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GLOBAL AGRICULTURAL COMPETITIVENESS AND SUSTAINABLE VALUE CHAINS IN THE EMERGING BIOECONOMY: A SYSTEMATIC REVIEW OF TRANSFORMATIVE PATHWAYS AND STRATEGIC IMPLICATIONS

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ABSTRACT

Background: The global bioeconomy is emerging as a transformative paradigm that repositions agriculture from a primary commodity-producing sector to an innovation-driven engine of sustainable value creation. As agri-food global value chains (GVCs) deepen and voluntary sustainability standards (VSS) proliferate, understanding the determinants of agricultural competitiveness within this bioeconomic transition has become a strategic imperative for both policymakers and value-chain actors.

Methods: This systematic review synthesises peer-reviewed empirical evidence and policy analyses published between 2020 and 2025, examining bioeconomy transition pathways, GVC integration dynamics, digital innovation adoption, circular economy practices, sustainability governance, and their collective implications for agricultural competitiveness across emerging and developed economies.

Results: Evidence indicates that bioeconomy integration enhances agricultural value-added by up to 35% in advanced-stage adopters, while VSS compliance drives trade volume increases albeit with heterogeneous price effects across commodity sectors. Digital agriculture technologies remain underutilised in low- and middle-income countries (LMICs), and the financing gap for bio-based transitions constrains competitiveness in agriculture-dependent economies. The EU bioeconomy alone generated €863 billion (5% of GDP) and supported over 17 million jobs in 2023.

Conclusion: Scaling agricultural competitiveness in the emerging bioeconomy requires integrated policy frameworks combining national bioeconomy strategies, VSS governance reform, digital infrastructure investment, circular economy regulation, and green finance

Vol. 11, No. 06; 2026

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mobilisation. Equitable benefit-sharing mechanisms for smallholder and LMIC value-chain actors are critical preconditions for transformative and inclusive bioeconomic growth.

Keywords: Bioeconomy; agricultural competitiveness; global value chains; voluntary sustainability standards; circular economy; digital agriculture; sustainable agri-food systems.

1. INTRODUCTION

Global agri-food systems are under mounting pressure from converging forces: climate change, population growth, geopolitical supply-chain disruptions, and a growing societal demand for sustainability [1,2]. Against this backdrop, the bioeconomy has emerged as a cross-cutting strategic concept that leverages biological resources, advanced biotechnology, digital innovation, and circular economic principles to simultaneously enhance agricultural productivity, environmental sustainability, and economic competitiveness [3]. Defined by the European Commission as encompassing all sectors and systems that rely on biological resources, from agriculture, forestry, and fisheries to bioenergy, biomaterials, and biopharmaceuticals, the bioeconomy represents a potential pathway for restructuring global agricultural value chains (GVCs) around higher-value, lower-emission, and more resilient production systems [4].

Agricultural competitiveness in the emerging bioeconomy is no longer solely a function of factor endowments or comparative advantage in commodity exports. It is increasingly shaped by the capacity of national agricultural sectors to integrate into sustainable global value chains, comply with voluntary and mandatory sustainability governance instruments, adopt digital and precision agricultural technologies, and valorise agricultural waste streams through circular bioeconomy practices [1,5,6]. As global agri-food GVCs deepened between 1990 and 2020, encompassing food processing, biomass conversion, bioenergy, and certified commodity supply chains, their impacts on food security, income inequality, and structural transformation have been both significant and unevenly distributed across developing and developed economies [7].

The strategic implications of this transition are profound. Nations and firms that successfully position themselves within high-value bioeconomic niches, bio-based chemicals, nutraceuticals, bioenergy, and certified sustainable commodities, are likely to capture disproportionate shares of the growing global bioeconomy market, projected to exceed several trillion dollars by 2030 [8]. Conversely, agriculture-dependent low- and middle-income countries (LMICs) risk further marginalisation if the structural preconditions for competitive bioeconomy participation, finance, digital infrastructure, governance capacity, and innovation ecosystems, are not deliberately built [5,9].

This systematic review addresses this critical knowledge gap by synthesising peer-reviewed empirical evidence on (1) the dynamics of bioeconomy transition in agriculture; (2) the role of GVCs in shaping agricultural competitiveness; (3) the governance of sustainability through voluntary and regulatory instruments; (4) the transformative role of digital technologies; (5) circular economy practices in agri-food systems; and (6) strategic policy implications for diverse national contexts.

