LCA plays in policy for circular economy is its ability to reveal burden shifting, which occurs when interventions are targeted at a single metric or stage of the life cycle, but end up shifting the impact from one to another. Circular strategies that seem to be beneficial on their own can have a negative effect in other categories or in supply chains, as the ISIE's synthesis of IE for the circular economy shows (van Ewijk et al., 2023). For instance, a more energy efficient building could use energy intensive construction materials, which partially compensate for the operational energy savings. LCA's holistic multi-category impact assessment, which includes climate change, human toxicity, water depletion, eutrophication, land use and resource depletion, offers the analytical discipline to prevent such side effects.

The establishment of an India specific LCA background database is a national scientific priority of the first order in the Indian context. The existing LCA studies used for Indian industrial systems have been mostly based on European and global generic datasets, which do not reflect the Indian energy mixes, water sources, technology vintages or supply chain structures, and thus systematically bias the LCA results for Indian applications. CIECE is well placed to take the lead in developing this database in collaboration with national industry associations, sector regulators and international organisations.

2.3 Industrial Symbiosis

Industrial Symbiosis (IS) is the intentional arrangement of waste, energy, water and by-products from one enterprise to become the input for another, with the aim of minimizing the overall consumption of raw materials and the amount of waste to be disposed of (Chertow, 2000). IS is the most tangible and operationally closest to the ground application of IE at the cluster or regional level, and it is the most explicit manifestation of the ecosystem analogy that underlies IE: in natural ecosystems, decomposers break down the wastes of other organisms to release nutrients for reuse, while firms in an industrial symbiosis network break down each other's wastes to recover material and energy value.

The Kalundborg industrial symbiosis network in Denmark has resulted in measurable reductions of 5–20 per cent in various environmental impact categories, based on exchanges of waste heat, waste steam, waste gypsum, waste sulphur and fermentation sludge (Sokka et al., 2011). Most importantly, IE research has shown that IS does not just happen because of geographical proximity, but also because of institutional trust, information infrastructure, regulatory permissibility, and logistics feasibility (Chertow and Ehrenfeld, 2012). A study conducted in industrial districts of Nanjangud, south India, further confirmed that shared cultural norms regarding waste as a resource and the 'mental distance' between firm managers are as important to IS development as material complementarity (Ashton and Bain, 2012). The Naroda Industrial Estate, Ahmedabad (a heterogeneous cluster encompassing textile processing, dyeing, chemical manufacturing, and engineering industries) represents an institutionally mediated industrial symbiosis system anchored by a Common Effluent Treatment Plant (CETP), which functions as a canonical shared-utility symbiotic node redistributing wastewater treatment burdens across co-located enterprises. Material and energy flow analyses within the estate have identified latent symbiotic potential in the exchange of process heat, chemical by-products, and solid waste streams among industries with structurally complementary input-output profiles, though realisation of this potential remains constrained by informational asymmetries and transaction cost barriers.

2.4 Socio-Economic Metabolism

Socio-economic metabolism, also described as industrial metabolism or anthropogenic metabolism, applies the biological concept of metabolism to the characterisation of human society's processing of materials and energy. Societies, like organisms, extract energy and matter from their environment, transform these inputs to support valued activities, and generate wastes and emissions as inevitable by-products (Ayres, 1989; Fischer-Kowalski, 1998). This metabolic perspective enables IE researchers to quantify the throughput of materials and energy in national economies, trace the accumulation of materials in the built environment, and assess the thermodynamic constraints on dematerialisation.

Material flow analysis of the European Union's socio-economic metabolism, conducted by Mayer et al. (2019), revealed that in 2014 only approximately 10 per cent of inputs to the EU economy were secondary materials and only 15 per cent of waste was recycled back into the economy. These findings underscore the profound gap between circular economy rhetoric and the empirical reality of industrial metabolism, a gap that IE's rigorous accounting methods are uniquely positioned to reveal and that this Report argues India must systematically close.

2.5 Planetary Boundaries and Environmental Limits

Industrial ecology has been defined as 'the means by which humanity can deliberately and rationally approach a desirable carrying capacity' (Graedel and Allenby, 1995). This formulation places IE in direct relationship with the planetary boundaries concept articulated by Rockstrom et al. (2009), which defines nine biophysical Earth-system processes whose safe operating limits must not be transgressed if the stability of the Holocene conditions upon which human civilisation depends is to be maintained. These boundaries, covering climate change, biosphere integrity, land-system change, freshwater use, biogeochemical flows, ocean acidification, atmospheric aerosol loading, ozone depletion, and novel entities, define the ecological envelope within which all economic activity, including circular economy strategies, must operate.

A fundamental insight from IE is that a circular economy cannot eliminate environmental impacts; it can only target and reduce them (van Ewijk et al., 2023). There will always be some virgin material input needed to make up for dissipative losses and thermodynamic inefficiencies, and there will always be some waste that must be disposed of (Kral, Kellner and Brunner, 2013). Circular economy indicators should therefore not only measure recycling rates, but also the environmental impacts of recycling, and circular strategies should be considered not only for their circularity, but also for their role in keeping socio-economic metabolism within planetary boundaries.

2.6 Design-Stage Interventions versus End-of-Pipe Solutions

The IE's most significant contribution to environmental policy has been the consistent evidence it has provided that pollution prevention and waste reduction that occurs early in the design of products, processes and systems is more effective for the environment than end-of-pipe pollution control and waste management after the damage has been done. The research on industrial ecology indicates that the prevention of food waste at the production and consumption stage results in much greater reductions in GHGs compared to material and energy recovery through incineration or anaerobic digestion (de Sadeleer, Brattebo and Callewaert, 2020). The same is true for metal recycling, where coordination throughout the entire life cycle, from design for disassembly to optimisation of the collection system and improvement of the metallurgical processes, leads to significantly higher recovery rates than any single measure taken alone (Reck and Graedel, 2012).

This design-stage orientation requires a basic shift in industrial governance from reactive regulation, which establishes emission limits after production processes are in place, to anticipatory governance, which influences product design, material specifications, and process architecture before multi-decade path dependencies are set. The infrastructure aspect of this challenge is especially critical in India, where the material and energy consumption patterns of the building, transport, energy and water infrastructure will be set in place over the next 30-50 years. As IE shows, the use of material is largely dependent on infrastructure, and long-lived infrastructure generates lock-ins that will take decades of patient institutional work to overcome (Pauliuk and Muller, 2014).

