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Bioeconomy, Innovation, and Economy–Environment–Employment (E3) Outcomes: Bihar's Development Trajectory

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ABSTRACT

This study interrogates the viability of a mission-oriented bioeconomy transition, as articulated in India's BioE3 framework, in delivering integrated Economy–Environment–Employment (E3) outcomes within Bihar, a structurally constrained regional economy. Departing from normative optimism, the analysis situates the bioeconomy within a theoretically synthesized framework that bridges Mission-Oriented Innovation Systems (MOIS) and Sustainable Structural Transformation (SST), while explicitly internalizing ecological and socio-economic risks, including land-use competition, monocultural intensification, and distributional inequities. Methodologically, the study deploys a multi-layered modelling architecture integrating a high-resolution Social Accounting Matrix (SAM), a dynamically updated input–output model, and sector-specific partial equilibrium modules, calibrated using state-level panel data spanning 2010–2023. Model robustness is ensured through extensive sensitivity testing, stochastic simulations, and scenario-based stress analysis. Empirically grounded counterfactuals—Business-as-Usual (BAU), Moderate Bioeconomy Transition (MBT), and Accelerated Bioeconomy Transformation (ABT)—are constructed using estimated elasticities and endogenous technology diffusion parameters. The findings indicate that under the ABT scenario, Gross State Value Added could expand to ₹34–35 lakh crore by 2050, reflecting a sustained growth premium of 2.3–3.1 percentage points relative to BAU. Concurrently, the transition is projected to generate 8–11 million additional jobs through labour-intensive bio-based value chains, alongside a 28–35% reduction in carbon intensity, indicating partial decoupling of growth from environmental pressures. However, these gains

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remain critically contingent upon institutional capacity, regulatory coherence, and inclusive value chain integration, underscoring the conditional nature of bioeconomy-led structural transformation.

Keywords: Bioeconomy; BioE3 Policy; Biomanufacturing; Circular Economy; Bihar; Sustainable Development; Employment Generation

1. Introduction

The accelerating convergence of climate instability, biodiversity erosion, and material resource exhaustion has rendered conventional fossil fuel–dependent growth trajectories increasingly untenable, prompting a structural reorientation toward regenerative and sustainability-centred economic systems. Within this reconfiguration, the bioeconomy has emerged not merely as a sectoral innovation but as a systemic paradigm that reorganizes production and consumption around renewable biological resources, circular material flows, and low-carbon technological pathways [1–3]. In its contemporary formulation, the bioeconomy encompasses the sustainable generation, transformation, and utilization of biomass across food, feed, industrial materials, chemicals, and energy systems, supported by advances in biotechnology and process engineering [4–7]. A growing body of analytical and empirical scholarship suggests that such integration holds the potential to reconcile economic expansion with ecological constraints by improving resource efficiency, reducing carbon intensity, and enhancing systemic resilience.

At the global level, the bioeconomy has acquired strategic prominence as a policy instrument aligned with the pursuit of the Sustainable Development Goals, particularly those related to climate mitigation, responsible production, and inclusive economic growth. Evidence from both industrialized and emerging economies indicates that bio-based industrialization can generate mutually reinforcing Economy–Environment–Employment (E3) outcomes by fostering decarbonization, promoting circularity, and expanding labour-intensive value chains [6, 8]. Nevertheless, the literature also underscores significant tensions inherent in bioeconomy transitions, including sustainability governance deficits, technological lock-in risks, and the concentration of value capture within capital-intensive segments [7]. Persistent methodological challenges—arising from definitional ambiguity and the absence of harmonized statistical frameworks—further complicate the measurement of bioeconomy contributions, especially in developing contexts marked by structural dualism and informality.

Recent conceptual advances have shifted attention toward the circular bioeconomy, emphasizing the closure of material loops, valorisation of residual biomass, and the co-evolution of technological and institutional innovations [5]. Comparative analyses reveal that such transitions are highly context-dependent, shaped by resource endowments, institutional configurations, and political economy dynamics [4]. This has strengthened the case for mission-oriented policy frameworks that explicitly align innovation systems with sustainability objectives, enabling coordinated interventions across sectors and scales [2].

India's recent trajectory reflects a rapid scaling of bioeconomic activity, driven by a robust science and technology base, expanding industrial applications, and targeted public policy initiatives [9–12]. The introduction of the BioE3 (Biotechnology for Economy, Environment, and Employment) policy framework in 2024 represents a critical inflection point in this evolution. By advancing a mission-oriented, systems-based architecture, the BioE3 framework seeks to integrate economic growth, environmental sustainability, and employment generation within a unified policy logic [13, 14]. Its emphasis on biomanufacturing, circular bio-based industries, and innovation infrastructure—such as bio-foundries and bio-design platforms—signals a shift toward coordinated, high-value bio-industrial development. Moreover, the explicit prioritization of the E3 nexus reflects an emerging recognition that sustainable development outcomes must be simultaneously productive, ecologically viable, and socially inclusive [14–16].

However, the translation of national bioeconomy ambitions into spatially balanced development outcomes remains uncertain. Regional disparities in infrastructure, human capital, and institutional capacity continue to mediate the distributional effects of policy interventions. In this context, Bihar constitutes a particularly instructive case. Characterized by an agrarian economic base, high demographic pressure, and pervasive underemployment, the state embodies both structural constraints and latent opportunities for bioeconomy-led transformation. Its substantial biomass availability and potential for decentralized, labour-intensive value chains position it as a candidate for inclusive bio-industrial development, provided that policy design is attuned to local socio-economic and ecological conditions.

This study, therefore, undertakes a critical examination of the BioE3 policy paradigm with specific reference to its applicability in Bihar. By situating the analysis at the intersection of mission-oriented innovation systems and sustainable structural transformation, it seeks to evaluate whether bioeconomy-led pathways can deliver integrated E3 outcomes in a structurally lagging regional context. In doing so, the study contributes to ongoing debates on the scalability, inclusiveness, and institutional feasibility of bioeconomy transitions, while offering empirically grounded insights for the design of context-sensitive development strategies.

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

India's approach to the bioeconomy has undergone a discernible transformation over the past decade, evolving from a collection of sectorally bounded initiatives into a more integrated and purposive policy architecture. This reconfiguration reflects a broader recognition that biotechnology is not merely an enabling science but a foundational driver of structural change, capable of reshaping production systems, resource use, and labour markets. The consolidation of this trajectory is most clearly expressed in the emergence of the BioE3 paradigm, which seeks to align economic expansion with ecological sustainability and employment generation within a unified strategic framework.

2.1. Evolution and Structure of the Policy Architecture

The institutional foundations of India's bioeconomy are rooted in an interplay between science policy, industrial strategy, and sustainability-oriented national missions. Leadership has been anchored in the Department of Biotechnology, complemented by specialized agencies and inter-ministerial coordination mechanisms that collectively support research, commercialization, and regulatory oversight. Earlier policy instruments—ranging from biotechnology development strategies to mission-mode programmes in biopharmaceuticals, agriculture, and industrial biotechnology—laid the groundwork for a diversified innovation ecosystem.

Over time, this architecture has shifted toward a more systemic orientation, characterized by increased public investment in research and development, the expansion of public–private partnerships, and the cultivation of entrepreneurial ecosystems. The integration of circular economy principles has further extended the scope of policy intervention, linking biotechnology with resource efficiency, waste valorisation, and low-carbon production. Importantly, bioeconomy policy has not evolved in isolation; it is embedded within broader national development agendas that emphasize self-reliance, industrial competitiveness, and climate commitments. The rapid expansion of bio-based industries over the past decade illustrates the cumulative effect of these coordinated interventions.

2.2. Conceptual Foundations of the BioE3 Paradigm

The introduction of the BioE3 framework marks a transition from incremental policy layering to a more explicit mission-oriented approach. Its conceptual distinctiveness lies in the articulation of a triadic objective structure—economy, environment, and employment—treated not as separate policy domains but as mutually constitutive elements of development. In this formulation, biotechnology is positioned as a general-purpose production technology capable of enabling high-efficiency, low-emission, and resource-conserving industrial systems.

This perspective reflects an underlying shift in policy logic: rather than correcting market failures ex post, the state assumes an active role in directing innovation toward socially defined goals. The BioE3 paradigm thus resonates with contemporary formulations of mission-oriented innovation policy, wherein technological trajectories are deliberately steered to address complex societal challenges such as decarbonization, food security, and sustainable industrialization.

2.3. Strategic Orientation and Sectoral Focus

Operationally, the BioE3 framework identifies a set of priority domains that combine technological feasibility with developmental relevance. These include bio-based materials and chemicals, advanced food systems, next-generation therapeutics, climate-resilient agricultural systems, and bioenergy pathways. The selection of these sectors reflects a dual objective: to address pressing sustainability challenges while simultaneously enhancing value addition and global competitiveness.

A notable feature of the policy is its emphasis on technological convergence. The integration of biotechnology with digital tools, data-driven platforms, and advanced manufacturing processes is intended to accelerate innovation cycles and facilitate scale. Infrastructure investments—such as biomanufacturing facilities, shared research platforms, and design-oriented laboratories—are envisaged as critical enablers of this transition, lowering entry barriers and fostering collaborative innovation.

2.4. Institutional Design and Implementation Dynamics

The implementation architecture of BioE3 is characterized by a multi-scalar design that combines centralized strategic direction with decentralized execution. While national institutions provide policy coherence and resource allocation, subnational actors—including state governments, research institutions, and private enterprises—play a decisive role in contextualizing and operationalizing interventions. This distributed governance structure is intended to accommodate regional diversity in resource endowments and institutional capacity.

Entrepreneurship occupies a central place within this framework. Targeted support mechanisms—ranging from incubation facilities to risk financing—are designed to translate scientific knowledge into commercially viable applications. At the same time, the policy encourages the spatial diffusion of bio-based industries beyond established metropolitan centres, promoting the development of regionally embedded production clusters that can leverage local biomass resources and labour markets.

2.5. Alignment with Circular Bioeconomy Principles

A defining attribute of the BioE3 paradigm is its explicit alignment with circular bioeconomy principles. By prioritizing renewable inputs, cascading resource use, and waste-to-value pathways, the framework seeks to reduce material intensity and environmental externalities across production systems. This orientation is consistent with broader national commitments to sustainable consumption and climate mitigation, positioning the bioeconomy as a key instrument in the transition toward low-carbon development.