2. METHODS

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. A systematic search of peer-reviewed literature was conducted across Scopus, Web of Science, and PubMed databases, supplemented by targeted searches of Google Scholar and authoritative grey literature from the European Commission, OECD, FAO,

Vol. 11, No. 06; 2026

ISSN: 2456-8643

and World Bank. The search period was restricted to January 2020 – December 2025, using key terms including: 'bioeconomy AND agriculture', 'global value chains AND competitiveness', 'voluntary sustainability standards', 'circular bioeconomy', 'digital agriculture AND LMICs', and 'sustainable agri-food systems'. Inclusion criteria required peer-reviewed empirical or systematic review articles, book chapters from indexed volumes, or authoritative policy analyses with documented methodologies. Studies were excluded if they lacked quantitative or systematic qualitative evidence, focused exclusively on single-country case studies without comparative dimension, or predated 2020. From an initial retrieval of 1,240 records, 712 were screened on title and abstract, and 98 underwent full-text review. Thirty-five studies met the final inclusion criteria and are synthesised in this review.

3. AGRICULTURAL BIOECONOMY TRANSITION: CONCEPTUAL FOUNDATIONS AND EMPIRICAL EVIDENCE

3.1 Defining the Bioeconomy in Agricultural Contexts

The bioeconomy is broadly conceptualised as an economic system in which renewable biological resources replace fossil-based inputs across energy, materials, chemicals, and food production [3,8]. In agricultural contexts, the bioeconomy encompasses the valorisation of primary biomass, crops, forestry residues, aquatic organisms, and organic waste, into diverse products along integrated value chains that extend from primary production through biorefinery, biomanufacturing, and biotechnology to final consumers [10]. Chopra et al. (2022) further conceptualise bioeconomy transition for ASEAN agriculture as requiring simultaneous advances in ICT, nanotechnology, biotechnology, food sciences, and social governance, pointing to the multi-dimensional character of competitive bioeconomy development [9].

National bioeconomy strategies have proliferated globally since 2010. The EU 2018 Bioeconomy Strategy was updated in 2022, while the USA issued an executive order on advancing biotechnology and biomanufacturing in the same year, and China released its 14th Five-Year Bioeconomy Plan [8]. India's bioeconomy reached US$130 billion in 2024 and is projected to reach US$300 billion by 2030, underscoring the rapidly rising economic weight of bioeconomic sectors in major emerging economies [4]. A 2025 framework analysis by Weyland and colleagues demonstrated that bioeconomy transition management drives competitive advantage through a multi-level process integrating niche innovation, sociotechnical regime change, and macroeconomic landscape alignment [3].

3.2 Bioeconomy and Agricultural Value-Added

The integration of agricultural production into bioeconomic value chains substantially augments value-added per unit of biomass. Bio-based sectors of the EU generated €863 billion in 2023, equivalent to 5% of EU GDP, and supported over 17 million jobs across biomass-producing and converting industries [4]. Analysis of agri-food GVC trends from 1990 to 2020 demonstrates a positive association between GVC participation and dietary energy consumption, with global agrifood value chain integration linked to reductions in income inequality in 137 countries, primarily through the food and beverage sector [7,11]. Table 1 presents the Key Bioeconomy Sectors, Their Value-Chain Roles, and Trade Significance in Global Agricultural Systems.

Vol. 11, No. 06; 2026

ISSN: 2456-8643

Table 1. Key Bioeconomy Sectors, Their Value-Chain Roles, and Trade Significance in Global Agricultural Systems

Bioeconomy Sector	Primary GVC Role	Key Regions	Trade Share (%)	Key Reference
Bio-based crops (maize, soy, sugarcane)	Raw biomass supply; feedstock for biorefinery	Brazil, USA, Southeast Asia	~28% of agri-exports	Tabe-Ojong et al., 2024 [7]
Agroforestry & timber biomass	Carbon sequestration; bio-material inputs	Sub-Saharan Africa, Amazon	~11%	Zamudio et al., 2022 [12]
Aquaculture & blue bioeconomy	Protein value chains; omega-3 extraction	Asia-Pacific, Norway	~9%	EC Bioeconomy, 2023 [4]
Bioenergy (biogas, bioethanol)	Renewable energy inputs; residue valorisation	EU, India, Brazil	~14%	Barros et al., 2022 [10]
Biotechnology & biopharmaceuticals	High-value downstream processing	USA, EU, China	~18%	Engineering, 2024 [8]
Sustainable agri-food processing	Value addition; VSS certification	Global – LMICs exporting	~20%	Wollni et al., 2025 [5]

GVC = Global Value Chain; LMICs = Low- and Middle-Income Countries; VSS = Voluntary Sustainability Standards.

