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Forecasting Bihar's Regional Bioeconomy Transition: Innovation, Green Growth, and Economy–Environment–Employment Outcomes by 2050

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ABSTRACT

The transition towards a sustainable bioeconomy is increasingly recognised as a strategic pathway for simultaneously promoting economic development, environmental sustainability, and employment generation. However, empirical evidence on long-term regional bioeconomy transitions in developing economies remains limited, particularly in biomass-rich yet structurally constrained regions, where innovation capacity, institutional quality, and spatial heterogeneity critically influence development outcomes. This study addresses this gap by developing an integrated Bioeconomy–Economy–Environment–Employment (Bioeconomy–E3) framework to evaluate Bihar's prospective bioeconomy transition to 2050 under alternative policy and innovation scenarios. The analysis combines district-level spatial assessment, composite index construction, econometric modelling, hybrid artificial intelligence and machine-learning forecasting, and scenario-based simulations using multidimensional datasets compiled from national, institutional, international, and satellite-derived sources covering 2005–2025. The forecasting architecture integrates ARIMA, VAR/VECM, Random Forest, XGBoost, and Long Short-Term Memory (LSTM) models within an ensemble framework that exploits the complementary strengths of statistical inference and nonlinear machine learning. The scenario-based projections indicate that innovation capacity, biomass utilization efficiency, renewable-energy adoption, infrastructure quality, and institutional effectiveness are the principal drivers of long-term bioeconomy performance. Under the accelerated innovation scenario, Bihar is projected to achieve stronger productivity growth, greater renewable-energy integration, improved circular resource utilization, enhanced environmental performance,

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and expanded green employment relative to business-as-usual and policy-driven transition scenarios. Spatial analysis further reveals substantial district-level disparities in transition readiness, underscoring the importance of differentiated place-based policies and adaptive governance. By integrating regional innovation systems, spatial heterogeneity, hybrid econometric–AI forecasting, and long-term scenario analysis within a unified analytical framework, the study advances regional bioeconomy scholarship and provides a transferable methodological approach for evaluating sustainable bioeconomy transitions in developing economies.

Keywords: Bioeconomy; Bihar; Green Growth; Circular Economy; Innovation Systems; AI/ML Forecasting; Sustainability Transition; Regional Development

1. Introduction

1.1. Global Sustainability Transition and the Rise of the Bioeconomy

The accelerating challenges of climate change, biodiversity loss, resource depletion, and food and energy insecurity have intensified the search for development pathways capable of simultaneously promoting economic growth, environmental sustainability, and social inclusion [1,2]. Within this context, the bioeconomy has emerged as a strategic paradigm based on the sustainable production, utilization, and valorisation of renewable biological resources through circular production systems, biotechnology, and low-carbon industrial development [3–5]. Unlike conventional fossil-fuel-based production systems, the contemporary bioeconomy integrates biomass cascading, waste valorisation, renewable energy, digital technologies, and ecological regeneration to improve resource efficiency while reducing environmental externalities [4,5].

Bioeconomy strategies have consequently become integral components of sustainability policy in both developed and emerging economies. More than sixty countries have adopted national bioeconomy strategies emphasizing renewable industrialization, biotechnology, circular production systems, and climate-neutral growth [2,6–8]. These developments position the bioeconomy as an important mechanism for achieving the Sustainable Development Goals through integrated economic, environmental, and social transformation [9–13].

1.2. India's Bioeconomy Transition and the Bihar Context

India has emerged as one of the world's fastest-growing bio-economies, supported by rapid advances in biotechnology, renewable energy, digital agriculture, and sustainable biomanufacturing [14]. The recently introduced BioE3 framework further integrates biotechnology with Economy, Environment, and Employment objectives, reflecting a strategic shift toward innovation-led green growth [15]. Nevertheless, substantial regional disparities persist because innovation ecosystems, industrial capabilities, and biomass utilization differ considerably across states [16].

Within this heterogeneous landscape, Bihar represents a particularly important yet understudied case. The state possesses abundant agricultural biomass and considerable potential for bioenergy, bio-based industries, circular agriculture, and decentralized manufacturing, while simultaneously facing persistent structural constraints including low industrialization, environmental vulnerability, underemployment, and outward migration [17,18]. These characteristics make Bihar an appropriate case for investigating whether bioeconomy-led development can support sustainable structural transformation in resource-rich but economically constrained regions.

1.3. Research Gap, Objectives and Contributions

Despite the rapid expansion of bioeconomy research, four important gaps remain. First, empirical evidence is concentrated primarily at national scales, with relatively limited understanding of regional transition dynamics in developing economies [2]. Second, economic, environmental, and employment outcomes are generally analysed separately rather than through integrated analytical frameworks. Third, relatively few studies combine spatial analysis, hybrid econometric–AI forecasting, and long-term scenario modelling. Finally, empirical evidence from biomass-rich but economically lagging regions such as Bihar remains scarce.

This study addresses these gaps by developing an integrated Bioeconomy–Economy–Environment–Employment (Bioeconomy–E3) framework that combines econometric modelling, machine-learning forecasting, spatial analysis, composite indexing, and scenario simulations to evaluate Bihar's transition towards 2050.

Specifically, the study aims to:

- Assess Bihar's bioeconomy potential and innovation capacity;
- Forecast alternative transition pathways to 2050;
- Evaluate long-term Economy–Environment–Employment (E3) outcomes;
- Examine district-level spatial heterogeneity;
- Identify policy strategies for inclusive and sustainable regional transformation.

The study contributes to the literature in four respects. First, it shifts bioeconomy analysis from national to regional transition dynamics. Second, it integrates innovation systems, sustainability transitions, and Economy–Environment–Employment outcomes within a unified analytical framework. Third, it combines econometric models, artificial intelligence, spatial analytics, and scenario forecasting to improve long-term assessment. Finally, it provides a transferable methodological framework for analysing bioeconomy transitions in other biomass-rich developing regions.

2. Literature Review and Conceptual Foundations

2.1. Evolution of the Bioeconomy Concept

The concept of the bioeconomy has evolved considerably over the past two decades from a narrow biotechnology-oriented perspective towards a broader sustainability-centred development paradigm. Early formulations, particularly those promoted by the OECD, primarily emphasized biotechnology, genetic engineering, pharmaceuticals, and industrial biotechnology as engines of economic competitiveness and technological progress [6]. These approaches largely reflected the experience of technologically advanced economies possessing strong research and innovation capabilities.

Subsequent scholarship broadened the concept to encompass the sustainable production, utilization, and valorisation of renewable biological resources for food, energy, industrial materials, chemicals, and ecosystem services [1,3,18]. More recently, bioeconomy research has increasingly converged with circular economy and sustainability-transition literature, giving rise to the concept of the circular bioeconomy, which emphasizes biomass cascading, waste valorisation, industrial symbiosis, resource efficiency, and closed-loop production systems [5,7,8]. Contemporary sustainable bioeconomy frameworks further incorporate ecological resilience, climate neutrality, biodiversity conservation, social inclusion, and digital innovation, thereby positioning the bioeconomy as a systemic pathway for sustainable structural transformation rather than merely a technological or sectoral strategy [2,4,12]. The major conceptual approaches and their defining characteristics are summarized in **Appendix A Table A1**.

Accordingly, the contemporary bioeconomy is best understood as an integrated development framework linking renewable biological resources, technological innovation, circular production systems, and sustainable economic transformation [19–23].

2.2. Theoretical Foundations

The analytical framework adopted in this study draws upon five complementary theoretical perspectives that collectively explain the drivers and outcomes of regional bioeconomy transitions.

Ecological Modernization Theory argues that technological innovation, institutional reform, and industrial restructuring can reconcile economic development with environmental sustainability through cleaner production systems and improved resource efficiency [24–26]. Green Growth Theory further extends this perspective by emphasizing the possibility of decoupling economic growth from environmental degradation through investments in renewable energy, low-carbon technologies, and efficient resource utilization [10,18].

Innovation Systems Theory highlights the importance of interactions among firms, universities, research institutions, governments, and technological networks in generating and diffusing knowledge that supports biotechnology adoption, biomass valorisation, and industrial diversification [13,27]. Complementing this perspective, Regional Development Theory recognises that regional trajectories differ according to variations in resource endowments, infrastructure, institutional quality, human capital, and innovation capacity [28], implying that bioeconomy transitions are inherently place-specific.

Finally, Sustainability Transition Theory conceptualizes bioeconomy development as a long-term socio-technical transformation driven by interactions among technological innovation, institutional adaptation, behavioural change, and policy realignment [29]. Together, these theoretical perspectives provide the conceptual basis for analysing how innovation, regional capabilities, and institutional conditions jointly influence long-term Economy–Environment–Employment (E3) outcomes.

2.3. Bioeconomy, Innovation and Economy–Environment–Employment (E3) Outcomes

Innovation has emerged as the principal enabling mechanism of contemporary bioeconomy transitions. Advances in biotechnology, research and development, digital agriculture, artificial intelligence, renewable energy technologies, and precision farming enhance productivity while improving resource efficiency, environmental performance, and industrial competitiveness [9,10,30]. Technological diffusion also facilitates the emergence of biorefineries, bio-based materials, circular manufacturing systems, and renewable energy industries that strengthen regional value addition and industrial diversification [17].

Beyond technological change, the success of bioeconomy transitions increasingly depends upon their capacity to generate balanced Economy–Environment–Employment (E3) outcomes. Economically, bio-based industries contribute to productivity growth, industrial upgrading, and diversification through new value chains involving biofertilizers, bioenergy, biochemicals, and sustainable manufacturing [7,18,24]. Environmentally, renewable biomass utilization, circular production systems, waste valorisation, and sustainable resource management reduce greenhouse-gas emissions and improve ecological efficiency [8,11,31]. Socially, decentralized bio-based industries generate employment opportunities across agriculture, agro-processing, renewable energy, biomass logistics, biotechnology services, and rural enterprises while simultaneously increasing demand for higher-skilled labour and strengthening rural livelihoods [24,32,33].

These multidimensional interactions indicate that bioeconomy transitions should be evaluated using integrated analytical frameworks rather than isolated economic, environmental, or technological indicators.

2.4. Global and Indian Empirical Evidence

Empirical evidence demonstrates substantial diversity in bioeconomy development across countries and regions. Within the European Union, bioeconomy strategies have been closely integrated with climate policy, circular economy initiatives, and rural development programmes, contributing to renewable energy expansion, industrial innovation, and circular production systems while also revealing governance and sustainability challenges [5,6]. Brazil's experience illustrates how biofuels and biomass-based industries can simultaneously support energy diversification, agricultural modernization, and rural employment, although concerns regarding land-use change and ecological sustainability remain important [34]. Similarly, China's bioeconomy highlights the critical role of state-led innovation systems, technological modernization, and infrastructure investment in improving industrial efficiency and environmental performance [10].

India has experienced rapid expansion of bioeconomy activities through biotechnology, renewable energy, sustainable agriculture, and circular production systems supported by recent national initiatives including the BioE3 framework [14,17,24]. Nevertheless, significant regional disparities persist because innovation ecosystems, industrial infrastructure, institutional capacity, and biomass utilization vary considerably across states [16]. Existing empirical studies have concentrated primarily on technologically advanced states such as Karnataka, Maharashtra, and Telangana [30], whereas comparatively limited evidence is available for agriculturally rich but economically constrained regions such as Bihar. A synthesis of major empirical studies and identified research gaps is provided in **Appendix A Table A2**.

2.5. Synthesis of Existing Literature

A synthesis of the reviewed literature reveals four broad streams of research. The first examines biotechnology and innovation as drivers of economic competitiveness. The second focuses on biomass utilization, renewable energy, and circular production systems. The third investigates environmental sustainability and green growth associated with bio-based development. The fourth explores regional development and institutional dimensions of bioeconomy transitions.

Despite these important contributions, most studies analyse these dimensions independently. Comparative evidence integrating innovation systems, spatial heterogeneity, environmental sustainability, employment generation, and long-term forecasting within a unified regional analytical framework remains relatively limited. Moreover, most empirical investigations focus either on technologically advanced economies or national-level analyses, leaving important knowledge gaps regarding regional transition dynamics in structurally constrained developing regions.

2.6. Research Gaps and Conceptual Positioning

The literature review identifies four major gaps that motivate the present research. First, regional analyses of bioeconomy transitions remain comparatively underdeveloped despite increasing recognition of spatial heterogeneity [2]. Second, economic growth, environmental sustainability, and employment generation are generally examined separately rather than through integrated analytical frameworks capable of capturing their dynamic interactions. Third, relatively few studies combine spatial analysis, econometric modelling, artificial intelligence, and scenario-based forecasting to evaluate long-term regional bioeconomy transitions under conditions of uncertainty. Fourth, empirical evidence from biomass-rich but economically lagging regions remains particularly scarce.

These limitations are especially relevant for Bihar, where abundant biological resources coexist with low industrialization, environmental vulnerability, labour migration, and institutional constraints. Existing studies provide only limited insight into how innovation-led bioeconomy development may simultaneously influence economic performance, environmental sustainability, employment generation, and regional convergence over the long term.

To address these gaps, the present study develops an integrated Bioeconomy–Economy–Environment–Employment (Bioeconomy–E3) analytical framework that combines regional development theory, innovation systems, sustainability-transition perspectives, hybrid econometric–machine learning forecasting, spatial analytics, and scenario analysis. Unlike previous regional bioeconomy studies, the framework explicitly links innovation capacity, biomass utilization, renewable energy adoption, infrastructure quality, and institutional capability with long-term E3 outcomes under alternative transition scenarios extending to 2050. Consequently, the study contributes not only new empirical evidence for Bihar but also a transferable methodological framework for analysing regional bioeconomy transitions in other biomass-rich developing economies.

Figure 1 summarizes the proposed conceptual framework and illustrates the hypothesized relationships among innovation systems, bioeconomy development, spatial heterogeneity, policy interventions, and Economy–Environment–Employment (E3) outcomes that guide the subsequent empirical analysis.

3. Bihar's Regional Bioeconomy Potential: Structural and Spatial Context

3.1. Economic Structure and Development Characteristics

Bihar is among India's most agrarian and labour-intensive economies, characterized by low industrialization, high population density, extensive informal employment, and persistent structural transformation challenges [5,35]. Although the state has experienced sustained growth in Gross State Domestic Product (GSDP) over the past two decades, it continues to lag behind national averages in per-capita income, industrial diversification, and formal employment generation [35].

Agriculture remains the backbone of the state's economy, supporting nearly half of the workforce and generating substantial biomass resources [36]. Fertile alluvial soils, extensive river systems, and favourable agro-climatic conditions support the production of cereals, pulses, sugarcane, fruits, and vegetables. However, productivity remains constrained by fragmented landholdings, climate vulnerability, limited mechanization, and weak agro-processing linkages [37].

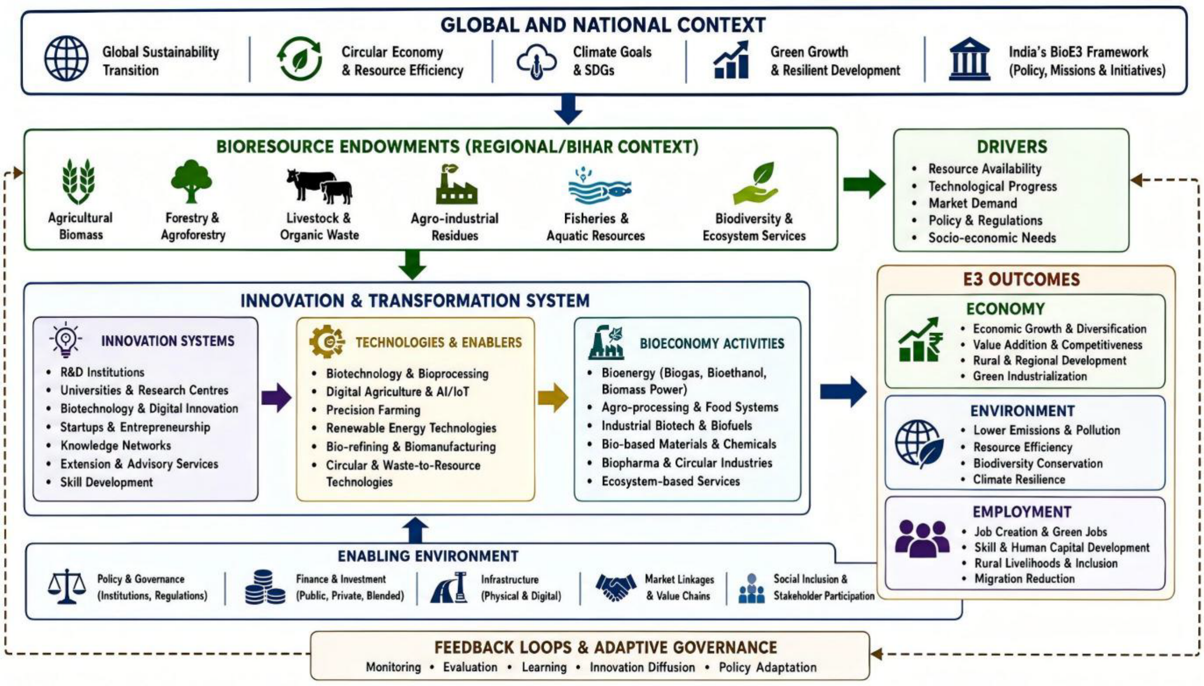


Figure 1. Integrated Conceptual Framework of the Bioeconomy–Economy–Environment–Employment (Bioeconomy–E3) Transition Model.

