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ARTICLE

# Bioeconomic Policy Pathways for Structural Transformation in India: An E3 (Economy–Environment–Employment) Framework for 2050

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## ABSTRACT

The growing need to reconcile economic growth with environmental sustainability and employment generation has positioned the bioeconomy as a central pathway for long-term structural transformation. However, existing research has largely examined economic, environmental, and labour-market dimensions separately, limiting understanding of their integrated developmental effects in emerging economies. This study develops an integrated 'Economy–Environment–Employment (E3)' analytical framework to evaluate the long-term implications of India's BioE3 (Biotechnology for Economy, Environment, and Employment) initiative through 2050. The analysis combines environmentally extended input–output modelling, dynamic scenario simulations, and a composite E3 transition index to compare baseline, policy-driven, and accelerated transformation pathways. The framework captures how inter-sectoral economic interactions influence environmental emissions and employment restructuring under alternative policy scenarios. The BioE3 architecture examined includes biomanufacturing clusters, bio-foundries, biotechnology innovation hubs, circular bioresource systems, targeted research and development incentives, and biotechnology-oriented skill-development programmes. Results indicate that the accelerated BioE3 pathway significantly expands bio-based manufacturing and knowledge-intensive services while reducing carbon intensity by approximately 42% relative to the baseline scenario by 2050. Simultaneously, the share of high-skilled employment rises from 18% to nearly 29%, indicating a transition toward innovation-intensive production systems. The findings further demonstrate that early investments in biotechnology infrastructure and innovation ecosystems generate cumulative and mutually reinforcing economic, environmental, and employment benefits. Nevertheless, the scale

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and spatial distribution of these gains depend on institutional coordination, regionally differentiated implementation, and sustained human-capital development. The study contributes a policy-oriented framework for assessing bioeconomic structural transformation in emerging economies.

***Keywords:*** Bioeconomy; Structural Transformation; BioE3 Policy; Circular Economy; Sustainable Development

# 1. Introduction

The intensifying pressures of climate change, ecological degradation, resource insecurity, and employment transition have increasingly challenged conventional models of fossil-intensive economic growth. As economies seek pathways capable of reconciling industrial expansion with environmental sustainability and social inclusion, the bioeconomy has emerged as an important framework for long-term structural transformation [1,2]. By integrating renewable biological resources, biotechnology-driven innovation, and circular production systems, the bioeconomy is increasingly viewed not merely as a sectoral strategy, but as a systemic transition capable of reshaping production, consumption, and technological trajectories across agriculture, manufacturing, energy, and services [3,4]. Recent international evidence further suggests that bioeconomic transitions can simultaneously contribute to decarbonization, industrial modernization, and knowledge-intensive employment generation, thereby positioning the bioeconomy within broader sustainability-transition and green-growth discourses [5,6].

The developmental significance of such transitions is particularly pronounced in India, where rapid economic growth coexists with rising environmental stress, regional disparities, and persistent labour-market challenges. India possesses substantial biological-resource diversity, expanding biotechnology capabilities, and increasing policy support for innovation-oriented development [7]. However, uneven technological capacities, fragmented industrial ecosystems, and disparities in infrastructure and human capital continue to constrain balanced structural transformation. These conditions raise a central policy question: can bioeconomic transitions generate mutually reinforcing economic, environmental, and employment outcomes within a heterogeneous emerging-economy context?

India's BioE3 (Biotechnology for Economy, Environment, and Employment) initiative represents an important policy response to this challenge. The framework promotes biotechnology-led industrial transformation through policy instruments including biomanufacturing hubs, bio-foundries, translational research platforms, circular bioresource systems, innovation financing, and biotechnology-oriented skill-development programmes [8]. Unlike conventional industrial policies focused narrowly on output growth, the BioE3 framework explicitly seeks to integrate economic competitiveness, ecological sustainability, and employment generation within a mission-oriented development architecture.

Despite growing policy and academic interest, important gaps remain in the existing literature. First, most studies evaluate economic, environmental, or employment effects separately, limiting understanding of their interdependence within broader structural-transition processes [9,10]. Second, existing analyses are frequently static or sector-specific, offering limited insight into long-run transformation dynamics under alternative policy pathways [11]. Third, insufficient attention has been devoted to regional heterogeneity and differential absorptive capacities in emerging economies, particularly in relation to biotechnology-led transitions [12,13]. Consequently, the developmental implications of bioeconomic transformation for integrated Economy–Environment–Employment (E3) outcomes remain inadequately examined.

Against this backdrop, the present study develops an integrated E3 analytical framework to assess how alternative BioE3 transition pathways may reshape India's structural transformation trajectory through 2050. The study addresses three interrelated research objectives: (i) to examine regional and sectoral variations in bioeconomic development patterns; (ii) to evaluate the extent to which BioE3-driven transitions can simultaneously improve economic performance, environmental sustainability, and employment generation; and (iii) to identify the policy mechanisms required for balanced and inclusive bioeconomic transformation.

Methodologically, the study combines environmentally extended input–output modelling, econometric analysis, efficiency-oriented analytical concepts, and dynamic scenario simulations within a unified long-run framework. The novelty of the study lies in its explicit integration of economic restructuring, environmental transition, and labour-market transformation into a single multidimensional E3 framework extending to 2050. In addition, the analysis incorporates national, sectoral, and regional dimensions simultaneously, thereby enabling a more comprehensive evaluation of policy effectiveness and spatial heterogeneity than existing bioeconomy studies.

The paper contributes to the emerging literature on mission-oriented sustainability transitions in four important respects. First, it develops a multidimensional analytical structure linking bioeconomic policy architecture with measurable E3 outcomes. Second, it advances dynamic long-term modelling of biotechnology-led structural transformation under alternative transition scenarios. Third, it integrates sustainability, efficiency, and employment dimensions within a coherent empirical framework. Finally, it situates India's BioE3 initiative within the broader international discourse on bioeconomy-driven development transitions, thereby providing a policy-relevant framework for understanding how emerging economies may pursue resilient, inclusive, and environmentally sustainable structural transformation.

## 2. BioE3 Paradigm, Global Bioeconomy Dynamics, and Structural Transformation in India

The contemporary global transition toward sustainable and innovation-driven development has significantly elevated the strategic importance of the bioeconomy within national and international policy frameworks. Increasing pressures arising from climate change, ecological degradation, resource insecurity, technological disruption, and labour-market restructuring have exposed the limitations of conventional fossil-intensive industrialization models and stimulated the search for alternative development pathways capable of simultaneously achieving economic growth, environmental sustainability, and social inclusion [1,2]. Within this evolving context, the bioeconomy has emerged not merely as a collection of biotechnology-related sectors, but as a broader systemic transformation framework integrating renewable biological resources, biotechnology-driven innovation, circular production systems, and knowledge-intensive industrial restructuring [3,4].

Globally, the bioeconomy has increasingly become associated with long-term structural transformation strategies involving decarbonization, technological modernization, industrial diversification, and sustainability-oriented competitiveness. Contemporary bioeconomic transitions are characterized by the convergence of biotechnology with artificial intelligence, digital manufacturing systems, automation, genomics, advanced materials, and data-driven industrial platforms [6]. Such convergence has accelerated innovation cycles, facilitated commercialization pathways, improved process efficiency, and expanded the scope of biotechnology applications across agriculture, manufacturing, healthcare, energy, environmental services, and logistics.

At the same time, international evidence demonstrates that bioeconomy trajectories remain highly heterogeneous across countries and regions owing to differences in institutional capacity, technological capability, resource endowments, industrial structures, governance systems, and policy priorities [3,6]. In the European Union, bioeconomy activities remain relatively concentrated in agriculture, forestry, biomass-intensive production systems, and food-processing industries, generating substantial employment absorption but comparatively lower technological intensity [3]. By contrast, emerging second-generation bioeconomy models increasingly emphasize advanced biomanufacturing, synthetic biology, industrial biotechnology, precision therapeutics, bioinformatics, and high-value bio-based industrial systems [4,7].

Importantly, critical scholarship cautions that bioeconomy transitions are not inherently sustainable and may generate significant trade-offs involving land-use pressures, biomass competition, biodiversity risks, resource extraction intensity, and uneven regional development if not accompanied by robust governance mechanisms and sustainability safeguards [14,15]. Consequently, contemporary bioeconomy policy increasingly emphasizes mission-oriented governance, circularity, adaptive regulation, integrated innovation ecosystems, and sustainability-transition frameworks capable of balancing industrial competitiveness with ecological resilience and social inclusion [6,9].

Within this broader international transition, India's evolving BioE3 (Biotechnology for Economy, Environment, and Employment) framework represents an important attempt to institutionalize biotechnology-led structural transformation through an integrated 'Economy–Environment–Employment (E3)' architecture. Rather than functioning as a narrowly sectoral biotechnology strategy, the BioE3 paradigm conceptualizes biotechnology as a cross-sectoral technological platform capable of reshaping production structures, environmental systems, labour-market dynamics, and regional development trajectories simultaneously.

## 2.1. Evolution of India's Bioeconomy Policy Architecture

India's bioeconomy policy architecture has evolved through a cumulative and multi-layered institutional process reflecting the growing recognition of biotechnology as a strategic instrument for sustainable development, industrial modernization, and global competitiveness. The institutional foundations of this trajectory were established through the creation of the Department of Biotechnology (DBT) in 1986, followed subsequently by the expansion of biotechnology governance institutions, translational research ecosystems, public–private innovation platforms, and mission-oriented policy interventions.

Over time, India's biotechnology policy orientation gradually shifted from a predominantly research-centric approach toward a more integrated innovation ecosystem encompassing scientific research, commercialization, entrepreneurship, industrial-scale biomanufacturing, and sustainability-oriented industrial transformation. Institutional developments such as the Biotechnology Industry Research Assistance Council (BIRAC), translational research programmes, biotechnology incubators, and innovation financing mechanisms contributed significantly to strengthening linkages between research systems and industrial deployment.

India's bioeconomy has expanded rapidly during the past decade, although available estimates differ across institutional sources due to variations in sectoral coverage, valuation methodologies, and treatment of biotechnology-enabled services. Official assessments released by the Department of Biotechnology and associated policy reports indicate that the size of India's bioeconomy increased from approximately USD 10 billion in 2014 to nearly USD 130–165 billion by 2024–2025, depending upon the inclusion of downstream biotechnology applications, digital bio-services, and biopharmaceutical exports. Consequently, the present study adopts a range-based interpretation rather than a fixed-point estimate in recognition of the evolving and heterogeneous nature of bioeconomy accounting.

This expansion has been driven by multiple biotechnology sub-sectors, including biopharmaceuticals, industrial biotechnology, agricultural biotechnology, bioenergy, bioinformatics, and biotechnology-enabled services, alongside increasing inter-sectoral integration across manufacturing and service value chains. The observed growth trajectory reflects not only market expansion, but also the cumulative effects of sustained public investment in scientific infrastructure, entrepreneurial ecosystems, biotechnology innovation systems, and mission-oriented industrial policies.

Importantly, official projections envisioning the expansion of India's bioeconomy toward approximately USD 300 billion by 2030 should be interpreted as strategic policy aspirations articulated within government roadmaps rather than deterministic outcomes generated independently by the present model. Accordingly, the current study employs the 2030 benchmark as a calibrated scenario parameter within the BioE3 simulation framework to evaluate the potential structural implications of accelerated bioeconomic transition under varying institutional and technological conditions. The modelling framework therefore does not assume automatic realization of this target; instead, it examines the economy–environment–employment consequences conditional upon differing levels of technological diffusion, institutional coordination, policy effectiveness, and investment intensity. This distinction is analytically significant because bioeconomic transitions remain path-dependent, institutionally contingent, and sensitive to governance capacity.

## 2.2. Pillars of India's Bioeconomy Transition

The policy architecture underlying India's bioeconomy expansion may be analytically interpreted through three interrelated pillars:

(i) Research and innovation support;
(ii) Industrial and entrepreneurial ecosystem development; and
(iii) Sustainability-oriented regulatory and circular-economy integration.