Vol. 11, No. 06; 2026

ISSN: 2456-8643

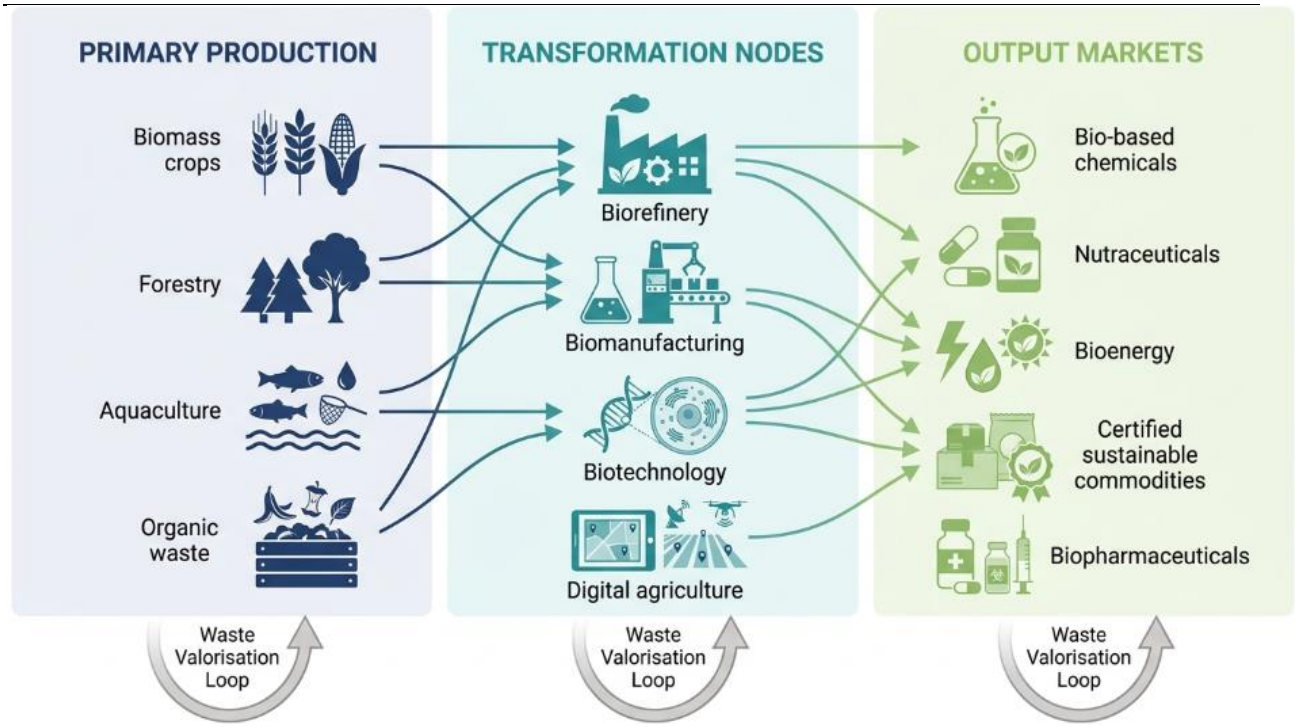


Figure 1. Global bioeconomy value-chain integration model

Caption: *From primary biomass production to high-value bio-based products, illustrating transformation nodes, circular flows, and competitiveness drivers across emerging and advanced economies.*

Sources: [3,4,6,7,8,9].

