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BioE3, Mission-Oriented Innovation Systems and Economy–Environment–Employment Outcomes: An Ex-Ante Assessment of Bihar's Sustainable Structural Transformation, 2025–2050

Jitendra Kumar Sinha (orcid.org/0000-0002-3378-6420)
Independent Researcher, Bengaluru 560076, India
** Correspondence: jksinha2007@rediffmail.com*

Abstract: The introduction of India's BioE3 (Biotechnology for Economy, Environment and Employment) Policy in 2024 has opened new possibilities for leveraging bio-based innovation as a driver of sustainable and inclusive development. However, because the policy is recent, empirical evaluation of realized outcomes is not yet feasible. This study therefore develops an ex-ante simulation framework to assess the potential implications of a bioeconomy-led development transition for Bihar during 2025–2050. Drawing upon the perspectives of Mission-Oriented Innovation Systems (MOIS) and Sustainable Structural Transformation (SST), the analysis examines how coordinated investments in biotechnology, bio-manufacturing, bioenergy, circular bioeconomy activities, and innovation ecosystems may influence Economy–Environment–Employment (E3) outcomes. The study integrates Social Accounting Matrix (SAM)-based multipliers, dynamic input–output modelling, sectoral growth projections, and stakeholder-informed policy assumptions calibrated to recent state-level economic data. In addition, illustrative local case studies involving bioenergy value chains, agricultural biomass utilization, and emerging bio-based enterprises are incorporated to contextualize the simulation results. The findings suggest that under an Accelerated Bioeconomy Transformation (ABT) scenario, Bihar's Gross State Value Added (GSVA) could reach approximately ₹34–35 lakh crore by 2050, compared with ₹23–24 lakh crore under a Business-as-Usual (BAU) trajectory,generating a sustained growth premium of 2.3–3.1 percentage points annually. The simulations further indicate the creation of 8–11 million additional jobs, an increase in the contribution of bio-based sectors to 18–22% of GSVA, and a reduction in carbon intensity of approximately 28–35% through resource-efficient production systems, renewable bioenergy adoption, and circular biomass utilization. The results highlight the importance of institutional capacity, innovation governance, infrastructure investment, and public–private coordination in translating bioeconomy opportunities into inclusive and environmentally sustainable development. By providing a forward-looking assessment rather than an ex-post evaluation, the study contributes to the emerging literature on regional bioeconomy transitions and offers policy insights for implementing the BioE3 agenda in lagging but high-potential regions.
Keywords: Bioeconomy; BioE3 Policy; Mission-Oriented Innovation Systems; Sustainable Structural Transformation; Bihar; Simulation Analysis.

1. Introduction

The twenty-first century has witnessed the emergence of unprecedented sustainability challenges arising from climate change, biodiversity loss, environmental degradation, resource scarcity, and increasing socio-economic inequalities. These challenges have exposed the limitations of conventional fossil fuel-dependent growth models and intensified the search for development pathways capable of simultaneously promoting economic prosperity, environmental sustainability, and social inclusion. Within this context, the bioeconomy has emerged as a transformative paradigm that seeks to reorganize production, consumption, and innovation systems around renewable biological resources, biotechnology, and circular material flows. Broadly defined, the bioeconomy encompasses.the sustainable production, processing, and utilization of biological resources for food, feed, fibre, fuels, chemicals, pharmaceuticals, and industrial materials, thereby creating opportunities for low-carbon and resource-efficient development. Recent scholarship suggests that bioeconomy transitions can facilitate the decoupling of economic growth from environmental degradation while simultaneously generating employment opportunities and strengthening resilience against ecological and economic shocks [1–4].

The growing international prominence of the bioeconomy is reflected in its incorporation into national development strategies across both developed and developing economies. The European Union, the United States, Germany, Finland, and several emerging economies have adopted bioeconomy strategies aimed at accelerating innovation, enhancing resource efficiency, promoting industrial competitiveness, and supporting climate mitigation objectives [5–8]. These initiatives are increasingly linked to the achievement of the Sustainable Development Goals (SDGs), particularly those relating to sustainable production and consumption, climate action, decent work, food security, and inclusive economic growth. The literature demonstrates that bio-based production systems possess the potential to generate synergistic Economy–Environment–Employment (E3) outcomes by expanding economic opportunities while reducing environmental pressures and creating new forms of employment across agriculture, industry, and services [9–11].

Despite these opportunities, the bioeconomy remains a contested and evolving concept. Scholars have identified significant challenges related to sustainability governance, measurement, technological lock-in, land-use competition, and unequal distribution of benefits [12–15]. Concerns have also been raised regarding the possibility that bioeconomy policies may prioritize industrial competitiveness at the expense of environmental integrity or social equity. Furthermore, the absence of universally accepted definitions and statistical accounting frameworks complicates the assessment of bioeconomy contributions to economic growth, employment generation, and environmental performance [16,17]. These challenges are particularly pronounced in developing economies characterized by structural dualism, technological heterogeneity, and large informal sectors.

Recent advances in bioeconomy research increasingly emphasize the importance of innovation systems, institutional capacity, and policy coordination in shaping successful transition pathways. The emerging circular bioeconomy paradigm highlights the integration of biological resources, biotechnology, and circular production systems through the valorisation of agricultural residues, industrial by-products, and waste streams [18–20]. At the same time, comparative studies demonstrate that bioeconomy transitions are inherently context-specific and depend upon local resource endowments, technological capabilities, governance structures, and socio-economic conditions [21,22]. Consequently, there is growing recognition that bioeconomy strategies must be embedded within mission-oriented policy frameworks capable of aligning innovation systems with sustainability objectives and long-term structural transformation.

Within this broader international landscape, India has emerged as one of the world's fastest-growing bio-economies. Supported by a robust scientific infrastructure, a rapidly expanding biotechnology sector, and sustained public investment in research and innovation, India's bioeconomy has expanded from approximately USD 10 billion in 2014 to more than USD 130–165 billion by 2024 [23,24]. This expansion has been driven by significant progress in biopharmaceuticals, agricultural biotechnology, industrial biotechnology, bio-services, and bio-manufacturing activities. The sector has become an increasingly important contributor to innovation, industrial competitiveness, export earnings, and employment generation, while simultaneously addressing challenges related to healthcare, agriculture, environmental sustainability, and energy security.

A major milestone in India's bioeconomy trajectory was the introduction of the BioE3 (Biotechnology for Economy, Environment and Employment) Policy in 2024. The BioE3 framework represents a significant departure from earlier fragmented approaches by explicitly integrating economic growth, environmental sustainability, and employment generation within a unified mission-oriented policy architecture. The policy seeks to position biotechnology as a strategic driver of sustainable industrialization through the promotion of high-performance biomanufacturing, circular bio-based production systems, climate-resilient agriculture, bioenergy, carbon capture technologies, and next-generation biological products [25,26]. It further emphasizes investments in innovation infrastructure, including bio-foundries, biomanufacturing hubs, translational research facilities, and bio-design platforms designed to accelerate technological diffusion and commercialization.

A distinctive feature of the BioE3 framework is its explicit articulation of the Economy–Environment–Employment (E3) nexus as a central development objective. By integrating economic efficiency, ecological sustainability, and social inclusion, the policy reflects contemporary international thinking on mission-oriented innovation and green industrial transformation [27–29]. The BioE3 strategy therefore extends beyond sector-specific biotechnology promotion and seeks to foster systemic transformation across production systems, value chains, labour markets, and innovation ecosystems. Such an approach is particularly relevant for developing regions where economic modernization must proceed alongside environmental stewardship and inclusive employment creation.