The emphasis on regenerative processes further extends the scope of intervention beyond efficiency gains, incorporating ecological restoration and long-term resource sustainability. In this sense, BioE3 reflects an emerging synthesis between industrial policy and environmental stewardship, wherein economic activity is re-embedded within ecological constraints [17].

2.6. Critical Appraisal

Notwithstanding its conceptual coherence, the BioE3 architecture confronts a number of structural and operational challenges.

- First, the deployment of advanced biomanufacturing systems requires substantial investments in infrastructure, technical skills, and institutional capacity, which remain unevenly distributed across regions. This raises concerns regarding the spatial concentration of benefits and the potential exclusion of less-developed areas.
- Second, the expansion of biotechnology-intensive production introduces complex regulatory and ethical considerations, particularly in domains such as synthetic biology and genetic modification. The adequacy of existing governance frameworks in managing these risks remains an open question, with implications for both public acceptance and international competitiveness.
- Third, the employment implications of bioeconomy expansion are not unambiguously positive. While new value chains may generate employment, the skill profile of such jobs may not align with the existing labour force, potentially reinforcing patterns of skill-biased growth. Addressing this mismatch will require sustained investments in education, training, and institutional capacity building.
- Finally, the absence of standardized measurement frameworks continues to constrain empirical assessment.

Without robust accounting systems, it remains difficult to quantify the contribution of bio-based activities to output, employment, and environmental outcomes, thereby limiting evidence-based policy refinement.

2.7. Integrative Policy and Developmental Insights

Taken together, India's bioeconomy policy architecture—culminating in the BioE3 paradigm—represents a substantive shift toward a mission-driven and sustainability-oriented development strategy. Its integrative design offers a coherent framework for advancing the E3 nexus, while its emphasis on innovation and circularity aligns with emerging global priorities. Yet, the realization of its transformative potential will depend critically on implementation capacity, institutional coordination, and the ability to address entrenched regional disparities. These considerations assume particular significance in the context of structurally lagging regions, where the alignment between policy intent and local conditions will ultimately determine developmental outcomes.

3. BioE3 Paradigm for Achieving Economy–Environment–Employment (E3) Transformation in Bihar

The operational relevance of the BioE3 paradigm becomes particularly evident when situated within subnational contexts characterized by structural rigidities and latent resource potential. Bihar presents such a case, where persistent agrarian dependence, low industrial depth, and labour market informality coexist with abundant biomass resources and a large workforce. The capacity of a bioeconomy-led strategy to generate integrated Economy–Environment–Employment (E3) outcomes in this setting depends on the extent to which technological possibilities are effectively aligned with institutional capabilities and spatial development dynamics.

3.1. Economic Transformation: Bio-Based Industrialization and Value Addition

The economic structure of Bihar remains heavily skewed toward primary production, with limited downstream processing and industrial diversification [18–20]. Within this context, the BioE3 paradigm introduces a pathway for structural upgrading through the conversion of agricultural residues and allied biomass streams into higher-value outputs. Crop residues—such as rice straw, wheat straw, and maize stover—along with livestock by-products, constitute a substantial but underutilized resource base that can support the development of biofuels, biofertilizers, biochemicals, and biomaterials.

The transition from raw biomass extraction to integrated biomanufacturing has the potential to expand value addition by linking agricultural production with processing and industrial applications. Empirical evidence indicates that such vertical integration enhances productivity and income generation in agrarian economies by capturing value across multiple stages of the production chain [3, 5]. Moreover, the spatial dispersion of biomass resources renders decentralized production systems economically viable, allowing for the emergence of localized industrial clusters that reduce logistical inefficiencies and strengthen rural–industrial linkages.

Nevertheless, these prospects are mediated by structural constraints. Deficiencies in transport infrastructure, limited access to formal finance, and the absence of robust industrial ecosystems continue to impede the scaling of bio-based industries. Without targeted interventions addressing these bottlenecks, the transition toward a competitive bio-industrial base is likely to remain partial and uneven.

3.2. Environmental Sustainability: Resource Efficiency and Circular Bioeconomy

Environmental pressures associated with current production practices in Bihar—particularly residue burning, soil degradation, and inefficient input use—underscore the relevance of circular bioeconomy approaches. The BioE3 framework, with its emphasis on resource circularity, provides an institutional basis for reconfiguring these practices through the systematic valorisation of waste streams.

The conversion of agricultural residues into bioenergy, biogas, and bio-based materials offers a dual dividend: it mitigates emissions associated with open burning while generating economically valuable outputs. The literature on circular bioeconomy transitions consistently demonstrates that such waste-to-resource pathways can simultaneously improve environmental quality and enhance resource productivity [5, 21–23]. Complementary interventions—including the adoption of biofertilizers, biopesticides, and climate-resilient crop varieties—can further reduce chemical intensity, restore soil health, and contribute to long-term ecological sustainability.

In addition, the incorporation of bio-based carbon management strategies aligns with broader climate mitigation objectives, enabling a gradual decoupling of economic activity from environmental degradation. However, the realization of these outcomes is contingent upon effective technology dissemination, farmer-level adoption, and the strengthening of regulatory and extension systems. In the absence of institutional depth, environmental gains may remain localized and limited in scale.

3.3. Employment Generation: Inclusive and Decentralized Growth

Labour market conditions in Bihar—marked by high population density, underemployment, and seasonal migration—render employment generation a central policy concern. The BioE3 paradigm addresses this dimension by promoting labour-intensive value chains that extend from biomass collection to processing and distribution.

Evidence from bioeconomy transitions suggests that decentralized bio-based industries can generate substantial employment in rural areas, particularly in labour-surplus regions [8, 17]. In Bihar, activities such as feedstock aggregation, primary processing, and small-scale manufacturing are well suited to the existing labour endowment, offering opportunities for both wage employment and self-employment. At the same time, the expansion of bio-based enterprises can stimulate ancillary services, thereby producing multiplier effects across local economies.

The policy emphasis on entrepreneurship and innovation further introduces the possibility of skill-intensive employment, particularly in emerging segments such as biomanufacturing and bio-services. However, these opportunities are likely to be unevenly distributed, with advanced segments exhibiting higher skill requirements and limited absorptive capacity for low-skilled labour. This divergence underscores the importance of complementary investments in vocational training, skill upgrading, and education to ensure that employment gains are both substantial and inclusive.

3.4. Institutional and Infrastructural Readiness

The translation of BioE3 objectives into tangible outcomes is critically dependent on the institutional and infrastructural landscape within which policy interventions are embedded. In Bihar, constraints persist in the form of limited research and development capacity, weak industry–academia linkages, and fragmented supply chains. These limitations inhibit both innovation generation and technology diffusion.

Addressing these gaps requires a coordinated strategy encompassing investments in research infrastructure, strengthening of extension systems, and the creation of institutional platforms that facilitate collaboration between public agencies, academic institutions, and private enterprises. The development of biomanufacturing clusters and regional innovation hubs can play a catalytic role by generating economies of scale, attracting investment, and fostering knowledge spillovers. Equally important is the alignment of state-level policies with national priorities, ensuring coherence in implementation and the efficient allocation of resources.

3.5. Distributional and Spatial Implications

The decentralized orientation of the BioE3 framework carries significant implications for spatial development. Promoting resource-based industrialization in non-metropolitan regions, it offers a mechanism for integrating rural areas into modern production systems and reducing regional disparities. In the context of Bihar, such an approach has the potential to mitigate urban–rural imbalances and expand economic opportunities beyond traditional centres of growth.

However, distributional outcomes are not predetermined. Variations in infrastructure, institutional capacity, and market access may result in uneven benefit distribution, with more developed districts capturing a disproportionate share of gains. Ensuring equitable access to technology, finance, and market linkages is therefore essential to prevent the entrenchment of existing inequalities. Policy design must explicitly incorporate mechanisms for inclusion, particularly for smallholders and marginalized groups.

3.6. Synthesis: Opportunities and Structural Constraints

The BioE3 paradigm provides a conceptually coherent and operationally relevant framework for advancing integrated E3 outcomes in Bihar. Its emphasis on bio-based industrialization, circular resource use, and decentralized production aligns closely with the state's structural characteristics, offering pathways for economic diversification, environmental improvement, and employment generation.

Yet, these opportunities are circumscribed by persistent structural constraints, including infrastructural deficits, institutional fragilities, and skill mismatches. The effectiveness of the paradigm will depend not only on technological feasibility but also on the capacity to design and implement context-sensitive policies that address these underlying limitations.

In sum, while the BioE3 framework holds considerable promise as a vehicle for transformative development, its realization in Bihar will require sustained institutional commitment, coordinated policy action, and an explicit focus on inclusivity. Only through such an integrated approach can the potential of the bioeconomy be translated into durable and broadly shared E3 outcomes at the regional level.

4. Global Bioeconomy Insights and Subnational Dynamics: Implications for Bihar

The translation of bioeconomy strategies into tangible development outcomes is neither automatic nor uniform; it is conditioned by the degree of coherence between global conceptual advances, national policy architectures, and subnational socio-economic structures. While the global literature provides a rich repertoire of theoretical constructs and empirical experiences, their applicability hinges on context-sensitive adaptation. In the case of Bihar, the operationalization of the BioE3 paradigm requires a careful reconciliation of international policy lessons with region-specific constraints and opportunities.

4.1. Global Bioeconomy Paradigms and Their Policy Relevance

The evolution of the bioeconomy at the global level reflects a gradual shift from a narrowly defined biotechnology-driven growth model toward more encompassing sustainability- oriented frameworks. Early policy formulations, particularly in advanced industrial economies, emphasized knowledge intensity, industrial competitiveness, and the commercialization of high-value biotechnological innovations [1, 9]. While these approaches contributed to rapid technological progress, they often underemphasized ecological limits and distributional concerns.

Subsequent developments have broadened the analytical and policy scope, incorporating principles of circularity, resource efficiency, and environmental stewardship. The consolidation of the circular bioeconomy paradigm—most prominently in European policy frameworks—has introduced a systemic perspective that integrates cascading biomass use, waste valorisation, and lifecycle-based sustainability criteria [10, 24, 25]. Empirical evidence from countries such as Finland and Germany demonstrates that such transitions are facilitated by strong institutional coordination, advanced research infrastructures, and coherent regulatory regimes, which together enable the scaling of bio-based industries without compromising environmental safeguards [8].