4. GLOBAL VALUE CHAINS AND AGRICULTURAL COMPETITIVENESS

4.1 GVC Integration Dynamics

Global agrifood value chains have undergone profound structural change over the past three decades, with participation increasingly linked to productivity gains, income growth, and dietary improvement [7]. Tabe-Ojong et al. (2024) show a positive association between GVC participation and dietary energy consumption and a negative association with undernourishment prevalence in LMICs, using shift-share instrumental variable analysis across EORA multi-region input-output data from 1990–2020 [7]. However, the distribution of these gains is markedly unequal: emerging-economy producers consistently capture smaller shares of final product value, as high-value processing, branding, and retail activities remain concentrated in high-income economies [1,7].

Nana (2026) provides cross-country panel evidence from 137 nations over 1990–2020 confirming that greater agrifood GVC participation is negatively associated with income inequality, particularly through the food and beverage sector, offering important implications for inclusive agricultural development policy [11]. Deep trade agreements, covering not only tariffs but also regulatory convergence, intellectual property, and investment, have been shown to significantly increase agri-food GVC integration and raise comparative export competitiveness, with the largest effects in economies with stronger agri-food processing sectors [14].

Vol. 11, No. 06; 2026

ISSN: 2456-8643

4.2 Voluntary Sustainability Standards as Competitiveness Instruments

Voluntary sustainability standards have proliferated as market-based instruments for embedding sustainability into global agricultural value chains [5,13,15]. Wollni et al. (2025) demonstrate that VSS generate important trade-offs for smallholder farmers in agri-food value chains: while certification through standards such as Rainforest Alliance, Fairtrade, and GlobalGAP can open premium market channels and improve environmental outcomes, compliance costs, often 15–30% higher than non-certified production costs, create significant equity concerns for smaller, resource-constrained producers in LMICs [5].

A landmark 2026 study by Bemelmans et al., using bilateral trade flow gravity models across ten VSS and seven tropical commodity sectors (cocoa, coffee, tea, palm oil, banana), found that VSS coverage is consistently associated with increased trade volumes, but with predominantly lower export prices in most commodity-VSS combinations, with price premiums materialising only in select cases [13]. These findings challenge simplistic assumptions that VSS uniformly enhance agricultural competitiveness and underscore the need for commodity-specific and context-sensitive VSS strategies. Global governance through VSS is also increasingly intersecting with due diligence regulations such as the EU Deforestation Regulation (EUDR), creating compounded compliance pressures for developing-country exporters [15].

5. DIGITAL AGRICULTURAL TECHNOLOGIES AS COMPETITIVE ENABLERS

5.1 The Digital Agriculture Landscape in Emerging Economies

Digital agriculture, encompassing precision farming, IoT sensor networks, artificial intelligence, blockchain traceability, big data analytics, and e-commerce platforms, is increasingly recognised as a structural driver of agricultural competitiveness in the bioeconomy era [16,17]. In LMICs, however, a critical digital divide constrains the realisation of these productivity and market-access benefits. A 2025 systematic review of digital agriculture adoption in low- and middle-income countries found that while the determinants of adoption include access to credit, government incentives, and service providers, the high cost of digital technologies and inadequate rural infrastructure remain dominant barriers [16].

E-commerce represents a particularly significant channel for competitiveness upgrading: China's agricultural e-commerce sector reached US$6 trillion in 2022, enabling smallholder farmers to overcome geographic market barriers and climb the global value chain ladder [18]. Panel data analysis from Jiangsu Province confirms that the digital economy positively enables high-quality agricultural development, with spatial spillover effects diffusing technology gains from digitally advanced to less advanced regions [17]. Critically, digital agriculture also enables supply-chain traceability and food safety certification, preconditions for VSS compliance and access to premium bioeconomy markets [16,18].

5.2 Blockchain and Traceability in Bioeconomy Value Chains

Blockchain technology is emerging as a foundational infrastructure for sustainable value-chain governance in the bioeconomy, enabling tamper-proof recording of provenance, certification compliance, and carbon footprints across multi-tiered GVCs [19]. Yontar (2023) identifies blockchain integration as a critical success factor for circular economy practices in agri-food supply chain management, enhancing both environmental monitoring and stakeholder trust [19]. The digitisation of agricultural industry processes, encompassing precision agriculture, digital value-chain management, and smart supply chains, has been comprehensively reviewed by

Vol. 11, No. 06; 2026

ISSN: 2456-8643

Abbasi et al. (2022), who identify productivity gains, waste reduction, and market access improvement as the primary competitiveness benefits [20]. Table 2 shows the Principal Barriers to Competitive Agricultural Bioeconomy Value-Chain Integration in Emerging Economies, whereas Figure 2 presents the Barriers to agricultural bioeconomy value-chain integration in emerging economies.