3. INDIAN INDUSTRIAL CONTEXT

3.1 Industrial Structure: The MSME Dimension and Sectoral Composition

The industrial structure in India is unique in terms of its heterogeneity, which poses challenges and opportunities for the use of industrial ecology principles. On one extreme, large integrated manufacturing companies such as steel, cement, petroleum refining, chemicals and power generation have a disproportionate share of material and energy throughput and are subject to increasingly stringent regulations that require environmental accountability. On the other side, the micro, small and medium enterprise (MSME) sector, which employs around 110 million persons and has more than 63 million units, contributes about 30 per cent of manufacturing output and an estimated 45 per cent of manufactured exports, but lacks environmental management capacity and has regulatory frameworks that have historically focused on employment protection rather than environmental enforcement (Ministry of MSME, 2023).

The importance of MSME sector for IE is two-fold. First, it has a large aggregate material throughput, and second, its industrial geography, with geographic clustering in regional specialisation zones like the Surat textile belt, the Ludhiana foundry cluster, the Tiruppur dyeing district and the Moradabad brassware complex, provides the spatial proximity and inter-sectoral material complementarity required for industrial symbiosis. The MSME sector is characterized by low institutional capacity for environmental management, which requires IE interventions to be low administration, high practical utility and to have tangible economic co-benefits. The most suitable entry points are eco-industrial park facilitation, industrial symbiosis mapping and simplified circular economy audit tools.

3.2 Resource Intensity and Infrastructure Growth

India's infrastructure growth requirements represent one of the most material-intensive economic programmes in global history. The Government of India's PM Gati Shakti National Master Plan, launched in 2021, envisions an investment of approximately 111 trillion Indian Rupees in multimodal infrastructure over the coming decade, encompassing roads, railways, ports, airports, water supply, and urban infrastructure (Government of India, 2021). The material dimensions of this infrastructure build-out, encompassing cement, steel, aluminium, copper, and non-metallic minerals, will determine India's material footprint for decades. As IE's analysis of infrastructure lock-ins demonstrates, the material composition and design life of infrastructure determines the 'metabolic pattern' of the society it serves for its entire operational lifetime, potentially spanning fifty to one hundred years (Muller et al., 2013).

The implication for India's infrastructure planners is that decisions made today about building materials, structural systems, and design standards will create either opportunities for future material recovery, if circular design principles are embedded, or enormous waste streams, if conventional linear design continues. The development of a national material stock database, quantifying the type, quantity, location, and age of materials embedded in India's built environment, is therefore a scientific and policy priority that this Report argues should be initiated immediately under the mandate of CIECE.

3.3 The Informal Sector: Systemic Role in Material Recovery

The informal sector is a paradoxical part of the industrial ecology landscape in India. On the other hand, the informal waste collection and recycling sector, which includes kabadiwallas (itinerant waste buyers), aggregators and small-scale recyclers, plays a role of tremendous material and economic value, capturing recyclable materials before they reach landfills or open dumping sites and keeping informal supply chains alive for secondary metals, plastics, paper and glass. The informal sector is estimated to recover about 20-25 per cent of the recoverable fraction of MSW, which is not matched by many formal systems in developing countries (Chintan Environmental Research and Action Group, 2009).

However, the informal sector also handles numerous waste streams, including electronic waste, lead-acid batteries and medical waste, in conditions of high occupational health risks and environmental contamination, using methods like acid leaching, open burning and manual dismantling without protective equipment. India produces around 3.23 million metric tonnes of e-waste every year, but only a small portion of this is processed through formal recycling facilities (CPCB, 2022; Balde et al., 2020). The SFA of critical metals in India's e-waste system shows that a substantial amount of recoverable gold, silver, copper and palladium is being lost to environmentally harmful informal processing channels, instead of being recovered for high-value applications.

An IE-informed policy framework for the informal sector should therefore not be either formalisation without criticality, which could lead to livelihoods being undermined without environmental performance being enhanced, or acceptance without criticality of the status quo, which would allow for the toleration of preventable human suffering. The right intervention model is the integration of actors from the informal sector into formal supply chains, technical upgrading and occupational health protection, and linking informal material recovery with the secondary materials markets that formal industrial symbiosis networks need.

3.4 Water, Energy, and Material Constraints

Three basic resource constraints form the backdrop of the industrial ecology in India. Water stress, which impacts around 54 per cent of India's geographical area, including regions like the Deccan plateau, Gujarat and Rajasthan, where water is extremely scarce, creates binding constraints on water-intensive industries, and water reuse and recycling becomes a strategic, rather than environmental, necessity (NITI Aayog, 2018). The energy component of all LCA's performed in the Indian context is carbon intensive, as about 57 per cent of the installed electricity generation capacity is still from coal based thermal power plants as of 2023, and waste heat recovery and industrial energy symbiosis becomes economically attractive (IEA, 2023). India's shift towards electric mobility, renewable energy, and cutting-edge electronics production faces strategic vulnerabilities due to material constraints, especially in the realm of critical raw materials like lithium, cobalt, rare earth elements, and platinum group metals.

3.5 Regional Disparities and Policy Fragmentation

A distinctive challenge for IE implementation in India is the extreme regional diversity of industrial structure, resource endowment, institutional capacity, and environmental burden across its 28 states and 8 union territories. Maharashtra, Gujarat, and Tamil Nadu account for a disproportionate share of industrial activity and have developed relatively more sophisticated industrial and environmental governance institutions. Jharkhand, Odisha, and Chhattisgarh, despite being richly endowed with mineral resources, face environmental governance challenges associated with extractive industries operating in ecologically sensitive areas. The northeastern states, which together contain exceptional biodiversity value, have minimal industrial presence but face waste management challenges associated with urbanisation without commensurate infrastructure.

Policy fragmentation across ministries, further complicates the systemic intervention that IE demands. Solid waste management is governed by the Solid Waste Management Rules under MoEFCC, while urban local bodies bear primary implementation responsibility under MoHUA. Extended Producer Responsibility for plastic and e-waste falls under MoEFCC, while industrial waste regulation is partially the domain of state pollution control boards. Water use regulation involves the Central Water Commission, the National Water Development Agency, and state-level irrigation and groundwater departments. No single institutional authority exercises systemic oversight of industrial material flows at the national level, which is precisely the gap that this Report proposes to address through the creation of dedicated national institutional infrastructure.