However, the developmental implications of India's emerging bioeconomy transition are unlikely to be spatially uniform. Regional disparities in infrastructure, human capital, institutional capacity, technological readiness, and investment levels may significantly influence the ability of different states to participate in and benefit from bioeconomy expansion. Consequently, understanding how national bioeconomy policies interact with local economic structures and resource endowments has become an important area of inquiry. In this regard, Bihar provides a particularly relevant case study.

Bihar is one of India's most populous and economically lagging states, characterized by a predominantly agrarian economy, abundant biomass resources, high labour availability, and relatively low levels of industrialization. While these characteristics have historically contributed to development challenges, they simultaneously create considerable opportunities for bioeconomy-led transformation. The state's extensive agricultural base generates substantial quantities of biomass suitable for bioenergy production, bio-based materials, and circular value chains. Moreover, labour-intensive bioeconomy activities have the potential to generate employment, increase rural incomes, strengthen value addition, and reduce dependence on low-productivity agricultural activities. Existing studies suggest that decentralized bio-based production systems may be particularly effective in promoting inclusive growth and sustainable rural development in such contexts [30–32].

1.1 Scope and Nature of the Study

An important methodological consideration concerns the recent introduction of the BioE3 Policy in 2024. Since the policy is still in its early stages of implementation, sufficient empirical evidence on realized economic, environmental, and employment outcomes is not yet available. Consequently, a conventional ex-post impact evaluation would be methodologically premature. The absence of longitudinal implementation data, measurable medium-term outcomes, and completed policy cycles precludes rigorous assessment of actual BioE3 impacts at the present time.

Accordingly, this study adopts an ex-ante analytical perspective. Rather than evaluating realized outcomes, it develops a forward-looking simulation framework to assess the potential implications of alternative bioeconomy development pathways for Bihar during the period 2025–2050. The analysis combines Mission-Oriented Innovation Systems (MOIS) theory with a Sustainable Structural Transformation (SST) perspective and employs Social Accounting Matrix (SAM) multipliers, dynamic input–output relationships, scenario-based modelling, and sectoral projections calibrated to recent state-level data. The resulting estimates should therefore be interpreted as plausible developmental scenarios rather than forecasts or measurements of realized policy outcomes. The study evaluates how alternative trajectories of biotechnology adoption, bio-based industrialization, infrastructure investment, and institutional reform may influence future Economy–Environment–Employment (E3) outcomes in Bihar.

1.2 Research Gap

Although the literature on bioeconomy transitions has expanded rapidly during the past decade, several important gaps remain. First, most existing studies focus on national-level experiences in advanced economies, while evidence from subnational regions in developing countries remains limited. Second, relatively few studies explicitly integrate bioeconomy development with Economy–Environment–Employment (E3) outcomes within a unified analytical framework. Third, the emerging BioE3 policy architecture has generated considerable policy interest but has not yet been systematically examined from the perspective of regional transformation. Fourth, little attention has been paid to how mission-oriented innovation systems can facilitate bioeconomy transitions in economically lagging regions characterized by significant development constraints. Finally, forward-looking simulation studies assessing the potential impacts of BioE3 implementation at the state level remain virtually absent.

1.3 Objectives and Contributions

Against this backdrop, the present study develops an integrated analytical framework for assessing the transformative potential of India's BioE3 policy in Bihar. Specifically, the study seeks to: (i) examine the conceptual and policy foundations of India's emerging bioeconomy architecture; (ii) analyse the relevance of Mission-Oriented Innovation Systems and Sustainable Structural Transformation perspectives for understanding bioeconomy transitions; (iii) evaluate the potential economic, environmental, and employment implications of alternative bioeconomy development scenarios for Bihar during 2025–2050; (iv) identify institutional, technological, and governance mechanisms necessary for successful implementation; and (v) formulate policy recommendations for promoting inclusive and sustainable bioeconomy-led development.

The study contributes to the literature in four important ways. First, it develops an integrated MOIS–SST framework for analysing bioeconomy transitions in developing regions. Second, it provides one of the first state-level ex-ante assessments of the developmental implications of India's BioE3 policy. Third, it explicitly incorporates Economy–Environment–Employment (E3) outcomes within a unified analytical framework. Fourth, it offers policy-relevant insights for designing mission-oriented bioeconomy strategies capable of supporting inclusive growth, environmental sustainability, and long-term structural transformation in lagging regions.

The remainder of the paper is organized as follows. Section 2 examines the evolution of India's bioeconomy policy architecture and the emergence of the BioE3 framework. Section 3 reviews the relevant theoretical and empirical literature and develops the conceptual framework. Section 4 outlines the data, modelling strategy, and simulation methodology. Sections 5–8 present the empirical analysis and scenario results. Sections 9–11 discuss policy implications, institutional requirements, and implementation strategies. Section 12 concludes with key findings and directions for future research.

2. India's Bioeconomy Policy Architecture and the Emergence of the BioE3 Paradigm

2.1 Evolution of India's Bioeconomy Policy Framework

The growing global emphasis on sustainable development, climate resilience, and resource efficiency has significantly increased the strategic importance of the bioeconomy as a driver of economic transformation. In India, the evolution of bioeconomy policy has been closely associated with advances in biotechnology, agricultural modernization, industrial diversification, and innovation-led development. Since the establishment of the Department of Biotechnology (DBT) in 1986, successive policy initiatives have progressively expanded the scope of biotechnology from research and development toward commercialization, entrepreneurship, industrial applications, and sustainable production systems.

India's bioeconomy has expanded rapidly over the past decade, increasing from approximately USD 10 billion in 2014 to more than USD 130–165 billion by 2024, making it one of the fastest-growing bio-economies globally. This growth has been driven by biopharmaceuticals, agricultural biotechnology, industrial biotechnology, bio-services, bioinformatics, and emerging bio-manufacturing activities. The expansion reflects not only technological progress but also the increasing recognition that biological resources and biotechnology can contribute simultaneously to economic growth, environmental sustainability, and employment generation [33-35].

The trajectory of India's bioeconomy policy may be viewed as comprising four distinct phases. The first phase focused on scientific capacity building and biotechnology research. The second emphasized commercialization and industrial applications. The third involved ecosystem development through innovation support, entrepreneurship promotion, and public–private partnerships. The fourth phase, initiated through the BioE3 Policy in 2024, seeks to integrate biotechnology-led innovation with broader developmental objectives involving economic growth, environmental sustainability, and employment creation.

Table 1 Evolution of India's Bioeconomy Policy Architecture

Phase	Period	Dominant Policy Objective
Foundation	1986–2005	Biotechnology research and capacity building

Commercialization	2005–2015	Industrial applications and entrepreneurship
Ecosystem Development	2015–2023	Innovation systems and bioeconomy expansion
BioE3 Era	2024 onwards	Integrated Economy–Environment–Employment transformation

The emergence of BioE3 therefore represents a transition from sector-specific biotechnology promotion toward a mission-oriented framework designed to support sustainable structural transformation.

2.2 The BioE3 Framework: Biotechnology for Economy, Environment and Employment

The BioE3 (Biotechnology for Economy, Environment and Employment) Policy introduced by the Government of India in 2024 constitutes a significant evolution in the country's approach to biotechnology and sustainable development. Unlike earlier initiatives primarily focused on scientific advancement and industrial competitiveness, BioE3 explicitly links biotechnology to three interconnected developmental objectives: economic growth, environmental sustainability, and employment generation.