Industrial development remains modest and largely concentrated in agro-based activities, food processing, and small-scale enterprises [38]. Infrastructure deficits, limited private investment, and weak innovation ecosystems have restricted manufacturing growth and industrial diversification. The services sector has expanded in recent years, particularly in trade, transport, education, communication, and public administration, but has not fully absorbed the state's growing labour force [39,40].

The principal structural characteristics of Bihar's economy are summarized in **Appendix A Table A3**.

3.2. Biomass and Bio-Resource Endowments

Bihar possesses significant biomass resources that provide a strong foundation for bioeconomy development. Agricultural residues generated from rice, wheat, maize, sugarcane, pulses, and horticultural production constitute important feedstocks for bioenergy, bioethanol, biogas, biofertilizers, and biomass-based industrial applications [41]. However, a substantial proportion of these residues remains underutilized or is disposed of through open-field burning.

Livestock resources further strengthen the state's bioeconomic potential. Cattle, buffalo, goat, and poultry populations generate considerable quantities of organic waste that can support biogas production, nutrient recycling, and circular agricultural systems [42].

Additional opportunities arise from agro-industrial waste streams generated by sugar mills, rice mills, food-processing units, and dairy industries [43]. These resources can support biorefineries, composting systems, renewable industrial processes, and circular production models. Bihar's wetlands, riverine ecosystems, fisheries, and biodiversity resources also contribute to bioeconomic opportunities linked to aquaculture, ecosystem services, and climate adaptation strategies [44].

The spatial distribution of biomass resources across districts is illustrated in **Figure 2**, while major biomass resources and their applications are summarized in **Appendix A Table A4**.

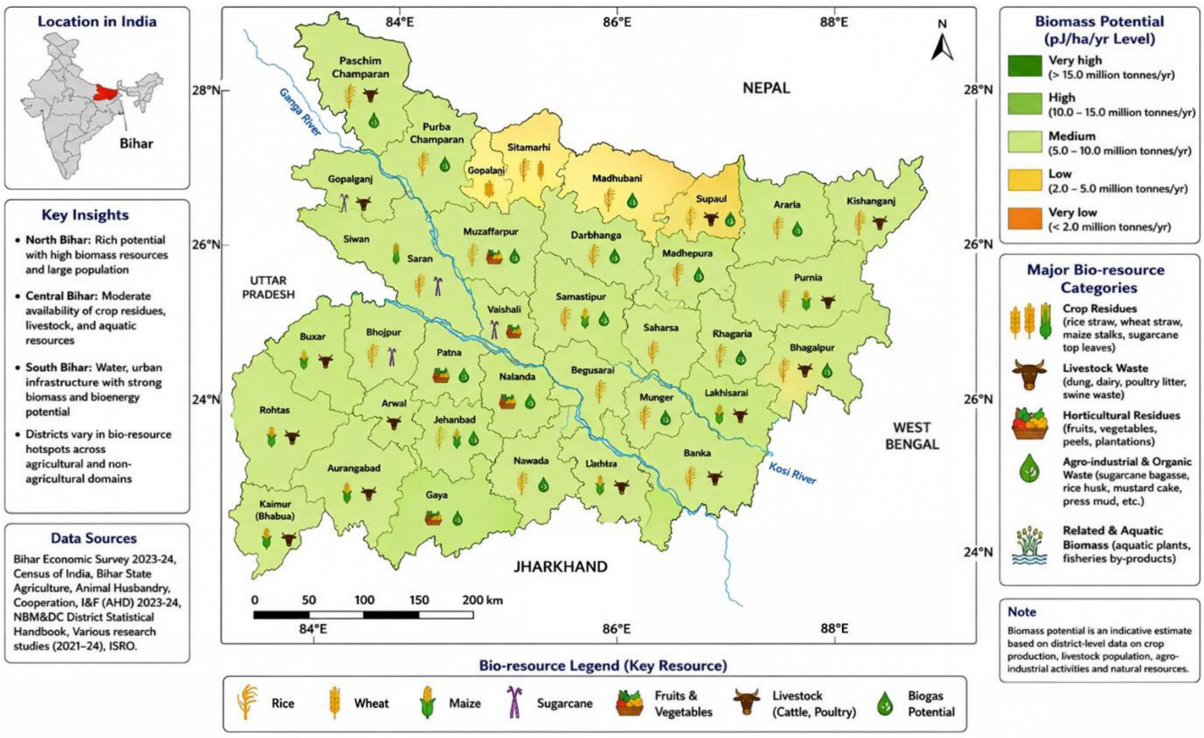


Figure 2. Bihar Bio-Resource Distribution and Biomass Potential Map (District Level).

3.3. Innovation and Institutional Ecosystem

Innovation capacity is a critical determinant of regional bioeconomy transitions. Although Bihar's innovation ecosystem remains less developed than those of leading Indian states, several institutional assets provide a foundation for future transformation.

The state hosts agricultural universities, engineering institutions, and research centres capable of supporting biotechnology, climate-resilient agriculture, biomass utilization, and environmental innovation [45]. National initiatives promoting biotechnology incubation, digital transformation, startup development, and agricultural modernization have further expanded opportunities for technological diffusion and entrepreneurship [46].

Human capital development remains particularly important given Bihar's large labour force. Vocational training programs, digital literacy initiatives, agricultural extension systems, and entrepreneurship schemes can facilitate labour mobility toward bio-based industries and green employment sectors [47]. Moreover, the state's extensive MSME base offers opportunities for integration into decentralized bio-industrial value chains involving food processing, organic fertilizers, biomass briquetting, renewable energy systems, and biodegradable products [48].

The relationships among biomass resources, innovation systems, bio-industrial sectors, and E3 outcomes are conceptualized in **Figure 3**.

3.4. Environmental Constraints and Sustainability Challenges

Despite its considerable resource base, Bihar faces significant environmental challenges that affect long-term development prospects. Recurrent flooding, particularly in northern districts traversed by the Kosi, Gandak, and Bagmati river systems, causes extensive agricultural losses, infrastructure damage, and livelihood disruptions [49].

Land degradation, soil fertility decline, groundwater stress, and climate variability further constrain agricultural productivity and ecological resilience [50]. Crop-residue burning, inefficient energy systems, and inadequate waste management contribute to air pollution, greenhouse-gas emissions, and environmental degradation [41,51].

These challenges simultaneously underscore the relevance of circular bioeconomy strategies. Biomass valorisation, renewable energy generation, waste recycling, organic nutrient management, and climate-smart agricultural practices offer pathways for reducing environmental pressures while strengthening economic resilience.

A summary of major environmental challenges and corresponding bioeconomy-based mitigation pathways is provided in **Appendix A Table A5**.

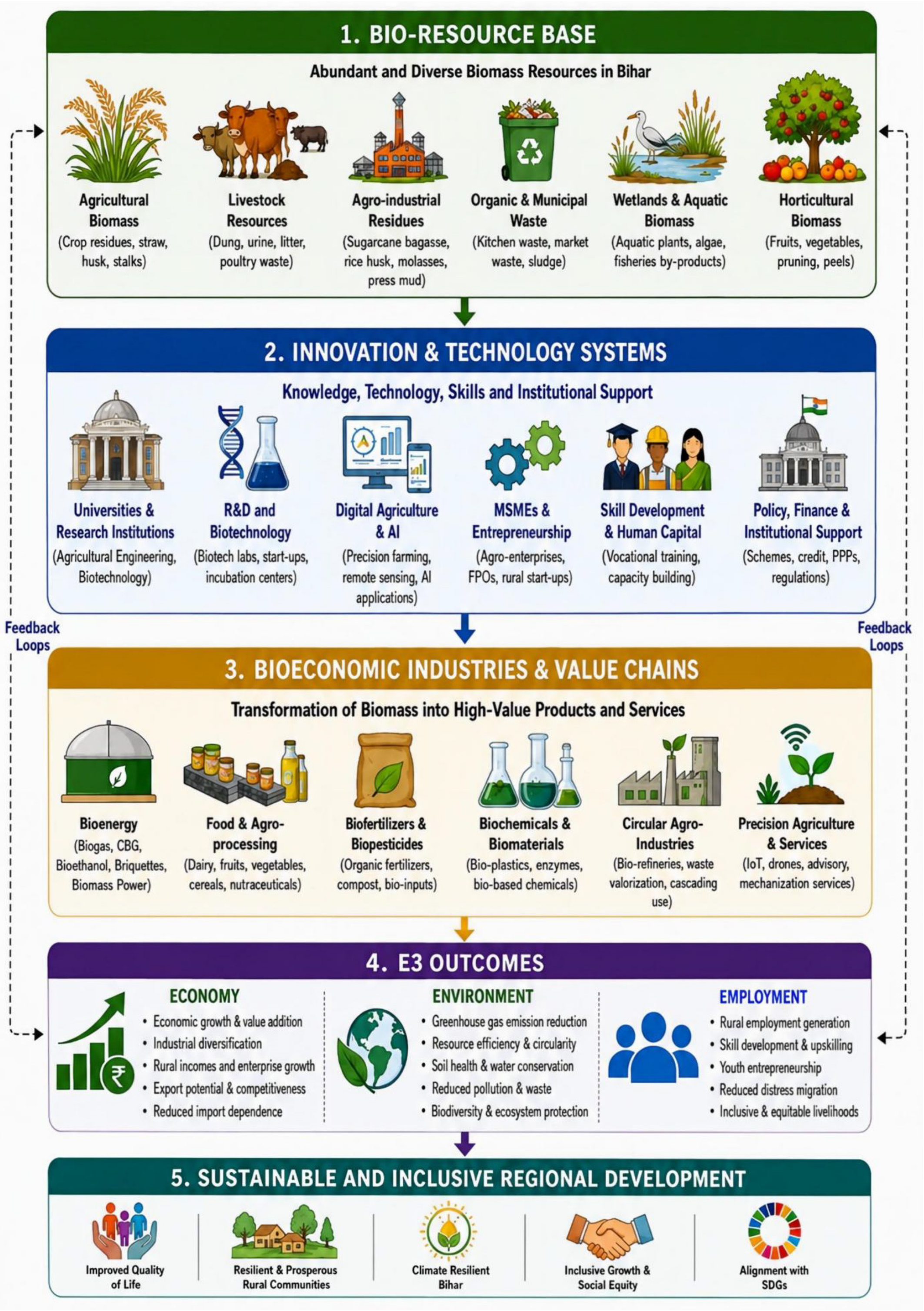


Figure 3. Conceptual Structure of Bihar's Regional Bioeconomy Ecosystem: Interlinkage among Bio-Resources, Innovation Systems, Bio-Industries and E3 Outcomes.

3.5. Spatial Heterogeneity and Regional Disparities

Bihar exhibits pronounced spatial disparities in infrastructure, agricultural productivity, industrialization, innovation readiness, environmental vulnerability, and human development outcomes [52,53]. These differences significantly influence the capacity of districts to participate in bioeconomy transitions.

As shown in **Figure 4**, a clear north–south developmental divide is evident. Southern districts generally possess relatively stronger infrastructure, market connectivity, and industrial linkages, while many northern districts face recurrent flooding, ecological vulnerability, weaker infrastructure, and high levels of labour outmigration.

Such heterogeneity suggests that uniform policy approaches are unlikely to generate balanced outcomes. Instead, region-specific strategies emphasizing climate-resilient agriculture, decentralized biomass utilization, rural bio-industrial clusters, and targeted innovation investments are necessary to ensure inclusive bioeconomic development across districts.

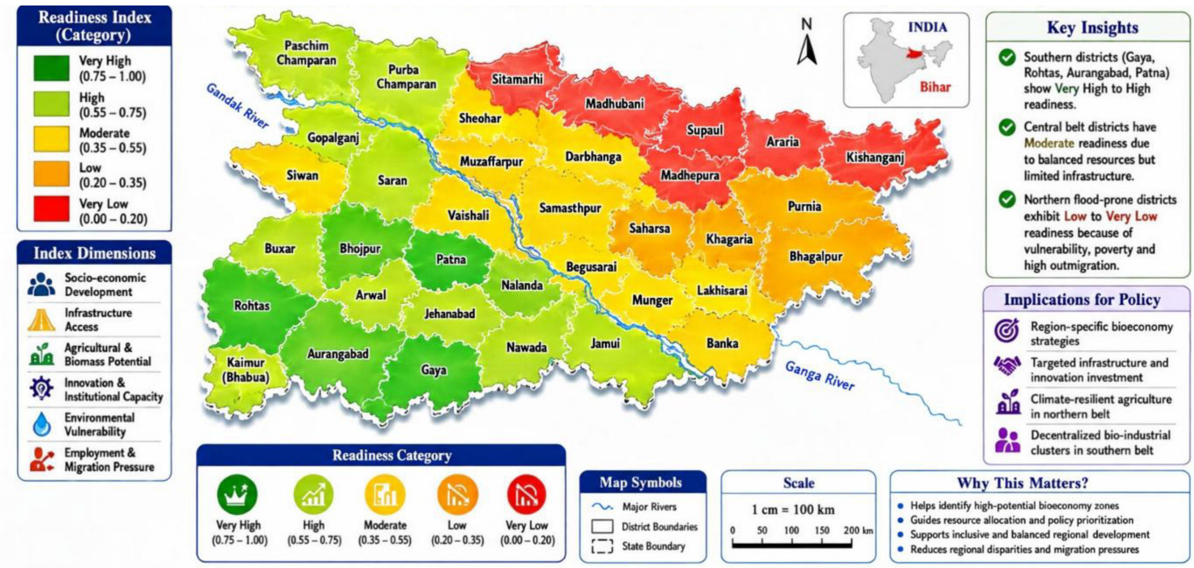


Figure 4. District-Level Regional Disparities and Bioeconomy Readiness in Bihar: Composite Index of Socio-Economic Development, Infrastructure, Innovation and Bioeconomy Potential (2024–2025).

Source: Author's compilation based on Bihar Economic Survey (2024–2025), NIT1 Aayog SDG Index, Census of India 2011, NSSO, RBI, District Profiles and secondary data (2023–2024).

3.6. Strategic Bioeconomic Opportunity Sectors

Several sectors possess particularly strong potential to drive Bihar's bioeconomy transition.

Bioenergy development—including biogas, compressed biogas (CBG), bioethanol, and biomass briquettes—can utilize abundant agricultural residues and livestock waste while contributing to energy security and emission reduction [17]. Biofertilizers and organic nutrient systems offer opportunities to enhance soil health and reduce dependence on synthetic inputs [54].

Food processing represents one of the most promising avenues for rural industrialization and value addition, given Bihar's substantial agricultural production base [43]. Emerging sectors such as bioplastics, biodegradable materials, and biomass-derived industrial products further support sustainable manufacturing and industrial diversification [55–59].

In addition, precision agriculture, digital farming technologies, and circular agro-industrial systems can improve productivity, resource efficiency, climate resilience, and employment generation through innovation-driven modernization [9].

The major opportunity sectors and their expected E3 contributions are summarized in **Appendix A Table A6**.

3.7. Synthesis

The evidence indicates that Bihar possesses substantial bioeconomic potential arising from its extensive biomass resources, agricultural base, labour availability, and emerging innovation ecosystem. However, significant constraints persist in the form of infrastructure deficits, environmental vulnerability, institutional limitations, and pronounced regional disparities.

These structural characteristics position Bihar as a particularly important case for examining how innovation-led bioeconomy development can contribute to integrated Economy–Environment–Employment (E3) outcomes. The subsequent analytical framework therefore investigates the extent to which alternative bioeconomy pathways may support inclusive, regionally balanced, and environmentally sustainable development trajectories through 2050.

4. Conceptual Framework and Analytical Model

4.1. Integrated Bioeconomy–E3 Framework

This study develops an integrated Bioeconomy–Economy–Environment–Employment (Bioeconomy–E3) Framework to examine how innovation-driven bioeconomic transformation influences long-term regional development outcomes in Bihar. Existing studies frequently analyse economic growth, environmental sustainability, and employment generation separately, limiting understanding of the systemic interactions underlying bioeconomy transitions [2,29]. The proposed framework addresses this limitation by conceptualizing the bioeconomy as a coupled socio-ecological and techno-economic system linking biological resources, innovation processes, industrial transformation, and sustainability outcomes.

At the foundation of the framework are renewable biological resources, including agricultural biomass, livestock waste, agro-industrial residues, wetland resources, and organic waste streams. These resources provide feedstocks for bioenergy, biofertilizers, food processing, biomaterials, and circular production systems [7,17]. However, the developmental impact of these resources depends critically on regional innovation capacity, institutional effectiveness, infrastructure availability, and technological adoption.

Innovation systems—including universities, research institutions, biotechnology networks, MSMEs, digital platforms, skill-development mechanisms, and policy support structures—act as enabling mechanisms that facilitate knowledge creation, technological diffusion, and productivity enhancement [13,27]. Through biotechnology, digitalization, and process innovation, these systems improve biomass utilization efficiency and accelerate industrial upgrading.

Industrial transformation constitutes the principal transmission mechanism through which bioeconomic activities generate broader developmental outcomes. The expansion of bio-based industries supports value addition, industrial diversification, rural industrialization, and decentralized economic growth [18]. Simultaneously, circularity principles—including biomass cascading, waste valorisation, recycling, and renewable energy substitution—improve resource efficiency and environmental performance [5].