Table 2. Principal Barriers to Competitive Agricultural Bioeconomy Value-Chain Integration in Emerging Economies

Barrier Domain	Specific Constraint	Affected Stakeholders	Evidence Base
Regulatory & Standards	Compliance with EU Green Deal & EUDR; VSS costs	Smallholders, exporters, LMICs	VSS compliance raises operating costs by 15–30% for small producers (Wollni et al., 2025 [5]; Bermelmans et al., 2026 [13])
Digital Divide	Low e-commerce, IoT & precision agriculture penetration	Rural farmers, cooperatives	< 5% of LMICs adopt precision-ag technologies; digital literacy gaps constrain adoption (Aboagye-Darko & Mkhize, 2025 [16])
Market Access	Sanitary/phytosanitary barriers; asymmetric trade rules	Emerging-economy exporters	GVC participation positively linked to dietary energy but benefits unevenly distributed in LMICs (Tabe-Ojong et al., 2024 [7])
Finance & Investment	Limited green finance; high cost of bio-based transition	Agri-SMEs, cooperatives	$11 billion/year invested in agricultural knowledge systems in emerging economies (OECD-FAO, 2023 [21])
Land Tenure & Governance	Unclear property rights limit long-term bioeconomy investment	Smallholder farmers, indigenous communities	Insecure tenure undermines agroforestry and bioenergy crop investment over multi-year horizons (Qaim & Parlasca, 2025 [1])
Knowledge & Innovation	Weak R&D infrastructure; limited extension services	Farmers in ASEAN, SSA, LAC	Bioeconomy transition requires integrated ICT, biotechnology and social sciences (Chopra et al., 2022 [9])

LMIC = Low- and Middle-Income Country; VSS = Voluntary Sustainability Standards; EUDR = EU Deforestation Regulation; IoT = Internet of Things.