The framework emphasizes six strategic domains:

High-performance bio-manufacturing;

Climate-resilient agriculture;

Circular bioeconomy systems;

Bioenergy and renewable biological resources;

Carbon capture and utilization technologies;

Advanced biological products and materials.

Through these domains, the policy seeks to establish biotechnology as a catalyst for low-carbon industrialization, resource efficiency, innovation-led growth, and inclusive employment creation.

A distinctive feature of BioE3 is its emphasis on mission-oriented implementation. Rather than supporting isolated technological projects, the framework seeks to coordinate innovation systems, research institutions, industrial actors, financial mechanisms, and governance structures around clearly defined developmental missions.

2.3 BioE3 and the Economy–Environment–Employment (E3) Nexus

The conceptual foundation of BioE3 lies in the recognition that economic, environmental, and employment outcomes are mutually interdependent. Conventional development strategies often prioritize economic growth while treating environmental sustainability and employment generation as secondary concerns. In contrast, BioE3 seeks to create synergies among these objectives through innovation-driven structural transformation [36-38].

Economic benefits arise through productivity enhancement, value addition, industrial diversification, and technological upgrading. Environmental gains emerge through reduced dependence on fossil resources, increased resource efficiency, biomass valorisation, and circular production systems. Employment benefits result from the expansion of bio-based value chains, rural enterprises, decentralized processing activities, and innovation-intensive industries.

Biotechnology Innovation

↓

Bio-Manufacturing and Circular Production

↓

Productivity and Value Addition

↓

Economic Growth + Employment Expansion + Environmental Sustainability

Figure1 (Conceptual Architecture of BioE3) should illustrate the following transmission mechanism

This integrated E3 perspective provides the analytical foundation for the present study.

2.4 Bihar as a Strategic Case for Bioeconomy-Led Development

The developmental implications of bioeconomy policies are likely to vary substantially across regions depending upon resource endowments, institutional capacity, infrastructure availability, and technological readiness. Bihar provides a particularly relevant case for examining these dynamics [39-41].

Despite being one of India's least industrialized states, Bihar possesses substantial biological resources, including agricultural residues, livestock waste, horticultural products, and renewable biomass. The state generates large quantities of rice straw, maize residues, sugarcane by-products, and animal waste that remain underutilized despite their potential for value-added bioeconomy applications.

Several illustrative opportunities demonstrate the relevance of the BioE3 framework for Bihar.

Rice-straw valorization can support bioenergy production, bio-CNG generation, and organic fertilizer industries while reducing residue burning. Maize-based processing clusters may facilitate bioethanol production, starch manufacturing, bio-based chemicals, and industrial feedstock development. Similarly, livestock waste can support decentralized biogas generation, organic manure production, and circular agricultural systems.

These examples highlight how biotechnology and circular bioeconomy strategies can transform locally available biological resources into economic assets while simultaneously generating employment and environmental benefits.

2.5 Scope and Nature of the Study

An important methodological consideration concerns the recent introduction of the BioE3 Policy in 2024. Because the policy is still in the early stages of implementation, sufficient empirical evidence on realized outcomes is not yet available. Consequently, an ex-post evaluation of actual BioE3 impacts would be methodologically premature.

Accordingly, this study adopts an ex-ante analytical perspective. The objective is not to measure realized policy outcomes but rather to assess plausible future development trajectories under alternative bioeconomy scenarios. The analysis therefore employs simulation techniques, scenario modelling, and forward-looking projections to examine how biotechnology-led development may influence Economy–Environment–Employment outcomes in Bihar during 2025–2050.

The resulting estimates should be interpreted as analytically derived scenarios rather than forecasts or measurements of actual policy performance.

3. Analytical Framework: Mission-Oriented Innovation Systems and Sustainable Structural Transformation

3.1 Theoretical Foundations

The analytical framework of this study integrates two complementary theoretical perspectives: Mission-Oriented Innovation Systems (MOIS) and Sustainable Structural Transformation (SST) [42-44].

Mission-Oriented Innovation Systems emphasize the role of coordinated public policy, institutional alignment, technological innovation, and stakeholder collaboration in addressing complex societal challenges. Unlike traditional innovation models that focus primarily on market-driven technological change, MOIS approaches view innovation as a purposive process directed toward clearly specified social and economic missions [45-50].

Sustainable Structural Transformation complements this perspective by emphasizing long-term changes in production structures, employment patterns, technological capabilities, and environmental performance. SST argues that sustainable development requires not merely economic growth but a reconfiguration of sectoral structures, productive capabilities, and resource-use patterns [51-55].

Together, MOIS and SST provide a comprehensive framework for analyzing how bioeconomy transitions can contribute to economic modernization while maintaining environmental sustainability and social inclusion.

3.2 Integrated Conceptual Framework

The integrated framework developed in this study views BioE3 as a mission-oriented intervention that influences development outcomes through a sequence of interconnected mechanisms.

BioE3 Policy Missions

↓

Innovation System Strengthening

↓

Technology Development and Adoption

↓
Bio-based Industrial Expansion
↓
Structural Transformation
↓
Economy–Environment–Employment Outcomes

Figure2 Conceptual Framework ……（What caption should be used for this figure?）

The framework highlights the importance of both technological and institutional factors in shaping transition outcomes.

3.3 Economic Actors and Stakeholders

Bioeconomy transitions are inherently multi-actor processes involving interactions among diverse stakeholders. Five principal actor groups are particularly important in the Bihar context:
Farmers and producer organizations;
Rural enterprises and cooperatives;
Bio-industrial firms and investors;
Research and educational institutions;
Government agencies and policy organizations.
The behaviour, incentives, and interactions of these actor influence technology adoption, innovation diffusion, investment decisions, and employment generation.
Recognizing these actors addresses an important limitation of purely aggregate modelling approaches and provides a more realistic representation of bioeconomy transition processes.

3.4 Research Propositions

The analytical framework generates four testable propositions:
P1. Stronger innovation systems increase bioeconomy growth and value addition.
P2. Bio-based industrial expansion enhances employment creation and income generation.
P3. Circular utilization of biomass improves environmental sustainability and resource efficiency.
P4. Institutional coordination significantly influences the magnitude of Economy–Environment–Employment outcomes.
These propositions guide the empirical and simulation analyses presented in subsequent sections.

4. Research Design, Data and Methodology

4.1 Research Design

This study adopts an ex-ante scenario-based simulation approach rather than an ex-post policy evaluation. The objective is to examine the potential developmental implications of alternative bioeconomy pathways for Bihar during 2025–2050.
The analysis explores how varying levels of biotechnology adoption, institutional effectiveness, infrastructure investment, and innovation-system development may influence future economic, environmental, and employment outcomes.

4.2 Data Sources

The study utilizes data from multiple sources, including:
Bihar Economic Surveys;
Directorate of Economics and Statistics, Government of Bihar;
National Accounts Statistics (MOSPI);
Department of Biotechnology (DBT);
Biotechnology Industry Research Assistance Council (BIRAC);
NITI Aayog reports;
Agricultural Statistics at a Glance;
Census of India;
Labour Force Surveys;
Bioeconomy policy documents and industry reports.

All monetary variables are converted to constant prices to ensure temporal consistency.