The first pillar concerns the expansion of biotechnology research and innovation systems through sustained public investment in scientific infrastructure, centres of excellence, translational research networks, and interdisciplinary innovation platforms. Recent initiatives such as Bio-RIDE (Biotechnology Research Innovation and Entrepreneurship Development) seek to consolidate previously fragmented programmes while strengthening commercialization pathways linking laboratory-scale innovation with industrial-scale deployment.

The second pillar relates to industrial ecosystem development and biotechnology entrepreneurship. India has experienced rapid expansion in biotechnology incubators, start-up financing systems, public–private partnerships, and biomanufacturing support mechanisms. The increase in biotechnology start-ups—from fewer than one hundred entities in the early 2010s to several thousand by the mid-2020s—illustrates the emergence of a broad innovation-oriented industrial ecosystem. Simultaneously, the gradual spatial diffusion of biotechnology activities beyond major metropolitan centres toward emerging regional clusters reflects the decentralization of bioeconomic capabilities across Indian states.

The third pillar involves the integration of sustainability objectives within biotechnology and industrial policy frameworks. India's evolving bioeconomy strategy increasingly incorporates circular-economy principles, resource-efficiency approaches, renewable biological-resource utilization, and climate-mitigation objectives associated with low-carbon and net-zero transition pathways. Consequently, the bioeconomy is increasingly conceptualized not merely as a biotechnology sector, but as part of a broader structural transformation agenda linking industrial modernization, ecological sustainability, and employment generation.

From an analytical perspective, this policy evolution signifies a transition from fragmented biotechnology promotion toward a more integrated and mission-oriented BioE3 development architecture. The significance of this transition lies not solely in biotechnology-sector expansion, but in the emergence of systemic interactions among innovation systems, industrial restructuring, environmental transition, and labour-market transformation.

### 2.3. Mission-Oriented Governance and Institutional Convergence

A defining feature of India's contemporary bioeconomy policy architecture is the increasing emphasis on mission-oriented governance and institutional convergence. Rather than relying on isolated sectoral interventions, recent policy initiatives adopt a systems-oriented perspective integrating multiple technological domains, stakeholders, governance levels, and sustainability objectives. This approach is consistent with contemporary theories of mission-oriented innovation systems emphasizing the role of coordinated public policy in addressing complex societal challenges through targeted technological transformation pathways.

In the Indian context, this convergence is particularly evident in the integration of biotechnology with artificial intelligence, digital technologies, advanced manufacturing systems, genomics, and sustainability-transition frameworks. Institutional initiatives involving bio-foundries, biomanufacturing hubs, Bio-AI platforms, translational innovation systems, and biotechnology-enabled industrial clusters represent strategic attempts to accelerate commercialization, enhance technological scaling, and reduce the time lag between scientific discovery and industrial application.

The policy architecture further incorporates multi-level governance mechanisms involving central–state coordination, industry–academia partnerships, international collaborations, innovation financing systems, and regionally differentiated implementation strategies. These arrangements are essential for overcoming coordination failures, mobilizing technological and financial resources, facilitating innovation diffusion, and reducing regional disparities in biotechnology capability formation. Nevertheless, the effectiveness of such institutional arrangements remains contingent upon regulatory coherence, governance quality, administrative capacity, and incentive alignment across stakeholders.

### 2.4. The BioE3 Paradigm and the E3 Structural Transformation Nexus

The formal approval of the BioE3 (Biotechnology for Economy, Environment, and Employment) policy by the Union Cabinet in August 2024 represented an important institutional consolidation of India's evolving bioeconomy strategy rather than the initiation of biotechnology-led development itself. Prior to the formal policy articulation, India had already experienced substantial growth in biotechnology-related activities, including vaccine manufacturing, biopharmaceutical production, agricultural biotechnology, biotechnology start-ups, and innovation-oriented research ecosystems [7,8]. Accordingly, pre-2024 biotechnology expansion should be interpreted as foundational enabling conditions upon which the BioE3 framework seeks to build rather than as outcomes generated directly by the policy.

Within this context, the BioE3 initiative represents a mission-oriented policy architecture intended to coordinate, scale, and accelerate existing biotechnology capabilities through an integrated 'Economy–Environment–Employment (E3)' framework. The policy emphasizes strategic interventions in high-performance biomanufacturing, bio-foundries, precision biotherapeutics, climate-resilient agriculture, circular bioresource systems, carbon-utilization technologies, and biotechnology-oriented human-capital development [6].

Conceptually, the BioE3 paradigm is organized around three mutually reinforcing dimensions:

- The first dimension concerns economic transformation through expansion of bio-based industries, technological upgrading, industrial diversification, productivity enhancement, and higher value addition across manufacturing and service sectors. Biotechnology-intensive sectors such as industrial biotechnology, biopharmaceuticals, precision therapeutics, bio-based chemicals, functional bio-products, and advanced biomanufacturing systems are expected to contribute to knowledge-intensive industrialization and greater technological self-reliance.
- The second dimension involves environmental sustainability through circular bioeconomy principles, renewable-resource utilization, lower carbon intensity, resource efficiency, and reduced dependence on fossil-based production systems. Biotechnology-enabled innovations involving bioenergy, climate-resilient crops, waste valorisation, carbon-utilization technologies, bioremediation systems, and circular production processes are expected to reduce environmental externalities while supporting long-term decarbonization objectives.
- The third dimension concerns employment generation and human-capital transformation through expansion of biotechnology ecosystems, innovation-intensive labour markets, research and development systems, logistics networks, quality-control systems, digital bioservices, and advanced manufacturing activities. The framework places particular emphasis on skill development, interdisciplinary technological competencies, and workforce-transition mechanisms necessary for technologically sophisticated production systems.

Together, these dimensions operationalize the E3 nexus by linking economic modernization, environmental transition, and employment generation within a unified policy architecture. The analytical significance of the BioE3 framework therefore lies in its attempt to reduce the conventional trade-offs between industrial growth and environmental sustainability by generating mutually reinforcing interactions among productivity enhancement, ecological transition, and skilled employment creation.

## 2.5. Circular Bioeconomy Transition and Sustainability Integration

A central component of the BioE3 paradigm is the transition from linear industrial production systems toward a circular and regenerative bioeconomy characterized by renewable biological-resource utilization, biological waste valorisation, closed-loop production systems, and lower environmental intensity. This transition seeks to improve resource efficiency while reducing environmental degradation associated with conventional fossil-intensive industrialization models. Biotechnology-enabled innovations involving bio-based materials, bioenergy systems, industrial bioprocesses, carbon-capture utilization, circular agricultural systems, and biological waste recovery are expected to support both environmental sustainability and industrial competitiveness simultaneously. The substitution of fossil-based inputs with renewable biological resources further contributes to decarbonization and long-term climate-transition objectives.

Importantly, the BioE3 framework is aligned with broader national sustainability initiatives, including the "Lifestyle for Environment (LiFE)" programme and India's net-zero transition commitments. Such alignment embeds biotechnology policy within a broader green-growth and sustainability-transition agenda, thereby reinforcing the role of biotechnology as a key enabling platform for environmentally sustainable industrialization.

Nevertheless, international evidence suggests that circular bioeconomy transitions may also generate sustainability risks involving biomass competition, biodiversity pressures, land-use conflicts, and regional inequalities if not supported by effective governance systems and ecological safeguards [14,15]. Consequently, the long-term sustainability of India's bioeconomy transition depends upon the integration of adaptive regulation, resource-governance systems, environmental monitoring, and institutional coordination mechanisms within the broader BioE3 framework.

## 2.6. Global Policy Paradigms and Implications for India

Comparative international evidence indicates that bioeconomy transitions are strongly influenced by institutional capability, technological infrastructure, innovation systems, and policy orientation. Existing literature broadly identifies three overlapping bioeconomy paradigms:

(i) Biotechnology-oriented models emphasizing industrial innovation and competitiveness;
(ii) Bioresource-oriented models focused on biomass utilization and rural development; and
(iii) Bioecology-oriented approaches prioritizing circularity, ecosystem sustainability, and regenerative production systems [6,9].

Most countries pursue hybrid combinations of these approaches depending on domestic resource conditions, technological capabilities, and development priorities. The European Union emphasizes circularity and sustainability integration, whereas the United States places greater emphasis on industrial biotechnology commercialization and technological competitiveness.

India's BioE3 framework aligns more closely with the second-generation innovation-intensive model, emphasizing advanced biomanufacturing, industrial biotechnology, digital convergence, synthetic biology, and knowledge-intensive industrial restructuring. Consequently, the expected transformation extends beyond simple expansion of bio-based sectors toward broader technological upgrading, productivity enhancement, industrial diversification, and regional restructuring.

International experience further demonstrates that successful bioeconomy transitions depend upon integrated innovation ecosystems linking research institutions, industrial clusters, commercialization systems, financing mechanisms, infrastructure networks, regulatory frameworks, and human-capital formation [16]. Importantly, employment effects vary substantially according to sectoral composition. Biotechnology-intensive industries often generate higher-skilled and higher-productivity employment but comparatively lower direct labour absorption relative to traditional biomass-intensive sectors.

For India, these findings imply that BioE3 outcomes are likely to remain regionally differentiated and institutionally contingent. Consequently, the realization of long-term E3 objectives depends not only on technological innovation, but also on governance quality, regional capability formation, human-capital development, infrastructure expansion, sustainability safeguards, and adaptive policy coordination across heterogeneous regional contexts.

## 2.7. Long-Term Structural Transformation Implications

The integration of biotechnology policy within a mission-oriented E3 framework has potentially significant implications for India's long-term structural transformation trajectory. By promoting high-value and knowledge-intensive industries, the BioE3 paradigm may alter the composition of output, employment structures, industrial organization, trade patterns, and regional development pathways.

The emphasis on biotechnology-enabled industrialization, digital integration, and decentralized biomanufacturing hubs may facilitate the emergence of new industrial sectors while simultaneously revitalizing traditional sectors through technological upgrading and circular production systems. The spatial dimension of the policy is particularly important because regionally distributed biomanufacturing hubs and biomass-based value chains may contribute to more balanced regional development and reduced spatial concentration of industrial activity.

Over the longer term, prospective transformation pathways include expansion of bio-based industries as major contributors to output and exports, greater integration of biotechnology with advanced manufacturing systems, deepening of domestic innovation ecosystems, increased technological self-reliance, progressive decarbonization of industrial systems, and emergence of regionally distributed biotechnology clusters.

However, these outcomes should be interpreted as conditional transition possibilities rather than deterministic outcomes. Their realization depends fundamentally upon effective policy implementation, sustained investment in research and infrastructure, institutional capability formation, regulatory coherence, financing systems, labour-market adaptability, and long-term governance coordination.

Overall, India's evolving bioeconomy policy architecture and the BioE3 paradigm represent an ambitious attempt to institutionalize biotechnology-led structural transformation through an integrated 'Economy–Environment–Employment framework'. By linking industrial modernization, sustainability transition, and employment generation within a mission-oriented policy architecture, the BioE3 framework provides a strategic pathway through which biotechnology-driven innovation may contribute to resilient, inclusive, and environmentally sustainable development in India over the long term.

# 3. Literature Review and Research Gap

Building upon the global dynamics discussed in Section 4, this section reviews the empirical and methodological literature directly relevant to the study objectives. The review focuses specifically on three analytical themes:

(i) Quantitative assessment of bioeconomy transitions;
(ii) Evidence regarding economic, environmental, and employment outcomes; and
(iii) Conceptual and methodological limitations motivating the present study.

## 3.1. Quantitative Approaches to Bioeconomy Analysis

Existing studies primarily employ input–output models, computable general equilibrium frameworks, panel econometrics, efficiency analysis, and spatial modelling approaches to evaluate bioeconomy transitions [16–18]. Input–output and equilibrium models have been widely used to examine sectoral interdependencies, multiplier effects, and macroeconomic impacts associated with bio-based industrialization.

More recent literature increasingly incorporates stochastic frontier analysis (SFA), data envelopment analysis (DEA), and eco-efficiency approaches to evaluate productivity, technological efficiency, and environmental performance [19,20]. Several studies also integrate undesirable outputs such as carbon emissions, thereby enabling simultaneous assessment of productivity and sustainability outcomes.