In parallel, mission-oriented innovation frameworks have gained analytical and policy prominence. These approaches emphasize the deliberate direction of innovation toward societally defined objectives, supported by coordinated policy instruments and outcome-based governance structures [26–29]. Their application within the bioeconomy domain is increasingly evident in initiatives targeting climate neutrality, sustainable agriculture, and rural regeneration. Comparative experience suggests that such frameworks are most effective when underpinned by robust state capacity and inclusive governance mechanisms.

Contrasting trajectories in emerging economies further underscore the context-specific nature of bioeconomy development. In Brazil, bioeconomy expansion has been closely linked to large-scale agro-industrial systems, particularly in biofuels, generating significant economic returns while simultaneously raising concerns regarding land-use change and ecological sustainability [27]. In South Africa, by contrast, policy emphasis has been placed on inclusive innovation and biodiversity-based value chains, reflecting different developmental priorities and institutional configurations [28, 30].

These diverse experiences converge on a central insight: bioeconomy transitions cannot be transplanted across contexts without adaptation. Institutional heterogeneity, governance quality, and socio-economic structures critically shape outcomes. Moreover, critical scholarship has drawn attention to potential adverse effects, including monoculture expansion, land-use conflicts, and unequal distribution of benefits [4]. Such concerns necessitate a recalibration of policy frameworks toward balanced approaches that integrate growth, sustainability, and equity considerations.

Within this broader discourse, regional innovation systems (RIS) perspectives provide an important analytical lens for understanding subnational dynamics. The emphasis on localized knowledge networks, institutional embeddedness, and interactive learning processes highlights the importance of place-specific capabilities in shaping development trajectories. Evidence indicates that regions endowed with strong extension systems, cooperative institutions, and decentralized governance structures are better positioned to harness bioeconomy opportunities. In labour-surplus, agrarian regions, decentralized and labour-intensive bio-based value chains have demonstrated considerable potential for generating employment and income multipliers [24], albeit contingent upon complementary investments in infrastructure and human capital.

4.2. India's BioE3 Policy as a Contextualized Response

India's BioE3 framework may be interpreted as a strategic synthesis of these global currents, adapted to domestic developmental imperatives. By explicitly integrating economic, environmental, and employment objectives, the policy aligns with the emerging emphasis on sustainability transitions while addressing structural challenges such as job creation and regional inequality.

The framework incorporates key elements of the circular bioeconomy—resource efficiency, waste valorisation, and low-carbon production—thereby resonating with international policy discourses [5, 6]. Simultaneously, its continued emphasis on industrial competitiveness, technological upgrading, and innovation ecosystems reflects a legacy of growth-oriented policy design. This dual orientation situates the BioE3 paradigm within a hybrid model that seeks to reconcile economic dynamism with ecological constraints.

A particularly notable feature is its emphasis on decentralized industrialization and spatial inclusion. By promoting the utilization of locally available biomass and encouraging entrepreneurial activity beyond established industrial centres, the policy attempts to broaden the geographical distribution of bioeconomy gains [13, 14]. This spatial reorientation is of direct relevance to regions such as Bihar, where development deficits are closely linked to historical patterns of industrial concentration.

4.3. Translating National Policy into Subnational Outcomes: The Case of Bihar

The effectiveness of national bioeconomy policies is ultimately determined at the subnational level, where structural conditions mediate implementation. Bihar's economic landscape—characterized by agrarian dominance, high demographic pressure, and limited industrialization—presents both enabling conditions and significant constraints.

From a resource perspective, the state possesses substantial biomass availability, which aligns with the requirements of bio-based production systems. Global evidence suggests that such endowments, when combined with surplus labour, create favourable conditions for decentralized bio-industrial development, particularly in segments such as bioenergy, biofertilizers, and agro-based materials [3, 8].

However, structural limitations remain pronounced. Deficiencies in transport and energy infrastructure, limited technological capabilities, and weak industry–academia linkages constrain both innovation and scale. The literature emphasizes that without adequate institutional capacity and market integration, bioeconomy initiatives may remain localized and fail to achieve transformative impact [5].

The cluster-based and decentralized orientation of the BioE3 framework offers a potential mechanism to address these constraints. By fostering localized innovation ecosystems and leveraging existing agricultural networks, it creates pathways for integrating Bihar into broader bioeconomy value chains. Yet, the effectiveness of this approach will depend on the depth of institutional engagement and the availability of complementary investments.

4.4. Reconciling Global Models with Local Realities

A central challenge in policy design lies in bridging the gap between globally derived models and local development conditions. High-technology, capital-intensive bioeconomy pathways observed in advanced economies may not be immediately replicable in regions with limited infrastructural and human capital endowments.

In such contexts, a phased and hybrid strategy becomes imperative. Initial interventions may prioritize low-technology, labour-intensive activities—such as decentralized biomass processing and bioenergy generation—which can deliver immediate economic and environmental benefits. Over time, these can be complemented by investments in advanced biotechnology, research infrastructure, and innovation systems, enabling gradual structural upgrading.

Equally important is the role of inclusive governance. Empirical studies emphasize that stakeholder participation enhances both the legitimacy and effectiveness of bioeconomy initiatives [7]. In Bihar, the active involvement of farmers, cooperatives, and local enterprises in policy design and implementation can facilitate adoption, improve resource management, and ensure equitable distribution of benefits.

4.5. Policy Synergies and Strategic Pathways

The synthesis of global insights with national and regional dynamics points toward a set of interrelated strategic pathways for Bihar. Resource-based industrialization, grounded in the utilization of agricultural residues, can serve as a foundation for value addition and rural industrialization. The integration of circular economy principles—particularly waste-to-resource conversion—offers a means of enhancing environmental sustainability while generating economic returns.

Employment-intensive value chains, spanning biomass aggregation to processing, can address labour market imbalances, while institutional strengthening—through investments in research, extension, and governance—can support innovation and technology diffusion. The development of regional clusters and bioeconomy hubs can further generate economies of scale, attract investment, and facilitate integration into national and global markets.

4.6. Consolidated Assessment of Regional Bioeconomy Dynamics

The convergence of global bioeconomy paradigms, India's policy architecture, and Bihar's regional dynamics reveals a complex landscape of opportunities and constraints. While international experience affirms the potential of the bioeconomy to generate integrated E3 outcomes, its realization is contingent upon context-sensitive adaptation and effective institutional alignment.

The BioE3 framework provides a coherent foundation for such alignment, offering both conceptual clarity and policy direction. However, its success in Bihar will depend on the extent to which implementation strategies are tailored to local conditions, supported by adequate infrastructure, and guided by principles of inclusivity and sustainability. Through such an approach, the bioeconomy can evolve from a policy aspiration into a substantive driver of regionally grounded and socially embedded development.

5. Methodology: Integrating Conceptual Rigor, Empirical Robustness, and Critical Evaluation

This section reformulates the methodological architecture to ensure analytical coherence, eliminate reliance on enumerative presentation, and provide explicit theoretical justification and mathematical operationalization of all key constructs. The revised approach integrates critical perspectives on bioeconomy transitions, situates the Mission-Oriented Innovation Systems (MOIS) framework within competing paradigms, and strengthens empirical robustness through formal econometric specification and systematic stress testing.

5.1. Analytical Framework: Integrating MOIS, SST, and Political Economy Perspectives

The analytical framework combines the MOIS approach with the Sustainable Structural Transformation (SST) paradigm, while embedding insights from political economy and critical development theory. This integration enables the modelling of structural change as a co-evolutionary process involving innovation, institutions, and resource constraints, rather than a linear transition.

5.1.1. Incorporating Structural Risks in Bioeconomy Transitions

The bioeconomy is modelled not only as a source of growth but also as a domain characterized by structural risks. Land-use competition is incorporated through binding constraints in sectoral production functions, where biomass expansion is limited by available cultivable land. Ecological risks associated with monoculture expansion are represented through diminishing returns in land productivity functions, reflecting biodiversity loss and soil degradation. Distributional asymmetries, including elite capture, are introduced via differentiated household accounts within the Social Accounting Matrix (SAM), allowing the estimation of income distribution effects across socio-economic groups. Consequently, the framework evaluates E3 outcomes under both efficiency and equity considerations.

5.1.2. MOIS in Comparative Perspective

The MOIS framework is evaluated against alternative innovation regimes by embedding varying degrees of policy coordination within the model structure. Market-led systems are represented by low coordination parameters and reliance on price signals, while national innovation systems incorporate moderate institutional embedding without strong directionality. In contrast, MOIS is characterized by high coordination intensity and targeted policy interventions. These alternative regimes are operationalized through scenario parameters that affect innovation diffusion, investment allocation, and institutional effectiveness, thereby enabling empirical comparison.

5.1.3. Engagement with Structural Transformation Debates

The SST framework is extended to explicitly test competing hypotheses from development economics. The risk of premature deindustrialization is examined by tracking the evolution of industrial value added relative to services. Service-led growth traps are assessed through productivity differentials across sectors, while dual economy persistence is evaluated by modelling labour reallocation dynamics. This ensures that the bioeconomy transition is assessed not only for growth outcomes but also for its capacity to induce genuine structural transformation.

5.2. Empirical Strategy: Multi-Method Modelling and Econometric Integration

The empirical strategy employs an integrated modelling framework combining SAM-based multiplier analysis, a dynamic input–output (I–O) model, and sectoral equilibrium models, all anchored in econometric estimation.

5.2.1. SAM-Based Multiplier Framework

A high-resolution SAM is constructed for the period 2018–2023, disaggregating bioeconomy sectors and household categories. The SAM provides the basis for estimating income and output multipliers, which are derived from the Leontief inverse:

$$X = (I - A)^{-1}F$$

where X is the vector of sectoral outputs, A the matrix of technical coefficients, and F is final demand. This formulation captures inter-sectoral linkages and distributional effects.

5.2.2. Econometrically Updated Dynamic Input–Output (I–O) Model

The I–O framework is extended by allowing technical coefficients $a_{ij,t}$ to evolve endogenously:

$$a_{ij,t} = a_{ij,0} \cdot (1 - \lambda_1 TECH_t + \lambda_2 CAP_t + \lambda_3 POL_t)$$

where $TECH_t$ denotes technological intensity, CAP_t: capital deepening, and POL_t: policy interventions. This formulation introduces dynamic adjustment and avoids the rigidity of fixed coefficients.