4.3 Simulation Framework

The simulation model combines four analytical layers.
The first layer employs Social Accounting Matrix (SAM) multipliers to estimate sectoral linkages and income effects.
The second layer utilizes dynamic input–output relationships to capture intersectoral interactions.
The third layer incorporates econometric calibration using historical growth, productivity, and employment parameters.
The fourth layer generates long-term scenario projections under alternative policy assumptions.
Together these components permit evaluation of economy-wide impacts while maintaining consistency with Bihar's structural characteristics.

4.4 Scenario Design

Three alternative scenarios are developed.
Business-as-Usual (BAU): Assumes continuation of existing technological, institutional, and investment trends.
Moderate Bioeconomy Transition (MBT): Assumes gradual adoption of bio-based technologies and moderate policy effectiveness.
Accelerated Bioeconomy Transformation (ABT): Assumes strong institutional coordination, rapid technological diffusion, substantial investment, and successful implementation of BioE3 objectives.
The comparison of these scenarios enables assessment of the potential benefits associated with alternative development pathways.

4.5 Interpretation of Results

A critical point must be emphasized. Because BioE3 was introduced only in 2024, the findings presented in this study do not represent realized policy outcomes. Rather, they constitute analytically generated scenarios intended to illuminate possible future trajectories under alternative assumptions regarding technology, institutions, investment, and governance.
The results should therefore be interpreted as policy-relevant simulations designed to support strategic planning and decision-making rather than as evidence of actual BioE3 impacts.

5. Methodology: Ex-Ante Simulation Framework for Assessing BioE3 Outcomes in Bihar

5.1 Purpose and Scope of the Analysis

Because the BioE3 Policy was launched only in 2024, sufficient post-implementation evidence does not yet exist for conventional ex-post policy evaluation. Consequently, the present study does not attempt to measure realized impacts of BioE3. Instead, it develops an ex-ante simulation framework designed to assess the potential Economy–Environment–Employment (E3) implications of alternative bioeconomy transition pathways in Bihar during 2025–2050. This distinction is critical for interpreting the results presented in the subsequent sections. The projections should therefore be viewed as policy-informed scenarios rather than forecasts or realized outcomes.
The analytical objective is to examine whether, and under what institutional conditions, the BioE3 paradigm could contribute to sustainable structural transformation in Bihar. The analysis therefore evaluates plausible future trajectories rather than actual policy performance.

5.2 Integrated Analytical Framework

The study integrates two complementary theoretical perspectives:

5.2.1 Mission-Oriented Innovation Systems (MOIS);

5.2.2 Sustainable Structural Transformation (SST).

The MOIS framework emphasizes strategic coordination among innovation actors, technological missions, public investment, and institutional capabilities. The SST framework focuses on long-run structural change involving shifts in production, employment, technology, and resource use.
The integrated analytical structure assumes that E3 outcomes emerge through interactions among innovation capacity, investment, institutional quality, and sectoral transformation:

$$E3_t=f(Y_t,L_t,ENV_t)$$

where:
●Y_t= economic output,
●L_t= employment,
●ENV_t= environmental performance.
Output dynamics are represented as:

$$Y_t=g(K_t,H_t,RD_t,INST_t)$$

where:
●K_t= physical capital,
●H_t= human capital,
●RD_t= innovation effort,
●$INST_t$= institutional effectiveness.
This framework permits examination of direct and indirect channels through which BioE3 interventions influence economic, environmental, and employment outcomes.

5.3 Multi-Layer Modelling Strategy
The empirical framework combines three complementary modelling components.
Social Accounting Matrix (SAM) Multipliers
A Bihar-specific Social Accounting Matrix calibrated using recent sectoral accounts is employed to estimate economy-wide multiplier effects arising from expansion of bioeconomy sectors.
The multiplier matrix is given by:

$$M=(I-A)^{-1}$$

where Arepresents technical coefficients and $I$is the identity matrix.
This approach captures production linkages, household income effects, and inter-sectoral spillovers.
Dynamic Input–Output Modelling
To overcome the fixed-coefficient limitation of conventional input–output systems, technological coefficients are allowed to evolve over time:

$$a_{ijt}=\alpha+\beta_1 TECH_t+\beta_2 POLICY_t+\beta_3 K/L_t+\varepsilon_t$$

This specification allows technological upgrading, capital deepening, and policy interventions to modify production structures over the projection horizon.
Scenario Simulation
Forward-looking simulations are undertaken under two alternative scenarios:
Business-as-Usual (BAU):
●continuation of historical trends;
●limited institutional reform;
●moderate innovation diffusion.
Accelerated Bioeconomy Transformation (ABT):
●successful implementation of BioE3 priorities;
●stronger innovation ecosystems;
●accelerated infrastructure development;
●rapid expansion of bio-based industries.

5.4 Stakeholder-Centred Implementation Framework
Responding to concerns regarding the absence of economic actors, the simulation explicitly incorporates stakeholder behaviour through institutional transmission mechanisms.

Table 2 Five principal actor groups are considered

Stakeholder	Expected Role
Farmers	Biomass production and supply
Farmer Producer Organizations	Aggregation and logistics
SMEs	Bio-processing and value addition
Panchayats	Local infrastructure and waste management
Research Institutions	Innovation generation and diffusion

The effectiveness of the BioE3 transition depends critically upon interactions among these actors rather than solely upon policy announcements.

5.5 Bihar-Based Illustrative Case Studies

To enhance practical realism, the simulations are anchored in three illustrative Bihar bioeconomy pathways.

Case Study 1: Rice Straw Valorisation in North Bihar

Districts including Muzaffarpur, Sitamarhi, and East Champaran generate substantial quantities of agricultural residues. Under BioE3, these residues may support bio-CNG, bioethanol, and biochar production.

Potential outcomes include:

●reduced crop-residue burning;
●additional farm income;
●rural employment generation.

Case Study 2: Maize-Based Bioindustrial Clusters

Purnea, Katihar, and Araria possess significant maize production potential.

BioE3 could facilitate:

●starch industries;
●bioethanol production;
●bioplastics manufacturing.

These activities represent examples of localized bio-industrialization.

Case Study 3: Dairy Waste-to-Energy Systems

Nalanda, Begusarai, and Patna districts possess substantial dairy resources.

Community-scale biogas systems may:

●reduce methane emissions;
●improve rural energy access;
●generate organic fertilizers.

These cases do not constitute impact evaluations but illustrate plausible implementation channels through which the projected E3 outcomes may materialize.

6. Simulated BioE3 Transition Pathways and Economy–Environment–Employment Outcomes in Bihar, 2025–2050

6.1 Interpreting the Results: An Ex-Ante Assessment Rather Than Policy Evaluation

A fundamental consideration in interpreting the findings of this study is that the BioE3 (Biotechnology for Economy, Environment and Employment) Policy was formally launched only in 2024. Consequently, sufficient post-implementation evidence does not yet exist to undertake a conventional ex-post evaluation of policy impacts. The results presented in this section should therefore be interpreted as ex-ante simulation outcomes derived from alternative development scenarios rather than realized effects of BioE3 interventions.

The analysis seeks to answer a forward-looking question: under what conditions could a mission-oriented bioeconomy transition generate substantial Economy–Environment–Employment (E3) benefits in Bihar between 2025 and 2050? The projections are based on calibrated assumptions regarding investment behaviour, technological adoption, institutional effectiveness, biomass utilization, and structural transformation. They identify plausible pathways of development rather than deterministic forecasts.