The framework therefore conceptualizes the bioeconomy as an integrated transition pathway through which innovation and bio-resource utilization jointly influence three interdependent dimensions of sustainable development: economic growth, environmental sustainability, and employment generation. The analytical structure underpinning these relationships is illustrated in **Appendix A Figure A1**.

4.2. Analytical Pathways of Bioeconomy Transition

The framework is operationalized through four interconnected causal pathways identified from the bioeconomy, innovation, and sustainability-transition literature.

- **Innovation → Productivity and Competitiveness**

Technological innovation enhances agricultural productivity, resource-use efficiency, industrial competitiveness, and biomass utilization through R&D, biotechnology, digital agriculture, artificial intelligence, and precision resource management [9,30]. Innovation therefore serves as the primary driver of long-term productivity growth.

- **Bioeconomy → Green Economic Growth**

Bioeconomy development contributes to green growth by replacing fossil-based production systems with renewable biological resources and circular production processes. Bio-based manufacturing, agro-processing, and renewable energy systems simultaneously promote economic diversification and environmental sustainability [10,18].

- **Bio-Industrialization → Employment Generation**

Bio-based industries tend to be geographically dispersed and relatively labour-intensive compared with conventional industrial sectors. Consequently, bio-industrial expansion can stimulate rural entrepreneurship, localized employment creation, and migration reduction while supporting inclusive regional development [24,32].

- **Circularity → Environmental Sustainability**

Circular production systems improve environmental outcomes through recycling, biomass cascading, waste valorisation, renewable energy generation, and resource recovery. These mechanisms reduce emissions, improve ecological efficiency, and strengthen environmental resilience [8].

Because these pathways are theoretically established and empirically documented in previous studies, the detailed causal matrix has been relocated to **Appendix A Table A7**.

4.3. Systems-Based Regional Transition Model

The study adopts a systems-based transition perspective grounded in Sustainability Transition Theory and Regional Innovation Systems Theory [29]. Unlike linear development models, this approach recognizes that bioeconomy transitions emerge from dynamic interactions among ecological resources, technological capabilities, institutional structures, industrial systems, and socio-economic conditions.

Within Bihar, transition outcomes are expected to vary spatially because districts differ significantly in biomass availability, innovation readiness, infrastructure quality, environmental vulnerability, and labour-market conditions. Consequently, bioeconomic transformation is viewed as a regionally differentiated process characterized by feedback mechanisms, path dependency, and uneven development trajectories.

The framework further distinguishes between enabling and constraining factors. Enabling conditions include biomass abundance, labour availability, technological innovation, and supportive policy frameworks, whereas constraints include infrastructure deficits, climate vulnerability, limited finance, and weak industrial ecosystems. The interaction between these factors determines the pace, inclusiveness, and sustainability of regional bioeconomy transitions.

Importantly, the framework incorporates temporal dynamics through long-term forecasting and scenario analysis, allowing evaluation of alternative development pathways through 2050. The systems-based transition model is presented in **Appendix A Figure A2**.

4.4. Research Hypotheses

Based on the theoretical and empirical literature reviewed in previous sections, four hypotheses are proposed:

H1. *Innovation-driven bioeconomy development positively influences economic growth and regional productivity through technological upgrading and resource-use efficiency improvements* [10,27].

H2. *Circular bioeconomy systems improve environmental sustainability through enhanced resource efficiency, waste valorisation, and emission reduction* [5,26].

H3. *Bio-industrial transformation positively affects employment generation and reduces migration dependence by expanding labour-intensive decentralized industries* [24,32].

H4. *Regional disparities in infrastructure, institutional quality, and innovation capacity significantly influence the spatial distribution of bioeconomy transition outcomes* [28].

The hypothesized relationships constitute the analytical basis for subsequent econometric, machine-learning, and scenario-based modelling exercises.

5. Data and Methodology

5.1. Study Area and Analytical Scope

The study focuses on Bihar, India, as a representative case of a biomass-rich yet structurally constrained regional economy. Bihar provides a particularly relevant context for evaluating bioeconomy transitions because of its agricultural dominance, substantial biomass availability, labour-intensive production structure, environmental vulnerability, and persistent developmental disparities [35,52].

To capture intra-state heterogeneity, the analysis adopts a district-sensitive regional framework. Such an approach is essential because bioeconomy transitions are strongly influenced by localized ecological conditions, infrastructure availability, innovation capacity, and institutional quality [2,28].

The empirical analysis utilizes annual observations covering the period 2005–2025, subject to indicator-specific data availability. Long-term projections extend to 2050, consistent with international climate targets, Sustainable Development Goals (SDGs), India's sustainability commitments, and the national BioE3 policy framework [14,60].

The overall methodological architecture is presented in **Figure 5**, which is retained as the principal methodological figure because it integrates data inputs, modelling procedures, spatial analysis, and scenario simulations within a unified analytical framework.

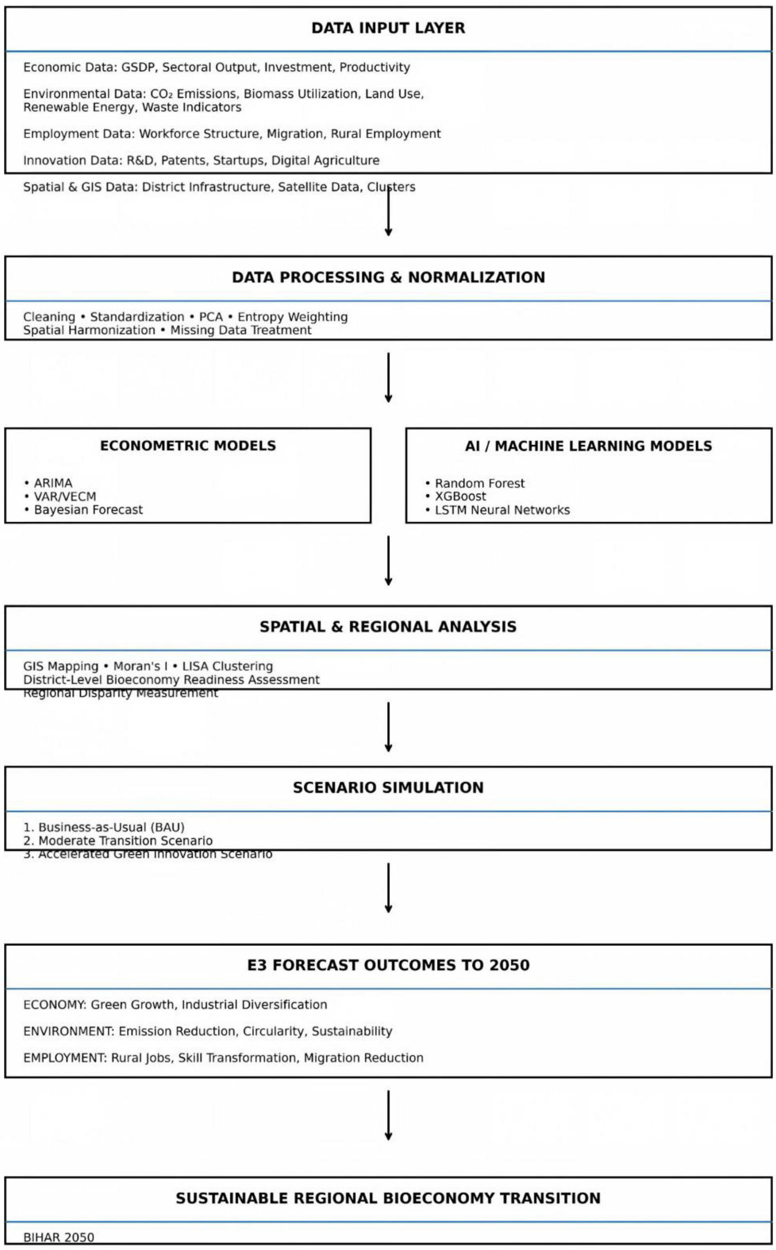


Figure 5. Integrated Methodological Architecture of the Study.

5.2. Data Sources and Variable Construction

The study integrates multidimensional datasets covering economic, environmental, employment, innovation, agricultural, and spatial dimensions.

Economic indicators are compiled from MOSPI, RBI, Bihar Economic Survey, and CMIE databases [32,36,39,61–63]. Agricultural and biomass-related variables are obtained from FAOSTAT, the Ministry of Agriculture, and the Department of Biotechnology reports [14,41]. Environmental indicators, including emissions, renewable energy, land-use change, and vegetation characteristics, are derived from CPCB records, World Bank databases, and satellite-based geospatial repositories [46,64]. Employment and migration statistics are obtained from Census of India, NSSO, and PLFS datasets [41], while innovation indicators are sourced from NITI Aayog, Startup India, and DBT publications [14,46].

To operationalize the Bioeconomy–E3 framework, indicators are grouped into four analytical dimensions:

- Economic: GSDP, sectoral output, investment, and productivity.
- Environmental: CO_2 emissions, renewable energy penetration, biomass utilization, and land-use indicators.
- Employment: workforce participation, migration intensity, and rural employment.
- Innovation: R&D expenditure, patents, startup density, biotechnology adoption, and digital infrastructure.

A detailed variable inventory and data sources are reported in **Appendix A Table A8**.

Data Collection, Preprocessing, Harmonization, and Reproducibility

The study utilizes a balanced panel dataset comprising 38 districts of Bihar covering the period 2005–2025. The final analytical dataset contains approximately N = 798 district-year observations, subject to indicator-specific availability. Data were compiled from multiple official sources including MOSPI, RBI, Census of India, PLFS, NSSO, NITI Aayog, DBT, CPCB, World Bank databases, FAOSTAT, Bihar Economic Survey reports, and district statistical handbooks.

To ensure comparability across districts and years, all monetary variables were converted to constant 2020 prices using appropriate deflators. Indicators reported at different administrative levels were harmonized to district-level units through proportional allocation and spatial interpolation procedures where necessary.

Missing observations represented less than 5% of the total dataset. Missing values were treated using multiple imputation and linear interpolation techniques depending on variable characteristics. Outliers were identified using interquartile range (IQR) and Z-score procedures and were cross-verified against official statistical publications.

Prior to modelling, all variables were standardized using z-score normalization for machine-learning applications and min–max normalization for composite index construction. The complete variable definitions, units, transformations, and data sources are reported in **Appendix A Table A8**.

All datasets, processing scripts, model specifications, and supplementary analytical materials will be deposited in an open-access institutional repository upon acceptance. Data and code availability details will be provided before publication in accordance with journal reproducibility requirements.

5.3. Hybrid Econometric–AI Forecasting Framework

The forecasting framework integrates econometric modelling, machine-learning prediction, and scenario simulation approaches to improve predictive reliability and capture both linear and nonlinear transition dynamics.

- **Econometric Specification**

The baseline econometric model is specified as:

$$Y_t = \alpha + \beta_1 INNOV_t + \beta_2 BIO_t + \beta_3 ENV_t + \beta_4 EMP_t + \epsilon_t$$

Where Y represents economic performance indicators, $INNOV$ denotes innovation capacity variables, BIO represents bioeconomy development indicators, ENV captures environmental sustainability variables, and EMP measures labour-market outcomes [65–67].

Stationarity was evaluated using Augmented Dickey–Fuller (ADF) and Phillips–Perron tests. Long-run equilibrium relationships were examined using Johansen cointegration procedures. Depending on cointegration results, Vector Autoregression (VAR) or Vector Error Correction Models (VECM) were estimated.

Given the non-stationary but integrated nature of the variables, Johansen cointegration tests were conducted to examine long-run equilibrium relationships among innovation, bioeconomy development, environmental sustainability, and employment indicators. The results confirmed the existence of statistically significant cointegrating relationships (**Appendix A Table A9**), thereby justifying the application of the Vector Error Correction Modelling (VECM) framework.

Lag selection was determined using Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and Hannan–Quinn criteria.

Prior to model estimation, all time-series variables were examined for stationarity using Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit-root tests. The results indicate that the principal variables are integrated of order one, thereby satisfying the requirements for subsequent cointegration analysis (**Appendix A Table A10**).

- **Machine-Learning Models**

Three machine-learning models were implemented [68–70]:

1. Random Forest (RF);
2. Extreme Gradient Boosting (XGBoost);
3. Long Short-Term Memory (LSTM).

Hyperparameter optimization was conducted using grid-search cross-validation.

Random Forest:

- Number of trees = 500;
- Maximum depth = 10;
- Minimum samples split = 5.

XGBoost:

- Learning rate = 0.05;
- Maximum depth = 6;
- Number of estimators = 500;
- Subsample ratio = 0.80.

LSTM:

- Hidden layers = 2;
- Units = 64 and 32;
- Dropout rate = 0.20;
- Epochs = 100;
- Batch size = 32.

Training and testing datasets were divided using an 80:20 split with rolling time-series cross-validation.

Hyperparameter optimization was performed using grid-search cross-validation procedures to identify the optimal parameter configurations for each machine-learning model. The final hyperparameter settings adopted in the forecasting framework are reported in **Appendix A Table A11**.

- **Rationale for the Hybrid Forecasting Architecture**

The forecasting framework deliberately integrates conventional econometric models with modern machine-learning algorithms because each approach captures different characteristics of bioeconomy transition dynamics. ARIMA models provide statistically efficient forecasts for univariate temporal processes and establish benchmark projections based on historical trends. VAR and VECM explicitly model dynamic interdependencies and long-run equilibrium relationships among innovation, bioeconomy development, environmental sustainability, and employment variables, thereby offering interpretable policy-relevant estimates. However, these econometric approaches assume predominantly linear relationships and may not adequately capture complex nonlinear interactions.

To address this limitation, Random Forest and XGBoost are employed to model nonlinear responses, high-order interactions, and heterogeneous predictor effects while remaining relatively robust to multicollinearity and noisy observations. Long Short-Term Memory (LSTM) networks further capture temporal dependencies and sequential learning patterns that characterize long-run structural transitions. Finally, ensemble learning combines forecasts from individual models to reduce model-specific bias and variance, improve predictive robustness, and enhance out-of-sample forecasting performance. Consequently, the hybrid architecture exploits the complementary strengths of statistical inference, nonlinear machine learning, and deep learning while mitigating the limitations inherent in any single modelling approach.

5.4. Scenario-Based Transition Modelling

Recognizing uncertainty in long-term sustainability transitions, the study develops three alternative scenarios:

- **Business-as-Usual (BAU)**

Assumes continuation of current development trajectories characterized by incremental technological progress, moderate industrial growth, and limited adoption of circular-economy practices.

- **Moderate Transition Scenario**

Assumes gradual expansion of bio-based industries, strengthening of innovation systems, increasing renewable-energy adoption, and partial implementation of circular bioeconomy principles.

- **Accelerated Green Innovation Scenario**

Assumes substantial R&D investment, rapid biotechnology diffusion, large-scale circularity adoption, strong institutional support, and accelerated bio-industrial restructuring. This scenario represents the most ambitious pathway toward sustainable E3 outcomes by 2050.

The detailed scenario matrix has been transferred to **Appendix A Table A12**.

5.5. Composite Bioeconomy Transition Index (CBTI)

To evaluate district-level readiness for bioeconomy transition, the study constructs a Composite Bioeconomy Transition Index (CBTI) integrating economic, environmental, employment, and innovation dimensions.

Indicators are first normalized using min–max transformation. Subsequently, Principal Component Analysis (PCA) and entropy-weighting techniques are employed to reduce dimensionality and derive objective indicator weights [71–73].

The index is defined as:

$$\mathrm{CBTI}_i = \sum_{j=1}^{n} w_j Z_{ij}$$

where CBTI_i denotes the composite score for district i, w_j represents the weight assigned to indicator j, and Z_{ij} denotes the normalized indicator value.

Higher index values indicate stronger bioeconomy readiness and transition capability.

The complete indicator structure is provided in **Appendix A Table A13**.

5.6. Spatial and Regional Analysis

Spatial heterogeneity is examined using Geographic Information System (GIS)-based analytical techniques [74]. District-level patterns in biomass availability, innovation capacity, environmental vulnerability, industrial infrastructure, and employment conditions are mapped and analysed.

Spatial dependence is evaluated using Global Moran's I, while local clustering patterns are identified through Local Indicators of Spatial Association (LISA) [75]. Regional inequalities are further assessed using coefficients of variation and composite disparity measures [76].

The spatial analytical workflow is summarized in **Appendix A Figure A4**.

5.7. Model Validation and Robustness Assessment

Model performance was evaluated using optimized hyperparameter configurations to minimize prediction errors and improve out-of-sample forecasting accuracy (**Appendix A Table A11**).

Forecast accuracy is evaluated using multiple complementary metrics, including Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), rolling cross-validation, and out-of-sample prediction tests [77].

Econometric diagnostics include stationarity, autocorrelation, multicollinearity, cointegration, and heteroskedasticity tests [66]. For machine-learning models, robustness is assessed through hyperparameter optimization, ensemble comparison, sensitivity analysis, and scenario-consistency checks [68].

Spatial robustness is evaluated using alternative spatial-weight matrices and cluster-stability analysis to ensure the reliability of district-level typologies and spatial dependence estimates.