Spatial and regional analyses further demonstrate that innovation capacity, infrastructure quality, industrial clustering, and institutional capability strongly influence bioeconomy performance and technological diffusion [3]. These findings are particularly relevant for India, where biotechnology ecosystems and industrial capabilities remain spatially concentrated across a limited number of states.

## 3.2. Bioeconomy, Sustainability, and Employment Outcomes

A growing empirical literature suggests that bioeconomy expansion can contribute to technological upgrading, resource efficiency, and reductions in carbon intensity under supportive institutional and policy conditions [21]. Sustainability-transition research further emphasizes the importance of governance quality, innovation systems, and adaptive institutional structures in shaping environmentally sustainable transformation pathways [7].

At the same time, evidence regarding employment outcomes remains mixed. While biotechnology-intensive sectors generate high-skilled employment and productivity gains, they may also exhibit relatively lower direct labour intensity and increasing skill polarization [22]. Consequently, recent studies caution that bioeconomy transitions do not automatically produce inclusive employment outcomes and may generate uneven regional and distributive effects.

Critical scholarship additionally argues that portions of the bioeconomy literature remain excessively "promissory," emphasizing technological potential while underestimating ecological limits, governance constraints, and socioeconomic inequalities [14]. Definitional inconsistencies regarding the boundaries of the bioeconomy further complicate empirical comparison and policy evaluation across countries and sectors [23].

## 3.3. Research Gap and Analytical Contribution

The reviewed literature highlights four major limitations. First, economic, environmental, and employment dimensions are frequently analysed separately rather than within an integrated E3 framework. Second, many studies remain static and sector-specific, limiting their ability to capture long-run structural transformation dynamics. Third, insufficient attention has been devoted to regional heterogeneity and uneven institutional capability in emerging economies. Fourth, existing analyses rarely integrate scenario modelling, efficiency concepts, and environmental assessment within a unified analytical structure.

Against this backdrop, the present study develops an integrated E3-oriented framework combining environmentally extended input–output modelling, econometric analysis, efficiency concepts, and dynamic scenario simulation to evaluate alternative BioE3 transition pathways in India through 2050. The analysis is intended not as a deterministic forecast, but as a structured framework for assessing policy sensitivities, regional heterogeneity, and long-run transformation dynamics associated with biotechnology-led development transitions.

# 4. Methodology: Integrated Modelling Framework, Data Architecture, and Scenario Design

This study develops an integrated quantitative framework to evaluate how bioeconomic policy pathways under the BioE3 paradigm influence long-term structural transformation within an Economy–Environment–Employment (E3) system. The methodological design is explicitly aligned with the three objectives of the study:

(i) Analysing regional heterogeneity in bioeconomy development;
(ii) Evaluating differentiated economic, environmental, and employment outcomes; and
(iii) Identifying policy mechanisms for balanced and inclusive regional transformation.

To address these objectives, the study combines environmentally extended input–output (EEIO) modelling, structural decomposition analysis (SDA), stochastic frontier-inspired efficiency concepts, dynamic scenario simulation, and composite index construction within a unified analytical architecture. The integrated framework enables simultaneous evaluation of production restructuring, environmental performance, labour transformation, and regional disparities over the period 2020–2050[20,23].

## 4.1. Integrated E3 Analytical Framework

The analytical structure represents the economy as an interdependent system of $n$ sectors comprising both conventional and bio-based activities. The foundational structure follows an augmented input–output framework:

$$x = Ax + y$$

where $x \in \mathbb{R}^n$ denotes the vector of gross output, $A \in \mathbb{R}^{n\times n}$ is the matrix of technical coefficients, and $y \in \mathbb{R}^n$ represents final demand.

The equilibrium solution is obtained through the Leontief inverse:

$$x = (I - A)^{-1}y = Ly$$

where $L$ captures total direct and indirect production requirements. This formulation enables tracing of inter-sectoral linkages and structural interdependencies associated with bioeconomic transformation[23,24].

The framework is extended through environmental and labour satellite accounts to estimate emissions, resource use, employment multipliers, and skill transitions.

## 4.2. Environmental and Employment Extensions

Environmental externalities are incorporated using the EEIO approach. Let $e$ denote sectoral emission coefficients and $r$ represent biomass or resource-use coefficients. Total environmental impacts are estimated as:

$$E = e^{'}Ly$$

and total resource utilization as:

$$R = r^{'}Ly$$

These expressions capture both direct and indirect environmental footprints embedded within production and consumption systems. EEIO models have been extensively applied in sustainability transition and carbon-accounting studies[17,25].

Employment effects are modelled through labour coefficients:

$$L = l^{'}Ly$$

where $l$ denotes employment intensity by sector. To analyse labour market restructuring, employment is decomposed into high-, medium-, and low-skilled categories:

$$l = l^{(h)} + l^{(m)} + l^{(l)}$$

This decomposition enables assessment of skill-biased technological change associated with biotechnology-intensive sectors and knowledge-based production systems[26–28].

## 4.3. Structural Decomposition and Efficiency Assessment

To identify the determinants of structural transformation, the study employs structural decomposition analysis (SDA). Variations in output are decomposed as:

$$\Delta x = \Delta L \cdot y_0 + L_0 \cdot \Delta y + \Delta L \cdot \Delta y$$

Similarly, changes in emissions are decomposed into technological, structural, and demand-side effects:

$$\Delta E = (\Delta e^{'})Ly + e^{'}(\Delta L)y + e^{'}L(\Delta y)$$

This framework isolates the relative contributions of:

- Technological efficiency improvements,
- Sectoral reallocation,
- Bio-based substitution,
- Demand expansion.

To complement SDA, the methodology incorporates concepts derived from stochastic frontier analysis (SFA), enabling comparison between observed sectoral performance and best-practice production frontiers. Efficiency benchmarking is particularly important for evaluating regional heterogeneity across Indian states characterized by differing technological capabilities, innovation ecosystems, and infrastructure conditions[20,26,29,30].

## 4.4. Dynamic Scenario Modelling

Long-term structural transformation dynamics are simulated through a recursive dynamic framework extending to 2050. The modelling approach is designed as a scenario-based analytical framework intended to evaluate the potential macroeconomic and sectoral implications of alternative bioeconomy transition pathways under the BioE3 strategy, rather than as a deterministic forecasting model.

Capital accumulation evolves according to the standard recursive accumulation identity:

$$K_{t+1} = (1 - \delta)K_t + I_t$$

where $K_t$ denotes the capital stock in period $t$, $\delta$ represents the sector-specific depreciation rate, and $I_t$ denotes gross investment.

Sectoral production is represented using an augmented Cobb–Douglas production structure:

$$Y_i = A_i K_i^{\alpha_i} L_i^{\beta_i} B_i^{\gamma_i}$$

where $Y_i$ denotes sectoral output; $K_i$ and $L_i$ represent capital and labour inputs respectively; and $B_i$ captures bio-based intermediate inputs, including biomass utilisation intensity, bio-based feedstock incorporation, biotechnology-enabled process integration, and related bio-manufacturing inputs.

The production elasticities $(\alpha_i,\ \beta_i,\ \gamma_i)$ are calibrated using benchmark national accounts aggregates, sectoral input–output relationships, and observed factor-income shares reported in India's macroeconomic and industrial statistics. The bio-based input coefficient $\gamma_i$ is not imposed exogenously as a policy assumption; rather, it is parameterised using observed differences in biomass dependence, biotechnology adoption intensity, and bio-based value-added shares across sectors. Sectors characterised by greater integration of bio-based production systems—such as biopharmaceuticals, bioenergy, industrial biotechnology, and bio-based chemicals—are therefore assigned relatively higher calibrated bio-input elasticities based on their empirically observed production structures.

Technological progress evolves dynamically according to:

$$A_i(t) = A_i(0)e^{\lambda_i t}$$

where $\lambda_i$ denotes the sector-specific rate of total factor productivity growth.

Importantly, the technological progress parameters are not arbitrarily assumed to be higher in bioeconomy sectors. Instead, alternative $\lambda_i$ trajectories are scenario-calibrated using evidence from observed productivity differentials, R&D intensity, patenting trends, biotechnology diffusion rates, and historical learning effects reported in the bioeconomy and industrial innovation literature. Under the BioE3 policy scenario, higher values of $\lambda_i$ are assigned only for sectors where policy support is expected to enhance innovation diffusion, scale economies, process efficiency, and endogenous technological upgrading. The baseline scenario, by contrast, assumes continuation of historical productivity trends without accelerated bioeconomy intervention.

Accordingly, the divergence between baseline and BioE3 scenarios emerges from differential innovation trajectories, investment allocation patterns, and bio-based input integration rather than from tautological assumptions of superior sectoral performance. The framework thereby captures cumulative learning effects, endogenous productivity enhancement, and structural transformation dynamics associated with sustained bioeconomy transition pathways [31–35].

## 4.5. E3 Composite Index and Variable Construction

To evaluate multidimensional outcomes, the study constructs a composite E3 index integrating economic, environmental, and employment dimensions:

$$E3 = w_1 E_c + w_2 E_n + w_3 E_m$$

where:

- $E_c$ denotes economic performance,
- $E_n$ environmental sustainability,
- $E_m$ employment performance.

Indicators are normalized using min–max scaling:

$$Z_i = \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)}$$

Weights are derived using entropy and principal component methods to minimize subjective bias in aggregation [24].

The principal variables include:

**Economic Indicators**

- Bioeconomy value added,
- Sectoral productivity,
- Gross value-added growth,
- Investment intensity.

**Environmental Indicators**

- Carbon intensity,
- Biomass utilization efficiency,
- Resource-use efficiency,
- Emission reduction coefficients.

**Employment Indicators**

- Employment elasticity,
- Skill intensity,
- Labour productivity,
- Sectoral employment multipliers.

Together, these indicators enable integrated evaluation of E3-oriented structural transformation across regions and scenarios.

## 4.6. Data Architecture and Regional Classification

The empirical implementation integrates multiple datasets through sectoral concordance matrices linking economic, environmental, technological, and labour indicators.

The principal datasets include:

- National Accounts Statistics and supply–use tables (Government of India) [36],
- World Bank World Development Indicators [37,38],
- Organisation for Economic Co-operation and Development (OECD) Inter-Country Input–Output (ICIO) database [39],
- EORA Multi-Region Input–Output database [40],
- International Energy Agency (IEA) emissions statistics,
- Global Carbon Project datasets [41–43],
- ILOSTAT and Periodic Labour Force Survey data [44,45],
- Department of Biotechnology and BIRAC reports [46–49].

To analyse regional heterogeneity, Indian states are classified into two broad groups:

**Advanced Bioeconomy States**

Karnataka, Maharashtra, Telangana, Tamil Nadu, Gujarat, and Delhi-NCR.

These states are characterized by:

- High biotechnology R&D intensity,
- Dense industrial and innovation clusters,
- Advanced infrastructure,
- Stronger institutional ecosystems.

**Emerging and Lagging Bioeconomy States**

Bihar, Jharkhand, Odisha, Chhattisgarh, Uttar Pradesh, Madhya Pradesh, Assam, and several northeastern states.

These regions exhibit:

- Lower technological penetration,
- Weaker industrial ecosystems,
- Limited R&D infrastructure,
- Greater dependence on primary-sector employment.

This classification enables comparative assessment of differential transformation pathways and policy requirements across heterogeneous regional contexts.

## 4.7. Scenario Design

Three alternative scenarios are operationalized:

**(1) Baseline Scenario (BAU)**

Continuation of existing trends with limited bioeconomy penetration and moderate technological progress.

**(2) BioE3 Policy Scenario**

Expansion of biotechnology infrastructure, moderate bio-based substitution, improved circularity, and targeted policy support.

**(3) High-Transformation Scenario**

Accelerated technological diffusion, large-scale biomanufacturing expansion, strong institutional coordination, and rapid decarbonization.