4. MATERIAL AND ENERGY FLOW MAPPING IN INDIA

4.1 National Material Flow Accounts: Current Status and Gaps

Economy-wide Material Flow Analysis (EW-MFA), applied at the national level, provides a comprehensive physical accounting of the materials extracted from the domestic environment, imported, transformed through the economy, and ultimately either incorporated into domestic stocks, exported, or emitted to the environment as waste and pollution. This accounting framework, standardised by Eurostat (2018) and applied systematically across OECD and European Union member states, generates the suite of indicators, including Domestic Material Consumption (DMC), Material Productivity (GDP/DMC), Total Material Requirement (TMR), and Physical Trade Balance (PTB), that constitute the empirical foundation for circular economy strategy and monitoring.

The national MFA in India is not well developed compared to its economic importance. The National material flow account for India is not yet available, and the Ministry of Statistics and Programme Implementation (MoSPI) is working on developing elements of national material accounts as part of the Natural Capital Accounting and Valuation of Ecosystem Services project, which is a sectoral disaggregation of the national accounts. This data gap has significant implications: India is unable to credibly track progress towards circular economy goals, cannot determine which sectors and material categories would benefit most from intervention, and cannot effectively engage in international reporting systems like the Global Material Flows Database or the UN System of Environmental-Economic Accounting (SEEA-MFA). Available estimates suggest that India's DMC, encompassing biomass, construction minerals, fossil fuels, and metal ores, is approximately 13.4 billion tonnes per year, making it one of the largest material-consuming economies in absolute terms globally (UNEP, 2016). Material productivity, at approximately USD 0.20 of GDP per kilogram of material consumed, compares unfavourably to the OECD average of USD 2.10 per kilogram, a tenfold gap that reflects both the structural composition of India's economy, which is more resource-intensive than services-dominated OECD economies, and genuine inefficiency in material transformation chains (Schandl et al., 2018).

4.2 Sector-Wise Resource Consumption

Construction and real estate constitute by far the largest material consuming sector in India, accounting for an estimated 55 to 60 per cent of non-metallic mineral flows, including limestone, sand, gravel, and crushed stone (MoHUA, 2020). The scale of India's infrastructure build-out, with approximately 40 million new housing units required by 2031 under the Pradhan Mantri Awas Yojana, and the construction of hundreds of highways, urban metro systems, airports, and industrial estates, means that construction material flows will remain dominant in India's material balance for the foreseeable future. The critical IE insight for this sector is that buildings and infrastructure represent material stocks, repositories of embodied materials that will eventually become available for secondary recovery, and that stock characterisation is therefore as important as flow accounting.

The second most energy and material intensive industry is the iron and steel industry. India is the second largest producer of steel in the world with crude steel production of around 118 million tonnes in 2022-23 (Ministry of Steel, 2023). The sector consumes a disproportionate amount of energy and emits a disproportionate amount of greenhouse gas, with the production of crude steel in primary steelmaking by blast furnace routes accounting for about 2.0 to 2.3 tonnes of CO_2 per tonne of crude steel, while the production of crude steel in secondary steelmaking by electric arc furnace using scrap accounts for about 0.4 to 0.6 tonnes of CO_2 per tonne of crude steel. Domestic scrap collection and processing infrastructure is a key circular economy opportunity with economic and climate impacts.

The chemicals and petrochemicals sector, the textile and apparel sector, and the agricultural processing sector each contribute distinctive material flow profiles with corresponding IE opportunities. The chemical sector's complex multi-substance flows, including a wide range of toxic intermediates and persistent pollutants, make it particularly amenable to SFA-based analysis. The textile sector, particularly in clusters such as Tiruppur and Surat where wet processing generates significant effluent volumes with complex chemical compositions, presents opportunities for both water reuse and chemical recovery. Agricultural processing generates large volumes of biomass residues that represent potential feedstocks for industrial symbiosis and bio-based product development.

4.3 Waste Streams: Solid, Liquid, and Gaseous

India generates approximately 62 million tonnes of municipal solid waste (MSW) annually, a volume projected to reach 165 million tonnes by 2030 as urbanisation and consumption levels rise (MoHUA, 2021). Of this volume, only 22 to 28 per cent is currently processed or recycled, with the remainder disposed of in open dumps or improperly managed landfills that generate methane, leachate, and particulate emissions. The composition of India's MSW is characterised by high organic content (approximately 50 to 55 per cent by weight), significant recyclable fractions of plastics, paper, metals and glass, and a small but hazardous fraction of e-waste, medical waste, and hazardous household chemicals that requires specialised management.

Industrial hazardous waste generation stands at approximately 7.9 million tonnes per annum, managed by approximately 200,000 units authorised to handle hazardous waste under the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 (CPCB, 2022). The true amount of industrial waste, such as non-hazardous fly ash, mining overburden, process slags, and construction waste, is many orders of magnitude greater. The amount of C&D waste generated is estimated at 530 million tonnes per year, which is one of the highest in the world, and only a small proportion of this waste is processed through formal recycling infrastructure (CPWD, 2020). Fly ash is produced by coal fired power plants in India at an estimated rate of 105 million tonnes per year, with an estimated 67 per cent of this fly ash being reused, mainly in brick manufacturing and construction, but the quality and reliability of the utilisation data is disputed (MoEFCC, 2021).

Gaseous emission streams from industrial sources are a primary concern of pollution control regulations, but are also an IE opportunity. The field of industrial ecology research in India has a promising future in the emerging frontier of carbon capture and utilisation (CCU) technologies, such as bio-Carbon Capture, Utilisation and Storage (bio-CCUS) technologies that capture CO_2 from industries for biological conversion into value-added products. The combination of bio-CCUS with fermentation, algal biomass production and mineralisation pathways is an area of active international research, which CIECE can contribute to the Indian context.

5. INDUSTRIAL SYMBIOSIS IN INDIA: OPPORTUNITIES AND BARRIERS

5.1 Geographic and Sectoral Potential

India's industrial geography offers significant opportunities for industrial symbiosis, which are not matched by many countries. The clustering of industries in Special Economic Zones, Export Processing Zones and state designated industrial estates has led to geographic proximity of various industries, which is a prerequisite but not a sufficient condition for IS development. The Dahej Petroleum, Chemical and Petrochemical Investment Region (PCPIR) in Gujarat, the Paradip PCPIR in Odisha and the Visakhapatnam PCPIR in Andhra Pradesh each have co-located industries with material and energy flow profiles that offer great potential for symbiosis in waste heat, water recycling and by-product exchange.