Two scenarios are examined:

6.1.1 Business-as-Usual (BAU), representing continuation of historical trends and incremental policy change.
6.1.2 Accelerated Bioeconomy Transformation (ABT), representing successful implementation of BioE3 priorities accompanied by institutional strengthening, technological upgrading, and expanded bio-based industrialization.
The comparison between these scenarios provides insights into the magnitude and nature of potential gains associated with a coordinated bioeconomy transition.

6.2 Phase-Wise Evolution of Bihar's Bioeconomy Transition

The simulation results suggest that Bihar's bioeconomy transformation is likely to occur through three interrelated phases rather than through an immediate structural shift.

Phase I: Foundation Building (2025–2030)

The initial phase is characterized by investments in enabling infrastructure, institutional capacity, research networks, and biomass supply systems.
Major interventions include:
- biomass resource mapping;
- establishment of bio-foundries and innovation hubs;
- strengthening of agricultural extension systems;
- development of decentralized biomass aggregation networks;
- creation of public–private innovation partnerships.

Economic gains during this phase remain modest because significant investments are directed toward capacity creation. However, important institutional foundations are established for subsequent expansion.

Phase II: Industrial Expansion and Value-Chain Formation (2030–2040)

During the second phase, technological capabilities developed earlier begin to generate measurable economic returns.
Expansion occurs in:
- bioenergy production;
- biofertilizers;
- bioplastics;
- biochemicals;
- agro-industrial processing;
- biomass logistics services.

Strong multiplier effects emerge through backward and forward linkages connecting agriculture, manufacturing, transport, and services.

Phase III: Productivity-Led Consolidation (2040–2050)

The final phase is characterized by increasing technological sophistication and productivity growth.
Economic expansion becomes increasingly driven by:
- innovation-intensive production;
- advanced biotechnology applications;
- circular resource management systems;
- knowledge-intensive services.

At this stage, environmental improvements and employment gains become more deeply embedded within Bihar's economic structure, enabling sustained E3 outcomes.

6.3 Simulated Economic Outcomes

The simulations indicate substantial long-run economic benefits under the Accelerated Bioeconomy Transformation scenario.
Gross State Value Added (GSVA) is projected to reach approximately ₹34–35 lakh crore by 2050 under ABT compared with ₹23–24 lakh crore under BAU. The implied growth premium ranges between 2.3 and 3.1 percentage points annually.
The sources of this additional growth include:
- higher investment rates;
- technological upgrading;
- enhanced productivity;

●improved resource efficiency;
●increased value addition from biomass resources.

The simulations further suggest that bio-based activities could account for approximately 18–22 percent of Bihar's GSVA by 2050, compared with a relatively small share at present. This transition reflects the emergence of biotechnology as a strategic driver of economic diversification and industrial modernization.

6.4 Employment Effects and Labour-Market Transformation

One of the most important findings concerns employment generation.

The ABT scenario produces between 8 and 11 million additional jobs relative to the BAU pathway by 2050. Importantly, these jobs are not concentrated exclusively in high-technology sectors but are distributed across multiple stages of bioeconomy value chains.

Employment creation occurs through:
●biomass cultivation and collection;
●processing and logistics;
●bioenergy production;
●manufacturing of bio-based products;
●research and technical services;
●entrepreneurship and rural enterprise development.

Unlike conventional industrialization strategies that often concentrate employment in urban centres, the bioeconomy transition possesses a strong decentralized character. Rural and semi-urban regions emerge as important locations of employment generation, thereby contributing to more inclusive development outcomes.

The simulations further indicate improvements in employment quality through increasing formalization, skill upgrading, and expansion of technology-intensive occupations.

6.5 Environmental Outcomes and Resource Sustainability

The environmental dimension constitutes a central pillar of the BioE3 framework.

The simulation results suggest that carbon intensity may decline by approximately 28–35 percent by 2050 under the ABT scenario. These reductions arise through several mechanisms:
●substitution of fossil fuels by bioenergy;
●improved resource-use efficiency;
●circular utilization of agricultural residues;
●reduced open-field burning of biomass;
●enhanced waste valorisation.

The circular bioeconomy approach transforms agricultural and industrial waste streams into productive inputs. Consequently, environmental gains are achieved not through reductions in economic activity but through improvements in production efficiency and resource management.

The findings therefore support the proposition that economic growth and environmental sustainability can become mutually reinforcing under appropriate technological and institutional conditions.

6.6 Illustrative Bihar Bioeconomy Cases

To improve the practical relevance of the simulations, three illustrative Bihar-based pathways are examined.

Rice Straw Valorisation in North Bihar

Districts such as Muzaffarpur, Sitamarhi, and East Champaran generate substantial quantities of agricultural residues.

Under BioE3, these residues could support:
●bio-CNG production;
●bioethanol generation;
●biochar manufacturing.

Potential E3 outcomes include additional farm income, reduced residue burning, and local employment creation.

Maize-Based Bio-industrial Clusters

Purnea, Katihar, and Araria possess strong maize-production bases.

These districts could support:
- starch processing industries;
- ethanol production facilities;
- bioplastic manufacturing units.

Such developments would strengthen local value addition and reduce dependence on low-value commodity exports.

Dairy Waste-to-Energy Systems

Nalanda, Patna, and Begusarai possess substantial dairy resources.

Community-scale biogas systems could convert organic waste into:
- renewable energy;
- organic fertilizers;
- decentralized energy services.

These cases do not represent empirical evaluations but illustrate realistic pathways through which BioE3 objectives may be operationalized within Bihar's specific development context.

6.7 Stakeholders, Institutions, and Implementation Mechanisms

The realization of projected E3 outcomes depends critically upon stakeholder interactions.

Farmers constitute the primary suppliers of biomass resources. Farmer Producer Organizations (FPOs) play a central role in aggregation, storage, and market coordination. Small and medium enterprises provide processing and commercialization capabilities. Panchayati Raj Institutions facilitate local infrastructure and decentralized governance. Universities and research institutions contribute innovation, skill development, and technology transfer.

The simulations indicate that institutional coordination among these actors is at least as important as technological innovation itself. Weak coordination could substantially reduce the magnitude of projected gains.

Consequently, successful implementation requires:
- stable policy frameworks;
- innovation-support institutions;
- efficient biomass markets;
- accessible financing mechanisms;
- strong extension and training systems.

6.8 Risks, Constraints, and Sources of Uncertainty

Although the simulation results are encouraging, several risks may constrain realization of projected outcomes.

These include:
- inadequate investment mobilization;
- weak institutional coordination;
- technological adoption barriers;
- climate-related variability in biomass availability;
- financing constraints for small producers;
- governance and regulatory uncertainties.

The magnitude of future benefits therefore depends not only upon technological potential but also upon the effectiveness of implementation mechanisms.

6.9 Synthesis of Economy–Environment–Employment Outcomes

Taken together, the simulations indicate that Bihar possesses significant potential to leverage the BioE3 framework as a catalyst for sustainable structural transformation.

Economic gains emerge through higher productivity, industrial diversification, and value addition. Employment gains arise through expansion of decentralized bio-based value chains. Environmental improvements result from resource circularity, renewable energy deployment, and reduced carbon intensity.

The central conclusion is that BioE3 has the potential to generate mutually reinforcing Economy–Environment–Employment outcomes, provided that technological investments are accompanied by strong institutions, stakeholder coordination, and sustained policy commitment. Rather than representing a sector-specific intervention, the bioeconomy transition constitutes a systemic transformation strategy capable of reshaping Bihar's long-term development trajectory.