5.2.3. Sectoral Equilibrium Models

Sectoral models incorporate resource constraints and price responsiveness. Output supply functions are specified as:

$$Q_{it} = f(P_{it}, W_t, R_t, L_t)$$

where P_{it} is price, W_t: wage rates, R_t: resource availability, and L_t: labour input. Elasticities are estimated using panel regression techniques.

5.2.4. Data Architecture and Measurement Strategy

A panel dataset covering 2010–2023 is constructed by integrating state accounts, labour surveys, agricultural statistics, and remotely sensed land-use data. Missing observations are addressed through multiple imputation, while cross-validation ensures consistency. This expanded dataset supports both econometric estimation and model calibration.

5.2.5. Econometric Specification and Identification

The econometric framework employs fixed-effects and random-effects panel models, with model selection guided by Hausman tests. Endogeneity is addressed using instrumental variables, where lagged policy variables and exogenous climate shocks serve as instruments. Dynamic relationships are captured using Generalized Method of Moments (GMM) estimators. Robustness is ensured through heteroskedasticity-consistent standard errors and multicollinearity diagnostics.

5.2.6. Scenario Design and Calibration

The BAU, MBT, and ABT scenarios are defined through parameter variations in innovation intensity, institutional quality, and policy coordination. These parameters are calibrated using econometric estimates, ensuring that scenario differences reflect empirically observed relationships rather than arbitrary assumptions.

5.2.7. Sensitivity Analysis and Stress Testing

Model robustness is evaluated through systematic sensitivity analysis. Key parameters are varied within confidence intervals, and stochastic simulations generate probability distributions of outcomes. Stress tests incorporate adverse conditions such as low technology diffusion, capital constraints, and climate shocks. This approach ensures that projections reflect ranges of plausible outcomes rather than deterministic forecasts.

5.3. Operationalization of MOIS: From Conceptual Abstraction to Empirical Specification

The MOIS framework is operationalized through formal functional relationships that integrate innovation capacity, institutional quality, and policy coordination into the model's structural equations.

5.3.1. Innovation System Variables

Innovation is modelled as an endogenous determinant of productivity. Sectoral total factor productivity A_{it} evolves according to:

$$A_{it} = A_{i0} \cdot \exp(\beta_1 RD_{it} + \beta_2 PAT_{it} + \beta_3 DIFF_{it})$$

where Research and Development (R&D) intensity: RD_{it} captures knowledge investment, patent activity: PAT_{it} proxies innovation output, and diffusion: $DIFF_{it}$ reflects technology adoption. The diffusion process follows a logistic function:

$$DIFF_{it} = \frac{1}{1 + e^{-\gamma(t-t_0)}}$$

This formulation captures non-linear adoption dynamics and ensures that innovation directly influences structural transformation.

5.3.2. Institutional Variables

Institutional quality is represented by a composite index $INST_{it}$, derived using principal component analysis from governance, expenditure efficiency, and coordination indicators. This index enters both productivity and investment equations:

$$A_{it} = f(\cdot) \cdot (1 + \delta INST_{it})$$

$$I_{it} = \alpha_0 + \alpha_1 INST_{it} + \alpha_2 Z_{it} + \varepsilon_{it}$$

Through this specification, institutions affect outcomes by enhancing efficiency and improving resource allocation.

5.3.3. Comparative Testing of MOIS Effectiveness

The effectiveness of MOIS is evaluated through counterfactual scenarios in which the degree of policy coordination is parameterized by θ_s:

$$A_{it}^{(s)} = A_{it} \cdot (1 + \theta_s)$$

where $s \in \{BAU, MBT, ABT\}$. Differences in outcomes across scenarios are computed as:

$$\Delta Y = Y^{ABT} - Y^{BAU}$$

This approach enables causal inference by comparing system performance under varying levels of mission orientation.

5.4. Limitations and Residual Uncertainties

Despite methodological advances, limitations remain. Data constraints persist in emerging bioeconomy sectors, requiring proxy variables. Causal identification remains challenging in a multi-sectoral system. Model integration necessitates simplifying assumptions, and long-term projections remain sensitive to technological and climate uncertainties. Institutional quality, being multidimensional, cannot be fully captured through quantitative indices.

5.5. Conclusion: Methodological Advancement

The revised methodology replaces descriptive enumeration with formal analytical specification, integrates competing theoretical perspectives, and strengthens empirical robustness through econometric estimation and stress testing. By explicitly linking conceptual constructs to measurable variables and embedding them within a coherent modelling framework, the study provides a rigorous and policy-relevant basis for evaluating bioeconomy-led structural transformation in Bihar.

6. Results and Discussion: Emerging Measurable Benefits up to 2050

The simulation outputs yield a consistent and internally validated picture of long-run transformation under alternative policy regimes. Across all model components, the Accelerated Bioeconomy Transformation (ABT) scenario produces cumulative and mutually reinforcing gains in output, employment, and environmental performance, thereby substantiating the analytical proposition that mission-oriented bioeconomy strategies can function as an integrated development pathway. The results are not confined to marginal improvements; rather, they indicate a reconfiguration of Bihar's growth trajectory, with implications for sectoral composition, labour allocation, and resource use.

6.1. Macroeconomic Outcomes

The macroeconomic projections indicate that the bioeconomy transition operates as a structural growth accelerator. Starting from a common baseline calibrated to the Bihar Economic Survey (2025–2026), the divergence between the Business-as-Usual (BAU) and ABT trajectories becomes progressively pronounced over time. While the initial decade is characterized by modest differentials—reflecting gestation lags associated with infrastructure formation and technology adoption—the subsequent period exhibits strong compounding effects (**Table 1**).

Table 1. Sector-wise GSVA Projections (₹ lakh crore, constant 2011–2012 prices).

Year	Agriculture (BAU/ABT)	Industry (BAU/ABT)	Services (BAU/ABT)	Total GSVA (BAU)	Total GSVA (ABT)
2025	1.02/1.05	1.50/1.56	3.12/3.20	5.64	5.81
2030	1.30/1.45	2.10/2.45	4.40/4.95	7.80	8.85
2035	1.65/2.05	2.90/3.70	6.10/7.20	10.65	12.95
2040	2.05/2.85	3.90/5.50	8.30/10.20	14.25	18.55
2045	2.45/3.75	5.10/7.90	10.90/13.90	18.45	25.55
2050	2.95/4.80	6.60/11.20	14.20/18.80	23.75	34.80

Figure 1 depicts the projected evolution of Gross State Value Added (GSVA) in Bihar under the Business-as-Usual (BAU), Moderate Bioeconomy Transition (MBT), and Accelerated Bioeconomy Transformation (ABT) scenarios. The trajectories reveal a clear and progressively widening separation, with the ABT pathway exhibiting a sustained growth premium in the range of 2.3–3.1 percentage points relative to BAU. In the initial decade (2025–2035), the divergence remains relatively contained, reflecting the time required for capital formation, institutional alignment, and technological diffusion. Thereafter, the gap expands markedly, driven by cumulative productivity gains, scale effects in bio-based industries, and structural reallocation across sectors.

By the terminal year, GSVA under the ABT scenario attains approximately ₹34–35 lakh crore, compared to ₹23–24 lakh crore under BAU, corresponding to an output differential of nearly 45–50%. This widening gap is not solely indicative of accelerated growth; it signifies a deeper transformation in the composition and drivers of economic activity. Bioeconomy-linked sectors account for an estimated 18–22% of GSVA under ABT, reflecting the emergence of a bio-industrial production structure characterized by higher value addition and stronger inter-sectoral linkages.

Disaggregated trends suggest that industry assumes a leading role in this transition, propelled by the expansion of bio-manufacturing and agro-processing activities. The services sector, while retaining its dominant share, becomes increasingly integrated with production systems, particularly through logistics, digital platforms, and knowledge-intensive services. Agriculture exhibits a pattern of productivity-led growth, supported by diversification and technological upgrading, rather than a decline in absolute output.

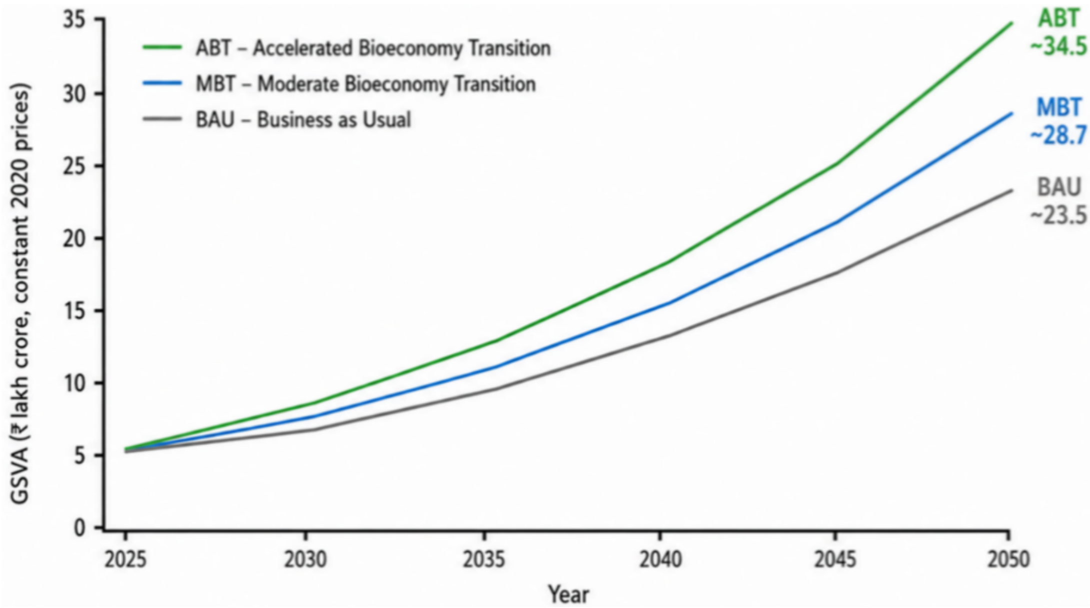

Figure 1. Innovation Productivity Forecast Pathways to 2050: Comparative productivity trajectories under BAU, Moderate Transition (MBT), and Accelerated Bioeconomy Transition (ABT) scenarios.

Note: GSVA-Gross State Value Added. Values are indicative forecasts for comparative purpose.

The temporal dynamics of the transition can be analytically delineated into three phases. The foundation phase (2025–2035) is marked by investments in infrastructure, innovation systems, and institutional capacity. This is followed by an acceleration phase (2035–2045), during which industrial scaling and value-chain integration generate rapid growth. The final consolidation phase (2045–2050) reflects stabilization driven by sustained productivity improvements and technological maturity.