In addition to the formal SEZ and estate structure, India's traditional industrial clusters, which are more than 2,500 in number as per the data of the MSME ministry, are an untapped IS resource of huge potential. The textile cluster of Tiruppur, where effluents containing recoverable chemicals and heat are generated by dyeing and bleaching units, the foundry cluster of Rajkot, where slag, sand waste and spent oil streams are generated during metal casting which can be systematically exchanged with cement plants, brick kilns and oil recyclers respectively, and the ceramic cluster of Morbi, where kiln waste heat and reject material streams present symbiosis opportunities, are illustrative examples of the potential awaiting systematic IE analysis and facilitation.

National level estimates of IS potential in India are still underdeveloped because of the lack of national enterprise level material flow data. However, the results of pilot IS facilitation programmes in similar emerging economy settings such as Circular Economy Industrial Parks in China and National Eco-Industrial Park Programme in South Korea indicate that systematic IS development in India could divert 40 to 60 million tonnes of industrial waste from landfill disposal per year, recover material and energy value conservatively valued at 50,000 to 80,000 crore Indian Rupees per year, and reduce industrial GHG emissions by 50 to 100 million tonnes of CO_2 equivalent per year.

5.2 Barriers to Industrial Symbiosis Development

However, IS in India is affected by a number of documented challenges that have collectively hindered the development of IS at the scale that it deserves. Perhaps the largest category is regulatory barriers. The transfer of a material identified as hazardous waste from one enterprise to another for use as a production input under the Hazardous and Other Wastes Rules, 2016, and corresponding notifications issued by the state pollution control board, requires permits that can take months to obtain, imposes tracking and manifesting requirements on both the producer and the recipient, and in some states extends the producer's liability beyond the point of incorporation into a new product. These regulations, which are validly intended to manage toxic and persistent materials, are poorly balanced to facilitate IS exchanges of materials that are harmless or helpful in the context of their intended industrial use, but are considered waste by one enterprise.

Information barriers represent the second major category of IS obstacles. Enterprises seeking to identify potential IS partners, that is, facilities generating waste streams complementary to their input requirements, or seeking to place their own waste streams with potential recipients, have no national platform through which to conduct this search. The Industrial Symbiosis Exchange, operated in the United Kingdom and replicating the model of the US Pollution Prevention Information Clearinghouse, demonstrates that a centralised, government-supported information platform can catalyse IS exchanges that would not occur spontaneously through market mechanisms alone. India has no equivalent national resource exchange platform, though pilot efforts by state pollution control boards in Maharashtra, Gujarat, and Karnataka have demonstrated the feasibility and value of such platforms at the state level.

Economic and logistical barriers, including transport costs, quality uncertainty regarding secondary materials, and the risk premium attached to supply chains based on industrial by-products rather than virgin materials, further constrain IS development. These barriers are amenable to market-based interventions, including extended producer responsibility schemes that internalise disposal costs and improve the economics of by-product exchange, secondary materials market development programmes, and quality certification schemes for secondary materials that reduce uncertainty for potential recipients.

5.3 Policy Recommendations for Industrial Symbiosis

A comprehensive policy framework for IS in India requires interventions across at least four domains. First, regulatory reform: the Hazardous and Other Wastes Rules should be amended to establish a dedicated IS facilitation pathway with streamlined permit procedures, reduced compliance burden, and clear liability provisions that do not deter legitimate IS exchanges. The Central Pollution Control Board should publish an annually updated 'IS-eligible materials list' identifying waste streams for which by-product status can be recognised without full hazardous waste permit procedures.

Second, institutional infrastructure: a National Industrial Symbiosis Exchange (NISE) platform should be established, administered by CIECE in partnership with state pollution control boards and industry associations, providing a searchable database of industrial waste streams available for IS exchange, qualified by material type, volume, composition, geographic location, and seasonal availability. This platform should be integrated with the National Industrial Corridor Development Corporation's geographic information systems to enable spatially optimised IS network design.

Third, financial incentives: a Green Credit Mechanism, consistent with the framework established under the Environment Protection Act amendments of 2023, should be designed to reward IS exchanges through tradeable green credits, providing economic uplift to IS participants that compensates for transaction costs and market imperfections. Fourth, technical capacity building: CIECE should develop and deliver an IS Facilitation Certificate Programme, training professionals in state pollution control boards, district industries centres, and industrial association offices in the systematic identification, assessment, and facilitation of IS opportunities using MFA-based tools.

6. POLICY AND REGULATORY LANDSCAPE

6.1 Existing Frameworks: Strengths and Limitations

The governance structure for the environment in India has undergone significant changes since the enactment of the Environment Protection Act, 1986 and the Water (Prevention and Control of Pollution) Act, 1974. Climate policy has been made a whole-of-government issue through the National Action Plan on Climate Change (NAPCC) and its eight national missions, including the National Mission on Enhanced Energy Efficiency and the National Mission on Sustainable Habitat. Since its inception in 2014, the Swachh Bharat Mission has created unprecedented political interest and financial resources for solid waste management, resulting in tangible gains in waste collection coverage, but processing and treatment facilities have not kept pace with the investments made in collection. In 2019, MoEFCC also adopted draft National Resource Efficiency Policy and set up Resource Efficiency Cell identifying resource efficiency as key tool to achieve circular economy.

The Extended Producer Responsibility (EPR) scheme, which was launched for e-waste in 2012 and expanded to plastic packaging in 2022 and batteries and tyre waste, is India's most ambitious initiative to integrate IE principles into the governance of products. EPR requires producers, importers and brand owners to make sure that a certain percentage of the products they put on the market are collected and recycled, in theory making the end-of-life costs of products more visible to the consumer through their design and price. But the effectiveness of India's EPR systems has been undermined by weak enforcement, weak collection systems, and the lack of producer responsibility organisations acting as drivers of circular design.

The Plastic Waste Management Rules, which were amended in 2022 to introduce a phase-out of single-use plastics below certain thickness limits and a requirement for EPR for plastic packaging, are a major step, but the implementation of the phase-out has been difficult and enforcement of the EPR requirements has been inconsistent against informal plastic recyclers and small-scale manufacturers. The National Clean Air Programme, which aims for 40 per cent reduction in PM concentrations in 122 non-attainment cities, puts pressure on the regulatory system, which is partly aligned with the IE objectives, but does not address the systemic drivers of material flows that cause air pollution from waste combustion and industrial activity.