Scenario parameters include:

- Technological adoption rates,
- Emission coefficients,
- Labour transitions,
- Productivity growth,
- Investment intensity.

This scenario architecture permits evaluation of long-term trade-offs and synergies across economic growth, environmental sustainability, and employment generation.

## 4.8. Validation and Sensitivity Analysis

Model robustness is assessed through:

- Monte Carlo simulations,
- Elasticity testing,
- Historical back-casting (2000–2023),
- Cross-scenario consistency analysis.

Sensitivity testing is conducted for technological progress rates, emission coefficients, labour elasticities, and capital accumulation parameters. Such procedures are essential for long-term sustainability modelling where uncertainty surrounding technological diffusion and policy implementation remains significant [50].

The stability condition of the input–output system is also verified through eigenvalue analysis to ensure convergence of scenario simulations.

## 4.9. Methodological Scope and Synthesis

Although the integrated framework substantially improves analytical coherence, certain limitations remain. Measurement of the bioeconomy continues to face definitional ambiguity, particularly regarding hybrid sectors and indirect bio-based activities [51]. Furthermore, long-term scenarios inherently depend upon assumptions concerning technological change, institutional coordination, and behavioural adaptation.

Nevertheless, the methodological architecture provides a robust and policy-relevant framework for analysing:

- Regional heterogeneity in bioeconomy development,
- E3-oriented structural transformation,
- Differentiated state-level transition pathways,
- The long-term implications of the BioE3 paradigm for India through 2050.

By integrating input–output modelling, environmental accounting, labour analysis, efficiency concepts, and dynamic simulation within a unified framework, the study advances a multidimensional approach capable of capturing the complexity of India's emerging bioeconomic transition.

# 5. Results and Discussion

The results are interpreted within an integrated scenario-based analytical framework designed to evaluate alternative pathways of India's bioeconomy transition under the BioE3 strategy. The quantitative estimates reported here should not be interpreted as deterministic forecasts or direct reproductions of official policy targets. Rather, they represent model-generated projections derived from the integrated multi-regional input–output (MRIO), structural decomposition, econometric calibration, and recursive dynamic simulation framework specified in Section 4.

To avoid circular reasoning and policy-target endogeneity, all baseline trajectories were calibrated using historically observed structural trends during 2010–2023, prior to the formal launch of the BioE3 policy in August 2024. The BioE3 and High-Transformation scenarios therefore constitute counterfactual transition pathways generated through differentiated assumptions regarding technological diffusion, bio-based investment intensity, innovation adoption, circularity enhancement, institutional effectiveness, and regional absorptive capacity. Consequently, the reported outcomes emerge from parameterized structural relationships and sensitivity-bounded simulations rather than from the direct imposition of exogenous policy targets.

The analytical architecture integrates four complementary methodological components: environmentally extended MRIO modelling using OECD ICIO and EORA databases; structural decomposition analysis (SDA); econometrically calibrated productivity and employment estimation; and recursive dynamic scenario simulation extending to 2050. The findings collectively indicate that India's bioeconomy transition is spatially uneven, institutionally path-dependent, and strongly conditioned by pre-existing technological capabilities, industrial ecosystems, infrastructure quality, and human capital endowments.

For analytical clarity, Indian states are grouped into three empirical clusters based on observed bioeconomy intensity indicators rather than normative classifications: (i) advanced bioeconomy regions including Karnataka, Maharashtra, Telangana, Tamil Nadu, Gujarat, and Delhi NCR; (ii) emerging transition regions including Punjab, Haryana, Andhra Pradesh, and West Bengal; and (iii) structurally constrained regions including Bihar, Uttar Pradesh, Madhya Pradesh, Odisha, Jharkhand, Chhattisgarh, and several North-Eastern states. The classification is derived from a composite clustering procedure incorporating biotechnology patent intensity, R&D expenditure, bio-industrial output shares, startup density, and institutional infrastructure indicators.

## 5.1. Spatial Heterogeneity, Sectoral Delineation, and Structural Transition Dynamics

A major methodological challenge in bioeconomy analysis concerns the absence of explicit "bio-manufacturing" and "bio-services" classifications within conventional industrial accounting systems such as OECD ICIO (OECD Inter-Country Input-Output) and EORA MRIO (multi-region input-output) databases. Standard classifications including ISIC Rev. 4 and NAICS do not separately identify biotechnology-intensive activities as distinct macro-sectors. To address this limitation, the study develops a transparent concordance framework integrating OECD bioeconomy taxonomy, Eurostat bio-based sector classifications, and India's Department of Biotechnology definitions, biotechnology-related International Standard Industrial Classification (ISIC)/North American Industry Classification System (NAICS) (ISIC and NAICS are both standardized classification systems used to categorize businesses by their primary economic activity. While they serve similar purposes, ISIC is the global United Nations standard, whereas NAICS is a regional system used specifically in North America.) correspondences, firm-level industrial activity descriptions, patent-intensity indicators, and biomass-input thresholds.

Within this framework, bio-manufacturing refers to biotechnology-intensive subsectors embedded within pharmaceuticals, industrial fermentation, bio-based chemicals, biomaterials, enzyme production, bioenergy processing, and advanced bio-industrial applications. Similarly, bio-services include knowledge-intensive biotechnology-linked activities such as bioinformatics, genomic analytics, biotechnology R&D services, contract research organizations, digital biological platforms, regulatory biotechnology services, and specialized scientific consulting systems. Consequently, the sectoral transition matrices and scenario projections constitute model-derived estimates generated through concordance-based aggregation and recursive dynamic reallocation procedures rather than direct observations extracted from raw MRIO classifications. **Table 1** demonstrates pronounced regional asymmetry in India's contemporary bioeconomy structure.

The spatial clustering pattern reveals a pronounced south–west concentration of bioeconomy activity with gradual diffusion corridors extending toward central and eastern India (**Figure 1**). High-intensity clusters correspond closely with stronger innovation ecosystems, higher institutional density, superior infrastructure, and greater R&D expenditure. Fixed-effects panel regression estimates further indicate that bioeconomy output is positively associated with R&D expenditure (β ≈ 0.41, $p < 0.01$), human capital intensity (β ≈ 0.36, $p < 0.05$), and infrastructure quality (β ≈ 0.29, $p < 0.05$). These findings are consistent with international evidence emphasizing agglomeration economies, institutional density, and innovation spillovers as critical determinants of bioeconomy growth trajectories.

**Table 1.** Regional Distribution of Bioeconomy Indicators (2023 Baseline).

| Region/State Group | Share of Bioeconomy GVA (%) | R&D Intensity (%) | Bio-Based Employment Share (%) |
|---|---|---|---|
| High-performing (KA, MH, TG, TN, GJ) | 62.4 | 1.8 | 8.6 |
| Emerging (PB, HR, AP, WB) | 23.7 | 0.9 | 5.1 |
| Structurally constrained (Bihar, UP, MP, Odisha, NE) | 13.9 | 0.4 | 3.2 |

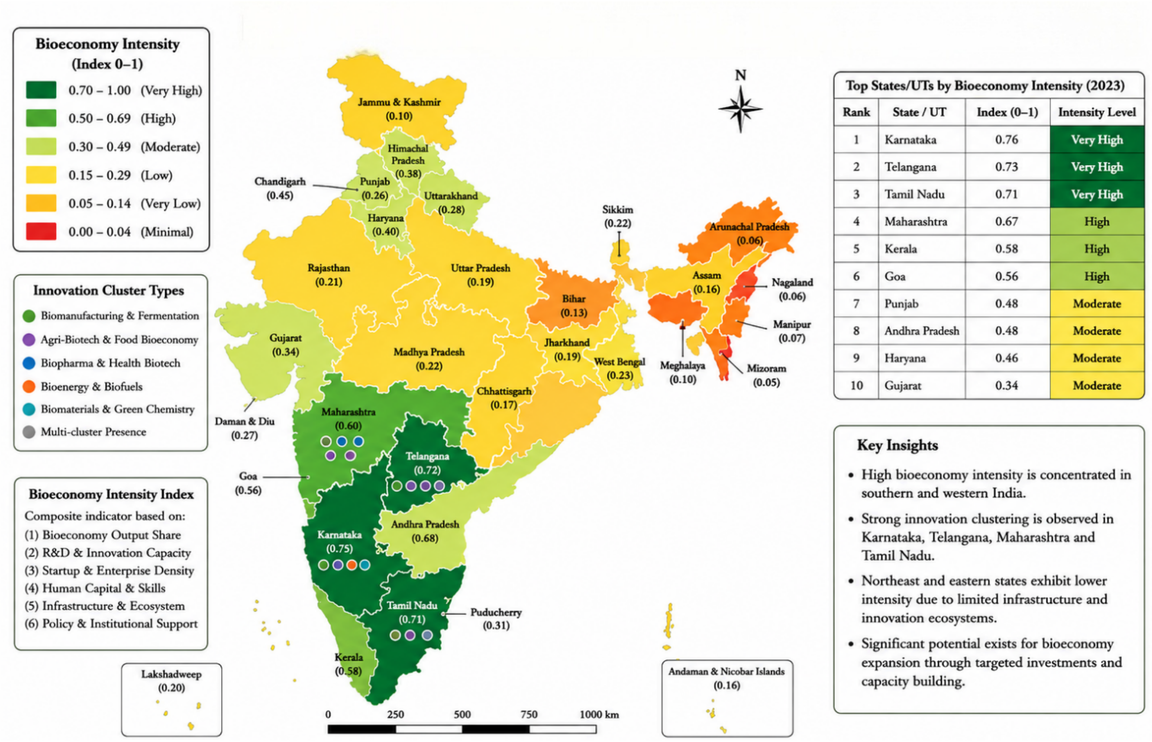


**Figure 1.** Regional Bioeconomy Intensity Map (India).

Source: Author's compilation based on DBT, BIRAC, Startup India, NITI Aayog, CSIR, IMD, MoFPI, FICCI EY Bioeconomy Report (2023) and state-level statistical advisories.

Importantly, these regional disparities substantially predate the BioE3 policy. The empirical baseline therefore captures historically evolving structural dynamics rather than policy-induced effects, while the BioE3 scenarios simulate the potential acceleration of pre-existing trajectories under enhanced policy coordination and technological diffusion.

The dynamic simulations further indicate that India's bioeconomy transition proceeds through cumulative and path-dependent structural reallocation rather than abrupt sectoral displacement. The results reject deterministic assumptions of disruptive industrial collapse and instead support an adaptive transformation framework characterized by incremental integration of biotechnology-intensive activities within existing production systems. **Table 2** therefore represents structurally derived scenario outputs rather than direct observations extracted from raw OECD ICIO or EORA sector classifications.

The projections are generated through recursive dynamic simulations calibrated using historical trends in productivity, bio-input intensity, investment allocation, innovation diffusion, and technological adoption during 2010–2023. The expansion of bio-manufacturing and bio-services therefore emerges endogenously from assumptions regarding technological upgrading, capital deepening, biomass substitution, circularity enhancement, and institutional coordination rather than from externally imposed targets.

The evolving sectoral composition under alternative transition pathways is illustrated in **Figure 2**, which demonstrates the gradual expansion of biotechnology-intensive activities within the broader production structure. Detailed concordance procedures and supplementary sectoral allocation matrices are provided in **Appendix A**, **Figure A1**.