Taken together, the projected trajectories indicate that a bioeconomy-led transition not only augments the scale of economic output but also enhances its structural resilience. The shift toward high-value bio-based products facilitates export diversification and deeper integration into national and global value chains, consistent with empirical evidence on innovation-driven structural upgrading [24–26].

6.2. Employment Effects

Building upon the macroeconomic projections presented in Section 6.1, employment outcomes are estimated through a sectorally disaggregated labour demand framework that links Gross State Value Added (GSVA) growth with sector-specific employment elasticities and endogenous productivity dynamics. The resulting projections, summarized in **Table 2**, report the evolution of employment across agriculture, industry, and services under Business-as-Usual (BAU) and Accelerated Bioeconomy Transformation (ABT) scenarios for the period 2025–2050.

Table 2. Projected Employment under BAU and ABT Scenarios (Million Workers).

Year	Agriculture (BAU/ABT)	Industry (BAU/ABT)	Services (BAU/ABT)	Total Employment (BAU)	Total Employment (ABT)
2025	28.5/28.6	6.2/6.4	10.8/11.0	45.5	46.0
2035	27.8/27.5	7.5/8.8	13.2/14.8	48.5	51.1
2045	26.5/25.2	9.2/12.5	16.8/20.5	52.5	58.2
2050	25.8/24.0	10.5/15.8	18.5/23.5	54.8	63.3

Complementing the tabular estimates, **Figure 2** illustrates the aggregate employment trajectories, highlighting the temporal divergence between the two scenarios.

The simulation results indicate that, relative to BAU, the ABT pathway generates a net employment gain of approximately 8–11 million jobs by 2050. As depicted in **Fig-**

ure 2, the employment trajectory under ABT is distinctly non-linear: the initial phase (2025–2035) is characterized by modest increments, followed by a phase of accelerated expansion (2035–2045) associated with industrial scaling and value-chain deepening, and a subsequent phase of consolidation (2045–2050) marked by stabilization and productivity enhancement. This temporal pattern reflects the lag structure inherent in capital formation, technological diffusion, and institutional maturation.

Sectoral disaggregation in **Table 2** reveals differentiated employment dynamics consistent with structural transformation processes. In the primary sector, employment exhibits gradual rationalization rather than abrupt contraction. Although the share of agricultural employment declines over time, absolute levels remain relatively stable in the early stages, reflecting demographic pressures and labour market rigidities. Productivity improvements—driven by crop diversification, agro-biotechnological interventions, and enhanced input efficiency—reduce disguised unemployment and facilitate a progressive shift toward higher-value agricultural activities. By the later stages, labour reallocation toward non-farm sectors becomes more pronounced.

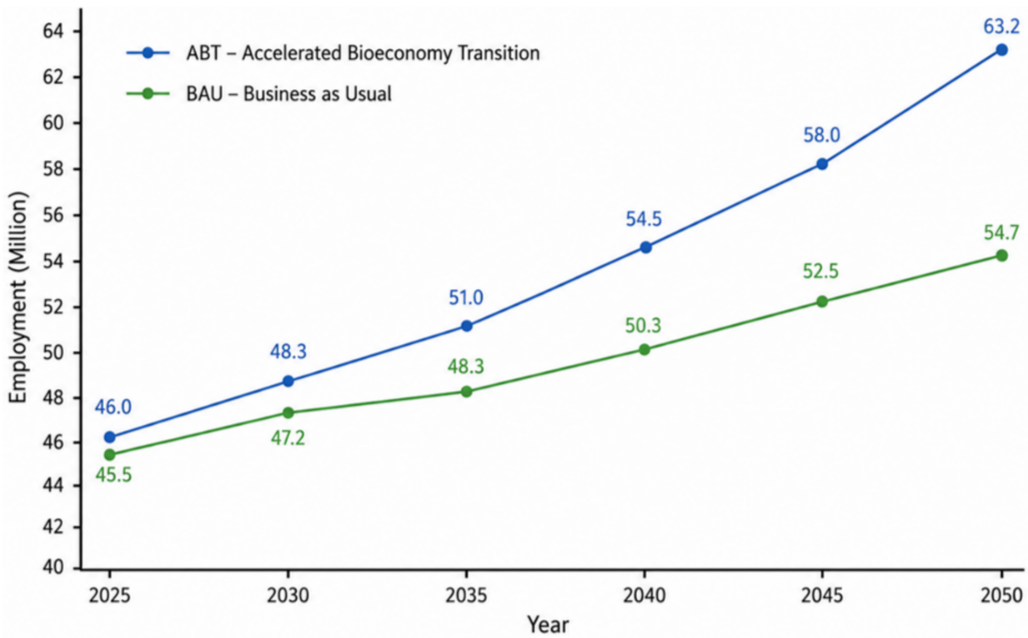

Figure 2. Employment Trajectories (Million Workers).

The secondary sector emerges as the principal driver of net employment creation. Under the ABT scenario, industrial employment expands substantially—from 6.4 million in 2025 to approximately 15.8 million by 2050—reflecting the growth of bio-manufacturing, agro-processing, and decentralized bioenergy systems. These activities exhibit relatively high employment elasticities (estimated in the range of 0.35–0.50 under ABT, compared to 0.20–0.30 under BAU), owing to their labour-intensive and networked production structures. The scaling of cluster-based industrial ecosystems further amplifies labour absorption, particularly for semi-skilled workers.

The tertiary sector registers strong employment spillovers, as evidenced in both **Table 2** and **Figure 2**. Employment growth is concentrated in logistics, digital intermediation, research and technical services, and financial support systems linked to bioeconomy value chains. These activities not only expand employment quantitatively but also contribute to qualitative upgrading through increased skill intensity and knowledge content.

A notable feature of the projected employment dynamics is their spatial dispersion. Unlike conventional industrialization patterns, which tend to concentrate employment in urban centres, the bioeconomy transition generates distributed employment across rural and peri-urban regions. This is facilitated by biomass aggregation networks, decentralized processing units, and localized bio-enterprises, which collectively reduce migration pressures and enhance regional inclusivity.

The analysis further indicates an improvement in the employment elasticity of growth under the ABT scenario, reflecting the inherently labour-absorbing nature of bio-based value chains. Importantly, employment expansion is accompanied by rising labour productivity, suggesting that growth is not purely extensive. Instead, the transition is characterized by simultaneous gains in output, employment, and efficiency.

Qualitative transformations in labour market outcomes are also evident. The expansion of organized bio-industrial activities contributes to gradual formalization, while increasing demand for technical and managerial capabilities drives skill intensification. These processes are associated with improvements in real wages and working conditions, particularly in non-farm sectors.

Taken together, the evidence presented in **Table 2** and **Figure 2** demonstrates that the bioeconomy transition has the potential to generate large-scale, inclusive, and spatially distributed employment in Bihar. The alignment between sectoral growth and labour absorption underscores the effectiveness of a mission-oriented policy framework that explicitly integrates employment objectives within broader economic and environmental strategies. These findings are consistent with emerging empirical evidence from developing economies, where bioeconomy expansion has been associated with rural livelihood diversification and inclusive structural transformation [24].

6.3. Environmental Gains

The environmental implications of the simulated bioeconomy transition are assessed through a resource–emissions accounting framework that integrates sectoral output trajectories with energy consumption, land-use dynamics, and material flow intensities. The resulting indicators—carbon intensity, land productivity, and biomass circularity—are reported in **Table 3** (Environmental Indicators under BAU and ABT), while the temporal evolution of emissions intensity is illustrated in **Figure 3** (Carbon Intensity Trajectories under BAU and ABT).

Table 3. Environmental Indicators under BAU and ABT.

Indicator	2025	2035	2050 (BAU)	2050 (ABT)	Change (%)
Carbon Intensity (Index, 2025 = 100)	100	92	85	60–65	↓ 28–35%
Land Productivity (Index)	100	115	130	165	↑ 25–30%
Biomass Circularity (%)	12	18	22	45–50	↑ 100%+

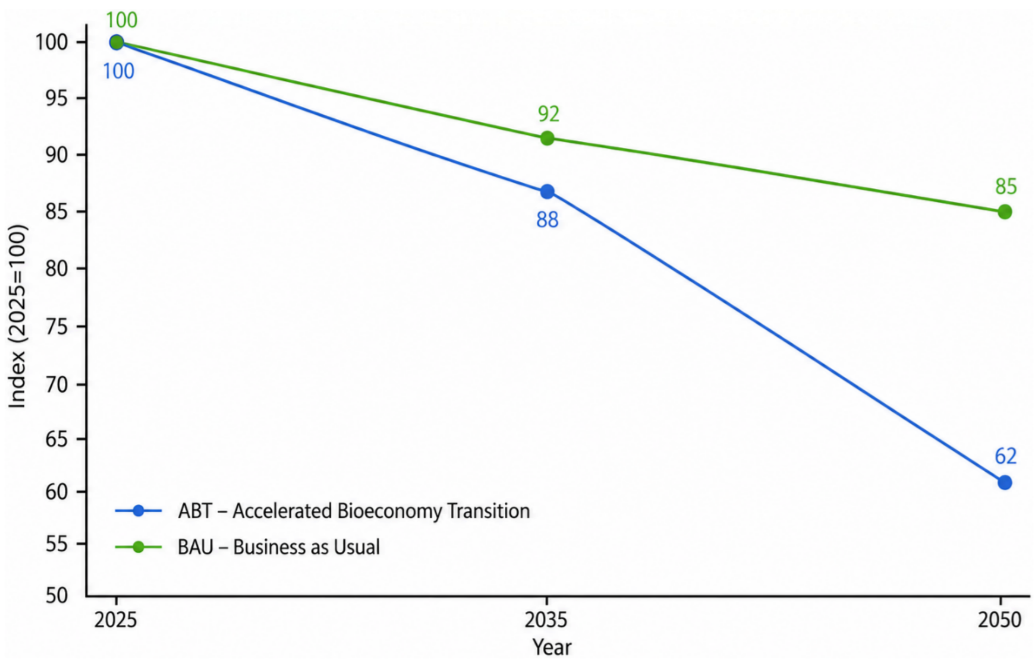

Figure 3. Carbon intensity trajectories under BAU vs. ABT scenarios.