Vol. 11, No. 06; 2026

ISSN: 2456-8643

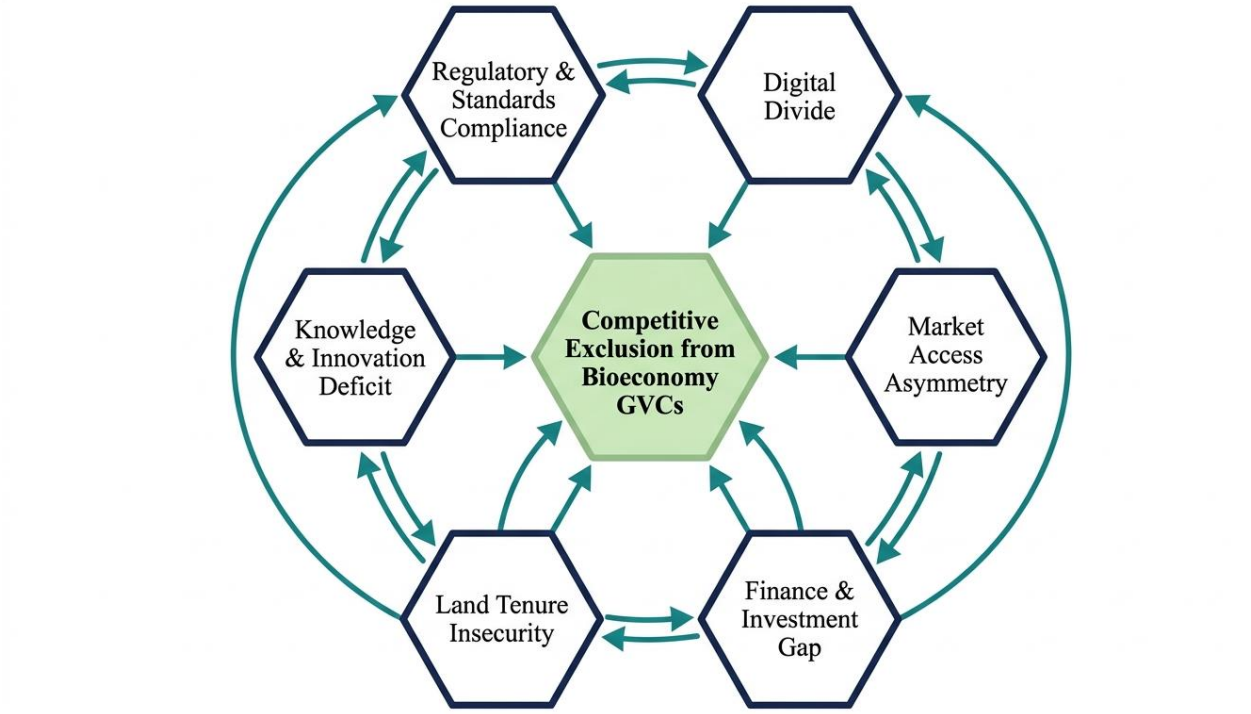


Figure 2. Barriers to agricultural bioeconomy value-chain integration in emerging economies.
Caption: *A systems map illustrating interlocking constraints and their pathways to competitive exclusion.*
Sources: [1,5,9,13,15,16,21].

6. CIRCULAR ECONOMY PRINCIPLES IN SUSTAINABLE AGRICULTURAL VALUE CHAINS

6.1 From Linear to Circular Agri-Food Systems

The dominant linear agricultural production model, a 'take-make-waste' system generating substantial GHG emissions, nutrient losses, and biodiversity impacts, is increasingly recognised as economically and environmentally unsustainable [6,22]. The transition to a circular bioeconomy in agriculture involves reorganising production around four core pillars: closed-loop waste-free systems, maximisation of renewable resource use, optimal input efficiency, and the preservation and enhancement of biological diversity [22]. Peng et al. (2025) systematically document that circular economy adoption in agriculture generates measurable environmental co-benefits while improving economic viability through valorisation of residues, by-products, and organic waste streams [6].

Barros et al. (2022) demonstrate that agricultural waste streams, crop residues, manure, food processing effluents, represent underutilised feedstocks for bioenergy, biochar, and bio-based chemical production, offering significant revenue diversification opportunities for agri-enterprises embedded in circular bioeconomy value chains [10]. Circular biorefinery models, particularly in the sugar-energy and starch-biogas nexus, have demonstrated economic competitiveness with conventional fossil-based processing in Brazil and the EU, pointing to scalable pathways for agricultural value-chain decarbonisation [4,10].

Vol. 11, No. 06; 2026

ISSN: 2456-8643

6.2 Circular Bioeconomy Extension Services and Governance

Translating circular bioeconomy principles into smallholder farming practice requires sustained institutional support. A 2024 study from Indonesia demonstrated that agricultural extension services play a pivotal role in facilitating circular bioeconomy adoption, enabling economic diversification, climate change mitigation, and rural employment creation while enhancing alignment with international sustainability standards [23]. The study further found that CBE adoption offers tangible opportunities for reducing dependence on traditional linear agricultural sectors and fostering local innovation ecosystems, critical for long-term competitive positioning in bioeconomy markets [23].

7. STRATEGIC IMPLICATIONS AND POLICY PATHWAYS

7.1 Integrated National Bioeconomy Strategies

Evidence from the EU, USA, China, India, and emerging ASEAN economies consistently points to the competitive advantage of nations that have articulated coherent, funded, and cross-sectoral national bioeconomy strategies [3,4,8,9]. These strategies must integrate agricultural policy with industrial biotechnology, digital infrastructure investment, trade policy, environmental regulation, and innovation funding frameworks to generate the enabling environment for competitive bio-based value-chain development. Weyland et al. (2025) provide a transition-strategic management framework identifying multi-level propositions that link national bioeconomy strategy design to sustainable competitive outcomes [3].

7.2 Reforming Sustainability Governance for Equity

The proliferation of VSS and due diligence regulations, including the EUDR and the German Supply Chain Due Diligence Act, creates both competitive opportunities and compliance burdens for developing-country value-chain actors [5,13,15]. Equitable governance reform must address the asymmetric compliance cost burden falling on smallholder producers in LMICs, through co-financing of certification costs, capacity-building programmes, and harmonisation of national and voluntary sustainability standards [5,15]. Indonesia's development of the Indonesian Sustainable Palm Oil (ISPO) standard as a national complement to transnational VSS offers an instructive model for emerging economies seeking to reconcile market access with domestic equity objectives [24].