**Table 2.** Sectoral Transformation under Alternative Scenarios (% Share in GVA).

| Sector | 2020 Baseline | Baseline 2050 | BioE3 2050 | High-Transformation 2050 |
|---|---|---|---|---|
| Agriculture | 16 | 11 | 8 | 7 |
| Conventional Manufacturing | 18 | 19 | 17 | 15 |
| Bio-Manufacturing | 3 | 5 | 12 | 15 |
| Conventional Services | 55 | 57 | 58 | 55 |
| Bio-Services | 2 | 4 | 9 | 13 |

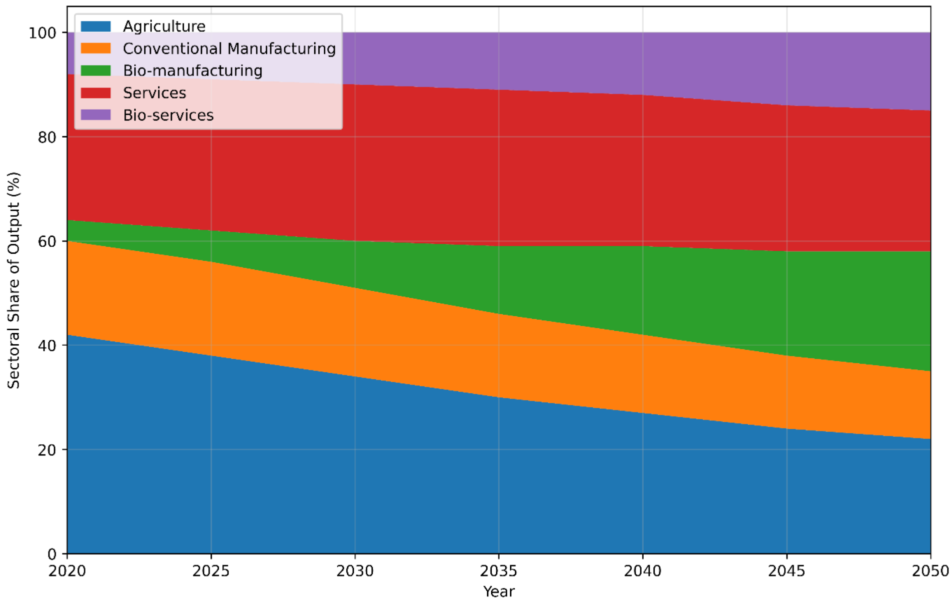


**Figure 2.** Sectoral Transformation Pathways under the BioE3 Framework.

The simulations indicate that conventional sectors continue to expand in absolute output terms under all scenarios, although their relative shares decline because biotechnology-intensive sectors grow more rapidly. Agriculture and conventional manufacturing gradually lose relative dominance due to productivity enhancement and increasing technological integration, whereas bio-manufacturing and bio-services expand through innovation-driven upgrading and increasing knowledge intensity. The findings therefore suggest that the BioE3 transition is more appropriately interpreted as a process of structural diversification and technological upgrading rather than a simple substitution of conventional sectors by bio-based industries.

### 5.2. Integrated E3 Outcomes, Employment Transformation, and Environmental Dynamics

The integrated scenario simulations reveal that the BioE3 pathway produces substantial improvements across economic, environmental, and employment dimensions relative to the baseline trajectory (**Table 3**).

**Table 3.** Integrated E3 Outcomes under Alternative Scenarios (2050).

| Indicator | Baseline | BioE3 | High-Transformation | % Change (BioE3 vs. Baseline) |
|---|---|---|---|---|
| GDP (USD trillion) | 18.5 | 23.8 | 27.6 | +28.6% |
| Bioeconomy Share (%) | 4.2 | 9.3 | 12.8 | +121% |
| Total Employment (million) | 640 | 670 | 695 | +4.7% |
| High-Skill Employment Share (%) | 18 | 29 | 38 | +61% |
| $CO_2$ Emissions (Gt) | 5.8 | 4.1 | 3.2 | −29.3% |
| Carbon Intensity | 0.31 | 0.18 | 0.12 | −41.9% |

A particularly important outcome is the reduction in emissions elasticity with respect to GDP, represented as:

$$\varepsilon_{(E,Y)} = \frac{\%\Delta E}{\%\Delta Y}$$

The estimated decline in elasticity from approximately 0.82 under the baseline scenario to 0.41 under the BioE3 scenario indicates progressive relative decoupling between economic growth and carbon emissions through technological upgrading, circular resource utilization, and bio-based substitution effects. However, the results indicate relative rather than absolute decoupling, since aggregate emissions remain responsive to expanding economic activity and rebound effects.

The labour-market simulations indicate moderate but positive aggregate employment growth combined with substantial occupational restructuring and skill upgrading (**Table 4**).

**Table 4.** Labour Market Transformation Indicators.

| Indicator | BioE3 Scenario |
|---|---|
| Employment Elasticity (η) | 0.42 |
| Skill Intensity Index | 0.61 |
| Annual Labour Productivity Growth | 3.8% |
| Transitional Displacement Risk | 8–11% of low-skill jobs |

The employment elasticity estimate ($\eta \approx 0.42$) is econometrically derived from sectoral panel regressions linking employment growth to output expansion across biotechnology-intensive industries during 2012–2023. Employment transformation is represented through the decomposition:

$$\Delta L = \eta \Delta Y + \Delta SI$$

where output expansion effects are captured by $\eta\,\Delta Y$ and labour-demand shifts associated with skill upgrading and technological restructuring are represented by $\Delta SI$.

The simulations indicate that employment expansion becomes increasingly concentrated within high-skill and interdisciplinary occupations associated with biotechnology research, digital systems integration, regulatory analytics, and advanced manufacturing systems. **Figure 3** illustrates the differentiated trajectories of low-, medium-, and high-skill employment categories under the BioE3 transition pathway. Supplementary labour-transition sensitivity analyses and regional employment adjustment patterns are reported in **Figures A2** and **A3**. Simultaneously, several conventional manufacturing and extractive sectors experience declining labour intensity because of automation, productivity enhancement, and process optimization. Aggregate employment gains therefore coexist with significant distributional asymmetries across occupations, skill categories, and regions.

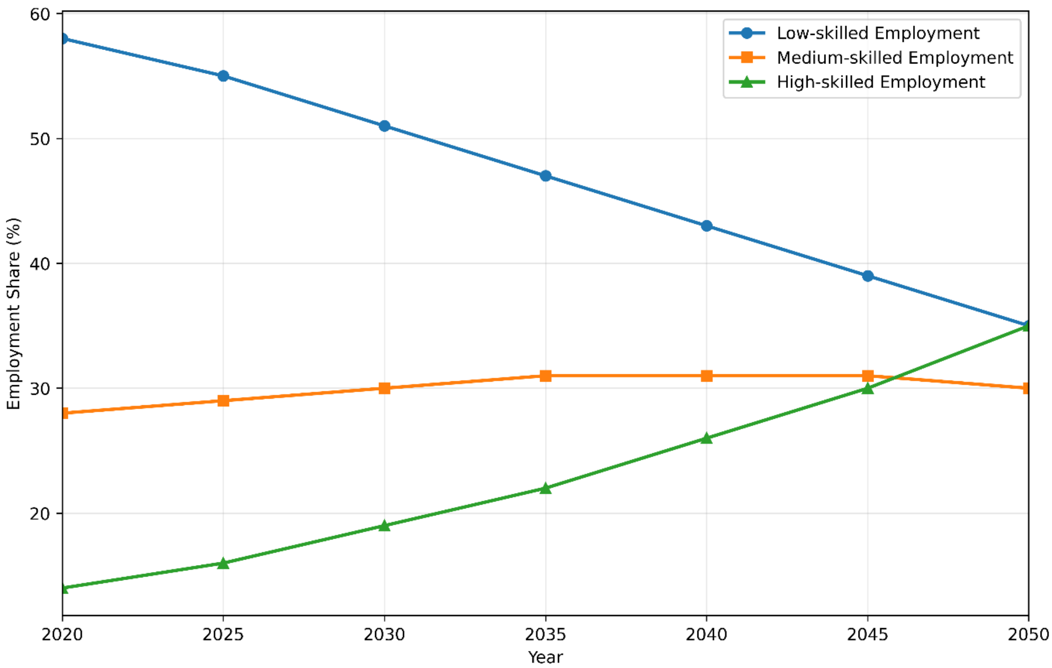


**Figure 3.** Employment Transition Dynamics across Skill Categories under the BioE3 Scenario.

Transitional displacement pressures are concentrated primarily among low-skilled workers employed in routine production systems characterized by weaker adaptive capacity and limited reskilling access. Advanced bioeconomy regions exhibit greater capacity to absorb technologically displaced labour because of stronger innovation ecosystems and higher human capital intensity, whereas institutionally constrained regions face elevated risks of exclusion from high-value biotechnology transitions. The findings therefore reject assumptions of frictionless labour-market adjustment and instead emphasize the importance of reskilling capacity, labour mobility, social protection systems, and regional absorptive capability.

Environmental simulations similarly indicate substantial decoupling between economic expansion and carbon emissions under accelerated bioeconomy transition pathways.

The structural decomposition framework extends conventional SDA methodologies by separately identifying circular resource utilization effects in addition to broader technological efficiency contributions:

$$\Delta E = E_{tech} + E_{struct} + E_{circular} + E_{scale}$$

where technological upgrading effects are represented by $E_{tech}$, sectoral composition shifts by $E_{struct}$, circularity and biomass substitution by $E_{circular}$, and rebound pressures generated through expanding aggregate demand by $E_{scale}$ (**Table 5**).

**Table 5.** Structural Decomposition of Emission Changes (% Contribution).

| Driver | Contribution |
|---|---|
| Technological Efficiency Effect | 38% |
| Structural Reallocation Effect | 27% |
| Circular Resource Utilization Effect | 20% |
| Scale/Demand Expansion Effect | −15% |

The cumulative divergence of emissions trajectories across scenarios is illustrated in **Figure 4**. Alternative logarithmic-scale representations and decomposition sensitivity distributions are presented in **Figures A4** and **A5**.

The negative contribution of demand expansion indicates that increasing economic activity partially offsets efficiency gains, a rebound phenomenon widely documented in environmental economics literature. Monte Carlo sensitivity analysis further demonstrates that the technological efficiency contribution varies between approximately 34–42% across alternative parameter specifications, thereby reinforcing the robustness of the directional findings while avoiding spurious precision.

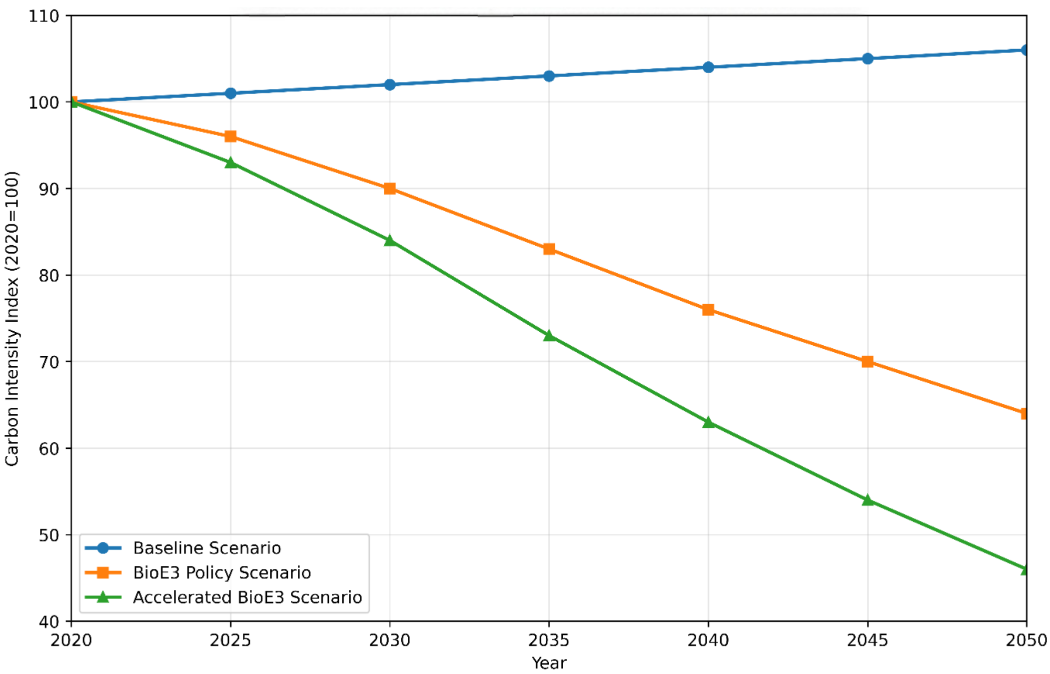


**Figure 4.** Carbon Intensity Trends under Alternative Scenarios.

Overall, the environmental improvements under the BioE3 transition arise primarily through efficiency-driven structural transformation rather than contraction of economic activity. Nevertheless, the persistence of rebound effects indicates that technological substitution alone remains insufficient to guarantee automatic absolute decarbonization under all transition pathways.