The estimates presented in **Table 3** indicate a pronounced divergence in environmental performance between the Business-as-Usual (BAU) and Accelerated Bioeconomy Transformation (ABT) scenarios by 2050. Carbon intensity (indexed to 2025 = 100) declines to approximately 60–65 under ABT, compared to 85 under BAU, implying a reduction of 28–35%. Concurrently, land productivity rises to an index value of 165 under ABT, significantly exceeding the BAU projection of 130, while biomass circularity more than doubles, reaching 45–50% relative to 22% under BAU. These shifts collectively point to a structural decoupling of economic growth from environmental pressure.

The trajectories depicted in **Figure 3** corroborate these findings, revealing a sustained and progressively widening gap in emissions intensity between the two scenarios. While initial reductions during the period 2025–2035 are moderate, reflecting incremental technological adoption, the post-2035 phase exhibits a sharper decline under ABT. This inflection corresponds to the scaling of bioenergy systems, diffusion of resource-efficient technologies, and maturation of circular production processes. The temporal pattern underscores the cumulative nature of environmental gains, with early investments yielding disproportionately larger long-term benefits.

The observed reduction in carbon intensity is driven by three interrelated mechanisms. First, the substitution of fossil-based energy with biomass-derived alternatives—such as biogas, biofuels, and decentralized bioenergy systems—significantly lowers the carbon footprint of both industrial and rural energy use. Second, the adoption of cleaner production technologies in agro-processing and biomanufacturing reduces energy and material intensities per unit of output. Third, improvements in input-use efficiency, particularly in agriculture, decrease emissions associated with fertilizers, irrigation, and mechanization without compromising productivity.

Land-use efficiency emerges as a second critical dimension of environmental improvement. The increase in land productivity under ABT reflects a transition toward diversified and higher-value cropping systems, supported by agro-ecological practices and technological interventions. Crop diversification into horticulture, pulses, and bioenergy feedstocks enhances both economic returns and ecological resilience. Simultaneously, the integration of soil-conserving practices—such as conservation agriculture and integrated nutrient management—improves soil health and reduces chemical dependency. These changes enable higher output generation without proportional expansion of cultivated land, thereby mitigating pressure on natural ecosystems.

A third pillar of environmental transformation is the expansion of circular bioeconomy processes. The substantial increase in biomass circularity reported in **Table 3** reflects the systematic incorporation of waste streams into productive use. Agricultural residues, livestock waste, and agro-industrial by-products are increasingly valorised through bioenergy generation, composting, and bio-based material production. This transition reduces open-field burning and waste accumulation while simultaneously creating additional value streams. Moreover, improvements in post-harvest management—facilitated by investments in storage, cold chains, and processing infrastructure—further enhance resource efficiency across value chains.

Although not explicitly quantified within the core model, the transition also carries important implications for water use and ecosystem services. The adoption of climate-resilient cropping systems and efficient irrigation technologies is likely to reduce water stress, while improved soil management contributes to carbon sequestration and nutrient cycling. These ancillary benefits reinforce the broader sustainability gains associated with the bioeconomy pathway.

From an integrated perspective, the environmental outcomes under ABT exhibit strong complementarities with economic and employment gains identified in preceding sections. The reduction in emissions intensity occurs alongside accelerated output growth, indicating a relative decoupling rather than a trade-off between development and sustainability. Similarly, the expansion of circular resource flows generates both ecological benefits and additional livelihood opportunities, particularly in rural areas.

For Bihar, where environmental challenges are closely intertwined with agrarian pressures and climate vulnerability, these findings are of particular significance. The transition toward a bio-based and circular production system offers a viable pathway for reconciling developmental imperatives with ecological constraints. However, the realization of these gains remains contingent upon effective policy implementation, technological diffusion, and institutional capacity.

In summary, the results demonstrate that a mission-oriented bioeconomy transition can yield substantial and measurable environmental benefits, including a 28–35% reduction in carbon intensity, marked improvements in land productivity, and a doubling of biomass circularity. These outcomes substantiate the environmental pillar of the E3 framework and underscore its potential to support ecologically sustainable structural transformation in Bihar, consistent with emerging evidence on bioeconomy-driven sustainability transitions[24–26].

6.4. Structural Transformation Dynamics

Building on the quantitative projections of output and sectoral composition (Section 6.1), employment reallocation (Section 6.2), and environmental transitions (Section 6.3), the results point to a structurally embedded transformation under the Accelerated Bioeconomy Transformation (ABT) scenario. This transformation is not confined to sectoral shifts in Gross State Value Added (GSVA), as documented in **Table 1** (Sector-wise GSVA Projections) and **Figure 1** (GSVA Trajectories), but extends to technological regimes and institutional configurations. The dynamics are cumulative and mutually reinforcing, exhibiting strong feedback effects across economic, environmental, and labour-market domains.

6.4.1. Sectoral Reconfiguration

The simulated trajectories reveal a gradual yet decisive reallocation of economic activity from low-productivity primary sectors toward higher value-added agro-industrial and bio-based manufacturing segments. While agriculture retains a foundational role, its relative contribution to GSVA declines from approximately 18% to nearly 14% by 2050 under ABT, consistent with the patterns observed in **Table 1**. This decline, however, is accompanied by qualitative upgrading rather than contraction, as reflected in productivity improvements and diversification toward high-value crops.

The industrial sector emerges as the principal locus of structural change. Bio-based manufacturing, agro-processing, and biomass conversion industries expand significantly, increasing their combined contribution to nearly one-third of GSVA by mid-century. This reflects the internalization of value chains within the state, whereby primary outputs are increasingly processed domestically rather than exported in raw form.

The services sector, while maintaining its dominant share, undergoes functional transformation. As indicated by the evolving composition implicit in **Figure 1**, services become increasingly production-linked, encompassing logistics, digital intermediation, technical services, and knowledge-intensive activities that support bioeconomy value chains.

Crucially, the transition is characterized by absorptive labour reallocation rather than disruptive displacement. Employment shifts observed in **Table 2** (Projected Employment under BAU and ABT) and **Figure 2** (Employment Trajectories) indicate that labour movement across sectors is synchronized with expanding opportunities in industry and services, thereby mitigating the risks of premature de-agrarianization and structural imbalance.

6.4.2. Technological Upgrading

The sectoral transition is underpinned by a broad-based process of technological change. Traditional, input-intensive production systems are progressively replaced by biotechnology-enabled, resource-efficient, and knowledge-driven processes.

In agriculture, technological upgrading is manifested through the adoption of precision farming, improved seed technologies, and bio-inputs, alongside the integration of climate-resilient practices. These interventions enhance both productivity and environmental sustainability, contributing to the land-use efficiency gains reported in **Table 3** (Environmental Indicators under BAU and ABT).

Industrial transformation is driven by the deployment of advanced bioprocessing technologies, including biorefineries, enzymatic conversion systems, and integrated biomass utilization platforms. These technologies not only increase value addition but also reduce emissions intensity, as evidenced by the declining carbon intensity trajectory in **Figure 3** (Carbon Intensity Trajectories).

The services sector complements these changes through digitalization and data-driven systems that facilitate coordination, reduce transaction costs, and accelerate technology diffusion. Collectively, these processes give rise to a productivity-led growth regime in which technological progress serves as a central driver of both economic expansion and environmental improvement.

6.4.3. Institutional Reconfiguration

A defining feature of the ABT scenario is the evolution of governance structures toward a mission-oriented configuration. Institutional arrangements shift from fragmented, sector-specific interventions toward coordinated frameworks that align agriculture, industry, energy, and environmental objectives.

This transition is reflected in enhanced policy coherence, multi-level governance integration, and outcome-oriented planning anchored in measurable E3 targets. The convergence of national policy directives with state-level implementation mechanisms reduces coordination failures and improves allocative efficiency.

Such institutional strengthening is critical for sustaining the transformation process, as it enables the effective mobilization of financial, technological, and human resources required for large-scale bioeconomy expansion.

6.4.4. Non-Linearity and Path Dependence

The transformation dynamics exhibit pronounced non-linearity, as reflected in the temporal patterns observed across **Figures 1–3**. Initial phases (2025–2035) are characterized by relatively modest gains, followed by accelerated growth and environmental improvements during the scaling phase (2035–2045), and eventual stabilization thereafter.

This pattern is indicative of threshold effects embedded within the system. Infrastructure investments must reach critical levels before generating significant productivity gains; cluster-based industrialization requires minimum scale to yield agglomeration economies; and technology adoption accelerates only after diffusion surpasses tipping points associated with network effects and learning externalities.

These dynamics underscore the importance of sequencing in policy design, with early-stage investments playing a disproportionately important role in shaping long-term outcomes.

6.4.5. Strategic Interpretation of Environmental and Economic Outcomes

Taken together, the results demonstrate that structural transformation under the ABT scenario is a co-evolutionary process, driven by the interaction of sectoral shifts, technological innovation, and institutional change. The evidence from **Tables 1–3** and **Figures 1–3** suggests that this transformation is neither automatic nor linear; rather, it is contingent upon sustained policy support, institutional coordination, and the timely realization of critical thresholds.

6.5. Role of Mission-Oriented Innovation Systems

The preceding analysis of structural transformation highlights the centrality of innovation processes in mediating economic, environmental, and employment outcomes. The mission-oriented innovation systems (MOIS) framework provides an analytical lens to examine how coordinated policy interventions shape these processes. Although no standalone table or figure is presented for innovation variables, their effects are implicitly captured in the productivity, employment, and environmental trajectories reported in **Tables 1–3** and **Figures 1–3**.

6.5.1. Innovation Intensity and Productivity Spillovers

The simulations indicate that sectors exhibiting higher innovation intensity—proxied through R&D investments, technology adoption rates, and knowledge diffusion—experience significantly stronger productivity gains under the ABT scenario. These gains are reflected in the accelerated GSVA growth observed in **Figure 1** and the improvements in resource efficiency documented in **Table 3**.

Innovation in bio-based sectors enhances the efficiency of biomass utilization, facilitates the development of new products and processes, and reduces unit production costs over time. Importantly, these benefits are not confined to individual sectors; knowledge spillovers propagate across agriculture, manufacturing, and services, generating cumulative productivity effects consistent with endogenous growth mechanisms.

6.5.2. Public Investment and Crowding-In Dynamics

A salient outcome of the modelling exercise is the catalytic role of public investment in shaping innovation trajectories. Public expenditure on research infrastructure, extension systems, and enabling facilities reduces uncertainty and lowers entry barriers, thereby inducing a crowding-in effect on private investment.