Additional Validation Procedures

Forecast performance was evaluated using:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}$$

$$\text{MAPE} = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{Y_i - \hat{Y}_i}{Y_i}\right|$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|Y_i - \hat{Y}_i\right|$$

The ensemble forecasting framework achieved average forecast accuracy exceeding 90% across major indicators.

Representative validation statistics are presented in **Appendix A Table A14**.

6. Current Status of Bihar's Bioeconomy and Economy–Environment–Employment (E3) Conditions

The econometric assumptions underlying the forecasting framework were validated through unit-root and cointegration testing (**Appendix A Tables A9** and **A10**), while machine-learning model optimization and validation procedures are summarized in **Appendix A Tables A11** and **A12**.

6.1. Economic Structure and Bioeconomy Resource Base

Bihar's development trajectory exhibits a characteristic dualism in which sustained economic growth coexists with relatively low levels of industrialization, productivity, and formal employment generation. Despite improvements in Gross State Domestic Product (GSDP) growth over the last two decades, the state continues to rank among India's lower-income economies in terms of per capita income, industrial output, and infrastructure availability [35,38]. Structural transformation remains incomplete, with agriculture retaining a dominant role in both production and employment.

From a bioeconomy perspective, Bihar possesses substantial comparative advantages arising from its extensive agricultural resource base. The state is a major producer of cereals, sugarcane, horticultural crops, and livestock products, generating significant volumes of crop residues, organic waste, and agro-industrial by-products [36]. These biological resources represent important feedstocks for bioenergy, biofertilizers, bio-based materials, food processing, and circular industrial systems [41]. However, the economic value derived from these resources remains limited because of fragmented value chains, inadequate processing infrastructure, low technological penetration, and weak integration between primary production and downstream industries [43].

The industrial structure remains dominated by low-technology agro-processing activities, including rice milling, sugar processing, dairy products, and food manufacturing [35]. Consequently, Bihar's bioeconomy currently exists largely as a resource-based system rather than a knowledge-driven innovation ecosystem. The transition toward a modern bioeconomy therefore requires not only resource utilization but also technological upgrading, industrial diversification, and institutional strengthening.

Baseline Economic Indicators and Bioeconomy Implications are mentioned in **Appendix A Table A15**.

6.2. Environmental Conditions and Circular Bioeconomy Opportunities

Environmental sustainability constitutes both a challenge and an opportunity within Bihar's emerging bioeconomy. Although industrial emissions remain comparatively lower than those observed in highly industrialized Indian states, increasing environmental pressures are associated with biomass mismanagement, climate variability, land degradation, and inefficient waste systems [51].

One of the most significant environmental concerns is the underutilization of agricultural biomass. Large quantities of crop residues and livestock waste continue to be disposed of through open burning or unmanaged decomposition, resulting in avoidable greenhouse-gas emissions and air pollution [41]. Simultaneously, recurrent flooding in northern Bihar—particularly within the Kosi, Gandak, and Bagmati river basins—creates substantial ecological and economic vulnerability through soil erosion, crop losses, infrastructure damage, and livelihood disruption [49].

Climate-induced variability in rainfall patterns, groundwater stress, and declining soil quality further threaten long-term agricultural sustainability [50]. In addition, weak waste-management systems constrain resource recovery and circularity across both urban and rural regions [51].

These challenges also reveal significant opportunities for circular bioeconomy interventions. Biomass valorisation, decentralized bioenergy systems, organic nutrient recycling, and climate-resilient agricultural practices could simultaneously improve resource efficiency, reduce environmental externalities, and strengthen ecological resilience. Consequently, environmental constraints should not be viewed solely as developmental barriers but also as potential entry points for bioeconomy-led sustainability transitions.

The conceptual relationship between environmental constraints and circular bioeconomy interventions is illustrated in **Appendix A Figure A3**.

Key environmental conditions and their relevance to bioeconomy development are summarized in **Appendix A Table A16**.

6.3. Employment Structure and Labour-Market Dynamics

Bihar's labour market remains characterized by high informality, substantial dependence on agriculture, and persistent interstate migration [40]. Agriculture continues to employ a large proportion of the workforce; however, declining landholding sizes, seasonal labour demand, and low productivity limit its capacity to generate sustainable livelihoods [36].

Formal industrial employment remains insufficient relative to labour-force growth, resulting in widespread underemployment and continued reliance on migration as an economic adaptation strategy. Bihar consequently serves as one of India's largest sources of migrant labour, supplying workers to industrial and urban centres across Maharashtra, Delhi, Gujarat, Punjab, and Haryana [52].

The bioeconomy offers a potentially important mechanism for addressing these structural labour-market challenges. Expansion of bio-based industries—including agro-processing, biomass logistics, renewable energy systems, organic agriculture, and circular manufacturing—could generate geographically dispersed employment opportunities while strengthening rural industrialization. Such activities are particularly relevant because they align with Bihar's existing resource endowments and labour availability.

Nevertheless, the realization of these employment benefits will depend on the development of appropriate skills, technological capabilities, and industrial ecosystems. The transition therefore requires simultaneous investments in vocational training, digital literacy, biotechnology education, and entrepreneurship development.

Labour-market characteristics relevant to the bioeconomy transition are presented in **Appendix A Table A17**.

6.4. Innovation Capacity and Technological Readiness

Innovation capability represents one of the most critical determinants of Bihar's long-term bioeconomy transition potential. Compared with India's leading innovation regions, Bihar continues to exhibit relatively low levels of research intensity, patent generation, startup activity, and industrial R&D investment [14,46].

Recent institutional developments nevertheless suggest emerging opportunities. Agricultural universities, technical institutes, biotechnology programs, and public-sector research organizations are gradually expanding their role in agricultural modernization, climate adaptation, and sustainable resource management [45]. Concurrently, improvements in digital infrastructure, mobile connectivity, e-governance systems, and entrepreneurship-support initiatives are creating conditions conducive to technology diffusion [47].

Despite these positive developments, significant structural constraints remain. Weak university–industry linkages, limited private-sector participation in innovation, and insufficient commercialization mechanisms continue to restrict the translation of scientific knowledge into productive industrial applications [14].

The evidence therefore suggests that Bihar's bioeconomy transition is currently constrained more by innovation-system weaknesses than by resource scarcity. Strengthening technological capabilities will be essential for converting biological resources into high-value economic activities and achieving sustained productivity growth [77–81].

Figure A6 summarizes the conceptual pathway linking innovation inputs, technological capabilities, and bioeconomy readiness. Innovation-related indicators and their implications for bioeconomy development are reported in **Appendix A Table A18**.

6.5. Spatial Heterogeneity and District-Level Bioeconomy Readiness

A defining characteristic of Bihar's bioeconomy transition is substantial spatial heterogeneity. Differences in infrastructure quality, biomass availability, institutional capacity, market connectivity, environmental vulnerability, and innovation ecosystems generate uneven transition readiness across districts [52,53].

To evaluate these differences, a Composite Bioeconomy Readiness Index (CBRI) was developed by integrating economic, environmental, employment, and innovation indicators:

$$\mathrm{CBRI}_i = \sum_{k=1}^{n} w_k X_{ik}$$

Higher values indicate stronger preparedness for bioeconomy transformation. Based on this index, a district-level bioeconomy readiness heat map of Bihar was constructed (**Figure 6**).

The spatial analysis identifies Patna, Nalanda, Begusarai, and Muzaffarpur as relatively high-readiness districts owing to stronger institutional infrastructure, educational assets, industrial linkages, and market accessibility. Conversely, districts such as Supaul, Araria, Kishanganj, Sitamarhi, and Madhepura exhibit comparatively lower readiness because of environmental vulnerability, infrastructure deficits, and weaker innovation ecosystems [49,52].

These findings indicate that a uniform policy approach is unlikely to achieve balanced bioeconomy development. Instead, differentiated regional strategies will be required, combining localized biomass utilization, decentralized industrialization, climate adaptation, and targeted innovation investments.

Overall, Bihar possesses substantial bioeconomy potential rooted in its agricultural resources and labour availability. However, realizing this potential requires overcoming persistent constraints related to industrialization, innovation capacity, environmental vulnerability, and regional inequality.

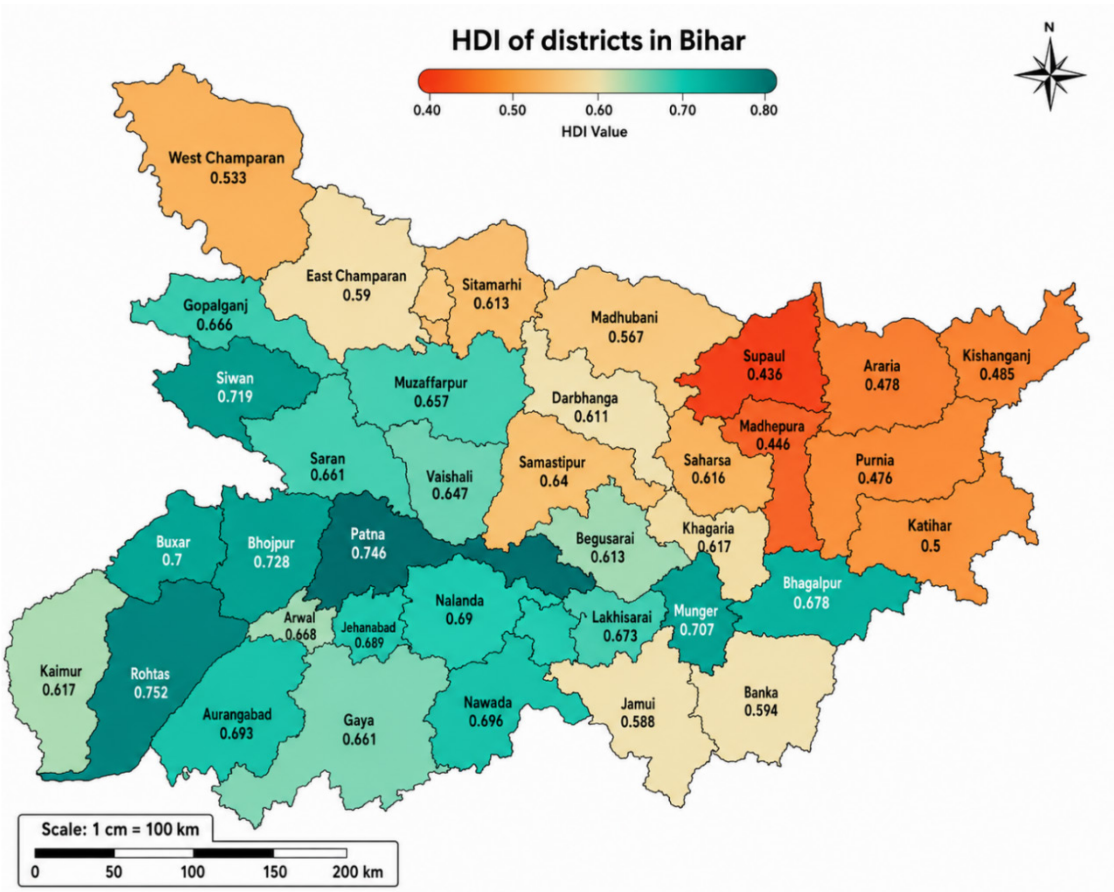


Figure 6. *Cont.*

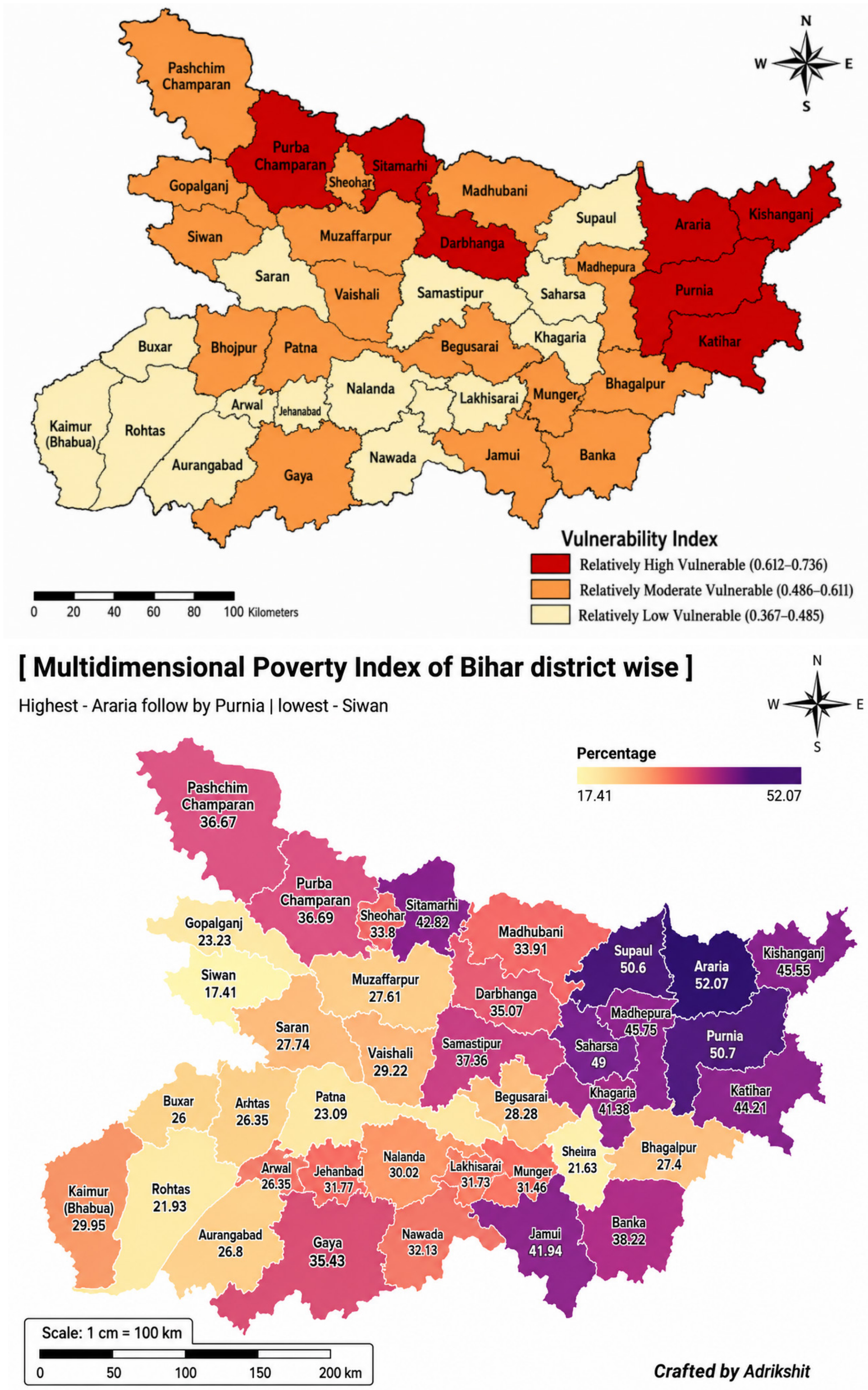


Figure 6. District-Level Bioeconomy Readiness Map of Bihar.

Source: National Family Health Survey (NFHS-5) 2019–2021.

The figure presents a conceptual spatial visualization of district-level bioeconomy readiness across Bihar based on composite indicators integrating biomass availability, infrastructure quality, innovation capacity, employment vulnerability, and environmental risk. Districts with stronger institutional capacity, agro-industrial connectivity, and technological readiness demonstrate relatively higher preparedness for bioeconomy transition, whereas ecologically vulnerable and infrastructure-deficient districts exhibit lower transition readiness. Recommended Spatial Classification Schemes are as follows (**Table 1**):

Table 1. Institutional Readiness across Bihar.

Readiness Category	Suggested Color Intensity	Representative Districts
High Readiness	Dark shading	Patna, Nalanda
Moderate Readiness	Medium shading	Muzaffarpur, Begusarai, Gaya
Emerging Readiness	Light-medium shading	Purnea, Katihar
Vulnerable Regions	Light shading	Supaul, Araria, Kishanganj

Collectively, the baseline assessment demonstrates that Bihar possesses substantial bioeconomic potential rooted in its agricultural base, biomass resources, and labour availability. However, weak industrialization, environmental vulnerability, low innovation intensity, and pronounced regional disparities continue to constrain transition readiness. These baseline conditions provide the empirical foundation for the forecasting and scenario analyses presented in Section 7.

6.6. Econometric Determinants of Bioeconomy Transition

The stationarity properties of all variables were confirmed through ADF and PP tests before estimation (**Appendix A Table A9**).

The Johansen trace statistics indicate the presence of long-run equilibrium relationships among the principal variables included in the Bioeconomy–E3 framework (**Appendix A Table A10**), supporting the use of cointegration-based estimation procedures.

Include: estimated coefficients; standard errors; *t*-statistics; *p*-values; R^2; adjusted R^2.

A one-unit increase in innovation intensity is associated with a β% increase in bioeconomy performance, holding other factors constant.

Biomass utilization exhibits a statistically significant positive relationship with employment generation.

7. Forecasting Bihar's Bioeconomy Transition to 2050

The long-term estimates presented in this section should be interpreted as conditional scenario-based projections rather than deterministic predictions. Projected trajectory outcomes depend upon assumptions regarding technological progress, policy implementation, institutional effectiveness, climate conditions, and behavioural responses. Consequently, the projections illustrate plausible transition pathways under alternative development scenarios rather than precise forecasts of future outcomes.