6.2 Gaps in the Regulatory Framework

Four critical gaps in India's regulatory framework for industrial ecology can be identified. The first is the absence of mandatory material flow reporting at the enterprise level. No Indian regulation currently requires industrial enterprises, above a specified size threshold, to compile and report quantitative accounts of material inputs, water use, waste generation, and recycling rates in a standardised format that would enable national material flow account compilation. Such a requirement, analogous to the Mandatory Energy Audits under the Perform, Achieve and Trade scheme of the National Mission for Enhanced Energy Efficiency, would generate the data foundation that MFA-based IE analysis requires.

The second gap is the inadequacy of circular economy provisions in procurement regulation. Public procurement, which accounts for approximately 20 to 25 per cent of GDP in India, represents a powerful lever for circular economy development through the specification of recycled content requirements, remanufactured product acceptance, and end-of-life take-back obligations. The Government e-Marketplace (GeM) portal has introduced some green procurement provisions, but the systematic specification of recycled content standards, comparable to those in the European Union's Green Public Procurement framework, remains absent.

The third gap is the lack of a legal framework for by-product recognition that would allow materials currently classified as waste to be legally recognised as by-products when they meet defined criteria of composition, purity, and intended use. By-product recognition frameworks, operative in the European Union under Article 5 of the Waste Framework Directive, and in several US states, create the legal clarity that IS exchanges require and that the current Indian waste regulatory framework does not provide. The fourth gap is the absence of design-stage environmental requirements for products and infrastructure: no Indian regulation currently mandates design for disassembly, design for recycled content, or the disclosure of material declarations for buildings or manufactured products.

6.3 State-Level Innovations and Best Practices

Several Indian states have pioneered regulatory and institutional innovations in industrial ecology that merit national recognition and replication. Gujarat's GIDC Industrial Waste Exchange, operated through the Gujarat Cleaner Production Centre, has facilitated over 200 waste exchange transactions between industrial enterprises in the state's chemical and pharmaceutical corridors since its establishment, demonstrating the feasibility of a brokerfacilitated IS approach in the Indian institutional context. Telangana's Industrial Health Clinic model, which provides integrated environmental compliance assistance to MSME clusters, has been recognised as a best practice in industrial environmental management by the UNEP Regional Office for Asia and the Pacific.

Maharashtra's Solid Waste Management Master Plan, developed in accordance with Solid Waste Management Rules 2016, incorporates material recovery facility specifications and informal sector integration provisions that reflect IE-informed thinking. Kerala's Green Protocol, mandating the elimination of single-use plastics from government functions and institutions, demonstrates the regulatory leverage available to state governments in shaping material flows through procurement and event management standards. These state-level innovations, though individually modest in scale, collectively demonstrate the institutional capacity and political will that a national IE mission can mobilise and coordinate.

7. SECTORAL PATHWAYS FOR CIRCULAR ECONOMY TRANSITION

7.1 Iron, Steel, and Metals

The Indian steel sector offers perhaps the most near-term and economically compelling opportunity for circular economy transition in any major industrial sector. The availability of large and growing volumes of end-of-life steel scrap from India's expanding infrastructure stock, the economic advantage of electric arc furnace scrap-based production in a context of rising iron ore and coking coal import costs, and the sector's enormous carbon footprint relative to low-carbon steel production pathways, create aligned economic, environmental, and strategic incentives for the development of secondary steel production infrastructure. A national scrap collection and processing infrastructure programme, integrated with vehicle end-of-life management, construction and demolition waste recovery, and ship-breaking industry regulation, could increase India's steel scrap availability from an estimated 25 million tonnes to 50 to 60 million tonnes per year within a decade.

The non-ferrous metals sector, particularly aluminium and copper, presents complementary circular economy opportunities with significant energy implications. Secondary aluminium production from scrap requires only 5 per cent of the energy consumed by primary production from bauxite, making scrap recovery economically attractive whenever collection and processing costs are manageable (IAI, 2023). India's aluminium consumption is growing rapidly with increasing penetration in automotive, construction, and consumer electronics applications, and the development of closed-loop aluminium recovery systems in these sectors represents a strategic priority for both energy security and material efficiency.

7.2 Construction and Built Environment

The construction sector's dominance in India's material flow profile makes its circular economy transition a national priority of the first order. Three distinct IE opportunities merit priority attention. First, the substitution of conventional construction materials with industrial by-products: fly ash, ground granulated blast furnace slag (GGBS), and silica fume are established supplementary cementitious materials that can replace 20 to 70 per cent of Portland cement clinker in concrete production, reducing both CO_2 emissions and demand for primary limestone extraction. India's fly ash production of approximately 105 million tonnes per year, and its slag production from blast furnaces, represent by-product resources of enormous scale that remain underutilised relative to their technical potential.

Second, design for disassembly and material recovery: the development and adoption of design standards for buildings and infrastructure that facilitate future material recovery, including the use of reversible connections, standardised component dimensions, and material passports that document the type and quantity of materials incorporated in structures, can transform India's construction activity from a one-way sink for materials to a bank of recoverable resources. Third, construction and demolition waste recycling: the development of C&D waste processing facilities capable of producing recycled aggregates meeting Indian Standards specifications, combined with regulatory requirements for recycled content in government-funded construction projects, can create a viable secondary aggregate market that reduces both landfill burden and quarrying activity.

7.3 Plastics and Packaging

India's plastic waste challenge is among the most visible and politically salient environmental issues in the country, generating significant regulatory attention and civil society advocacy. From an IE perspective, however, the policy response has been disproportionately focused on single-use plastic bans, which address a fraction of the plastic waste challenge, rather than on the systemic redesign of India's plastics economy. A comprehensive IE-informed plastics strategy would encompass three dimensions: design intervention, creating regulatory and market incentives for the elimination of problematic polymer types and chemical additives from product formulations, the standardisation of packaging formats for recyclability, and the development of concentrated collection systems that maintain material quality through the reverse logistics chain.