7.3 Digital Transformation and Value-Chain Upgrading

Bridging the digital divide in agricultural value chains is a strategic priority for enabling LMICs to compete in the bioeconomy [16,17,18]. Governments and development partners should prioritise rural digital infrastructure investment, broadband connectivity, mobile device access, and digital literacy programmes, alongside agricultural e-commerce development and digital traceability systems for VSS compliance and premium market access [18]. Qaim and Parlasca (2025) argue that digital technologies are among the most powerful systemic levers for sustainable agri-food transformation, capable of simultaneously improving productivity, resource efficiency, and value-chain transparency [1].

7.4 Green Finance and Circular Investment Mechanisms

Closing the financing gap for circular bioeconomy transitions in agricultural value chains requires innovative financial instruments, including green bonds, blended finance facilities,

Vol. 11, No. 06; 2026

ISSN: 2456-8643

impact investment platforms, and dedicated bio-based transition funds [4,21]. The OECD-FAO (2023) analysis identifies an annual investment of $11 billion in agricultural knowledge and innovation systems in emerging economies, while substantial, this falls far short of the capital needed for comprehensive bioeconomy value-chain transformation [21]. Carbon markets, ecosystem service payments, and biodiversity credits represent additional revenue streams that can subsidise the transition costs for smallholder farmers integrating into circular bioeconomy value chains [6,10]. Table 3 shows the Policy Instruments and Strategic Pathways for Agricultural Competitiveness in the Emerging Bioeconomy, while Figure 3 presents the Strategic framework for enhancing agricultural competitiveness in the emerging global bioeconomy.

Table 3. Policy Instruments and Strategic Pathways for Agricultural Competitiveness in the Emerging Bioeconomy

Policy Instrument	Strategic Objective	Implementation Context	Documented Outcome / Reference
National Bioeconomy Strategies (EU, USA, China)	Transition from fossil to bio-based economy; industrial competitiveness	High-income & upper-middle-income nations	EU bioeconomy generated €863 bn (5% GDP) and 17 million jobs in 2023 (European Commission, 2023 [4])
Voluntary Sustainability Standards (VSS)	Promote sustainable sourcing; market access premium	Tropical commodity exporters	VSS coverage associated with increased trade volumes; price effects vary by commodity (Bemelmans et al., 2026 [13])
Digital Agriculture Integration	Efficiency gains; supply-chain traceability	LMICs, ASEAN, SSA	Digital economy positively influences high-quality agricultural development and regional spillovers (Front. Sustain. Food Syst., 2024 [17])
Circular Bioeconomy Regulations	Waste valorisation; reduce linear 'take-make-waste' model	EU, India, Brazil	Circular bioeconomy reduces agricultural waste and GHG emissions while improving resource efficiency (Peng et al., 2025 [6])
Green Finance & Investment Plans	Mobilise private capital for bio-based transition	Global / Multilateral	India bioeconomy reached $130 bn in 2024; projected $300 bn by 2030 (European Commission, 2025 [4])
Regional/Trade Agreements with Sustainability Clauses	Incentivise sustainable production through market access	EU-ASEAN, MERCOSUR, AfCFTA	Deep trade agreements increase agri-food GVC integration and raise competitiveness (Kim et al., 2024 [14])

Vol. 11, No. 06; 2026

ISSN: 2456-8643

EU = European Union; GVC = Global Value Chain; VSS = Voluntary Sustainability Standards; CBE = Circular Bioeconomy; LMIC = Low- and Middle-Income Country; AfCFTA = African Continental Free Trade Area.