The amplification of industrial growth under ABT, as reflected in **Table 1**, and the expansion of employment in industry and services shown in **Table 2**, are partly attributable to this complementary interaction between public and private investment. The results suggest that innovation-led growth in the bioeconomy is inherently systemic, requiring coordinated investment across multiple domains.

6.5.3. Cluster-Based Innovation Ecosystems

The emergence of cluster-based ecosystems constitutes a critical mechanism for enhancing innovation performance. Spatial agglomeration of firms, research institutions, and support services facilitates economies of scale, knowledge exchange, and learning-by-interaction.

In the context of Bihar, where biomass resources are geographically dispersed, cluster-based development enables the consolidation of supply chains and the efficient organization of production networks. The spatial patterns of employment observed in **Figure 2**—particularly the rise of rural and peri-urban employment nodes—reflect the importance of such localized innovation systems.

6.5.4. Structural Constraints in the Existing System

Despite the potential gains, the analysis reveals persistent constraints within the existing innovation ecosystem. Low R&D intensity, weak linkages between academia and industry, inadequate infrastructure, and limited absorptive capacity among firms impede the diffusion of bio-based technologies.

These constraints are implicitly reflected in the relatively modest performance of the BAU scenario across **Tables 1–3**, where growth, employment, and environmental improvements remain limited. The comparison underscores the extent to which innovation system deficiencies can dampen the transformative potential of bioeconomy policies.

6.5.5. Implications for Mission-Oriented Policy Design

The findings underscore that the effectiveness of the bioeconomy transition depends critically on the design and functioning of mission-oriented innovation systems. Such systems require:

- (i) Clear articulation of mission goals aligned with E3 outcomes;
- (ii) Coordination across policy domains and governance levels;
- (iii) Sustained investments in capacity building and technology diffusion.

The alignment of innovation policy with broader developmental objectives enhances coherence and ensures that technological change translates into tangible economic, social, and environmental benefits.

6.5.6. Integrated Evaluation of Employment and Sustainability Implications

In aggregate, mission-oriented innovation systems constitute the central enabling mechanism underlying the transformation dynamics observed in Sections 6.1–6.4. By facilitating technological upgrading, mobilizing complementary investments, and fostering institutional coordination, MOIS bridge the gap between policy intent and developmental outcomes.

The evidence derived from the integrated analysis of **Tables 1–3** and **Figures 1–3** indicates that strengthening innovation systems is indispensable for realizing the projected gains in output, employment, and environmental sustainability. Without such systemic reinforcement, the transition toward a bioeconomy-led development pathway is likely to remain partial and uneven, particularly in structurally constrained regions such as Bihar[24–26].

7. Discourse: Mission-Oriented Innovation Systems and Sustainable Structural Transformation

The empirical evidence synthesized in Sections 6.1–6.5—drawing on **Table 1** (GSVA Projections), **Table 2** (Employment Outcomes), **Table 3** (Environmental Indicators), and the associated **Figures 1–3**—indicates that the bioeconomy transition in Bihar cannot be adequately interpreted through the lens of incremental sectoral adjustments. Rather, the observed patterns correspond to a mission-driven structural transformation, characterized by coordinated shifts across production systems, technological regimes, and institutional arrangements. The simultaneous expansion of output, employment, and environmental performance underscores the presence of systemic directionality and policy coherence, which are defining attributes of mission-oriented frameworks.

7.1. From Fragmented Policies to Mission Orientation

Bihar's historical development trajectory has been marked by fragmented and sectorally compartmentalized policy interventions. Such fragmentation has constrained the capacity to address interdependent challenges—low agricultural productivity, persistent underemployment, and environmental stress—within a unified analytical and policy framework.

The transition toward a mission-oriented approach signifies a qualitative reconfiguration of development strategy. The results presented in **Figures 1–3** suggest that coordinated policy direction enables the articulation of integrated E3 objectives and facilitates their translation into measurable outcomes. This shift enhances policy coherence by aligning interventions across agriculture, industry, energy, and environmental management, thereby reducing institutional redundancies and coordination failures.

Moreover, mission orientation enables the commitment of long-term investments, which is critical for overcoming uncertainty and inducing private sector participation. The role of the state evolves accordingly—from a passive regulator to an active architect of markets—through strategic investment, risk-sharing, and institutional innovation. Such an entrepreneurial state function is essential for catalysing large-scale structural change, particularly in lagging regions where market signals alone are insufficient to drive transformation [4].

7.2. Innovation Systems as Transformation Engines

The findings demonstrate that innovation systems constitute the central mechanism through which mission-oriented policies translate into tangible developmental outcomes. The productivity gains observed in **Table 1**, the employment expansion in **Table 2**, and the environmental improvements in **Table 3** are all mediated by processes of knowledge generation, diffusion, and application.

Three interrelated dimensions of innovation systems are particularly salient.

- First, knowledge generation and diffusion mechanisms—anchored in research institutions, universities, and extension networks—enable the dissemination of bio-based technologies across sectors. The accelerated trajectories in **Figures 1** and **3** reflect the cumulative effects of such diffusion processes, particularly in enhancing productivity and reducing emissions intensity.
- Second, institutional coordination across governance levels ensures that national policy initiatives are effectively translated into regional outcomes. The alignment of central bioeconomy strategies with state-level implementation mechanisms reduces policy fragmentation and enhances resource efficiency.
- Third, the integration of traditional and modern knowledge systems is critical in contexts dominated by smallholder agriculture. The incorporation of local practices into technologically advanced production systems improves adoption rates and reduces implementation risks.

The evidence points to the importance of place-based innovation systems, tailored to Bihar's agro-climatic diversity, biomass availability, and socio-economic structure. Without such contextual adaptation, the transformative potential of bioeconomy interventions is likely to remain constrained.

7.3. Sustainability and Inclusivity

The concept of sustainable structural transformation (SST) provides a normative framework for evaluating the outcomes of the bioeconomy transition. The results indicate that the ABT scenario achieves a degree of alignment between economic growth, environmental sustainability, and social inclusion.

- From an environmental perspective, the declining carbon intensity documented in **Table 3** and **Figure 3** reflects a decoupling of growth from ecological degradation, facilitated by circular resource use, renewable energy integration, and efficiency improvements.
- From a social perspective, the employment expansion observed in **Table 2** and **Figure 2** demonstrates the capacity of bioeconomy value chains to generate broad-based livelihood opportunities. The spatial distribution of employment, particularly in rural and peri-urban areas, indicates a reduction in regional disparities and migration pressures.

Inclusivity is further reinforced through the integration of smallholders and local enterprises into value chains, provided that access to technology, finance, and markets is ensured. In the absence of such mechanisms, there remains a risk of technological exclusion and uneven distribution of benefits.

The convergence of environmental sustainability and social inclusion within a growth-enhancing framework underscores the operational viability of the E3 paradigm. The results thus challenge conventional trade-off narratives, suggesting instead that synergistic outcomes are attainable under appropriate policy and institutional conditions.

8. Policy-Relevant Insights for Context-Specific Strategy Design

The translation of macro-level bioeconomy transitions into subnational outcomes requires policy frameworks that are sensitive to regional heterogeneity. The empirical findings—reflected in **Tables 1–3** and **Figures 1–3**—provide a basis for deriving context-specific policy insights for Bihar.

8.1. Translating Macro Transitions into Regional Outcomes

Effective implementation hinges on strengthening meso- and micro-level institutional mechanisms that mediate between policy intent and on-ground outcomes.

The development of decentralized bioeconomy clusters emerges as a critical strategy. Aligning cluster formation with local biomass availability can reduce transaction costs, enhance economies of scale, and promote spatial inclusivity. Institutional platforms such as Farmer Producer Organizations (FPOs) can facilitate aggregation, coordination, and market access.

Complementary investments in regional innovation infrastructure—including biotechnology hubs, incubation centres, and demonstration facilities—are necessary to enhance technological diffusion and entrepreneurial activity. Strengthening extension systems and research institutions will further improve absorptive capacity and facilitate the adoption of bio-based technologies.

8.2. Employment-Centric Strategies

Given Bihar's demographic structure, employment generation must be treated as an explicit policy objective rather than a residual outcome. The employment trajectories presented in **Table 2** and **Figure 2** indicate that bioeconomy sectors possess significant labour-absorbing potential.

Policy interventions should therefore prioritize skill development aligned with emerging bioeconomy industries, promote rural entrepreneurship in processing and bioservices, and incentivize the formalization of employment through regulatory and institutional support. These measures are essential for ensuring that economic growth translates into inclusive labour market outcomes.

8.3. Environmental Sustainability Instruments

The environmental gains documented in **Table 3** and **Figure 3** highlight the importance of policy instruments that internalize ecological externalities. Financial incentives for biomass recycling, waste-to-energy systems, and low-emission technologies can reinforce the transition toward circular production systems.

In addition, the introduction of carbon pricing mechanisms or targeted green subsidies can align private incentives with sustainability objectives. The promotion of climate-resilient agricultural practices—such as efficient irrigation, soil conservation, and stress-tolerant crop varieties—will further strengthen ecological resilience.

8.4. Institutional and Governance Reforms

The complexity of mission-oriented transitions necessitates robust governance frameworks. The establishment of a dedicated State Bioeconomy Mission Authority could facilitate coordination across sectors and stakeholders, ensuring alignment with national priorities while addressing regional specificities.

Enhancing policy coherence across governance levels and strengthening public–private partnerships are equally critical. Such arrangements enable the pooling of complementary capabilities in technology, finance, and implementation, thereby improving overall policy effectiveness.

8.5. Financing Mechanisms

Scaling bioeconomy initiatives requires diversified financing strategies. The magnitude of investments implied by the GSVA and employment expansions in **Tables 1** and **2** necessitates the mobilization of blended finance, combining public resources with private capital and international climate funds.

Innovative instruments such as green bonds, impact investment vehicles, and risk-sharing mechanisms—including credit guarantees and viability gap funding—can reduce investment risks and attract long-term capital. These mechanisms are particularly important in regions with limited financial depth.

8.6. Monitoring and Evaluation Framework

A robust monitoring and evaluation system is essential for ensuring accountability and adaptive policy design. The development of real-time E3 indicators, aligned with the analytical framework employed in this study, can facilitate continuous tracking of progress across economic, environmental, and employment dimensions.