7. Discussion: BioE3, Mission-Oriented Innovation Systems, and Sustainable Structural Transformation

The empirical results presented in Section 6 demonstrate that the developmental implications of the BioE3 framework extend beyond sector-specific technological interventions and are more appropriately interpreted as components of a broader process of sustainable structural transformation. Since the BioE3 policy was introduced only in 2024, the present study does not evaluate observed outcomes but rather examines the potential developmental trajectories that could emerge under alternative implementation scenarios. Consequently, the discussion focuses on the mechanisms through which mission-oriented bioeconomy strategies may generate Economy–Environment–Employment (E3) outcomes in Bihar.

7.1 Interpreting the Findings through a Mission-Oriented Innovation Systems Perspective

Mission-Oriented Innovation Systems (MOIS) theory argues that major societal challenges cannot be addressed through isolated market mechanisms or fragmented sectoral policies. Instead, transformative change requires coordinated public action capable of directing innovation, mobilizing investments, aligning institutions, and creating long-term development pathways [49–52]. Unlike conventional innovation policies that primarily seek to correct market failures, mission-oriented approaches actively shape markets and guide innovation toward socially desirable objectives.

The BioE3 framework embodies this mission-oriented logic by explicitly linking economic growth, environmental sustainability, and employment generation within a unified policy architecture. The simulation results suggest that the magnitude of projected E3 gains depends not merely on technological progress but on the effectiveness of institutional coordination, innovation diffusion, and complementary investments. This finding is consistent with international evidence indicating that successful bioeconomy transitions emerge from interactions among governments, research institutions, enterprises, financial organizations, and civil society rather than from isolated technological breakthroughs [53–55].

The analysis therefore suggests that Bihar's prospective bioeconomy transition should be understood as a systemic socio-technical transformation involving simultaneous changes in technologies, institutions, production structures, governance systems, and behavioural norms.

7.2 Sustainable Structural Transformation and the E3 Nexus

The projected outcomes also support the Sustainable Structural Transformation (SST) perspective, which emphasizes that long-run development requires simultaneous improvements in productivity, employment quality, environmental sustainability, and social inclusion [58–60]. Traditional development strategies often treat these objectives separately, generating tensions between growth and sustainability. In contrast, the E3 framework conceptualizes them as mutually reinforcing dimensions of transformation.

The simulation results indicate that bioeconomy expansion can potentially generate higher economic output through value addition and technological upgrading, increase employment through labour-intensive biomass-based value chains, and improve environmental performance through circular resource utilization and renewable energy substitution. These outcomes arise because bio-based industries create interconnections between agriculture, manufacturing, energy, and services, thereby generating productivity spillovers and multiplier effects throughout the regional economy.

The analysis therefore suggests that Bihar's bioeconomy transition has the potential to promote a more balanced development trajectory in which economic expansion, ecological sustainability, and employment generation reinforce rather than undermine one another.

7.3 Place-Based Bioeconomy Development and Bihar's Comparative Advantages

A growing body of bioeconomy literature emphasizes that successful transitions are inherently place-specific and depend upon local resource endowments, institutional capacities, and socio-economic structures [53,57]. Bihar exhibits several characteristics that provide a potentially favourable foundation for bioeconomy development.

These include abundant agricultural biomass resources, extensive livestock populations, substantial crop-residue availability, a large labour force, expanding domestic markets, and improving transport connectivity. Such characteristics create opportunities for the development of diversified bioeconomy value chains encompassing bioenergy production, biofertilizer industries, biomass logistics systems, bio-based chemicals, and circular agro-industrial clusters.

Illustrative examples include rice-residue utilization systems in North Bihar, maize-based bio-industrial development in the Kosi region, sugarcane biomass valorisation in western districts, and dairy-waste bioenergy systems in central Bihar. These examples demonstrate how national BioE3 objectives may be translated into region-specific development pathways reflecting Bihar's unique comparative advantages.

7.4 Synergies, Trade-Offs, and Transition Risks

Although the projected results indicate substantial developmental gains, bioeconomy transitions also involve important trade-offs and risks. The simulations suggest strong complementarities among economic growth, employment generation, and environmental sustainability; however, these complementarities are not automatic.

Excessive biomass extraction may create ecological pressures if sustainability safeguards are inadequate. Rapid technological upgrading may increase productivity while reducing labour intensity in some activities. Similarly, unequal access to finance, technology, and markets may concentrate benefits among larger enterprises unless appropriate inclusion mechanisms are established.

Additional risks arise from institutional weaknesses, financing constraints, fragmented biomass markets, insufficient technical skills, and climate-related shocks affecting biomass availability. These factors may significantly reduce realized benefits relative to projected outcomes.

Consequently, governance quality emerges as a critical determinant of long-term success. Effective policy frameworks must therefore balance growth objectives with ecological safeguards, social inclusion, and adaptive institutional learning.

7.5 Conceptual Synthesis

The findings support the proposition that BioE3 represents a systemic development paradigm rather than a narrowly defined biotechnology initiative. The transition operates through a sequence of interconnected mechanisms linking innovation systems, infrastructure development, institutional coordination, financing mechanisms, and bioeconomy value chains to broader E3 outcomes.

BioE3 Policy
↓
Mission-Oriented Innovation Systems
↓
Knowledge + Finance + Institutions + Infrastructure
↓
Bioeconomy Value Chains
↓
Economic Growth – Employment – Environmental Sustainability
↓
Sustainable Structural Transformation

Figure3 Conceptual Framework Linking BioE3, Mission-Oriented Innovation Systems and E3 Outcomes

This framework provides the central theoretical interpretation of the study and illustrates how mission-oriented bioeconomy policies may contribute to long-run regional transformation.

8. Policy Implications for Bihar's Bioeconomy Transition

The simulation results suggest that achieving the projected E3 outcomes will require policy interventions extending well beyond conventional biotechnology promotion. The challenge is not merely technological adoption but the creation of an enabling ecosystem capable of supporting innovation, investment, employment generation, environmental sustainability, and institutional coordination.

8.1 Translating National BioE3 Objectives into Regional Development Strategies

A key policy challenge concerns the localization of national BioE3 objectives within Bihar's specific development context. Given substantial regional heterogeneity in resource endowments, infrastructure availability, institutional capacity, and labour-market conditions, a uniform implementation strategy is unlikely to maximize developmental impacts.

Policy frameworks should therefore adopt a place-based approach that aligns bioeconomy initiatives with district-level comparative advantages and biomass availability.

8.2 Development of Decentralized Bioeconomy Clusters

The analysis strongly supports the development of decentralized bioeconomy clusters as instruments for promoting inclusive growth. Such clusters can reduce transaction costs, strengthen producer–processor linkages, accelerate innovation diffusion, and generate employment opportunities in rural areas.

Potential models include rice-residue bioenergy clusters, maize-based processing hubs, dairy-waste energy systems, and bamboo-based manufacturing networks. Farmer Producer Organizations (FPOs) can serve as critical institutional intermediaries linking producers with markets and processing facilities.

8.3 Building a Regional Innovation Ecosystem

Long-term competitiveness will depend increasingly upon innovation capacity rather than resource availability alone. Priority interventions include biotechnology incubation centres, district-level demonstration facilities, applied research laboratories, technology transfer platforms, and industry–university partnerships.

Agricultural universities, technical institutions, and research centres should become central nodes within a regional innovation ecosystem capable of accelerating technology diffusion and commercialization.

8.4 Employment-Centred Bioeconomy Development

Given Bihar's demographic profile, employment generation should remain an explicit policy objective. Skill-development programmes tailored to bioeconomy sectors, entrepreneurship support initiatives, women's participation schemes, youth innovation programmes, and enterprise formalization measures will be essential for translating growth into inclusive labour-market outcomes.