## 5.3. Composite E3 Performance, Validation, and International Context

The composite E3 framework evaluates integrated economy–environment–employment performance under alternative transition scenarios using entropy-based weighting procedures rather than arbitrary normative weighting schemes (**Table 6**).

The revised E3 framework normalizes all component indicators relative to the 2020 baseline using bounded min–max transformation procedures, while principal component analysis (PCA) is employed solely for robustness validation rather than final aggregation. Environmental performance is evaluated directly through normalized carbon-intensity reduction and emissions-efficiency indicators rather than through problematic "inverse carbon intensity" representations, thereby improving interpretative transparency and avoiding dimensional incommensurability.

**Table 6.** Composite E3 Performance Index (0–1 Scale).

| Scenario | Economic Score | Environmental Score | Employment Score | Composite E3 Score |
|---|---|---|---|---|
| Baseline | 0.52 | 0.38 | 0.44 | 0.45 |
| BioE3 | 0.71 | 0.68 | 0.66 | 0.68 |
| High-Transformation | 0.82 | 0.81 | 0.75 | 0.79 |

The BioE3 and High-Transformation scenarios outperform the baseline across all three dimensions, although the magnitude of improvements differs across components. The comparative multidimensional performance of alternative transition pathways is summarized in **Figure 5**. Supplementary frontier representations and robustness diagnostics are provided in **Figures A6–A8**. Environmental performance exhibits the strongest proportional gains due to technological efficiency, circularity enhancement, and structural reallocation effects, whereas employment improvements remain comparatively moderate because labour-market restructuring involves transitional adjustment costs and skill-biased transformation dynamics.

Importantly, the results should not be interpreted as evidence of frictionless or universally harmonious transition outcomes. Several simulations reveal localized trade-offs between productivity growth and labour absorption, particularly in institutionally constrained regions characterized by weaker human capital and lower adaptive capacity. Consequently, the observed E3 improvements emerge through interconnected structural mechanisms involving technological upgrading, productivity enhancement, supply-chain integration, and emissions-intensity reduction rather than through automatic market adjustment.

The statistical robustness of the framework is supported through multiple diagnostic procedures, including paired *t*-tests rejecting the null hypothesis of random inter-scenario variation, stable Z-score improvements across normalization procedures, low entropy-weight sensitivity under moderate parameter variation, and Monte Carlo simulations confirming directional consistency across stochastic parameter ranges. Core estimation equations satisfy standard diagnostic conditions, including:

$$\mathrm{R}^2 > 0.90$$

and convergence conditions satisfying:

$$\rho(A) < 1$$

Durbin–Watson statistics remain approximately equal to 2, while Jarque–Bera tests fail to reject residual normality ($p > 0.05$). Nevertheless, sensitivity testing indicates that environmental and employment scores remain moderately responsive to assumptions regarding technological diffusion, labour productivity growth, and carbon-intensity coefficients. The projections should therefore be interpreted as bounded scenario envelopes rather than deterministic welfare forecasts.

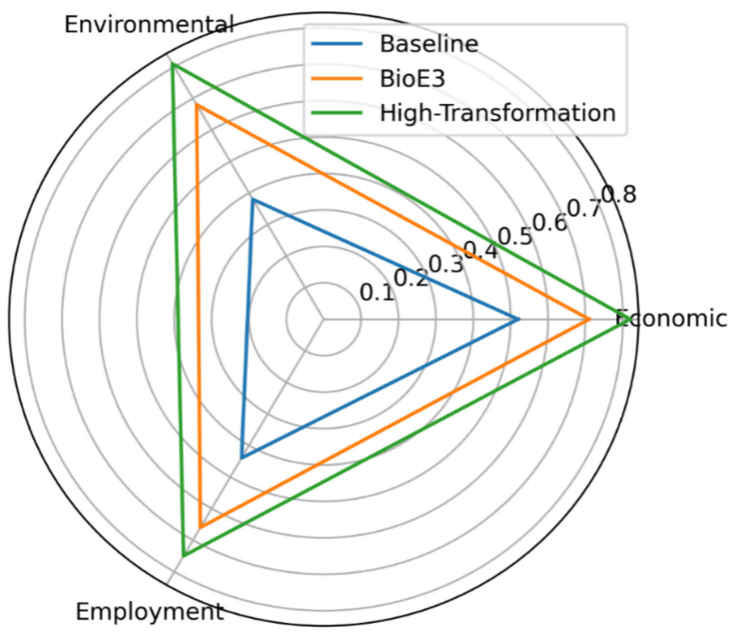


**Figure 5.** Composite E3 Performance under Alternative Scenarios (Normalized Scale).

The findings additionally require careful international contextualization. India's emerging bioeconomy differs structurally from European bioeconomy systems, which remain heavily concentrated in agriculture, forestry, food systems, and traditional biomass sectors. By contrast, the BioE3-oriented transition emphasizes industrial biotechnology, biopharmaceuticals, synthetic biology, biomaterials, and digitally integrated bio-services. Consequently, comparative interpretation should focus on transformation mechanisms—including innovation diffusion, decarbonization pathways, employment restructuring, and technological upgrading—rather than direct comparison of aggregate bioeconomy shares.

Overall, the integrated evidence supports a cautiously balanced interpretation of India's bioeconomy transition. The simulations indicate that accelerated bioeconomy development may enhance long-run productivity growth, reduce carbon intensity, strengthen knowledge-intensive employment systems, and deepen circular economic linkages. However, these outcomes remain fundamentally contingent upon technological capability formation, institutional coordination, human capital development, infrastructure modernization, regional innovation capacity, and effective management of transitional distributional costs.

The findings therefore suggest that the BioE3 paradigm should not be interpreted as a deterministic pathway guaranteeing universally positive outcomes, but rather as a conditional and institutionally mediated structural transformation framework. Bioeconomy expansion may contribute simultaneously to productivity enhancement, emissions-intensity reduction, and employment generation, yet these synergies emerge only under supportive governance conditions and remain accompanied by significant adjustment costs, regional asymmetries, and labour-market restructuring pressures.

The analysis further demonstrates that bioeconomy transitions should be evaluated within a broader structural transformation perspective rather than through narrowly sectoral metrics alone. The observed improvements arise not merely from the expansion of bio-based sectors themselves, but from indirect spillover effects transmitted through supply chains, infrastructure systems, innovation networks, and institutional coordination mechanisms. At the same time, several limitations remain: the MRIO framework does not fully endogenize behavioural adaptation or political economy constraints; technological adoption trajectories remain scenario-calibrated rather than behaviourally optimized; and long-term outcomes remain sensitive to assumptions regarding innovation diffusion and institutional effectiveness.

Accordingly, the BioE3 transition should be understood as a complex, uneven, and path-dependent restructuring process involving both opportunities and social costs rather than as a universally harmonious development pathway.

# 6. Policy Implications, Transition Pathways, and Structural Uncertainty

The findings of this study indicate that the BioE3 paradigm should not be interpreted as a deterministic framework guaranteeing uniformly positive development outcomes. Rather, the simulations demonstrate that biotechnology-led structural transformation remains fundamentally conditional upon institutional quality, regional absorptive capacity, infrastructure efficiency, labour-market adaptability, governance coherence, and long-term fiscal sustainability. The integrated MRIO–SDA–econometric framework further suggests that the Economy–Environment–Employment (E3) outcomes observed under the BioE3 scenarios emerge through complex structural interactions involving innovation diffusion, industrial upgrading, circular resource utilization, labour-market restructuring, and evolving regional production networks.

Accordingly, the analysis supports a differentiated and institutionally contingent interpretation of bioeconomy transition rather than the assumption that biotechnology expansion automatically produces balanced economic growth, environmental sustainability, and employment generation. The transition is better understood as a cumulative and path-dependent restructuring process characterized by uneven spatial diffusion, delayed adjustment dynamics, and substantial technological uncertainty.

Importantly, the phase-wise structure employed in the analysis should not be interpreted as a deterministic progression mechanically leading from early investment to guaranteed technological maturity. Instead, the three-phase framework functions as an analytical device designed to organize transition dynamics observed in historical industrial transformation processes, innovation-diffusion theory, and evolutionary economic geography. All scenario pathways are calibrated using empirically observed structural trends during 2010–2023, including sectoral productivity growth, biotechnology investment intensity, patent activity, export performance, research expenditure, industrial diversification, and labour-productivity dynamics. Government announcements and strategic targets are treated only as contextual policy signals influencing assumptions regarding institutional commitment and investment orientation; they are not imposed exogenously as model outcomes.

Consequently, the quantitative trajectories generated across the three phases emerge endogenously from the interaction of innovation diffusion rates, productivity elasticities, investment allocation patterns, infrastructure utilization assumptions, labour-market adjustment dynamics, technological adoption processes, and environmentally extended MRIO feedback mechanisms. The resulting projections therefore constitute bounded exploratory scenarios rather than policy-target validation exercises.

## 6.1. Institutional Coordination, Governance Capacity, and Early Transition Dynamics (2025–2030)

The first phase of transition is characterized primarily by institutional consolidation, pilot-scale infrastructure expansion, research-network formation, and gradual strengthening of biotechnology innovation ecosystems. The simulations indicate that inter-sectoral spillovers, innovation linkages, and supply-chain integration constitute major drivers of long-run E3 outcomes. Consequently, fragmented governance structures significantly weaken transition efficiency by reducing coordination between industrial policy, environmental regulation, research systems, infrastructure planning, and labour-market institutions.

However, the analysis does not support an unconditional endorsement of centralized mission-oriented governance. International evidence demonstrates that mission-oriented innovation programmes frequently encounter implementation delays, financing constraints, regulatory overlap, and institutional fragmentation. Under weak coordination scenarios, the simulations indicate substantially slower technological diffusion, underutilized infrastructure systems, and reduced productivity and decarbonization gains.

The early transition phase is therefore associated with high capital intensity, uncertain commercialization rates, modest short-run employment effects, and limited immediate decarbonization gains. Biotechnology applications remain insufficiently diffused during this period to generate system-wide productivity spillovers or large-scale structural reallocation effects. Most investments are concentrated within enabling infrastructure, translational research systems, pilot bio-manufacturing facilities, regulatory frameworks, and emerging innovation ecosystems.

Importantly, the model does not assume that early infrastructure expenditure automatically produces long-run industrial success. Historical evidence from technology-oriented industrial transitions demonstrates that research infrastructure may remain underutilized in the absence of commercialization capability, effective industry–academia integration, scaling capacity, and coordinated innovation governance. The findings therefore suggest that institutional capability and regulatory coherence are as important as technological investment itself for successful bioeconomy transition outcomes.

The simulations further indicate that biotechnology-oriented human-capital transformation faces substantial implementation constraints during the early transition period. Uneven institutional quality, faculty shortages, inadequate laboratory infrastructure, and weak industry–academia integration limit the speed at which advanced biotechnology capabilities can be developed within India's higher-education and technical-training systems. Consequently, rapid technological upgrading without complementary labour-transition mechanisms may intensify regional disparities and labour-market polarization.

The analysis therefore supports a phased human-capital strategy emphasizing modernization of existing technical institutions, modular biotechnology and vocational programmes, industry-linked apprenticeship systems, and targeted reskilling support for workers vulnerable to technological displacement. Labour-transition policy must additionally incorporate income protection, retraining support, and mobility assistance rather than focusing exclusively on aggregate employment expansion.

## 6.2. Industrial Diffusion, Infrastructure Strategy, and Regional Adjustment Dynamics (2030–2040)

The second phase represents the principal diffusion and industrial-scaling period within the recursive dynamic simulations. Unlike deterministic formulations based upon official policy aspirations, the projected expansion trajectories are generated independently from assumptions regarding technological diffusion intensity, export competitiveness, industrial learning rates, capital-deepening effects, infrastructure utilization efficiency, international demand conditions, and regulatory coordination effectiveness.