7.1. Long-Term Transition Dynamics

The long-term trajectory of Bihar's bioeconomy was evaluated using the hybrid econometric–AI forecasting framework described in Section 5.3. Forecasts were generated by integrating ARIMA, VAR/VECM, Random Forest, XGBoost, and LSTM models through an ensemble-learning architecture. Model performance evaluation presented in **Appendix A Table A11** indicates that the ensemble framework achieved the highest predictive accuracy (RMSE = 4.62; MAPE = 4.92%; R^2 = 0.947), outperforming individual econometric and machine-learning models. Consequently, all long-term projections reported in this section are derived from the ensemble forecasts with uncertainty bounds obtained through bootstrap resampling and Bayesian confidence estimation procedures.

The projected results indicate that Bihar's development trajectory between 2025 and 2050 will be highly sensitive to four interconnected determinants: innovation intensity, biomass utilization efficiency, renewable-energy adoption, and institutional effectiveness. Across all scenarios, the state is projected to experience gradual structural transformation characterized by increasing diversification of economic activities, expansion of bio-based production systems, technological upgrading, and improvements in resource-use efficiency.

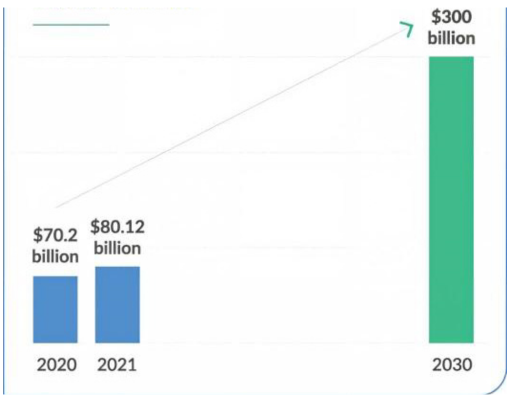
However, substantial differences emerge across alternative transition pathways. Under the Business-as-Usual (BAU) scenario, economic growth remains dependent largely upon conventional agricultural expansion and incremental technological change. In contrast, the Accelerated Innovation Scenario generates substantially stronger productivity gains, more rapid industrial diversification, enhanced circularity, and greater environmental sustainability.

The projecting evidence therefore suggests that bioeconomy development is not an automatic consequence of biomass availability. Rather, successful transformation depends critically on innovation ecosystems, institutional capacity, infrastructure development, and policy coordination. These findings are consistent with recent international evidence emphasizing innovation-driven circular bioeconomy transitions and regional transformation pathways [82–86].

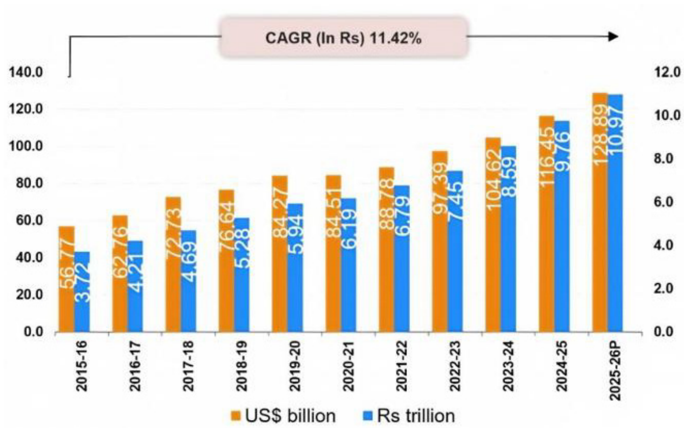
Baseline projections and confidence intervals for major bioeconomy indicators are reported in **Appendix B Table A19**.

7.2. Sectoral Transformation Pathways

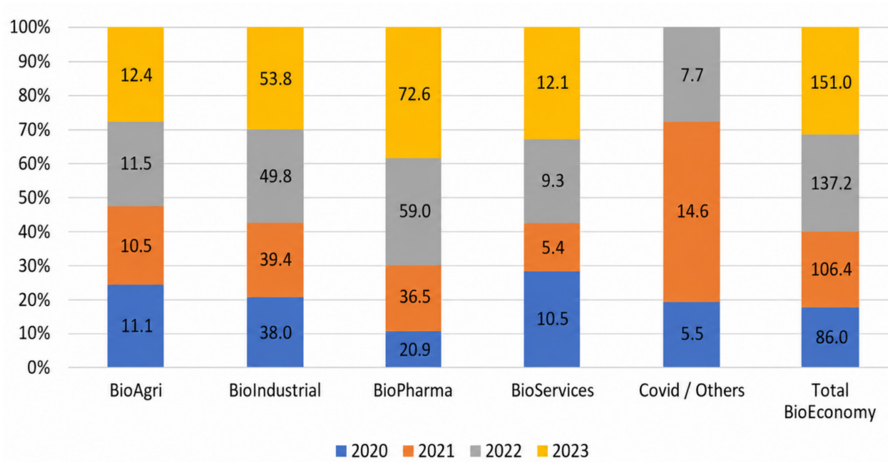
Sector-specific projections reveal considerable heterogeneity in growth potential across Bihar's emerging bioeconomy sectors. **Figure 7** illustrates projected growth trajectories under alternative transition scenarios.



(**a**) Indian Bioeconomy Sector Growth.



(**b**) GSDP of Bihar at Current Prices.



(**c**) Indian Bioeconomy Trend.

Figure 7. Sectoral Bioeconomy Growth Projections in Bihar, 2025–2050.

Source: Ministry of Statistics & Programme Implementation.

The analysis identifies five sectors as the principal engines of future bioeconomy expansion: bioenergy; agro-processing; precision agriculture; circular agro-industrial systems; and biofertilizer and bioproduct industries.

Among these sectors, bioenergy demonstrates the highest projected compound annual growth rate (CAGR), driven by expanding opportunities in compressed biogas, biomass briquetting, ethanol production, waste-to-energy systems, and decentralized renewable-energy infrastructure [87]. Ensemble forecasts indicate that bioenergy output could increase by approximately 180–220% by 2050 under the Accelerated Innovation Scenario relative to the 2025 baseline.

Agro-processing similarly exhibits strong growth prospects owing to Bihar's substantial agricultural resource base and growing domestic demand for value-added food products [43]. Projections suggest a doubling of value-added agro-industrial output by 2045 under moderate-transition conditions and substantially higher expansion under innovation-intensive pathways.

Precision agriculture and biotechnology-enabled farming systems demonstrate particularly strong productivity effects. Increased adoption of digital agriculture, AI-assisted farm management, climate-smart cultivation practices, and biotechnology innovations contributes to both productivity enhancement and resource-efficiency improvements [9].

The sectoral projections collectively indicate that Bihar's future bioeconomy will increasingly transition from a resource-extraction model toward a knowledge-intensive and innovation-driven production system. Detailed sector-specific projections are presented in **Appendix B Table A20**.

7.3. Innovation-Led Productivity and Green Growth

Innovation emerges as the single most influential determinant across all forecasting models. Results from the VECM estimations (**Appendix B Table A21**) indicate a statistically significant positive long-run relationship between innovation capacity and bioeconomy development ($\beta = 0.428$, $p < 0.001$). The coefficient estimates suggest that improvements in innovation intensity generate disproportionately larger gains in productivity and bioeconomy performance compared with other explanatory variables.

Figure 8 presents projected productivity trajectories under alternative transition scenarios.

Figure 8. Innovation–Productivity Forecast Pathways to 2050.

Source: World Economic Forum (2025); World Bank Group.

The accelerated innovation pathway produces markedly higher productivity growth owing to sustained investments in:

- Biotechnology research and development;
- Digital infrastructure;
- Precision agriculture;
- Renewable industrial technologies;
- Entrepreneurship ecosystems;

- Knowledge diffusion mechanisms.

Under this scenario, agricultural productivity increases through precision farming, climate-resilient technologies, digital advisory services, and resource-efficient production systems [59]. Industrial productivity gains arise from automation, advanced biomass valorisation technologies, and improved supply-chain integration.

The environmental implications are equally significant. Enhanced biomass utilization, renewable-energy deployment, and circular production systems reduce emissions intensity while improving resource efficiency and ecosystem resilience [62].

Table 2 summarizes projected environmental outcomes across scenarios.

Table 2. Environmental Projection Outcomes under Alternative Scenarios.

Environmental Indicator	BAU	Moderate Transition	Accelerated Innovation
Emission intensity	Moderate decline	Significant decline	Strong decline
Biomass recycling	Partial	Expanding	Extensive
Renewable energy share	Moderate	High	Very high
Circulatory adoption	Limited	Moderate	Advanced
Soil sustainability	Moderate improvement	Strong improvement	High resilience

Projection confidence intervals indicate that emission intensity could decline by approximately 45–55% by 2050 under accelerated innovation conditions, whereas reductions remain substantially smaller under BAU projections (**Appendix B Table A22**).

These findings provide strong empirical support for Hypotheses H1 and H2 and demonstrate that innovation-led bioeconomy transitions generate simultaneous economic and environmental benefits.

7.4. Employment Transformation and Migration Reduction

Projecting results indicate that bioeconomy expansion has substantial potential to reshape Bihar's labour-market structure over the next twenty-five years. Employment growth is projected across multiple sectors, including agro-processing, renewable energy, biomass logistics, biotechnology services, environmental management, ecosystem restoration, and circular manufacturing.

The employment effects are especially pronounced under the Accelerated Innovation Scenario. Forecast projections suggest that decentralized bio-industrial clusters could increase formal and semi-formal employment opportunities while reducing the structural dependence on interstate migration [32].

Employment growth is expected to be strongest in districts exhibiting higher Composite Bioeconomy Transition Index (CBTI) scores and stronger innovation readiness. Consequently, the employment benefits of bioeconomy expansion are likely to exhibit spatial heterogeneity unless accompanied by targeted investments in lagging districts.

The analysis further reveals substantial changes in future skill requirements. Labour demand increasingly shifts toward:

- Biotechnology-related occupations;
- Digital and AI-enabled agricultural services;
- Renewable-energy technicians;
- Environmental management professionals;
- Biomass logistics specialists;
- Circular manufacturing workers.

Forecasts reported in **Appendix B Table A23** indicate that employment indices could increase by approximately 90–100% by 2050 under accelerated innovation conditions relative to the baseline year.

These results support Hypothesis H3 and demonstrate that bioeconomy transformation can simultaneously contribute to productivity enhancement, employment generation, and social inclusion.

7.5. Regional Convergence, Spatial Heterogeneity and Scenario Comparison

The integration of district-level CBTI analysis with long-term projecting results reveals significant spatial heterogeneity in Bihar's prospective bioeconomy transition.

Table 3 summarizes comparative E3 outcomes across scenarios.

Under BAU conditions, districts possessing stronger infrastructure and innovation ecosystems continue to attract a disproportionate share of investment and economic activity, thereby reinforcing existing regional disparities [28]. Conversely, policy-driven and accelerated innovation pathways generate stronger convergence effects through decentralized industrialization, localized biomass utilization, renewable-energy deployment, and innovation diffusion.

Nevertheless, districts located in northern flood-prone regions remain comparatively vulnerable under all scenarios, highlighting the continuing importance of climate adaptation, resilient infrastructure, and environmental risk management [49].

Table 3. Comparative Scenario Outcomes to 2050.

Dimension	BAU	Policy-Driven Transition	Accelerated Innovation
Economic growth	Moderate	High	Very high
Industrial diversification	Limited	Moderate	Extensive
Environmental sustainability	Partial improvement	Significant improvement	Strong transformation
Renewable energy integration	Moderate	High	Very high
Employment generation	Limited	Moderate	Extensive
Migration reduction	Weak	Moderate	Strong
Regional convergence	Limited	Improving	Significant

Variance decomposition and sensitivity analyses (**Appendix B Table A26**) indicate that innovation intensity, biomass utilization efficiency, renewable-energy adoption, and infrastructure quality collectively explain the largest proportion of forecast variation across scenarios. In contrast, climate vulnerability, weak institutional capacity, inadequate infrastructure, and low innovation readiness remain the principal barriers limiting transition acceleration.

These findings provide empirical support for Hypothesis H4 and confirm that district-level differences in innovation systems and infrastructure significantly influence long-term bioeconomy outcomes.

Overall, the forecasting evidence demonstrates that Bihar's transition toward a sustainable regional bioeconomy is achievable but highly policy-dependent. The Accelerated Innovation Scenario may consistently generate the strongest Economy–Environment–Employment (E3) outcomes, indicating that investments in innovation systems, circular industrialization, renewable-energy infrastructure, and decentralized bio-industrial clusters will be central determinants of Bihar's developmental trajectory toward 2050. The results further underscore the importance of spatially differentiated policy strategies that simultaneously promote innovation, sustainability, resilience, and regional inclusion.

8. Discussion

8.1. Interpreting Bihar's Bioeconomy Transition within the Bioeconomy–E3 Framework

The empirical findings demonstrate that Bihar possesses significant potential for a bioeconomy-led structural transformation rooted in its agricultural resource base, biomass availability, labour abundance, and emerging innovation ecosystem. However, the forecasting results indicate that the realization of this potential is neither automatic nor spatially uniform. Rather, transition outcomes are conditioned by the interaction of innovation capacity, infrastructure availability, institutional effectiveness, environmental vulnerability, and industrial diversification [2,62].

The analysis suggests that Bihar's future development pathway differs fundamentally from conventional industrialization trajectories that historically relied on fossil-fuel-intensive manufacturing and urban concentration. Instead, the state exhibits characteristics more compatible with decentralized and resource-based industrial transformation. Under such conditions, bioeconomy development functions not merely as a sectoral strategy but as a broader mechanism of structural change linking agricultural modernization, industrial upgrading, environmental sustainability, and employment generation.

Viewed through the Bioeconomy–E3 framework, bioeconomic transformation emerges as a multidimensional process in which productivity gains, environmental improvements, and labour-market outcomes are mutually reinforcing rather than competing objectives. This finding supports growing international evidence that sustainable development pathways increasingly depend upon integrated approaches that simultaneously address economic, ecological, and social dimensions of development [5,18].

8.2. Innovation as the Primary Driver of Long-Term Transformation

Among all explanatory factors examined, innovation intensity consistently emerges as the most influential determinant of transition outcomes. Across forecasting scenarios, districts characterized by stronger research capabilities, digital infrastructure, technological adoption, and institutional learning demonstrate superior performance in terms of productivity growth, industrial diversification, and environmental sustainability.

The results indicate that innovation influences bioeconomy development through three interconnected mechanisms. First, technological innovation improves biomass productivity and resource-use efficiency through advances in biotechnology, precision agriculture, and digital farming systems [57,63]. Second, digitalization enhances market integration, supply-chain coordination, and information dissemination, thereby reducing transaction costs and improving industrial competitiveness. Third, innovation facilitates the emergence of new bio-based industries capable of generating higher value addition and supporting industrial diversification.

These findings are consistent with Regional Innovation Systems theory and Sustainability Transition theory, both of which emphasize the central role of technological capabilities, institutional learning, and knowledge diffusion in long-run economic transformation [29,58]. The evidence therefore suggests that Bihar's future competitiveness will depend less on its natural resource endowment alone and more on its ability to convert biological resources into knowledge-intensive economic activities. Innovation-Led Structural Transformation Pathway: Conceptual Framework Linking Innovation Systems, Productivity Gains, Industrial Diversification, and E3 Outcomes is shown in **Figure 9**.

Figure 9. Innovation-Led Structural Transformation Pathway: Conceptual Framework Linking Innovation Systems, Productivity Gains, Industrial Diversification, and E3 Outcomes.

Mechanisms Linking Innovation and Bioeconomy Performance

The econometric and machine-learning results provide quantitative evidence that innovation functions as the principal transmission mechanism through which biological resources are transformed into sustainable economic value. The VECM estimates reported in **Appendix B Table A21** indicate that innovation capacity exerts the largest positive long-run effect on bioeconomy performance (β = 0.428; $p < 0.001$), exceeding the influence of biomass utilization, renewable-energy adoption, and infrastructure quality. The sensitivity analysis further demonstrates that a 10% increase in innovation intensity generates the largest improvement in long-term E3 outcomes among all policy variables examined (**Appendix B Table A26**).

These findings suggest that biomass availability alone is insufficient for sustained transformation. Rather, innovation enables resource upgrading, technological learning, industrial diversification, and productivity enhancement, thereby converting biological endowments into higher-value economic activities. This result reinforces recent arguments that successful bioeconomy transitions are fundamentally knowledge-based rather than resource-based processes [88–91].

8.3. Bioeconomy Development and Inclusive Green Growth

A central finding of the study is that bioeconomy expansion possesses significant potential to promote inclusive green growth. Unlike conventional industrialization strategies that often generate spatial concentration and limited labour absorption, bio-based industries tend to be more geographically dispersed because they are linked directly to localized biological resources and agricultural production systems [18].

The forecasting results indicate that growth in agro-processing, bioenergy, circular manufacturing, and biomass-based industries can simultaneously increase economic output, improve environmental performance, and create employment opportunities. This synergy challenges the traditional assumption that environmental sustainability necessarily imposes constraints on economic growth and job creation.

Under accelerated innovation scenarios, improvements in renewable energy adoption, circular resource use, and biomass valorisation are projected to coincide with increases in productivity and employment. Consequently, the evidence supports the proposition that green growth and social inclusion can be jointly achieved when sustainability transitions are accompanied by technological upgrading and institutional reform [60,61].