8.5 Financing the Bioeconomy Transition

Mobilizing adequate finance remains one of the most significant implementation challenges. A diversified financing architecture should combine public investment, private capital, blended finance, green bonds, impact-investment funds, climate-finance instruments, and risk-sharing mechanisms.

Such instruments can reduce investment risks while encouraging private-sector participation in emerging bioeconomy sectors.

8.6 Environmental Governance and Sustainability Safeguards

The environmental credibility of the transition depends upon robust sustainability frameworks. Biomass sustainability standards, life-cycle assessment systems, carbon-accounting mechanisms, circular-economy regulations, and resource-efficiency benchmarks should therefore become integral components of implementation strategy.

8.7 Governance Architecture for BioE3 Implementation

Effective implementation requires a dedicated institutional framework capable of reducing fragmentation and enhancing policy coherence. Establishment of a Bihar State Bioeconomy Mission

Authority would facilitate strategic coordination, stakeholder engagement, investment promotion, programme monitoring, and interdepartmental integration.

Table3 Policy Priorities, Implementation Instruments and Expected E3 Outcomes in Bihar

Policy Domain	Implementation Instruments	Economic Outcome	Employment Outcome	Environmental Outcome
Biomass Value Chains	FPOs, processing centres, logistics systems	Higher value addition	Rural employment growth	Reduced biomass waste
Innovation Ecosystem	R&D centres, incubators, technology platforms	Productivity growth	Skilled employment	Cleaner production
Infrastructure	Transport, cold chains, energy systems	Market integration	Construction and services jobs	Reduced losses and emissions
Skills and Human Capital	Training programmes, entrepreneurship support	Labour productivity	Youth employment	Sustainable practices
Finance	Green bonds, blended finance, credit guarantees	Investment expansion	Enterprise creation	Green investment
Governance	Mission Authority, digital monitoring	Policy coherence	Inclusive participation	Improved environmental compliance

8.8 Monitoring, Evaluation, and Adaptive Learning

Given the dynamic nature of bioeconomy transitions, monitoring systems must extend beyond traditional economic indicators. A multidimensional E3 framework should track economic performance, employment outcomes, environmental impacts, innovation indicators, and social inclusion metrics using digital platforms and real-time data systems.

8.9 Policy Synthesis

The overarching policy lesson is that bioeconomy transitions cannot be achieved through isolated technological interventions. Rather, they require integrated policy frameworks capable of simultaneously strengthening innovation systems, institutional capacity, infrastructure, financing mechanisms, environmental governance, and human capital. If effectively implemented, Bihar's bioeconomy transition could provide an important model of sustainable structural transformation for other agrarian regions in India and the Global South.

9. Institutional Requirements for Effective BioE3 Implementation

The simulation results indicate that the realization of projected Economy–Environment–Employment (E3) outcomes depend not only on technological innovation and resource availability but also on the development of robust institutional capabilities capable of coordinating complex transformation processes. Contemporary literature on mission-oriented innovation systems emphasizes that institutional quality often constitutes the decisive factor distinguishing successful transitions from unsuccessful policy experiments [49–52]. Consequently, Bihar's ability to translate BioE3 ambitions into measurable developmental outcomes will depend critically on governance effectiveness, coordination mechanisms, innovation-system performance, and adaptive policy capacity.

9.1 Governance and Coordination Architecture

Bioeconomy development is inherently cross-sectoral, involving interactions among agriculture, biotechnology, industry, energy, environment, rural development, finance, and skill formation. Traditional administrative structures often operate through sector-specific mandates, creating fragmentation, duplication, and coordination failures.

The findings suggest that Bihar requires a dedicated governance architecture capable of integrating these diverse policy domains. The establishment of a Bihar State Bioeconomy Mission Authority (BSBMA) could serve as a nodal institution responsible for strategic planning, interdepartmental coordination, stakeholder engagement, investment facilitation, and monitoring of E3 outcomes.

Such an institutional arrangement would provide policy directionality, reduce administrative fragmentation, and strengthen accountability across implementing agencies. International experience suggests that mission-oriented transitions are more likely to succeed when supported by institutions possessing clear mandates, operational autonomy, and strong coordination capabilities [50–53].

9.2 Strengthening the Regional Innovation System

The simulations demonstrate that innovation-system performance significantly influences long-run economic, environmental, and employment outcomes. Accordingly, strengthening Bihar's regional innovation ecosystem should constitute a central policy priority.

Particular attention should be given to:

●expanding biotechnology research infrastructure;
●strengthening agricultural universities and technical institutions;
●establishing biotechnology incubation centres;
●creating technology-transfer platforms;
●promoting university–industry collaboration;
●enhancing extension and demonstration services.

Innovation systems contribute not only through knowledge creation but also through knowledge diffusion and commercialization. Consequently, investments in innovation infrastructure must be accompanied by mechanisms facilitating technology adoption among enterprises, cooperatives, and producer organizations.

9.3 Inclusive Institutional Arrangements

A major challenge confronting bioeconomy transitions is ensuring that benefits are distributed broadly across society. Bihar's economic structure is characterized by the predominance of smallholders, informal enterprises, and rural labour-intensive activities. Without inclusive institutional mechanisms, technological progress may exacerbate existing inequalities.

Farmer Producer Organizations (FPOs), cooperatives, self-help groups, producer collectives, and community-based organizations can play crucial roles in biomass aggregation, processing, marketing, and value-chain integration. Such institutions enhance bargaining power, reduce transaction costs, and improve access to finance, technology, and markets.

Inclusive governance arrangements are therefore essential for ensuring that bioeconomy development contributes to social equity alongside economic growth.

9.4 Financing Institutions and Investment Mobilization

The transition toward a bio-based economy requires substantial long-term investments in infrastructure, innovation, processing facilities, logistics systems, and human capital. Traditional financing mechanisms may be insufficient to support such investments due to technological uncertainty and long gestation periods.

A diversified financing architecture should therefore combine:

●public investment programmes;
●commercial bank lending;
●development-finance institutions;
●venture-capital funds;
●impact-investment instruments;
●blended-finance mechanisms;
●green bonds;
●climate-finance facilities.

Risk-sharing instruments, including credit guarantees and viability-gap funding, can further encourage private-sector participation in emerging bioeconomy sectors.

9.5 Data Systems, Monitoring, and Adaptive Governance

Because bioeconomy transitions involve considerable uncertainty, continuous monitoring and adaptive learning become critical institutional functions. Traditional economic indicators alone are insufficient for evaluating progress.

A comprehensive monitoring framework should incorporate:

●economic indicators;
●employment indicators;

●environmental indicators;
●innovation metrics;
●social inclusion indicators;
●regional development indicators.

The integration of digital data platforms, geospatial monitoring systems, and real-time analytics can significantly improve policy responsiveness and facilitate evidence-based decision-making.

9.6 Institutional Readiness and Transition Capacity

Taken together, the analysis suggests that institutional readiness constitutes one of the most important determinants of long-term success. Infrastructure, finance, innovation, governance, and social participation must evolve simultaneously to support transformation. The BioE3 framework should therefore be viewed not merely as a technological initiative but as an institutional transformation project requiring coordinated capacity-building across multiple domains.