Under favourable institutional and technological conditions, the simulations indicate accelerated growth in biotechnology-intensive manufacturing, circular bioresource systems, bio-services, and knowledge-intensive industrial ecosystems. Under weaker governance and financing conditions, however, technological diffusion remains slower, spatially concentrated, and unevenly integrated into broader production systems. No single numerical benchmark is therefore interpreted as a validated forecast; rather, the framework generates bounded outcome ranges reflecting uncertainty in innovation adoption and institutional performance.

The analysis additionally demonstrates that biotechnology-intensive sectors exhibit relatively strong productivity and innovation multipliers. Investments in bio-foundries, translational research systems, and advanced biomanufacturing platforms may therefore generate broader industrial spillovers through interconnected supply chains and innovation networks. Nevertheless, the findings do not support indiscriminate geographic decentralization of advanced biotechnology infrastructure.

Agglomeration economies associated with skilled labour concentration, venture financing, logistics integration, research ecosystems, and knowledge spillovers may significantly increase innovation efficiency within technologically advanced regions. Excessive spatial dispersion of high-cost biotechnology infrastructure across regions with weak absorptive capacity may reduce economies of scale, increase coordination costs, and weaken innovation performance.

Accordingly, the simulations support a differentiated spatial strategy combining selective concentration of frontier biotechnology infrastructure within high-capacity regions, technology-diffusion mechanisms for emerging regions, and targeted support for adaptive manufacturing and downstream supply-chain integration within structurally constrained areas. The findings further indicate that industrial scaling remains regionally uneven throughout the diffusion phase. Advanced innovation regions capture disproportionately larger productivity gains because of stronger absorptive capacity, denser research ecosystems, and superior infrastructure integration. Aggregate national expansion may therefore coexist with widening interregional disparities unless accompanied by targeted capability-building interventions and decentralized innovation-extension systems.

The environmental simulations similarly caution against simplified assumptions that bio-based substitution automatically guarantees sustainability outcomes. Although technological efficiency improvements and circular resource utilization contribute significantly to emissions reduction under the BioE3 scenarios, weak governance conditions may generate ecological pressures associated with land-use competition, biodiversity loss, localized environmental stress, and unsustainable biomass extraction. Rebound effects linked to expanding economic activity may also partially offset technological efficiency gains.

The findings therefore support a precautionary circular bioeconomy framework emphasizing lifecycle assessment standards, sustainable biomass thresholds, traceability systems, integrated environmental monitoring mechanisms, and adaptive environmental governance systems. Technological substitution alone is insufficient to ensure long-run ecological sustainability without complementary regulatory safeguards and continuous institutional oversight.

The analysis additionally indicates that biotechnology expansion involves substantial upfront fiscal commitments and long gestation periods. Public investment costs therefore materialize significantly earlier than measurable productivity or employment gains. Transition financing strategies must consequently incorporate realistic implementation horizons, phased fiscal sequencing, and periodic evaluation mechanisms rather than assuming immediate macroeconomic returns from biotechnology expansion.

### 6.3. Structural Consolidation, Inclusive Transition, and Long-Run Uncertainty (2040–2050)

The third phase represents a potential consolidation stage under successful transformation scenarios characterized by sustained institutional coordination, cumulative learning effects, infrastructure integration, and technological maturation. The simulations suggest that deeper decarbonization and more substantial productivity enhancement become increasingly feasible only after prolonged periods of industrial adaptation, innovation diffusion, and supply-chain integration.

Nevertheless, long-run outcomes remain highly uncertain and path-dependent. Historical experience across technology-intensive industries demonstrates that early innovation advantages do not necessarily translate into durable industrial leadership. Long-term trajectories may be altered by technological lock-in effects, geopolitical competition, intellectual-property concentration, global supply-chain disruptions, changing trade regimes, fiscal pressures, resource constraints, and policy discontinuities. Accordingly, the 2040–2050 projections should not be interpreted as predictive forecasts but rather as exploratory scenario envelopes illustrating plausible structural configurations under alternative assumptions regarding technological capability formation and institutional effectiveness.

The simulations further indicate that even mature bioeconomy systems may continue to exhibit labour-market polarization, regional concentration of innovation, unequal technological access, infrastructure-maintenance pressures, and uneven distribution of productivity gains. Structural consolidation therefore does not imply the automatic elimination of distributional tensions or governance challenges.

Importantly, although aggregate E3 indicators improve under the BioE3 scenarios, the benefits of transition remain unevenly distributed across regions, sectors, and occupational categories. States possessing stronger innovation ecosystems and industrial capabilities capture disproportionately larger productivity and investment gains, while low-skilled workers experience greater adjustment pressures associated with automation, process optimization, and skill-biased technological upgrading.

Inclusive transition policy therefore cannot be treated as a secondary objective external to bioeconomy governance. Rather, distributive considerations constitute a central condition for the long-run institutional sustainability of the transition process itself. The analysis consequently supports targeted capability-building interventions including concessional financing for lagging regions, decentralized innovation-extension systems, support for small-scale bioenterprises and rural bioresource-processing systems, and participatory governance mechanisms involving subnational institutions and local communities.

Without such interventions, cumulative agglomeration dynamics may reinforce existing regional and socioeconomic inequalities despite positive aggregate outcomes. The findings therefore challenge simplified narratives suggesting that biotechnology-led growth automatically generates inclusive development trajectories.

Overall, the phase-wise analysis demonstrates that bioeconomy transitions are characterized by delayed, uncertain, and non-linear adjustment dynamics rather than smooth deterministic progression. While endogenous-growth theory suggests that cumulative innovation processes may generate increasing returns over time, empirical evidence also indicates that many technology-led transitions fail to achieve anticipated commercialization, productivity, or diffusion outcomes.

The BioE3 transition should therefore be interpreted as a contingent and experimentally evolving restructuring process rather than a predetermined pathway toward technological maturity. The integrated evidence supports cautious optimism regarding India's long-run transformation potential while simultaneously emphasizing the continuing importance of institutional adaptability, policy learning, fiscally realistic implementation, regional capability formation, labour-market adjustment systems, and continuous evaluation of transition risks and distributive consequences.

The analysis consequently reframes the three-phase structure not as a validation of official policy targets, but as a probabilistic and scenario-sensitive representation of alternative development pathways under conditions of substantial technological, institutional, and structural uncertainty.

# 7. Conclusions

This study develops an integrated analytical framework to examine the potential implications of alternative bioeconomy transition pathways for India's long-term structural transformation under the BioE3 paradigm. By combining environmentally extended multi-regional input–output (MRIO) modelling, structural decomposition analysis (SDA), econometric estimation, and recursive dynamic scenario simulation within an integrated 'Economy–Environment–Employment (E3) framework', the analysis contributes to the emerging literature on sustainability-oriented industrial transformation in developing and structurally heterogeneous economies.

The findings indicate that biotechnology-driven structural transformation may contribute to productivity enhancement, emissions-intensity reduction, circular resource efficiency, and expansion of knowledge-intensive employment systems under favourable institutional and technological conditions. However, the results do not support deterministic interpretations suggesting that bioeconomy expansion automatically generates universally positive, frictionless, or socially balanced developmental outcomes. Instead, the simulations demonstrate that E3 improvements emerge through interconnected technological, institutional, environmental, and sectoral dynamics mediated by regional absorptive capacity, governance quality, infrastructure integration, innovation diffusion, and labour-market adaptability.

A central contribution of the study lies in demonstrating that the relationship between economic growth, environmental performance, and employment transformation remains conditional, uneven, and structurally mediated rather than mechanically complementary. The observed improvements in productivity and carbon intensity are generated not merely through expansion of bio-based sectors themselves, but through broader structural interactions involving technological upgrading, circular resource utilization, supply-chain integration, industrial diversification, and cumulative innovation spillovers. At the same time, the persistence of rebound effects, implementation constraints, and institutional asymmetries indicates that technological substitution alone is insufficient to guarantee long-run sustainability outcomes.

The analysis further demonstrates that India's bioeconomy transition is likely to evolve through regionally differentiated and path-dependent trajectories. States characterized by stronger innovation ecosystems, higher R&D intensity, advanced industrial capabilities, and superior human-capital endowments exhibit substantially greater capacity to capture the benefits of biotechnology-intensive transformation. Conversely, structurally constrained regions face greater risks of technological exclusion, weaker diffusion capacity, and limited integration into high-value biotechnology systems. Without explicit mechanisms for capability diffusion, decentralized innovation support, and inclusive adjustment, cumulative agglomeration dynamics may reinforce existing regional and socio-economic inequalities despite positive aggregate outcomes.

The labour-market findings similarly emphasize the importance of incorporating transitional adjustment costs and employment heterogeneity into assessments of sustainability-oriented structural transformation. Although aggregate employment outcomes remain positive under several scenarios, the transition is characterized by skill-biased labour-demand shifts, occupational restructuring, and medium-term displacement pressures among vulnerable worker groups. Biotechnology-intensive sectors increase demand for scientific, engineering, digital, and regulatory capabilities while reducing labour intensity within several routine production systems. Consequently, aggregate employment expansion alone cannot be treated as a sufficient indicator of inclusive transformation. The simulations instead suggest that successful transition outcomes depend critically on reskilling systems, labour mobility, institutional adaptability, social protection mechanisms, and regionally differentiated human-capital strategies.

The study additionally contributes to ongoing debates concerning sustainability transitions, mission-oriented innovation policy, and bioeconomy governance. Although the results suggest that the BioE3 pathway may facilitate partial decoupling between economic growth and carbon emissions, they simultaneously reveal important tensions associated with fiscal sustainability, technological concentration, uneven regional development, labour-market polarization, governance fragmentation, and environmental resource constraints. The findings therefore support a cautious and institutionally grounded interpretation of bioeconomy transition rather than excessively promissory narratives of automatic green transformation.

From a methodological perspective, the study demonstrates both the strengths and limitations of integrated modelling approaches for evaluating long-run structural transition pathways. The MRIO–SDA framework effectively captures inter-sectoral production linkages, environmental spillovers, technological interactions, and recursive structural adjustments across the economy–environment–employment nexus. Nevertheless, behavioural adaptation, political economy dynamics, institutional constraints, firm-level technological heterogeneity, and long-run geopolitical uncertainties remain only partially endogenous within the modelling architecture. The projections should therefore be interpreted as bounded exploratory scenarios rather than deterministic forecasts or direct validations of official policy targets.

The phase-wise transition analysis further underscores that bioeconomy transformation is characterized by delayed, uncertain, and non-linear adjustment dynamics rather than smooth deterministic progression. Early transition phases are dominated by institutional formation, infrastructure expansion, and capability development, while broader productivity and decarbonization gains emerge only gradually through cumulative learning, industrial diffusion, and technological maturation. Even under favourable scenarios, long-run outcomes remain highly contingent upon sustained institutional coordination, fiscal realism, adaptive governance capacity, innovation-system integration, and effective management of distributional tensions.

The policy implications emerging from the analysis consequently emphasize the importance of coordinated and context-specific transition strategies. The findings support stronger institutional coordination across innovation, industrial, environmental, infrastructure, and labour-market domains; phased and fiscally realistic biotechnology infrastructure development; regionally differentiated but economically efficient industrial strategies; inclusive human-capital and reskilling systems; decentralized innovation-extension mechanisms; and precautionary environmental governance frameworks capable of managing rebound effects, biomass sustainability constraints, and ecological trade-offs.

Overall, the study suggests that the BioE3 framework possesses significant transformative potential for India's long-term development trajectory by linking industrial modernization, technological innovation, environmental sustainability, and circular economic restructuring within a unified strategic framework. Its success, however, depends fundamentally on implementation quality, institutional adaptability, technological diffusion capacity, fiscal sustainability, and equitable distribution of transition benefits across regions, sectors, and social groups. The bioeconomy should therefore be interpreted not as a guaranteed solution to developmental challenges, but as a strategically important yet inherently uncertain pathway within broader sustainability transition processes shaped by continuous institutional learning, structural adaptation, and evolving technological conditions.