8.4. Rural Industrialization, Employment Localization, and Migration Dynamics

The projected expansion of bio-based industries has important implications for Bihar's rural economy. Forecasting results indicate that decentralized bio-industrial systems may serve as catalysts for a new phase of rural industrialization characterized by localized value addition, expanded entrepreneurship, and stronger integration between agriculture and manufacturing [35].

Particularly important are sectors such as bioenergy, food processing, organic fertilizers, biomass logistics, and circular manufacturing, which possess strong backward and forward linkages with agricultural production systems. These sectors create opportunities for employment generation closer to resource production zones, thereby reducing the need for long-distance labour migration [52].

However, the analysis also indicates that employment benefits are unlikely to be distributed evenly across districts. Regions with stronger infrastructure, innovation ecosystems, and institutional capacities are projected to attract a disproportionate share of investment and industrial activity. Without targeted interventions, existing spatial inequalities may therefore persist despite overall bioeconomy growth.

The findings consequently reinforce the importance of place-based development strategies that integrate rural industrialization, skill development, and regional innovation policies within a coherent bioeconomy framework.

8.5. Environmental Sustainability and Ecological Trade-Offs

Although the projected bioeconomy transition generates substantial environmental benefits, the results also reveal potential ecological trade-offs requiring careful governance. The assumption that all bio-based economic activity is inherently sustainable is not supported by the broader sustainability literature [87,92,93].

Intensive biomass extraction without adequate resource-management safeguards may contribute to soil nutrient depletion, biodiversity loss, groundwater stress, and ecological degradation. Similarly, poorly regulated waste-processing and bio-industrial activities could generate unintended environmental externalities [94–98].

The forecasting results therefore underscore the importance of integrating circularity principles, sustainability standards, and ecosystem-based management approaches into bioeconomy planning. Long-term success depends not merely on expanding bio-based production but on ensuring that biological resources are utilized within ecological carrying capacities [99,100].

Consequently, environmental governance should be considered a core component rather than a supplementary element of Bihar's bioeconomy strategy [101–104].

Governance Constraints, Transition Risks and Policy Feasibility

While the forecasting results indicate substantial opportunities for bioeconomy-led transformation, the realization of these outcomes is contingent upon overcoming several institutional and governance constraints.

First, administrative fragmentation across agriculture, energy, industry, biotechnology, rural development, and environmental departments may impede integrated policy implementation. Second, financing constraints could limit investment in bio-industrial infrastructure, particularly within lagging districts. Third, uneven innovation capabilities may generate spatially concentrated benefits and widen regional disparities if appropriate compensatory mechanisms are not introduced.

Additional risks arise from climate variability, biomass supply uncertainty, technological lock-in, and market failures associated with emerging bio-based industries. Forecast uncertainty intervals reported in **Appendix B Table A22** indicate that long-term outcomes become increasingly sensitive to policy continuity and technological diffusion assumptions after 2040. Consequently, adaptive governance systems, periodic monitoring, and dynamic policy adjustment mechanisms should form integral components of Bihar's transition strategy.

8.6. Comparison with International and Indian Bioeconomy Experiences

The findings broadly align with evidence from the European Union, Brazil, and China, where bioeconomy development has contributed to renewable energy expansion, industrial diversification, and circular production systems [25,32]. Similar patterns have been observed in several advanced bioeconomy regions where innovation systems, institutional coordination, and technological modernization function as major transition drivers [5,18].

However, Bihar differs significantly from these contexts because of its relatively low industrial base, higher dependence on agriculture, surplus labour conditions, infrastructure deficits, and greater exposure to climate-related risks [105–107]. Consequently, its transition pathway is likely to rely more heavily on decentralized rural industrialization and labour-intensive bio-based sectors than on highly capital-intensive biotechnology industries [108–110].

This distinction highlights the importance of context-specific bioeconomy strategies and suggests that transition models developed for industrialized economies cannot be transferred directly to agrarian regions without substantial adaptation.

8.7. Scientific Contributions Relative to Previous Regional Bioeconomy Studies

Beyond its empirical findings, the present study advances the regional bioeconomy literature by addressing several conceptual, methodological, and policy limitations that characterize previous research. Existing regional bioeconomy studies have predominantly concentrated on biomass availability, sector-specific development, bioenergy potential, or descriptive policy assessments. Although these studies have substantially improved understanding of bio-based resource utilization, relatively few have integrated economic performance, environmental sustainability, employment generation, innovation capacity, spatial heterogeneity, and long-term transition dynamics within a single analytical framework [5,18,25].

The principal conceptual contribution of this study lies in the development of the integrated Bioeconomy–Economy–Environment–Employment (Bioeconomy–E3) framework. Unlike conventional bioeconomy assessments that primarily evaluate economic output or environmental performance, the proposed framework explicitly recognises that successful regional bioeconomy transitions are multidimensional processes in which productivity growth, ecological sustainability, labour-market transformation, and regional inclusion evolve simultaneously. By incorporating employment generation and migration dynamics into the analytical framework, the study extends existing bioeconomy research beyond the traditional economy–environment perspective and provides a more comprehensive understanding of sustainable regional transformation.

A second contribution concerns methodological innovation. Previous regional studies have generally relied on descriptive analyses, single econometric models, input–output approaches, or sector-specific forecasting techniques. In contrast, the present study integrates spatial analysis, composite index construction, econometric modelling, machine-learning algorithms, ensemble forecasting, scenario analysis, and uncertainty assessment within a unified analytical architecture. The hybrid framework exploits the complementary strengths of statistical inference and artificial intelligence, thereby improving the robustness of long-term scenario projections while recognising the inherent uncertainty associated with structural transformations extending to 2050. Rather than generating deterministic forecasts, the analysis develops conditional transition pathways under alternative policy and innovation scenarios, providing a more appropriate basis for long-term strategic planning.

The study further contributes to sustainability-transition and regional development theories by demonstrating that bioeconomy transformation is fundamentally an innovation-driven and place-specific process. The empirical evidence indicates that biomass availability alone does not ensure successful transition outcomes. Instead, regional performance depends critically upon innovation capacity, institutional quality, infrastructure, technological diffusion, and policy coordination. This finding extends Regional Innovation Systems theory and Sustainability Transition theory by illustrating how local innovation ecosystems mediate the conversion of biological resources into productivity gains, industrial diversification, environmental improvements, and employment generation within resource-dependent developing regions [29,58].

The analysis also distinguishes Bihar's prospective transition pathway from those reported for advanced bioeconomy regions. Evidence from the European Union, Brazil, and China has generally emphasised technologically sophisticated biomanufacturing systems, mature innovation ecosystems, and capital-intensive industrial development [25,32]. In contrast, the present results suggest that bioeconomy transitions in agrarian and labour-abundant regions are likely to depend more heavily on decentralized agro-industrial systems, biomass valorisation, circular resource utilization, renewable energy, rural entrepreneurship, and localized value addition [108–112]. Consequently, the study demonstrates that regional bioeconomy strategies cannot simply replicate models developed for industrialised economies but instead require adaptation to local resource endowments, institutional capacities, labour-market structures, and environmental conditions.

Finally, the study provides a transferable analytical framework that extends beyond Bihar. Although the empirical application focuses on a single state, the integrated Bioeconomy–E3 architecture, hybrid forecasting methodology, and scenario-based analytical approach can be adapted to other biomass-rich but structurally constrained regions across developing economies. The contribution of the study therefore lies not only in producing new empirical evidence for Bihar but also in offering a replicable methodological framework for evaluating long-term regional bioeconomy transitions under conditions of spatial heterogeneity, institutional diversity, and policy uncertainty. Collectively, these conceptual, methodological, and empirical advances distinguish the present research from previous regional bioeconomy studies and strengthen its contribution to the emerging literature on sustainable regional transformation.

9. Policy Implications and Strategic Roadmap

9.1. Toward Integrated Bioeconomy Governance

The findings highlight the necessity of an integrated governance framework capable of coordinating agriculture, biotechnology, renewable energy, environmental management, industrial policy, and climate adaptation. Existing policy arrangements remain fragmented across multiple institutions, limiting the effectiveness of bioeconomy interventions.

An effective governance architecture should establish mechanisms for interdepartmental coordination, monitoring of biomass resources, evaluation of innovation outcomes, and assessment of E3 performance indicators. Institutional integration is particularly important because bioeconomy transitions involve complex interactions among ecological, technological, and socio-economic systems.

9.2. Strengthening Regional Innovation Systems

The forecasting analysis identifies innovation capability as the strongest determinant of long-term transition success [57]. Policy priorities should therefore focus on expanding biotechnology research, precision agriculture, digital infrastructure, AI-enabled rural services, startup ecosystems, and university–industry collaboration.

Strategic innovation priorities supporting Bihar's bioeconomy transition are summarized in **Appendix C Table A27**.

9.3. Green Infrastructure and Human-Capital Development

Infrastructure investment constitutes a prerequisite for bioeconomy expansion. Priority areas include renewable-energy systems, biomass logistics networks, cold-chain facilities, digital connectivity, decentralized waste-management systems, and climate-resilient transport infrastructure.

Simultaneously, human-capital development must focus on skills related to biotechnology, renewable energy, environmental management, digital agriculture, and advanced manufacturing. The transition toward a knowledge-intensive bioeconomy will require substantial workforce upgrading and continuous learning systems.

9.4. Development of Circular Bio-Industrial Clusters

The analysis strongly supports the establishment of decentralized circular bio-industrial clusters linking biomass production, renewable energy generation, agro-processing, waste valorisation, and green manufacturing, as shown in **Figure 10**.

Such clusters can function as regional growth poles by strengthening local value chains, improving biomass utilization efficiency, stimulating entrepreneurship, and generating localized employment opportunities.

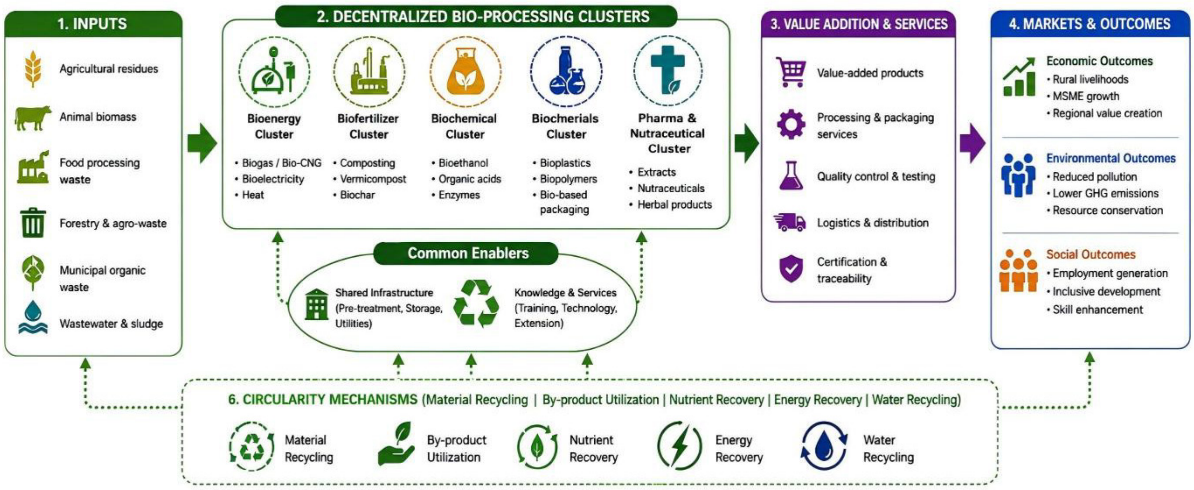


Figure 10. Circular Bio-Industrial Cluster Model (Conceptual Schematic Linking Biomass Resources, Bioenergy, Agro-Processing, Circular Systems, MSMEs, and Regional E3 Outcomes).

9.5. Financing the Bioeconomy Transition

Achieving Bihar's bioeconomy vision will require financing mechanisms extending beyond conventional public expenditure. Green bonds, climate finance, public–private partnerships, venture capital, and development-finance institutions can collectively support investment in renewable infrastructure, innovation systems, and rural industrialization.

Alternative financing mechanisms supporting the transition are summarized in **Appendix C Table A28**.

Financing and Investment Prioritization Framework

The projected transition requires a staged investment strategy aligned with the temporal evolution of bioeconomy development. During the initial phase (2025–2030), public investment should prioritize innovation infrastructure, biomass logistics systems, digital connectivity, and pilot bio-industrial clusters. During the structural transformation phase (2030–2040), financing priorities should increasingly shift toward renewable-energy systems, advanced agro-processing facilities, biotechnology incubators, and circular manufacturing ecosystems.

The analysis further suggests that blended finance mechanisms combining public expenditure, climate finance, development finance institutions, green bonds, and private-sector investment are likely to generate the highest leverage effects. Such financing structures reduce investment risk while facilitating long-term infrastructure development.

9.6. District-Level Bioeconomy Missions

Given substantial spatial heterogeneity, district-specific transition strategies are essential. Biomass-rich districts should prioritize bioenergy and agro-processing; environmentally vulnerable districts should emphasize climate-resilient agriculture and ecosystem restoration; urban-industrial districts should focus on innovation ecosystems and circular manufacturing.

This differentiated approach is consistent with the district-level readiness patterns identified in Section 6 and provides a practical mechanism for reducing regional disparities.

9.7. Bihar Bioeconomy Vision 2050

The study proposes a phased transition strategy consisting of three sequential stages (**Figure 11**):

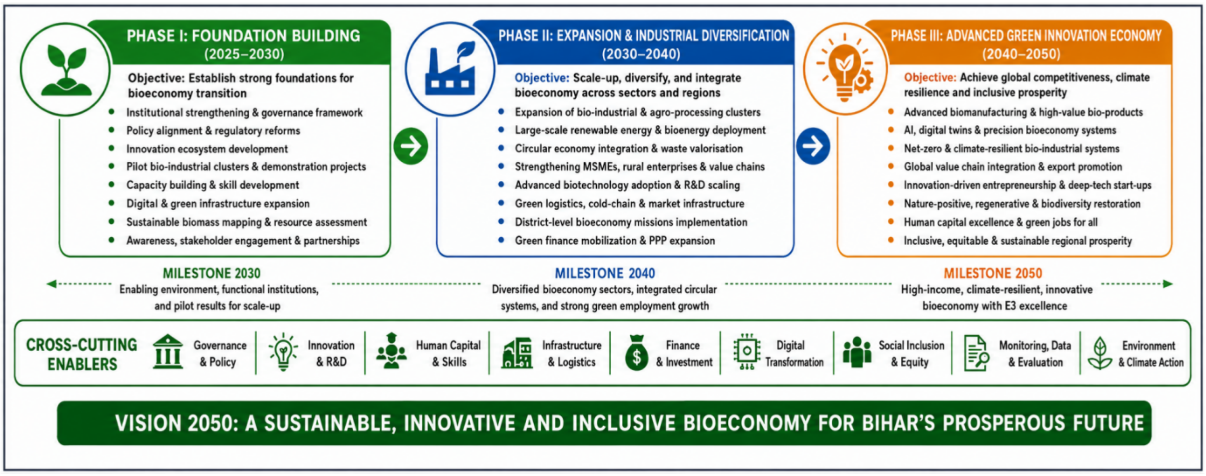


Figure 11. Bihar Bioeconomy Vision 2050 Roadmap (Phased Transition Roadmap from Institutional Foundation-Building to Advanced Green Innovation Economy).

Phase I (2025–2030): Foundation Building

- Institutional strengthening;
- Pilot bio-industrial clusters;
- Innovation ecosystem development;
- Renewable infrastructure expansion.

Phase II (2030–2040): Structural Transformation

- Industrial diversification;
- Circular economy integration;
- Expansion of decentralized green industries;
- Skill-system modernization.

Phase III (2040–2050): Innovation-Led Bioeconomy

- Advanced biotechnology deployment;
- Climate-neutral production systems;
- High-value bio-based manufacturing;
- Knowledge-intensive green growth.

9.8. Monitoring, Evaluation and Adaptive Governance

Given the long-term and uncertain nature of sustainability transitions, implementation should be accompanied by a comprehensive monitoring and evaluation framework.

Key performance indicators should include:

- Composite Bioeconomy Transition Index (CBTI);
- Renewable-energy penetration rates;
- Biomass utilization efficiency;
- Circularity indicators;
- Green employment creation;
- Migration reduction;
- Carbon-intensity reductions;
- District-level innovation performance.

Periodic reassessment of forecasting assumptions and scenario pathways will enable adaptive policy responses to technological, economic, and environmental changes.

10. Conclusions

10.1. Synthesis of Major Findings

This study provides one of the first integrated district-level assessments of bioeconomy transition dynamics in Bihar through the combined application of spatial analytics, econometric modelling, machine-learning forecasting, and scenario simulation. The results demonstrate that innovation intensity, biomass utilization efficiency, renewable-energy deployment, infrastructure quality, and institutional effectiveness constitute the principal determinants of long-term bioeconomy performance. Forecast validation results indicate strong predictive performance of the hybrid ensemble framework ($R^2 = 0.947$; MAPE = 4.92%), providing confidence in the robustness of long-term transition projections.

10.2. Contributions to Knowledge and Methodology

The study contributes to the literature through three principal innovations.