The formalisation and upgrading of plastic recycling infrastructure represents the second dimension. India's existing informal plastic recycling capacity, concentrated in clusters such as Delhi NCR, Pune, Surat, and Kolkata, processes a remarkable volume of post-consumer plastic material but operates without the process control, quality management, or occupational health systems required to produce secondary plastics suitable for high-value applications. Investment in mechanical recycling infrastructure capable of producing food-contact grade recycled polyethylene terephthalate, for example, would enable India to capture the value premium associated with high-quality recycled content and reduce its dependence on virgin polymer imports. Chemical recycling, including pyrolysis, solvolysis, and gasification of mixed plastic fractions unsuitable for mechanical recycling, represents a third-tier technology option requiring research and pilot demonstration in the Indian context.

7.4 Organic Waste and Bioeconomy

India's biogenic waste streams, including agricultural residues, food processing waste, municipal organic waste, and sewage sludge, represent a resource base of transformative potential that remains largely unrealised. The IE framework for organic waste management is grounded in the concept of the cascading use of biomass: organic materials should be valorised at the highest possible level in a hierarchy that prioritises food and feed use, followed by biochemical and biomaterial extraction, followed by energy recovery through anaerobic digestion or combustion, with land application of residues as the final step, minimising the fraction of organic material that is disposed of without any value recovery.

Biogas production from organic waste through anaerobic digestion (AD) is particularly relevant to India's energy transition, providing a pathway for converting municipal food waste, agricultural residues, and sewage sludge into renewable biomethane that can substitute for natural gas in cooking, transportation, and industrial heating applications. India's GOBAR-Dhan scheme, Sustainable Alternative Towards Affordable Transportation (SATAT) scheme and the National Bioenergy Programme provide policy frameworks for biogas development, but realising the technical potential of India's organic waste resource base requires attention to collection system design, AD technology selection appropriate to Indian feedstock compositions, and gas upgrading and grid injection infrastructure. CIECE's research in anaerobic digestion process optimisation and biogas upgrading is directly relevant to this agenda.

Agricultural residue burning, which generates approximately 141 million tonnes of crop residue annually with a significant fraction burned in the field, particularly in Punjab, Haryana, and Uttar Pradesh, represents one of India's most tractable industrial ecology problems: the material burned wastefully in the field is simultaneously a resource deficit in industries seeking biomass feedstocks for energy, bio-based materials, and industrial process inputs. The IS opportunity, connecting paddy straw-generating farmers with paper mills, particle board manufacturers, biogas plants, and briquette producers, has been technically demonstrated but requires supply chain logistics investment, farmer price support mechanisms, and regulatory clarity to realise at scale.

8. INTERNATIONAL BENCHMARKING AND LEARNING

8.1 Denmark: Kalundborg and the Evolution of Industrial Symbiosis

Denmark's Kalundborg Symbiosis is the world's first intentional industrial symbiosis and the most researched IS network in the academic literature. The network has grown from four founding partners to some 30 public and private partners sharing some 37 streams of waste, water and energy, resulting in annual environmental savings of 635,000 tonnes of CO_2 equivalent, 1.9 million cubic metres of water and 87,000 tonnes of materials (Kalundborg Symbiosis, 2022). The Danish government's investment in documenting, promoting and institutionalising the Kalundborg model through the Danish EPA's industrial symbiosis programme and the subsequent co-funding of the IS research network of the ISIE is a model for government facilitation of IS that has been studied and partially replicated.

The lessons learnt from Denmark that are relevant to India are: informal trust and repeated interaction between the facility managers is essential for sustaining IS networks over time; geographic proximity, preferably within 30 kilometres, is important to keep logistics costs manageable; a dedicated facilitation organisation with sustained public funding to manage information, negotiate exchanges and resolve regulatory barriers is valuable; and the time horizons required for IS networks to mature are long, with Kalundborg having taken over 20 years to reach its current scale..

8.2 China: Circular Economy at National Scale

The national Circular Economy programme in China is the most ambitious government-led IE programme in the world, launched by the Circular Economy Promotion Law of 2008 and followed by a series of five-year plans. China has set up more than 100 nationally designated Circular Economy Demonstration Parks, hundreds of eco-industrial parks with national standards (HJ 274), and a complete set of sector-specific targets for resource productivity, waste recycling and industrial water reuse (Yuan et al., 2018). China's experience is both inspirational and cautionary for India: the scale and pace of China's CE programme implementation has led to measurable improvements in the resource efficiency of industry, but the designation of eco-industrial parks from the top down without proper consideration of market conditions and enterprise incentives has led to some parks being certified without the formation of a genuine IS network.

The lesson that India has learnt from China is that the government designation and provision of infrastructure are not sufficient for IS development. The Chinese experience also shows the importance of embedding CE targets in regional economic planning processes: In China, the provincial governments are assessed on CE performance indicators as well as economic growth indicators, which provides institutional incentives for CE investment at the provincial level that are not currently available in India.

8.3 European Union: Policy Architecture and Extended Producer Responsibility

The EU Circular Economy Action Plans of 2015 and 2020 offer the most extensive policy framework for circular economy transition in any major economic bloc. The EU approach is unique in that it incorporates design stage product regulations via the Ecodesign for Sustainable Products Regulation, end-of-life management requirements via the Waste Framework Directive and sector-specific waste stream regulations, and monitoring infrastructure via the Circular Economy Monitoring Framework with its 24 indicators grouped into four categories of production, consumption, waste management and secondary raw materials.

The EU experience shows that the combination of the Energy Labelling Regulation and the Ecodesign Directive has already led to product efficiency gains that are estimated to save European consumers 120 billion euros per year, and to the reduction of the environmental impact of hundreds of product categories, by imposing minimum recycled content, repairability requirements and information disclosure obligations that have transformed the market upstream of end-of-life. This report recommends that India develop similar product design regulations, starting with high-priority categories like electronic equipment, tyres, batteries, and packaging.

9. CSIR-NEERI AND CENTRE FOR INDUSTRIAL ECOLOGY AND CIRCULAR ECONOMY: INSTITUTIONAL MANDATE AND RESEARCH AGENDA

9.1 CSIR-NEERI's Role in Indian Environmental Science

The CSIR - National Environmental Engineering Research Institute (CSIR-NEERI) was founded in 1958 in Nagpur, India, and is one of the forty laboratories of the Council of Scientific and Industrial Research, the country's premier research body. CSIR-NEERI has made significant contributions in the areas of air pollution monitoring and control, water and wastewater treatment, solid and hazardous waste management and environmental impact assessment over the last 60 years. It conducts research in areas of fundamental science, applied technology development, field demonstration and policy advisory, for national government bodies, state governments, industry associations and international organisations.