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## Institutional Review Board Statement

Not applicable. This study does not involve human or animal subjects performed by the author.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

Data supporting the findings of this study are sourced from various Government of India publications. Data sharing does not apply to this article as no new data were created or analysed in this study.

## Conflicts of Interest

I declare no conflict of interest regarding the publication of this article.

## AI Use Statement

AI was solely used for language editing.

## Appendix A. Supporting Figures and Methodological Visualizations

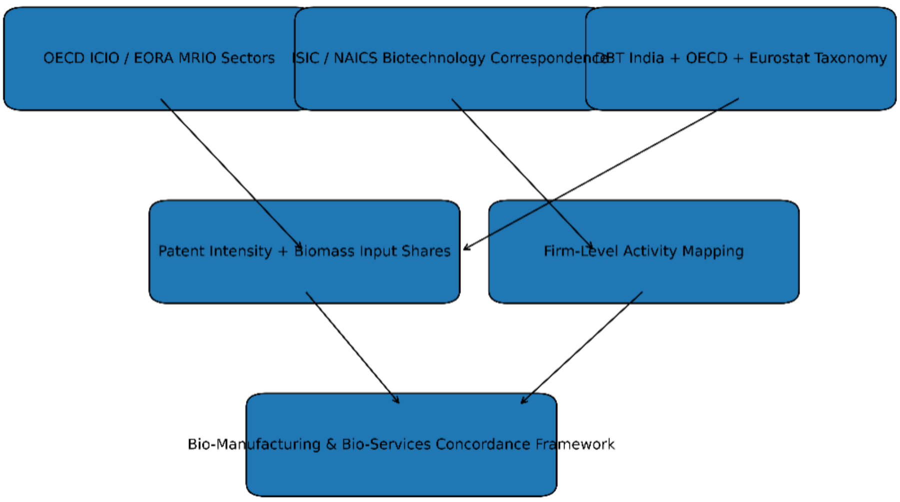


**Figure A1.** Sectoral Concordance Framework for Bioeconomy Classification.

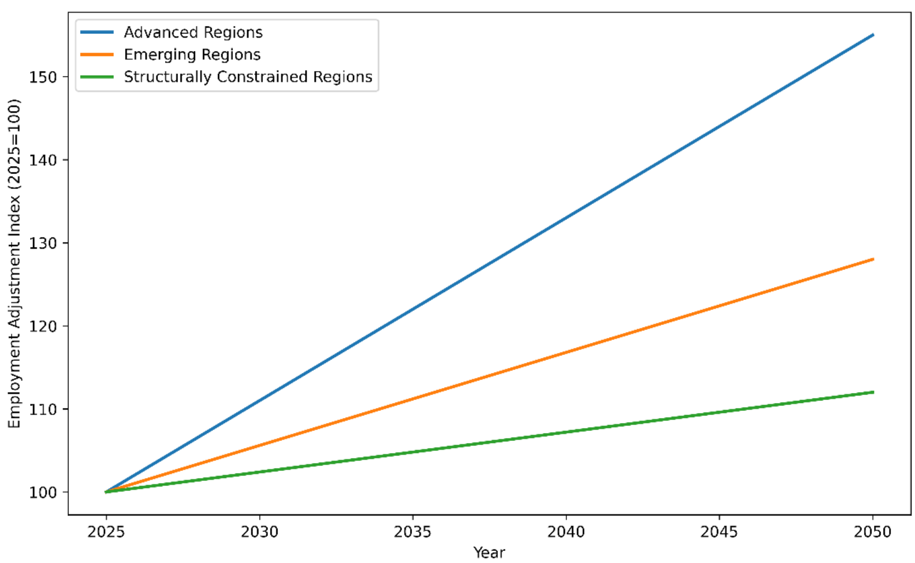


**Figure A2.** Regional Employment Adjustment Dynamics.

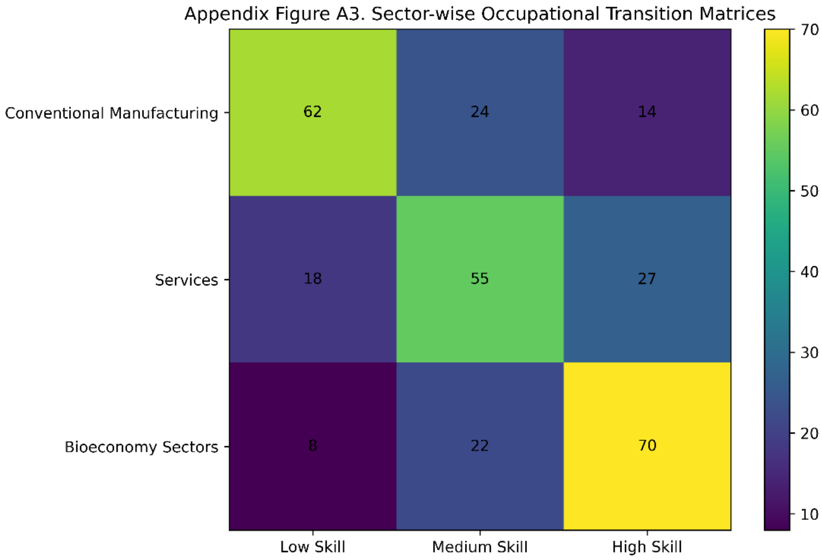


**Figure A3.** Sector-Wise Occupational Transition Matrices.

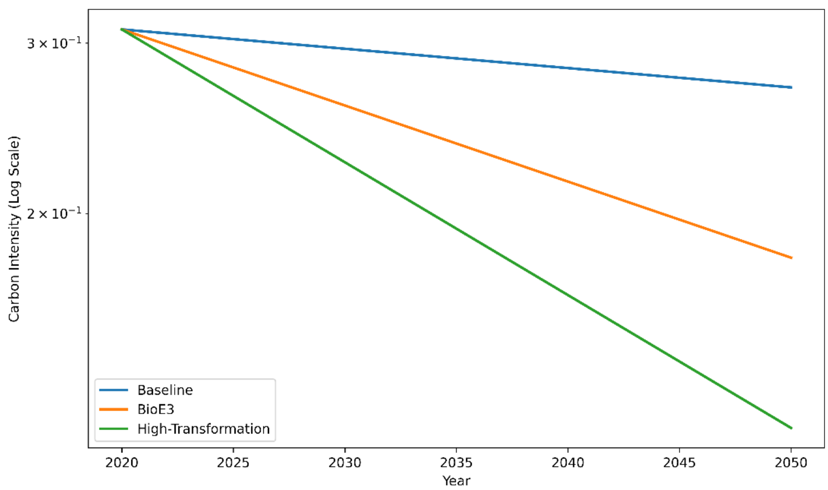


**Figure A4.** Logarithmic Representation of Carbon Intensity Trajectories.

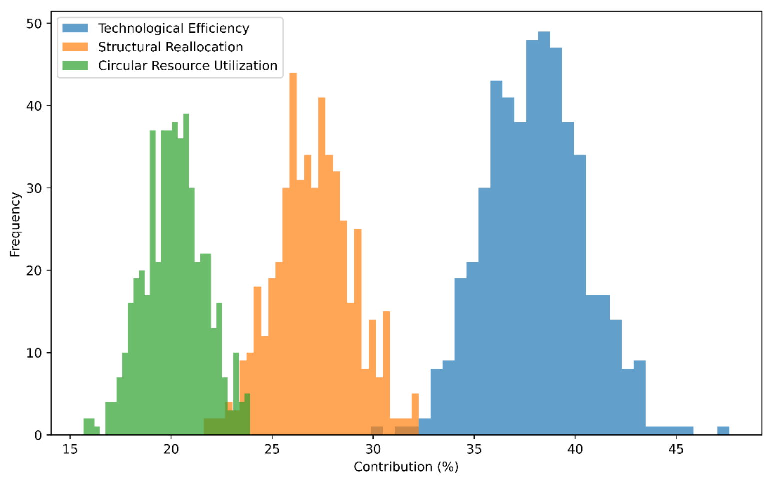


**Figure A5.** Monte Carlo Sensitivity Distribution for Emission Decomposition Effects.

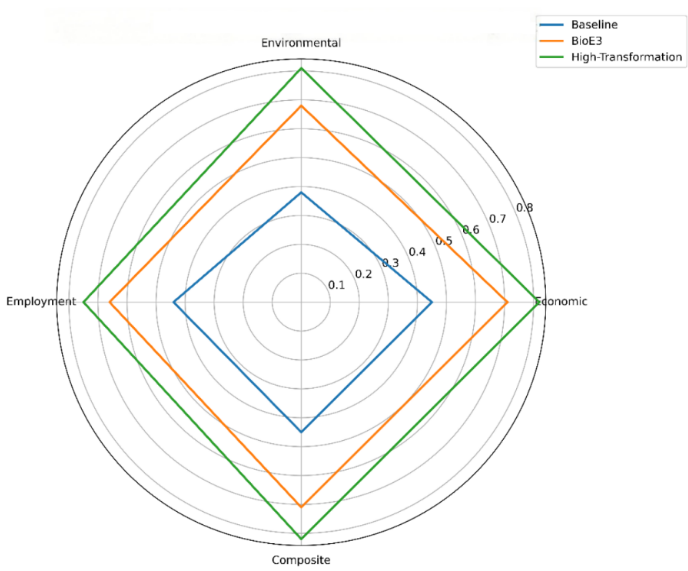


**Figure A6.** Supplementary Frontier Visualization of E3 Dynamics.

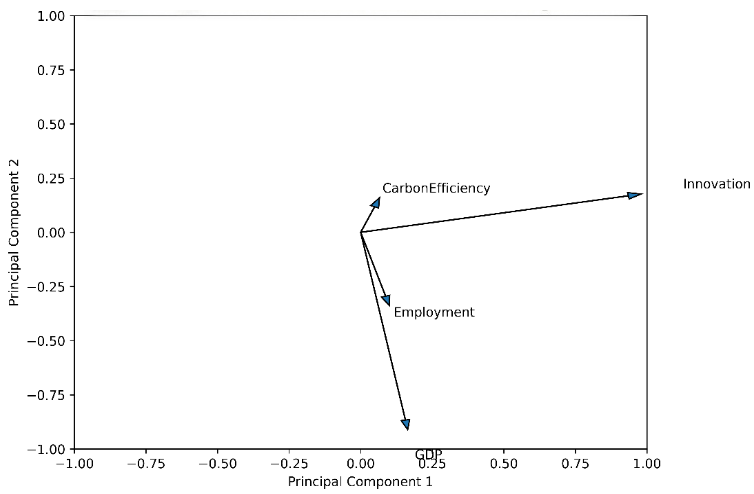


**Figure A7.** PCA Robustness and Indicator Loading Structure.

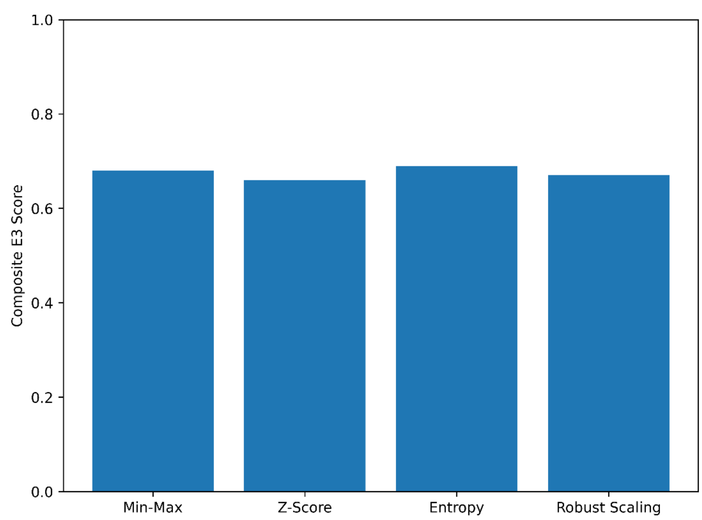


**Figure A8.** Alternative Normalization Sensitivity Results.

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