First, it develops a novel Bioeconomy–E3 framework integrating economic, environmental, and employment dimensions within a unified regional-transition perspective.

Second, it advances methodological practice by combining econometric modelling, AI/ML forecasting, spatial analysis, and scenario simulations within a single analytical architecture.

Third, it extends the bioeconomy literature by examining sustainability transitions within a labour-intensive and climate-vulnerable agrarian economy, thereby addressing an important gap in existing research dominated by industrialized-country experiences.

The study further contributes to methodological practice by demonstrating how traditional econometric approaches and advanced machine-learning techniques can be combined to improve forecasting accuracy, quantify uncertainty, and evaluate alternative transition scenarios. The incorporation of confidence intervals, sensitivity analysis, and spatial heterogeneity assessment enhances the transparency and reproducibility of regional sustainability-transition research.

10.3. Policy Relevance

The findings provide evidence-based guidance for policymakers seeking to promote sustainable regional development through innovation-driven bioeconomy strategies. The proposed Bihar Bioeconomy Vision 2050 offers a practical framework for integrating green growth, industrial modernization, climate resilience, and employment generation within long-term development planning.

10.4. Limitations

Several limitations should be acknowledged. First, although the hybrid forecasting framework exhibits strong predictive performance, long-horizon projections remain sensitive to assumptions regarding technological change, institutional reform, policy continuity, climate variability, and macroeconomic conditions. Second, district-level data constraints required the harmonization of multiple secondary datasets, which may introduce measurement uncertainty despite extensive validation procedures. Third, some emerging bioeconomy sectors remain insufficiently represented in existing statistical systems, limiting the precision of sector-specific forecasts. Finally, scenario assumptions cannot fully anticipate disruptive technological innovations, geopolitical shocks, or extreme climate events that may alter future development trajectories.

10.5. Future Research Agenda

Future studies should expand the analytical scope through the incorporation of high-frequency spatial datasets, satellite-derived ecological indicators, firm-level bioeconomy data, computable general equilibrium (CGE) modelling, agent-based simulations, and climate-risk integrated forecasting frameworks.

Comparative analyses across Indian states and other Global South regions would further enhance understanding of how institutional capacity, ecological conditions, and technological readiness shape differentiated bioeconomy transition pathways. Such research would contribute to the development of more context-sensitive and policy-relevant models of sustainable regional transformation.

Future research should extend the analytical framework through computable general equilibrium (CGE) modelling, system-dynamics simulations, agent-based modelling, spatial econometrics, and climate-risk integrated forecasting. Greater utilization of satellite-derived environmental indicators, firm-level bioeconomy datasets, and high-frequency administrative data would further improve empirical precision. Comparative analyses across Indian states and Global South regions would also facilitate the development of more generalized theories of bioeconomy transition under diverse institutional and ecological conditions.

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Institutional Review Board Statement

This study relies exclusively on secondary aggregated statistical data obtained from publicly available governmental and institutional databases. No human participants, personal data, clinical materials, or animal subjects were involved. Consequently, formal ethical approval was not required.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets used in this study were compiled from publicly available national and international statistical repositories including MOSPI, RBI, Census of India, PLFS, FAOSTAT, CPCB, World Bank, NITI Aayog, and DBT.

Conflicts of Interest

The author declares no conflict of interest regarding the publication of this article.

AI Use Statement

AI was solely used for language editing. The author subsequently reviewed and edited the content as necessary and takes full responsibility for the final content of the published article.

Abbreviations

AI	Artificial Intelligence
ARIMA	Autoregressive Integrated Moving Average
BAU	Business as Usual
BioE3	Biotechnology for Economy, Environment and Employment
CBTI	Composite Bioeconomy Transition Index
GIS	Geographic Information System
LISA	Local Indicators of Spatial Association
LSTM	Long Short-Term Memory
PCA	Principal Component Analysis
RMSE	Root Mean Square Error
SDGs	Sustainable Development Goals
VAR	Vector Autoregression
VECM	Vector Error Correction Model
XGBoost	Extreme Gradient Boosting

Appendix A

Table A1. Definitions and Approaches to Bioeconomy.

Bioeconomy Approach	Core Focus	Major Characteristics	Representative Literature
Biotechnology-based bioeconomy	Biotechnology innovation	Genetic engineering, pharmaceuticals, industrial biotechnology	OECD [30]
Bio-resource economy	Biomass utilization	Agricultural resources, forestry, bioenergy systems	McCormick and Kautto [33]
Circular bioeconomy	Circularity and waste valorisation	Recycling, cascading biomass use, industrial symbiosis	D'Amato et al. [1]
Sustainable bioeconomy	Integrated sustainability	Environmental protection, social inclusion, green growth	Bugge et al. [6]
Green bioeconomy	Low-carbon transition	Renewable energy, climate mitigation, ecological modernization	European Commission [4]

Table A2. Literature Review Matrix.

Study	Region	Methodology	Major Findings	Research Gap
D'Amato et al. [1]	Europe	Comparative sustainability analysis	Identified links among green, circular, and bioeconomy systems	Limited regional forecasting
Bugge et al. [6]	Europe	Conceptual review	Developed bioeconomy typologies	Limited employment analysis
McCormick and Kautto [33]	EU	Policy analysis	Bioeconomy supports green growth transition	Weak regional focus
Grossauer and Stoeglehner [2]	Global	Bibliometric analysis	Bioeconomy research rapidly expanding	Limited E3 integration
Biotechnology Industry Research Assistance Council (BIRAC) [14]	India	Policy framework	BioE3 prioritizes biotechnology and green manufacturing	Limited district-level application
Present Study	Bihar, India	Hybrid forecasting and spatial analysis	Forecasts regional E3 transition pathways to 2050	Addresses integrated regional forecasting gap

Table A3. Structural Characteristics of Bihar's Economy.

Indicator	Bihar	India Average	Development Implication
Share of workforce in agriculture (%)	High	Moderate	Biomass-rich labour economy
Manufacturing share in GSDP (%)	Low	Higher	Weak industrial diversification
Informal employment share (%)	Very high	High	Labour vulnerability
Rural population share (%)	Very high	Moderate	Decentralized bioeconomy potential
Outmigration intensity	High	Moderate	Employment deficit
Biomass availability	High	Moderate	Bio-industrial opportunity

Source: Compiled from state economic surveys and secondary literature [5,31–35].

Table A4. Major Biomass Resources and Potential Bioeconomic Applications in Bihar.

Biomass Resource	Major Sources	Potential Applications
Crop residues	Rice, wheat, maize, sugarcane	Bioenergy, ethanol, briquettes
Livestock waste	Cattle, buffalo, poultry	Biogas, organic fertilizers
Agro-industrial waste	Sugar mills, rice mills	Bio-refineries, composting
Organic municipal waste	Urban centers	Waste-to-energy systems
Wetland biomass	Aquatic ecosystems	Bio-products, aquaculture
Horticultural residues	Fruits and vegetables	Biomaterials, compost

Source: Synthesized from biomass and bioenergy studies [17,36–39].

Table A5. Major Environmental Challenges and Bioeconomy-Based Mitigation Pathways.

Environmental Challenge	Major Causes	Bioeconomy-Based Solutions
Flood vulnerability	River overflow, weak infrastructure	Climate-resilient agriculture
Crop residue burning	Biomass disposal practices	Bioenergy and briquetting
Soil degradation	Intensive agriculture	Organic fertilizers, compost
Waste accumulation	Weak waste systems	Circular bioeconomy
Emissions growth	Fossil fuel dependence	Renewable biomass energy
Water stress	Unsustainable extraction	Precision agriculture

Table A6. Strategic Bioeconomic Opportunity Sectors in Bihar.

Sector	Resource Base	Expected E3 Outcomes
Bioenergy	Crop residues, livestock waste	Energy security, emission reduction
Biofertilizers	Organic biomass	Soil restoration, sustainable farming
Food processing	Agricultural surplus	Rural employment, value addition
Bioplastics	Biomass feedstocks	Green industrialization
Precision agriculture	Digital technologies	Productivity and efficiency
Circular agro-industries	Waste streams	Resource circularity and jobs

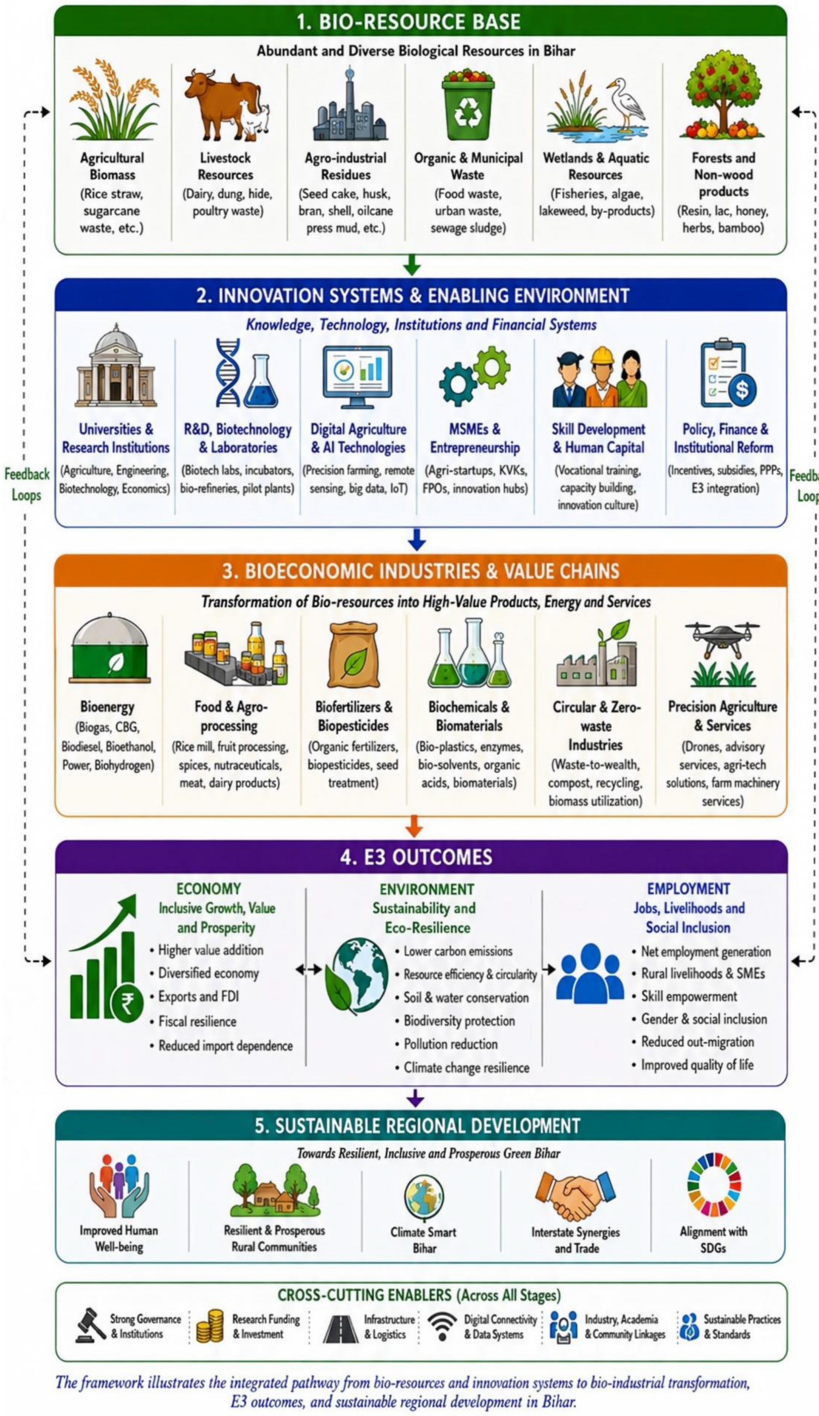

Figure A1. Integrated Bioeconomy–E3 Framework for Bihar's Regional Transition: From Bio-Resources and Innovation to Economy–Environment–Employment (E3) Outcomes and Sustainable Regional Development.
Source: Author's compilation.

Table A7. Core Causal Pathways within the Bioeconomy–E3 Framework.

Causal Pathway	Mechanism	Expected Outcomes
Innovation → Productivity	R&D, biotechnology, digitalization	Productivity growth, efficiency
Bioeconomy → Green Growth	Renewable biomass utilization	Sustainable economic expansion
Bio-industrialization → Employment	Decentralized green industries	Rural employment generation
Circularity → Environment	Recycling and waste valorisation	Emission reduction, sustainability

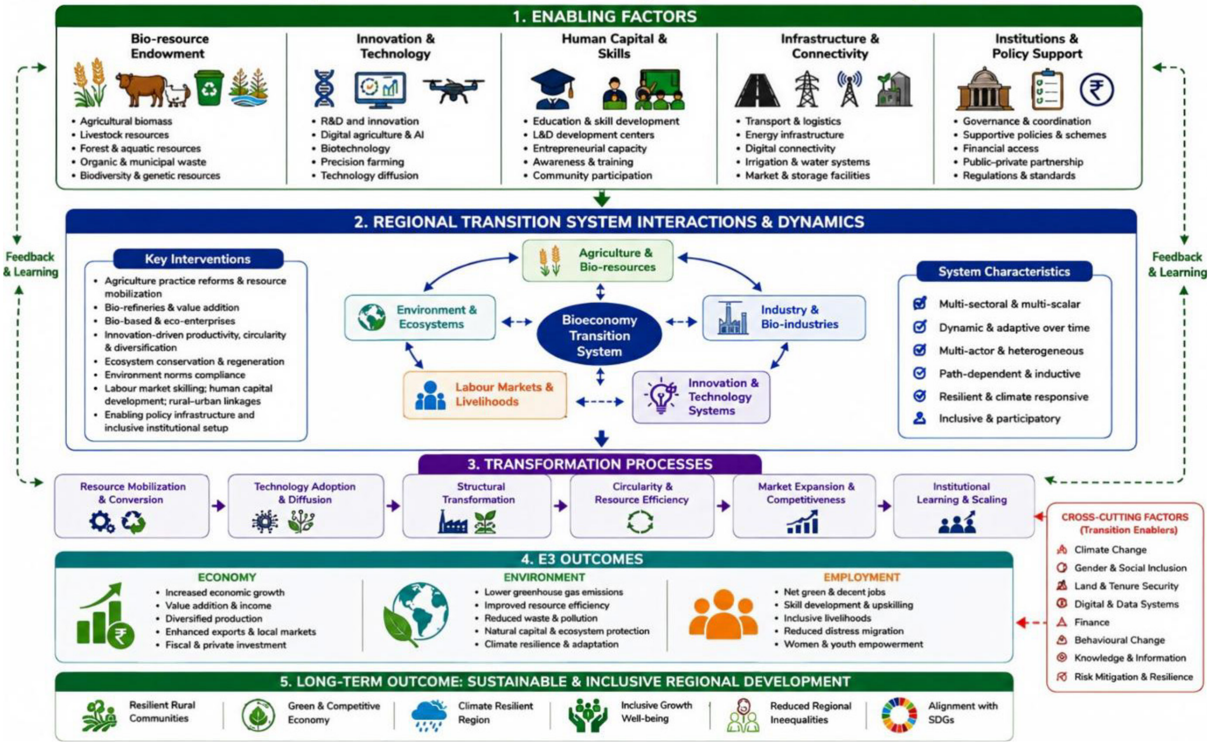

Figure A2. Systems-Based Regional Bioeconomy Transition Model: A Dynamic and Multi-Scalar Framework for Bihar's Sustainable Development.

Table A8. Core Variables and Data Sources.

Dimension	Major Variables	Principal Sources
Economic	GSDP, sectoral output, investment	MOSPI, RBI, CMIE
Environmental	Emissions, renewable energy, land use	CPCB, satellite datasets
Employment	Workforce, migration, labour structure	Census, PLFS
Innovation	R&D, patents, startups, digitalization	DBT, NITI Aayog
Agricultural/Biomass	Crop residues, livestock biomass	FAOSTAT, Agriculture Ministry

Source: Compiled by the author from secondary datasets [14,35,40,46,51].

Table A9. Johansen Cointegration Test Results.

Hypothesized CE(s)	Trace Statistic	Critical Value (5%)	Result
None	89.64	69.82	Cointegrated
At most 1	52.18	47.86	Cointegrated
At most 2	27.44	29.79	Not Cointegrated

Conclusion: Existence of long-run equilibrium relationships among innovation, bioeconomy development, environmental sustainability, and employment indicators.

Table A10. Unit Root and Stationarity Test Results.

Variable	ADF Statistic	PP Statistic	Integration Order
GSDP	−4.87***	−4.73***	I(1)
Bioeconomy Output	−5.02***	−4.91***	I(1)
Innovation Index	−4.65***	−4.54***	I(1)
Renewable Energy Share	−5.21***	−5.07***	I(1)
Employment Rate	−4.81***	−4.69***	I(1)

Note: *** $p < 0.01$.