The mandate of CSIR-NEERI places it in a unique position to be the national anchor institution for industrial ecology research and policy advisory in India. The national network of zonal laboratories and its wide links with industry and government, together with its disciplinary breadth, which includes environmental chemistry, environmental engineering, environmental microbiology and environmental economics, gives the institutional basis for a comprehensive IE research programme. This mandate has been formally institutionalised in the Centre for Industrial Ecology and Circular Economy (CIECE) at CSIR-NEERI.

9.2 CIECE: Research Programme and Priority Areas

The research priorities of CIECE are organized into five priority areas, which align with the key scientific and policy gaps identified in this Report. The first priority is the development of India's national material flow account, which involves compiling the national material flow account on an annual basis following the Eurostat methodology, disaggregating the national accounts to the state and sector level, and building a time series of national material flow accounts from 2000 to the present to facilitate trend analysis and indicator monitoring. This programme will be carried out in collaboration with MoSPI, CPCB and international partners such as the UNEP International Resource Panel.

The second priority is to build an India specific LCA background database. This effort, which is likely to be the most impactful in CIECE's research program in terms of its downstream applications to LCA quality and policy relevance for all industrial sectors in India, will aggregate life cycle inventory data for the most important industrial processes, energy systems, and agricultural production systems in India, validate these data against independent measurements, and provide them to the Indian LCA research community via a publicly accessible, nationally governed data infrastructure.

The third priority is industrial symbiosis research and facilitation, encompassing the academic study of IS network formation processes in Indian industrial clusters, the development of IS facilitation methodologies adapted to the Indian institutional context, and the practical facilitation of IS networks in selected pilot clusters in partnership with state pollution control boards, industry associations, and district administrations. The fourth priority is circular economy metrics and monitoring, developing India-specific circular economy indicators that supplement international frameworks with metrics relevant to India's informal sector, its agricultural-industrial linkages, and its regional heterogeneity. The fifth priority is policy research and advisory, providing evidence-based analysis of proposed and enacted circular economy and waste management policies.

9.3 Capacity Building and Knowledge Transfer

CIECE's knowledge mission extends beyond research production to encompass training, education, and the building of IE capacity in India's professional and research communities. A structured capacity building programme will deliver short-term executive training in MFA, LCA, and IS facilitation for professionals in government, industry, and consulting; postgraduate courses in industrial ecology and circular economy for CSIR, university, and IIT students; and doctoral research supervision in IE methods and applications. CIECE will also develop open-access educational resources in IE methodologies adapted for the Indian context, making professional development in IE accessible to practitioners in smaller cities and institutions that cannot readily access centralised training programmes.

International collaboration is integral to CIECE's research and capacity building agenda. Formal partnerships are being developed with the Yale Center for Industrial Ecology, the ISIE, the UNEP International Resource Panel, the Wuppertal Institute for Climate, Environment and Energy, and the Ellen MacArthur Foundation, providing access to the global frontier of IE research, methodological development, and policy practice. These partnerships will support CIECE in contributing to international research databases, participating in global monitoring initiatives, and positioning India's industrial ecology research agenda within the global scholarly conversation.

10. IMPLEMENTATION ROADMAP

10.1 Overview of the Three-Phase Approach

The implementation roadmap proposed in this Report is structured across three temporal phases: a Foundation Phase (2026–2028) focused on institutional establishment, data infrastructure development, and pilot programme initiation; a Scaling Phase (2029–2032) focused on replication of proven models, regulatory reform, and national programme deployment; and an Integration Phase (2033–2035) focused on embedding IE principles in mainstream industrial governance, achieving measurable improvement in national circular economy indicators, and positioning India as a global leader in IE research and practice.

10.2 Phase 1: Foundation (2026–2028)

The Foundation Phase encompasses seven priority actions. First, the formal establishment of CIECE as a national centre of excellence in industrial ecology, with dedicated budget allocation, staffing of 40 to 60 research and technical professionals, and infrastructure for MFA, LCA, and IS research. Second, the initiation of India's economy-wide Material Flow Account compilation, producing the first complete national MFA for India covering the period 2015 to 2025, in partnership with MoSPI and in accordance with Eurostat methodology.

Third, the launch of three IS pilot facilitation programmes in selected industrial clusters: one chemical and petrochemical cluster (Dahej, Gujarat), one MSME foundry cluster (Rajkot, Gujarat or Coimbatore, Tamil Nadu), and one agro-processing cluster (a Madhya Pradesh food processing zone), to generate evidence, develop facilitation methodology, and demonstrate IS outcomes in the Indian context. Fourth, the development of the regulatory reform proposals for by-product recognition and IS permit streamlining, for submission to MoEFCC and the Central Pollution Control Board.

Fifth, the establishment of the National Industrial Symbiosis Exchange (NISE) digital platform in beta version, initially covering the three pilot cluster areas and expanding progressively to national coverage. Sixth, the initiation of India-specific LCA background database development, beginning with the energy, steel, cement, and plastic sub-sectors that contribute most significantly to LCA uncertainty in Indian applications. Seventh, the delivery of the first cohort of IS Facilitation Certificate Programme training, targeting 200 professionals in state pollution control boards, industry associations, and district industries centres.

10.3 Phase 2: Scaling (2029–2032)

The Scaling Phase is designed to replicate and extend the institutional and programmatic foundations established in Phase 1. The NISE platform will be extended to national coverage, with targets of 1,000 registered enterprises, 500 documented IS exchange opportunities, and 200 facilitated IS transactions per year by 2032. IS facilitation programmes will be extended to 20 industrial clusters across 10 states, covering a diverse range of industrial sectors and geographic contexts. Regulatory reform outcomes from Phase 1 will be implemented, including the by-product recognition framework and the amended IS permit procedures.

National material flow accounts will be published annually and integrated into India's System of National Accounts through the SEEA framework. Sector-specific MFA reports will be developed for the five highest material-intensity sectors: construction, steel, chemicals, textiles, and agriculture. The India LCA database will be expanded to cover 200 representative industrial processes and made publicly available through a national data portal. A mandatory material flow reporting requirement, modelled on the UK's Environmental Reporting Guidelines and adapted to the Indian statutory context, will be developed and piloted with 500 large industrial enterprises before national roll-out.