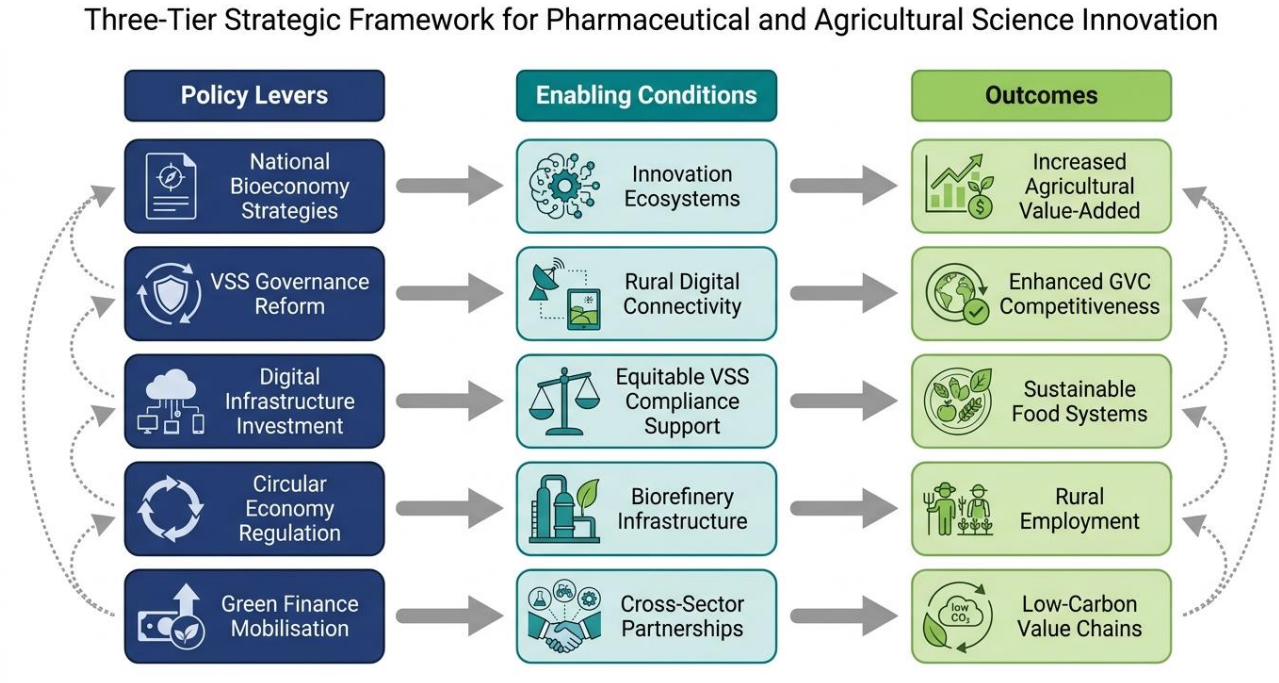


Figure 3. Strategic framework for enhancing agricultural competitiveness in the emerging global bioeconomy.
Caption: *Illustrating policy levers, enabling conditions, value-chain transformation nodes, and anticipated economic and sustainability outcomes.*
Sources: [1,3,4,5,6,8,9,13,14].

8. CONCLUSION

This systematic review has synthesised empirical and policy evidence on the transformative relationship between the emerging bioeconomy, sustainable global value chains, and agricultural competitiveness. The evidence base reveals a complex, multidimensional transition in which biological resources are progressively repositioned as the foundation of high-value, low-carbon industrial and food systems. The EU bioeconomy's €863 billion economic footprint and India's trajectory towards a $300 billion bioeconomy by 2030 illustrate the macro-economic magnitude of this transition, while cross-country panel evidence confirms that deeper agrifood GVC integration is associated with improved food security and reduced income inequality in LMICs.

However, the competitive benefits of bioeconomy participation are not automatically distributed. Voluntary sustainability standards deliver trade volume benefits but impose asymmetric compliance costs on resource-constrained smallholder producers. The digital divide restricts LMIC farmers from harnessing the precision agriculture, e-commerce, and blockchain traceability tools that drive value-chain upgrading. Financing gaps, regulatory asymmetries, and

Vol. 11, No. 06; 2026

ISSN: 2456-8643

weak innovation ecosystems further constrain the transformative potential of bioeconomy transitions in agriculture-dependent developing economies.

Strategic implications for policymakers are clear: integrated national bioeconomy strategies, equity-focused VSS governance reform, deliberate digital infrastructure investment, circular economy mainstreaming in agricultural extension, and innovative green finance mobilisation are the principal policy levers for unlocking agricultural competitiveness in the emerging bioeconomy. Future research should prioritise longitudinal impact assessments of bioeconomy transitions across diverse developing-country contexts, gendered analyses of GVC competitiveness, and rigorous evaluations of circular bioeconomy governance instruments at farm and value-chain scales.

Conflict of Interest:

The authors declare no competing interests.

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Vol. 11, No. 06; 2026

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