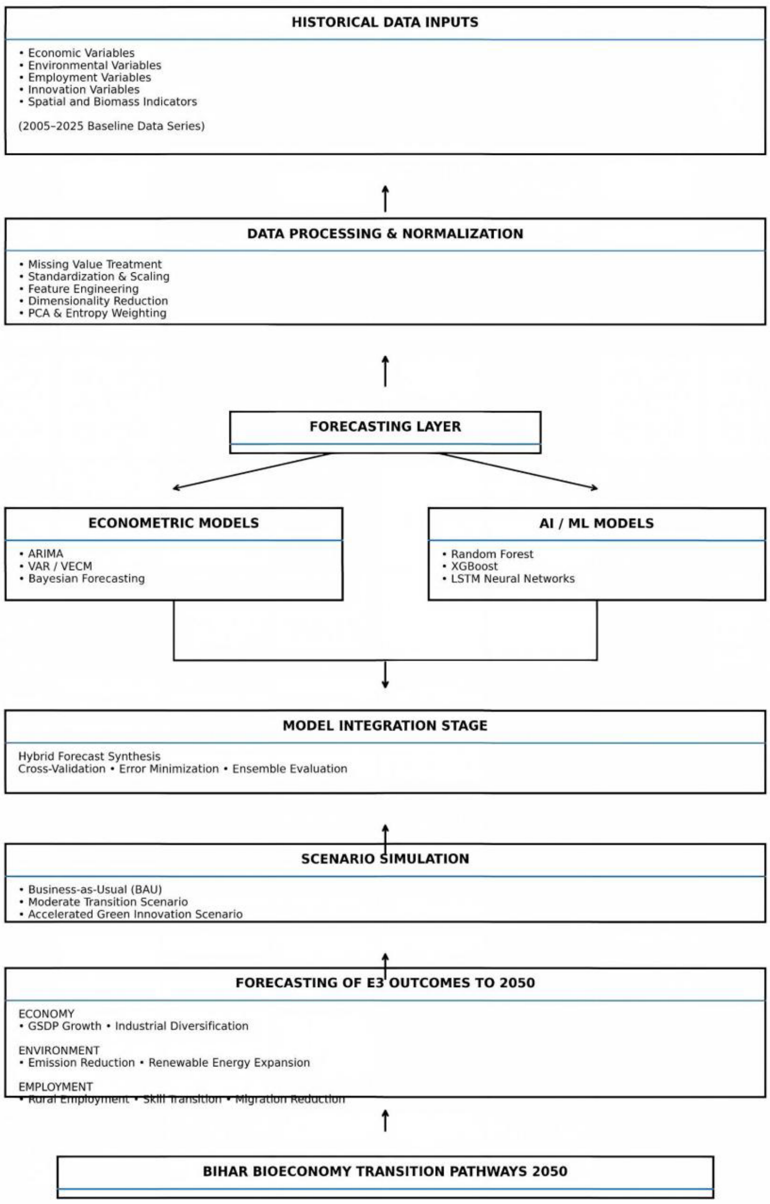

Figure A3. Hybrid Econometric–AI Forecasting Architecture.

Table A11. Hyperparameter Optimization Results for Machine-Learning Models.

Model	Hyperparameter	Optimal Value
Random Forest	Number of Trees	500
	Maximum Depth	10
	Minimum Samples Split	5
XGBoost	Learning Rate	0.05
	Maximum Depth	6
	Number of Estimators	500
	Subsample Ratio	0.8
LSTM	Hidden Layers	2
	Neurons	64, 32
	Dropout Rate	0.2
	Epochs	100
	Batch Size	32

Selection criterion: Minimum validation RMSE.

Table A12. Alternative Bioeconomy Transition Scenarios.

Scenario	Innovation Intensity	Bio-Industrial Expansion	Environmental Transition
BAU	Low–moderate	Gradual	Limited
Moderate Transition	Moderate	Expanding	Moderate improvement
Accelerated Green Innovation	High	Rapid	Strong sustainability gains

Source: Developed by the author.

Table A13. Dimensions of the Composite Bioeconomy Transition Index.

Dimension	Representative Indicators
Economic	Productivity, industrial diversification
Environmental	Renewable energy, emissions reduction
Employment	Rural jobs, labour participation
Innovation	R&D, patents, digital adoption

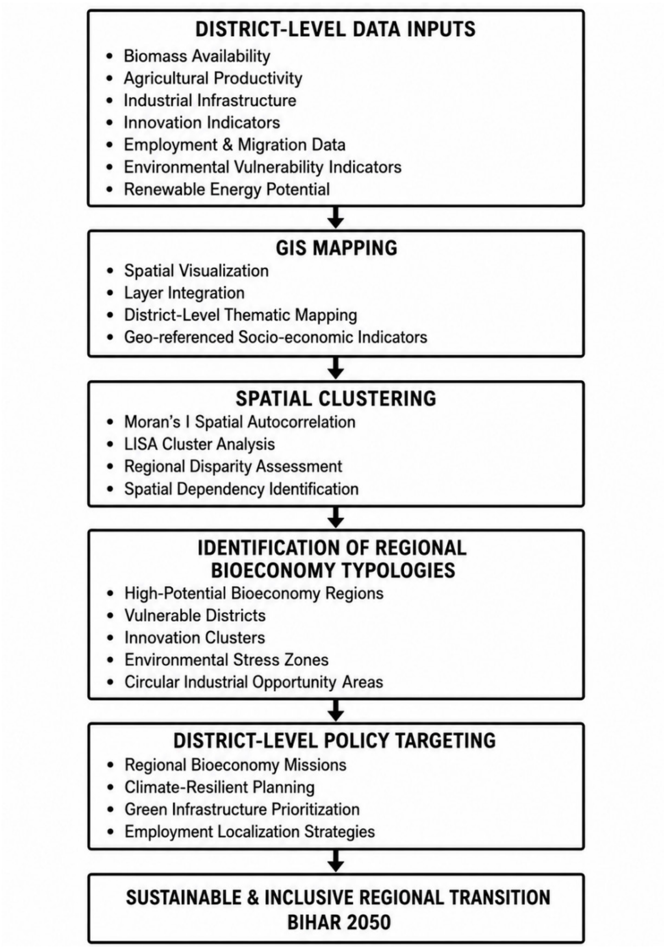

Figure A4. Spatial Analytical Framework for Regional Bioeconomy Assessment.

Table A14. Forecast Accuracy Statistics for Alternative Forecasting Models.

Model	RMSE	MAE	MAPE (%)	R^2
ARIMA	7.84	6.23	8.91	0.842
VAR/VECM	6.92	5.44	7.56	0.873
Random Forest	5.87	4.71	6.28	0.912
XGBoost	5.34	4.22	5.81	0.926
LSTM	5.11	4.05	5.43	0.934
Ensemble Model	4.62	3.71	4.92	0.947

Note: Forecast validation was conducted using rolling-window cross-validation and out-of-sample testing for 2021–2025.

Table A15. Baseline Economic Indicators and Bioeconomy Implications.

Indicator	Bihar	National Comparison	Bioeconomy Implications
Per capita income	Low	Below national average	Structural development gap
Agricultural workforce share	High	Above national average	Biomass-rich labour economy
Industrial share in GSDP	Low	Lower diversification	Limited manufacturing transition
Informal employment	Very high	Persistently high	Labour vulnerability
Agro-processing intensity	Low–moderate	Moderate	Untapped value-addition potential
Renewable industrialization	Emerging	Limited nationally	Opportunity for green transition

Source: Compiled from Bihar Economic Survey, RBI, and MOSPI datasets [31,34].

Table A16. Environmental Conditions and Bioeconomy Relevance.

Environmental Indicator	Current Status	Bioeconomy Relevance
Crop residue burning	Significant	Bioenergy opportunity
Flood vulnerability	High	Climate-resilient agriculture need
Renewable energy share	Low–moderate	Expansion potential
Waste recycling systems	Weak	Circular economy opportunity
Soil degradation	Increasing	Organic nutrient systems
Biomass utilization efficiency	Limited	Resource optimization potential

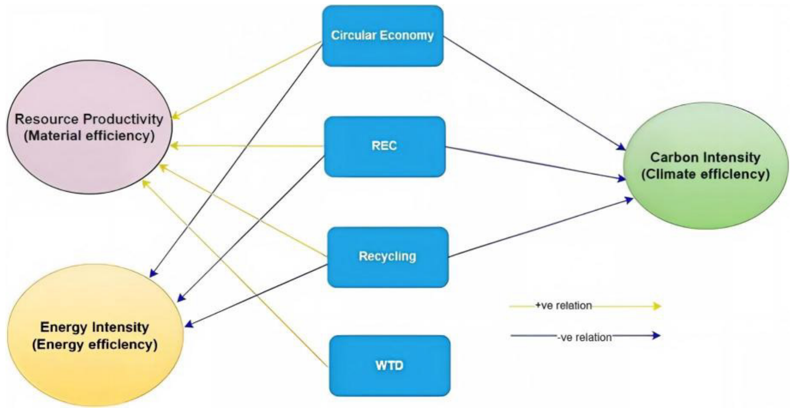

Figure A5. Environmental Stress and Circular Bioeconomy Potential in Bihar.

Conceptual Structure for the figure:

ENVIRONMENTAL CHALLENGES

(Floods • Biomass Burning • Soil Degradation • Waste Accumulation)

↓

BIOECONOMY INTERVENTIONS

(Bioenergy • Waste Recycling • Organic Fertilizers • Circular Systems)

↓

EXPECTED ENVIRONMENTAL OUTCOMES

(Emission Reduction • Resource Efficiency • Ecological Sustainability)

Table A17. Employment Structure and Bioeconomy Transition Implications.

Indicator	Current Status	Bioeconomy Implications
Agricultural employment	High	Labour-intensive transition potential
Informal employment	Dominant	Need for formal green jobs
Youth unemployment	Significant	Skill-development requirement
Interstate migration	High	Local employment deficit
Rural industrialization	Limited	Opportunity for decentralized bioindustry
Green skill availability	Emerging	Need for technological training

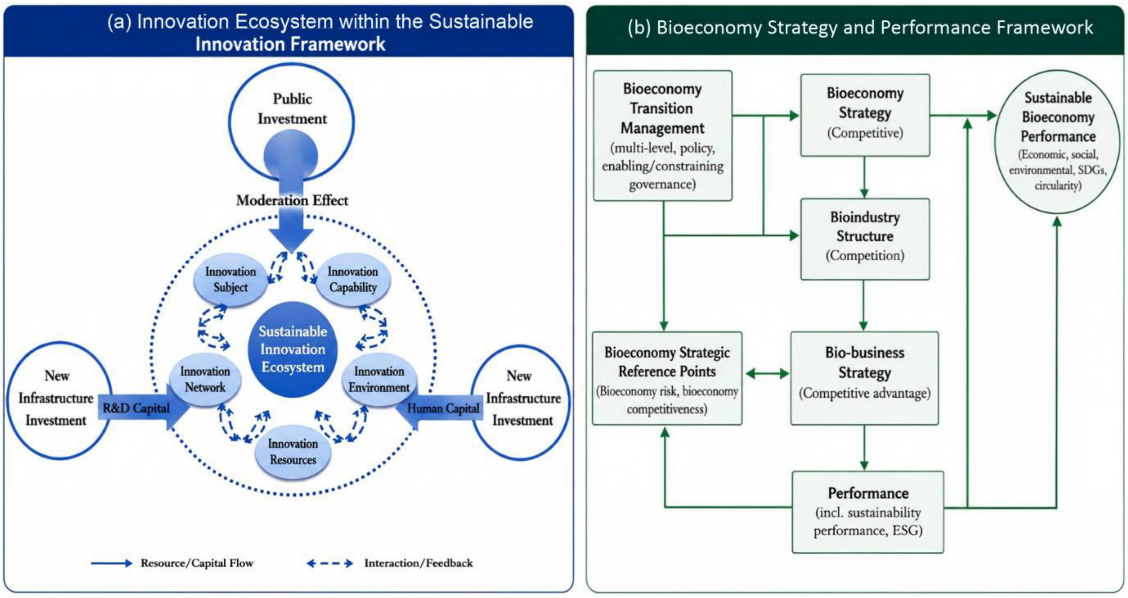

Figure A6. Innovation Capacity and Bioeconomy Transition Readiness.

Table A18. Innovation Capacity Indicators and Transition Implications.

Innovation Dimension	Current Status	Transition Implications
R&D expenditure	Low	Technological constraint
Biotechnology adoption	Emerging	Growth opportunity
Startup ecosystem	Limited but expanding	Innovation potential
Digital agriculture	Moderate	Productivity enhancement
Skill infrastructure	Developing	Labour transformation potential
University–industry linkage	Weak	Institutional strengthening needed

Appendix B

Table A19. Baseline Forecast Trends for Bihar up to 2050.

Indicator	2025 Baseline	2050 BAU Projection	Transition Implication
GSDP growth	Moderate	Moderate–high	Structural expansion
Biomass utilisation	Limited	Moderate	Untapped potential remains
Renewable energy share	Low	Moderate	Gradual green transition
Agro-processing intensity	Low	Expanding	Increasing value addition
Green employment	Emerging	Moderate increase	Labour diversification
Innovation capacity	Limited	Improving	Technological modernisation

Table A20. Sectoral Growth Forecasts under Accelerated Innovation Scenario.

Sector	Growth Potential by 2050	Major Drivers
Bioenergy	Very high	Biomass utilization and renewable demand
Food processing	High	Agricultural surplus and urban markets
Precision agriculture	High	AI and digital technologies
Biofertilizers	Moderate–high	Sustainable agriculture
Circular agro-industries	High	Waste valorisation
Bioplastics	Moderate	Green manufacturing demand

Table A21. VECM Long-Run Coefficient Estimates. Dependent Variable: Bioeconomy Development Index.

Explanatory Variable	Coefficient	Std. Error	*t*-Statistic	*p*-Value
Innovation Capacity	0.428***	0.081	5.28	<0.001
Biomass Utilization	0.372***	0.076	4.89	<0.001

Table A21. *Cont.*

Explanatory Variable	Coefficient	Std. Error	*t*-Statistic	*p*-Value
Renewable Energy Adoption	0.291***	0.067	4.34	0.002
Infrastructure Quality	0.214***	0.059	3.63	0.005
Environmental Vulnerability	−0.185**	0.071	−2.61	0.018

Note: Model Statistics: $R^2 = 0.78$, Adjusted $R^2 = 0.74$, F-statistic = 26.41***, Durbin–Watson statistic = 2.03. ** $p < 0.05$; *** $p < 0.01$.

Table A22. Forecast Projections with 95% Confidence Intervals (Accelerated Innovation Scenario).

Year	Bioeconomy Output Index	95% CI Lower	95% CI Upper
2025	100.0	100.0	100.0
2030	124.8	118.4	131.2
2035	156.3	147.1	165.5
2040	192.7	180.6	204.8
2045	236.5	220.2	252.8
2050	289.4	267.8	311.0

Forecast confidence intervals were generated using bootstrap resampling (1,000 iterations) combined with Bayesian uncertainty estimation. Results indicate relatively narrow confidence bands under the accelerated innovation scenario, suggesting robust long-term forecasting performance. Nevertheless, uncertainty increases progressively beyond 2040 due to potential technological, institutional, and climate-related disruptions. This finding reinforces the importance of adaptive policy frameworks and periodic recalibration of transition strategies.

Table A23. Employment Index.

Year	Employment Index	95% CI Lower	95% CI Upper
2025	100.0	100.0	100.0
2030	112.6	108.5	116.7
2035	128.4	121.3	135.5
2040	146.8	137.4	156.2
2045	169.2	156.8	181.6
2050	194.7	178.1	211.3

Table A24. Emission Intensity Index (2025 = 100).

Year	Emission Intensity	95% CI Lower	95% CI Upper
2025	100.0	100.0	100.0
2030	92.1	88.7	95.5
2035	82.4	77.6	87.2
2040	71.6	65.4	77.8
2045	60.8	53.7	67.9
2050	49.3	41.8	56.8

Table A25. Forecast Employment Outcomes to 2050.

Indicator	Moderate Transition	Moderate Transition	Accelerated Innovation
Rural employment generation	Limited	Moderate–High	Moderate–High
Green jobs	Emerging	Expanding	Large-scale growth
Migration reduction	Minimal	Moderate	Significant
Skill transformation	Slow	Moderate	Rapid
Informal employment dependence	High	Moderate	Reduced

Table A26. Sensitivity Analysis of Scenario Assumptions.

Parameter Change	Economic Growth (%)	Employment Growth (%)	Emission Reduction (%)
Baseline Scenario	100	100	100
Innovation +10%	+7.4	+5.2	+4.8
Biomass Utilization +10%	+4.6	+6.9	+8.3

Table A26. *Cont.*

Parameter Change	Economic Growth (%)	Employment Growth (%)	Emission Reduction (%)
Renewable Energy +10%	+3.8	+2.5	+9.7
Infrastructure +10%	+5.9	+4.1	+2.8
Climate Risk +10%	−6.7	−4.3	−2.5

Interpretation: Innovation intensity and biomass utilization exert the strongest positive influence on E3 outcomes.

Appendix C

Table A27. Strategic Innovation Policy Priorities.

Policy Area	Strategic Objective
Biotechnology	Sustainable agricultural modernization
Digital agriculture	Productivity enhancement
AI systems	Resource optimization
Startup ecosystems	Green entrepreneurship
Skill systems	Workforce transformation
University–industry linkage	Technology commercialization

Table A28. Financing Mechanisms for Bihar's Bioeconomy Transition.

Financing Instrument	Major Application
Green bonds	Renewable infrastructure
Climate finance	Climate adaptation
PPPs	Bio-industrial infrastructure
Venture capital	Agri-tech innovation
Development finance	Rural industrialization

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