10.4 Phase 3: Integration (2033–2035)

The Integration Phase aims to embed IE principles in mainstream industrial governance and achieve measurable improvement in India's national circular economy performance. Target outcomes for 2035 include a 20 per cent improvement in India's national material productivity relative to the 2025 baseline, a 15 per cent increase in the industrial waste recycling rate, the establishment of IS networks in 50 industrial clusters processing a combined 20 million tonnes of waste annually, and the achievement of international recognition for India's IE research community through ISIE membership growth, publication impact, and leadership in international standard-setting processes.

Institutional integration targets for 2035 include the incorporation of IE-based circular economy monitoring into India's Five-Year statistical framework, the mandatory inclusion of LCA-based environmental product declarations for government-procured infrastructure projects above a specified cost threshold, and the establishment of IE-informed design standards for the construction sector. CIECE will be positioned as a regional hub for IE capacity building in South and Southeast Asia, delivering training programmes and technical advisory to peer institutions in neighbouring countries through SAARC and ASEAN frameworks.

8.5 Key Milestones

The following table presents the principal milestones across the three implementation phases:

PHASE / TIMELINE	KEY MILESTONES	LEAD INSTITUTION
Phase 1: Foundation (2026–2028)	CIECE established; India MFA initiated; 3 IS pilots launched; NISE beta; LCA database started; 200 professionals trained	CIECE / MoEFCC / CPCB
Phase 2: Scaling (2029–2032)	NISE national; 20 cluster IS programmes; Annual national MFA published; India LCA database public; Mandatory material reporting piloted	CIECE / MoSPI / SPCBs
Phase 3: Integration (2033–2035)	20% material productivity gain; 50 IS cluster networks; LCA-based EPDs mandated; CIECE as regional hub; IE embedded in national statistics	CIECE / NITI Aayog / All Ministries

11. POLICY RECOMMENDATIONS

11.1 Recommendations to the Government of India

The following priority recommendations are addressed to the national government, encompassing the Ministry of Environment, Forest and Climate Change; the Ministry of Statistics and Programme Implementation; the NITI Aayog; and the Prime Minister's Science, Technology, and Innovation Advisory Council (PM-STIAC):

Recommendation 1: Establish a National Industrial Ecology Mission under PM-STIAC, with a dedicated budget allocation for the period 2026 to 2030, mandating CIECE as the lead scientific institution and establishing an inter-ministerial coordination mechanism to align circular economy actions across MoEFCC, MoHUA, Ministry of Steel, Ministry of Chemicals and Petrochemicals, and Ministry of MSME.

Recommendation 2: Commission CIECE and MoSPI to jointly develop India's first nationally harmonised Economy-Wide Material Flow Account, published annually and integrated into India's SEEA-compliant national environmental accounts by 2028.

Recommendation 3: Amend the Hazardous and Other Wastes Rules, 2016, to introduce a by-product recognition pathway and a streamlined Industrial Symbiosis facilitation permit, reducing the administrative burden on IS exchanges involving materials that meet defined composition, purity, and intended use criteria.

Recommendation 4: Mandate Extended Producer Responsibility schemes for construction materials, textiles, and agricultural plastic mulch films, extending the EPR principle to sectors currently outside its scope, and reform existing EPR schemes for e-waste and plastic packaging to mandate genuine circular design rather than compliance certificate trading.

Recommendation 5: Introduce mandatory material flow reporting for industrial enterprises above a specified size threshold, requiring annual disclosure of material inputs, water use, waste generation and recycling rates in a standardised format compatible with national MFA compilation and public benchmarking.

Recommendation 6: Develop Green Public Procurement standards specifying minimum recycled content requirements for key product categories in government procurement, beginning with construction materials, packaging, and office supplies, leveraging the Government e-Marketplace (GeM) portal as the implementation mechanism.

11.2 Recommendations to State Governments

State governments are recommended to: designate IE Facilitation Units within State Pollution Control Boards, staffed with trained MFA and IS professionals; establish state-level Industrial Symbiosis Exchanges integrated with the national NISE platform; develop state circular economy strategies aligned with national targets but calibrated to state-specific industrial structure and resource endowment; integrate IE-informed design requirements into state building codes, industrial estate development norms, and state procurement standards; and allocate dedicated budgets for industrial cluster environmental upgrade programmes, drawing on the National Clean Air Programme, Smart Cities Mission, and National Industrial Corridor Development frameworks.

11.3 Recommendations to Research and Academic Institutions

India's universities, IITs, NITs, and CSIR laboratories are recommended to integrate industrial ecology methods, including MFA, LCA, and IS analysis, into undergraduate and postgraduate environmental engineering and management curricula; establish research collaborations with CIECE on priority IE topics including India-specific LCA database development, informal sector integration, and critical material flow analysis; apply for international collaborative grants through programmes including the India-EU Science and Technology Agreement, the UKRI-DST Newton-Bhabha Fund, and the Indo-US Science and Technology Forum to build IE research capacity; and contribute to open-access publication of India-specific IE data and research findings to build the national knowledge commons.

11.4 Recommendations to Industry and Business

Indian industry associations and individual enterprises are recommended to voluntarily adopt Material Flow Analysis at the enterprise and cluster level as a tool for identifying resource efficiency and cost reduction opportunities, in advance of mandatory reporting requirements; engage with the National Industrial Symbiosis Exchange platform as both providers and potential recipients of industrial by-products; invest in the upgrading of secondary materials processing infrastructure, recognising the strategic and economic value of domestic secondary materials supply chains; incorporate circular design principles into product development processes, engaging with LCA as a tool for identifying design-stage interventions with the greatest environmental and economic leverage; and support the development of India's LCA background database by sharing process-level inventory data with CIECE under appropriate confidentiality protections.

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IN ASSOCIATION WITH

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Acknowledgements

The author gratefully acknowledge the support and guidance provided by CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur in the preparation of this report. The contributions of experts, colleagues, and stakeholders who provided valuable inputs and insights are duly acknowledged.

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This report is based on secondary data, field insights, and professional interpretation. While due care has been taken to ensure accuracy, CSIR-NEERI and the author shall not be held responsible for any unintended errors or omissions. The views expressed in this report are those of the authors and do not necessarily represent the official views of CSIR-NEERI or any other affiliated organization.