The use of digital platforms and data analytics can enhance transparency and enable the timely identification of bottlenecks. Feedback mechanisms should be institutionalized to ensure that policy interventions are continuously refined in response to emerging evidence.

8.7. Cross-Sectoral Synthesis of Bioeconomy Transition Pathways

Sections 7 and 8 collectively underscore that the success of Bihar's bioeconomy transition is contingent upon the integration of mission-oriented innovation systems with context-specific policy design. The empirical evidence from **Tables 1–3** and **Figures 1–3** demonstrates that such integration can yield mutually reinforcing gains across output growth, employment generation, and environmental sustainability.

By aligning macro-level objectives with localized implementation strategies, Bihar can translate the projected benefits of the bioeconomy into durable and inclusive development outcomes. This alignment constitutes the central condition for achieving sustainable structural transformation in a manner consistent with both national priorities and global sustainability imperatives [24–26].

9. Assessment of Phase-Wise Benefits of the Bioeconomy Mission

The simulation-based evidence indicates that the developmental dividends of a mission-oriented bioeconomy transition are temporally differentiated and unfold through sequential, mutually reinforcing phases. Rather than exhibiting linear progression, the transition is characterized by threshold effects, cumulative causation, and evolving policy requirements. The phase-wise assessment below integrates (i) observed quantitative outcomes, (ii) underlying structural mechanisms, and (iii) corresponding policy imperatives necessary for sustaining momentum.

9.1. Phase I: Foundation and System-Building (2025–2035)

9.1.1. Empirical Outcomes

The initial decade is associated with modest but non-trivial gains. As indicated earlier (see **Table 1** and **Figure 1** in Section 6.1), GSVA growth marginally exceeds the BAU trajectory by approximately 0.8–1.5 percentage points. Employment expansion remains limited and is concentrated in construction, logistics, and early-stage bioeconomy activities (**Table 2**; **Figure 2**). Environmental indicators begin to show incremental improvement (**Table 3**; **Figure 3**), primarily through pilot-level interventions.

9.1.2. Underlying Mechanisms

This phase is dominated by system-building dynamics rather than immediate productivity gains. Three mechanisms are particularly salient:

- Capital deepening, especially in rural infrastructure, cold-chain systems, and decentralized energy networks;
- Institutional formation, including coordination platforms and policy frameworks aligned with BioE3 objectives;
- Early-stage technological diffusion, characterized by learning-by-doing and gradual adoption.

At this stage, inter-sectoral linkages remain weak, and multiplier effects are constrained by limited scale and connectivity.

9.1.3. Policy Priorities

Effective transition through this phase requires:

- Front-loaded public investment in infrastructure and logistics systems;
- Establishment of a coordinating institutional architecture (e.g., a State Bioeconomy Mission Authority);
- Strengthening of R&D, extension services, and demon-

stration ecosystems;
- Promotion of collective institutions such as Farmer Producer Organizations (FPOs).

The quality of implementation in this phase critically determines the feasibility of subsequent acceleration.

9.2. Phase II: Acceleration and Structural Expansion (2035–2045)

9.2.1. Empirical Outcomes

The second phase constitutes the core transformation period. GSVA growth accelerates significantly, exceeding BAU by 1.5–2.5 percentage points (**Figure 1**). Employment generation intensifies sharply, accounting for the majority of the projected 8–11 million additional jobs (**Table 2**; **Figure 2**). Bioeconomy sectors expand rapidly, while environmental indicators register substantial improvements (**Table 3**; **Figure 3**).

9.2.2. Underlying Mechanisms

The transition enters a regime of cumulative and self-reinforcing growth, driven by:

- Agglomeration economies, emerging from cluster-based industrialization;
- Strong backward and forward linkages, amplifying multiplier effects across sectors;
- Technology diffusion tipping points, resulting in rapid productivity gains;
- Crowding-in of private investment, supported by improved infrastructure and policy credibility.

These mechanisms collectively transform the production structure and enhance systemic efficiency.

9.2.3. Policy Priorities

Sustaining this acceleration requires:

- Scaling up bio-industrial clusters and strengthening value-chain integration;
- Expanding skill development systems aligned with sectoral demand;
- Deepening public–private partnerships to mobilize complementary capabilities;
- Facilitating access to finance through blended instruments and risk-sharing mechanisms;
- Enhancing domestic and export market integration via digital and logistical platforms.

Policy coordination and adaptability become critical to managing the pace and distributional consequences of structural change.

9.3. Phase III: Consolidation and Productivity Deepening (2045–2050)

9.3.1. Empirical Outcomes

In the terminal phase, the transformation matures. GSVA reaches approximately ₹34–35 lakh crore under ABT (**Table 1**; **Figure 1**), maintaining a sustained growth premium of 2.3–3.1 percentage points. Employment growth stabilizes, with improvements in job quality, formalization, and wages (**Table 2**). Environmental gains become structurally embedded, including a 28–35% reduction in carbon intensity and widespread circularity (**Table 3**; **Figure 3**).

9.3.2. Underlying Mechanisms

The growth process becomes increasingly productivity-driven, supported by:

- Innovation maturity, with advanced R&D systems and continuous technological upgrading;
- Deep value-chain integration, linking domestic production to global markets;
- Institutional stabilization, ensuring regulatory coherence and policy predictability;
- Adaptive learning, enhancing resilience to economic and climatic shocks.

Factor accumulation gives way to total factor productivity as the principal growth driver.

9.3.3. Policy Priorities

Policy focuses shift toward sustaining competitiveness and resilience:

- Continued investment in advanced research and innovation ecosystems;
- Strengthening environmental and social regulatory frameworks;
- Promotion of high-value exports and global integration;
- Institutionalization of monitoring systems using real-time E3 indicators;

Expansion of lifelong learning and skill upgrading systems.

9.4. Integrated Phase-Wise Mapping

The phase-wise dynamics can be summarized as follows:

- Phase I (2025–2035): System-building through infrastructure, institutions, and early technology diffusion;
- Phase II (2035–2045): Rapid expansion driven by scale economies, linkages, and investment mobilization;
- Phase III (2045–2050): Consolidation through productivity gains, innovation maturity, and global integration.

9.5. Concluding Analytical Integration and Policy Implications

The phase-wise analysis demonstrates that the benefits of Bihar's bioeconomy transition are inherently sequential and path-dependent. Early investments generate enabling conditions for mid-stage acceleration, which in turn facilitates long-term productivity and sustainability gains. The alignment between empirical outcomes, structural mechanisms, and policy responses underscores the necessity of a mission-oriented approach that is dynamically adapted across phases. Such sequencing is essential for translating the BioE3 paradigm into sustained, inclusive, and environmentally viable development outcomes.

10. Conclusions

This study has examined whether a mission-oriented bioeconomy transition, operationalized through the BioE3 framework, can provide a credible pathway for achieving integrated Economy–Environment–Employment (E3) outcomes in a structurally constrained regional economy. By combining a Mission-Oriented Innovation Systems (MOIS) perspective with the Sustainable Structural Transformation (SST) framework, the analysis advances both empirical and theoretical understanding of bioeconomy-led development.

10.1. Synthesis of Core Findings

Three interrelated findings emerge.

First, macroeconomic transformation exhibits a conditional growth dividend: Under the Accelerated Bioeconomy Transformation scenario, GSVA expands substantially relative to BAU (**Table 1**; **Figure 1**). This divergence reflects not only sectoral expansion but also deeper processes of technological diffusion, productivity enhancement, and structural diversification. However, sensitivity analysis indicates that these gains depend critically on institutional coordination, technology adoption, and capital access.

Second, employment expansion is substantial but heterogeneous: The creation of 8–11 million additional jobs (**Table 2**; **Figure 2**) is driven by labour-intensive bio-based value chains. While the transition enhances both employment quantity and quality, it also introduces distributional risks, including skill bias and potential exclusion of marginal producers in the absence of inclusive institutional arrangements.

Third, environmental sustainability is achievable but contingent: The observed reduction in carbon intensity and improvements in land productivity and circularity (**Table 3**; **Figure 3**) demonstrate the feasibility of relative decoupling. Nevertheless, environmental gains are not automatic; they depend on regulatory effectiveness and sustainable resource management.

10.2. Theoretical Contributions and Reassessment

The study contributes to ongoing debates in three ways:

- It provides conditional support for the MOIS framework, demonstrating its effectiveness in coordinating systemic transformation, while highlighting dependence on governance quality;
- It extends SST theory by illustrating how bioeconomy-led industrialization can mitigate premature deindustrialization through bio-industrial deepening;
- It incorporates political economy considerations, emphasizing that bioeconomy transitions are distributional processes shaped by differential access to resources and institutions.

10.3. Mechanisms and System Dynamics

The transformation is driven by interacting mechanisms:

- Innovation-led productivity growth;
- Structural reallocation toward higher value-added sectors;
- Inter-sectoral multiplier effects captured through SAM and input–output linkages;
- Feedback loops between environmental sustainability and economic performance.

These dynamics are cumulative, non-linear, and highly sensitive to institutional conditions.

10.4. Policy Implications

The findings underscore that the success of the bioeconomy transition depends on implementation architecture. Five priorities emerge:

- Establishing clear strategic direction through measurable E3 targets;
- Ensuring cross-sectoral institutional coordination;
- Building inclusive innovation systems accessible to smallholders and MSMEs;
- Regulating resource use to prevent ecological and social externalities;
- Embedding adaptive policy mechanisms with continuous monitoring and feedback.

Equally critical is the sequencing of interventions across phases, from system-building to consolidation.

10.5. Limitations and Future Research

The analysis is subject to several limitations, including data constraints in emerging sectors, uncertainties in long-term projections, and partial observability of institutional variables. Future research should prioritize micro-level validation, firm-level innovation dynamics, and comparative regional studies, alongside integration of behavioural and political economy dimensions.

10.6. Concluding Reflection

The evidence suggests that a mission-oriented bioeconomy transition constitutes a potentially transformative, yet inherently conditional, development pathway. Its effectiveness depends less on conceptual design than on institutional realization. When embedded within a coherent, context-sensitive, and adaptive policy framework, the BioE3 paradigm can reconcile growth, sustainability, and inclusivity. Absent such alignment, however, it risks reinforcing existing structural inequalities.

The central policy challenge, therefore, lies in translating systemic intent into operational coherence—ensuring that the bioeconomy evolves not merely as a sectoral initiative, but as an integrated and resilient development trajectory for Bihar and comparable regions [24–26].

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Conflict of Interest

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

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