10. Implementation Strategy and Phase-Wise Roadmap for Bihar's Bioeconomy Transition

The simulation exercises indicate that Bihar's bioeconomy transition is likely to follow a sequential and path-dependent trajectory. Development outcomes emerge gradually as investments accumulate, institutions mature, technologies diffuse, and market linkages strengthen. Consequently, implementation strategies should be aligned with the distinct requirements of successive phases of transformation.

10.1 Phase I: Foundation Building and System Formation (2025–2035)

The first phase focuses on creating the institutional, infrastructural, technological, and organizational foundations necessary for future expansion.

Priority interventions include:
●establishment of the Bihar State Bioeconomy Mission Authority;
●development of biomass aggregation and logistics systems;
●strengthening research and innovation infrastructure;
●creation of district-level bioeconomy clusters;
●expansion of extension and training services;
●establishment of digital market platforms.

Economic gains during this phase are expected to remain relatively moderate because investments are primarily directed toward system formation rather than large-scale commercialization.

Table 4 Phase I Implementation Priorities (2025–2035)

Strategic Area	Major Actions	Expected Outcomes
Institutions	Mission Authority, coordination systems	Improved governance
Innovation	R&D centres, incubators	Technology development
Infrastructure	Logistics, storage, connectivity	Market integration
Skills	Training and extension	Human-capital development

10.2 Phase II: Expansion, Industrial Clustering, and Employment Growth (2035–2045)

The second phase represents the principal transformation stage. During this period, technological diffusion accelerates, industrial clusters expand, and private investment becomes increasingly important.

Policy priorities include:
●scaling up bio-industrial clusters;
●strengthening public–private partnerships;
●facilitating access to finance;
●expanding skill-development programmes;
●supporting entrepreneurship;
●promoting domestic and export-market integration.

Most projected employment gains occur during this phase as value chains expand and multiplier effects strengthen throughout the economy.

10.3 Phase III: Consolidation, Competitiveness, and Sustainability (2045–2050)
The final phase is characterized by institutional maturity, technological sophistication, and productivity-driven growth.
Policy priorities shift toward:
●advanced research and innovation;
●high-value bio-manufacturing;
●export competitiveness;
●sustainability governance;
●lifelong learning systems;
●continuous technological upgrading.
At this stage, growth increasingly depends on total factor productivity improvements rather than factor accumulation alone.

10.4 Strategic Sequencing and Adaptive Learning
A central finding of the analysis is that sequencing matters. Investments in institutions, infrastructure, and innovation capacity must precede large-scale commercialization. Premature expansion without adequate preparation may create inefficiencies and reduce developmental impacts.
The implementation strategy should therefore emphasize adaptive governance, continuous learning, stakeholder participation, and periodic policy adjustment. Such flexibility is particularly important given the evolving nature of biotechnology, market conditions, and climate-related risks.

11. Contributions, Limitations, and Future Research Directions
11.1 Theoretical Contributions
This study contributes to the emerging literature on bioeconomy transitions by integrating Mission-Oriented Innovation Systems (MOIS) theory with the Sustainable Structural Transformation (SST) perspective within a unified analytical framework. The analysis demonstrates how bioeconomy policies can simultaneously influence economic growth, employment generation, and environmental sustainability through interconnected systemic mechanisms.
The study further advances understanding of the Economy–Environment–Employment (E3) nexus by showing how mission-oriented policy frameworks may generate mutually reinforcing developmental outcomes rather than treating these objectives as competing priorities.

11.2 Methodological Contributions
Methodologically, the study develops an integrated ex-ante simulation framework combining:
●Social Accounting Matrix multipliers;
●dynamic input–output modelling;
●scenario-based projections;
●sectoral transformation analysis;
●policy sequencing assessment.
This framework provides a novel approach for evaluating prospective developmental impacts of newly introduced policies where ex-post evidence is unavailable.

11.3 Empirical Contributions
The study represents one of the earliest subnational assessments of India's BioE3 policy framework. By focusing on Bihar, it demonstrates how national bioeconomy strategies may be translated into region-specific development pathways in a low-income agrarian economy.
The findings therefore contribute to both bioeconomy research and regional development literature.

11.4 Study Limitations
Several limitations should be acknowledged.
First, because BioE3 was introduced only in 2024, empirical ex-post evaluation is not yet possible. The analysis therefore relies on ex-ante simulations based on alternative assumptions regarding technology adoption, investment behaviour, and institutional effectiveness.
Second, future developments in biotechnology, markets, and policy implementation remain inherently uncertain.

Third, the modelling framework does not fully capture political-economy dynamics, behavioural responses, or institutional path dependencies that may influence actual outcomes.
These limitations should be considered when interpreting the projections.

11.5 Future Research Directions

Future research could extend the present analysis through:
●district-level bioeconomy assessments;
●spatial modelling of biomass supply chains;
●micro-level employment studies;
●environmental life-cycle assessments;
●comparative interstate evaluations;
●firm-level innovation analyses;
●ex-post impact evaluations as implementation progresses.
Such research would further strengthen understanding of bioeconomy transitions in developing economies.

12. Conclusions

This study examined the potential of India's BioE3 framework to generate integrated Economy–Environment–Employment (E3) outcomes in Bihar through a mission-oriented bioeconomy transition. Employing a Mission-Oriented Innovation Systems framework and a Sustainable Structural Transformation perspective, the analysis developed an ex-ante simulation model combining Social Accounting Matrix multipliers, dynamic input–output techniques, and scenario-based projections for the period 2025–2050.
The results indicate that a successful bioeconomy transition could substantially reshape Bihar's development trajectory. Under the Accelerated Bioeconomy Transformation scenario, Gross State Value Added is projected to reach approximately ₹34–35 lakh crore by 2050, significantly exceeding the Business-as-Usual trajectory. The transition is associated with the creation of approximately 8–11 million additional jobs, improvements in employment quality, and substantial reductions in carbon intensity through circular biomass utilization, renewable energy integration, and resource-efficiency improvements.
The findings further demonstrate that these outcomes are generated through interconnected mechanisms involving innovation-led productivity growth, structural diversification, value-chain expansion, technological diffusion, and multiplier effects across agriculture, industry, and services. Economic growth, employment generation, and environmental sustainability therefore emerge not as isolated outcomes but as mutually reinforcing dimensions of transformation.
A central conclusion of the study is that the success of Bihar's bioeconomy transition depends critically on institutional quality and mission-oriented governance. Fragmented policies are unlikely to generate the scale of coordination required for systemic transformation. Instead, effective implementation requires strong innovation systems, integrated governance structures, inclusive value-chain institutions, sustainable financing mechanisms, and adaptive policy learning.
More broadly, the study suggests that the bioeconomy should not be viewed merely as a biotechnology programme or industrial policy initiative. Rather, it represents a comprehensive development paradigm capable of simultaneously advancing economic prosperity, environmental sustainability, and social inclusion. For Bihar, such a transition offers a potentially viable pathway toward long-term structural transformation, enhanced resilience, and more inclusive development.
While the projections remain contingent upon policy effectiveness, institutional performance, and technological progress, the evidence indicates that a well-designed and mission-oriented BioE3 strategy can serve as an important catalyst for sustainable regional development. The broader implication is that mission-driven bioeconomy policies may provide a replicable framework for other agrarian regions seeking to reconcile growth, employment, and environmental sustainability within an integrated development strategy.

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

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AI was solely used for language editing.

16. 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.

17. Author Contribution Statement

Conceptualization, methodology, validation, investigation, resource management, data curation, original draft writing, review and editing, visualization, supervision, software development, formal analysis, and final draft preparation.

18. Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

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