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The Scarcity Paradox in Eco-Innovation: Mechanisms, Boundary Conditions, and Environmental Outcomes

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Abstract

Eco-innovation is increasingly invoked as a pragmatic route to environmental protection and sustainable development, particularly where soil integrity, water quality, and public health are under pressure. However, much of the dominant literature implicitly assumes that meaningful eco-innovation depends on institutional maturity, financial slack, and high R&D intensity, creating a persistent paradox: the most acute climate and pollution burdens often occur in settings where governance capacity and innovation resources are weakest. The significance of this review lies in resolving that tension by clarifying when scarcity suppresses eco-innovation and when it catalyzes it across multiple sectors. Accordingly, this study aims to synthesize and reframe interdisciplinary evidence on eco-innovation under scarcity and sustainability constraints, drawing across agrarian systems, manufacturing, and service-oriented domains. Using a structured narrative review approach, peer-reviewed studies were screened and thematically integrated to identify core mechanisms, boundary conditions, and environmental outcomes. Across the evidence base, scarcity shapes eco-innovation primarily through three interconnected mechanisms: frugal innovation, institutional bricolage, and networked learning which enables locally serviceable solutions and accelerates adoption when minimal enabling infrastructure is present. The results reveal a consistent constraint-to-creativity pathway in which ecological stress and resource limits stimulate frugal, locally embedded, and restorative eco-innovations, particularly when reinforced by minimal but credible institutional scaffolding, incentives, and learning networks. At the same time, diffusion remains uneven where institutional voids, weak extension and support infrastructures, and limited risk governance constrain adoption quality and scaling. The review concludes by proposing an environmental-outcome-centered synthesis framework that evaluates eco-innovation by verifiable reductions in toxicity, emissions, waste, and ecosystem pressure rather than novelty alone, and by outlining targeted pathways for strengthening diffusion infrastructure, standardizing frugal solutions, and aligning circular strategies with measurable ecological gains.

Keywords: Eco-innovation, Resource scarcity, Environmental governance, Frugal innovation, Institutional voids, Grassroots innovation, Sustainability transitions, Circular economy, Toxicity reduction

INTRODUCTION

Eco-innovation is commonly understood as the systematic development and diffusion of products, processes, and practices that improve sustainability and reduce environmental harm (Rennings, 2000; Omoyajowo, Ogunyebi, Ogunkanmi, Oludoye, and Gupta, 2025a). In agricultural systems, this environmentalist mandate is operational rather than rhetorical, because eco-innovations are increasingly invoked as practical instruments for safeguarding soil and water integrity while sustaining agricultural productivity (Horbach, Rammer, & Rennings, 2012; Omoyajowo *et al.*, 2025a).

A popular and foundational construct in the mainstream eco-innovation canon is that robust environmental innovation is most plausible where institutional maturity, regulatory enforcement, and investment capacity are strong (York & Venkataraman, 2010; Hojnik & Ruzzier, 2016; Horbach *et al.*, 2012). Yet this axiom yields a paradox: climate change and pollution are intertwined drivers of the contemporary ecological crisis, and their gravest burdens often concentrate in settings where governance capacity and environmental safeguards remain fragile (Hart, 1995; Omoyajowo *et al.*, 2025a).

Recent mixed-methods evidence from Nigerian cocoa farmers demonstrates how scarcity-linked eco-innovation outcomes can be undermined when behavioural learning is not matched with enabling disposal infrastructure. In a survey and interview study, unsafe pesticide-container disposal (e.g., dumping in streams or leaving containers on farms) persisted, while safer behaviour was positively associated with risk knowledge and access to collection facilities, and negatively associated with farmer age; qualitatively, social norms and association membership shaped disposal decisions and the effectiveness of pilot collection cages, which often failed due to limited training and awareness (Oludoye *et al.*, 2026). This coupled behavioural–systemic constraint illustrates why the scarcity paradox is conditional: frugal practices and local ingenuity require minimal institutional complements (training, standards, take-back/recycling pathways) to translate into verifiable reductions in toxicity and exposure.

In agrarian landscapes, the environmental stakes are especially pronounced. Indiscriminate pesticide use can generate toxic residues that enter food chains and infiltrate ecosystems, while inadequate training and weak protective resources intensify exposure risks and deepen environmental contamination (Omoyajowo *et al.*, 2025a; Ostrom, 2010). Sustainable agriculture therefore becomes an ecological imperative, because protecting soils, waterways, and biodiversity requires deliberate shifts away from harmful agrochemical routines toward environmentally restorative practices (Hart, 1995; Omoyajowo *et al.*, 2025a).

Within this review's framing, ecological innovations are defined as new ideas, technologies, and practices that improve sustainability and reduce environmental harm (Omoyajowo *et al.*, 2025a; Rennings, 2000). In rice farming, such eco-innovations include improved fertilizers such as slow-release types, biopesticides with lower ecological and health risks, advanced crop varieties, and precision agriculture tools that reduce waste and strengthen long-term soil fertility (George, McGahan, & Prabhu, 2012; Omoyajowo *et al.*, 2025a).

However, the diffusion of such eco-innovations remains uneven and, in many contexts, distressingly low, even where environmental need is acute. Evidence from Nigerian paddy systems indicates very low adoption of ecological innovations alongside limited access to safety training and institutional support, a pattern that undermines both environmental protection and occupational wellbeing (Rogers, 2003; Omoyajowo *et al.*, 2025a).

This diffusion gap invites a more ecologically attentive theory of innovation under constraint. Rather than treating scarcity as a simple barrier, an emerging view suggests that environmental stress and resource limits can catalyze adaptive problem-solving, encouraging frugal reinvention and locally embedded solutions when formal pathways are inaccessible (George *et al.*, 2012; Pansera & Sarkar, 2016). Institutional scholarship further clarifies how informal rules and community norms can reinforce pro-environmental behavior and compensate, at least partially, for weak formal regulation (North, 1990; Ostrom, 2010).

Despite these advances, eco-innovation scholarship remains fragmented, often privileging firm-level capabilities and policy instruments while insufficiently integrating contamination pressures, institutional voids, informal knowledge systems, and environmental stewardship as co-determinants of eco-innovation trajectories (Hart, 1995; Horbach *et al.*, 2012; Hojnik & Ruzzier, 2016; Omoyajowo *et al.*, 2025).

Accordingly, this review pursues three linked objectives. First, it synthesizes the mechanisms through which scarcity can suppress eco-innovation or catalyze it, with emphasis on frugality, institutional bricolage, and networked learning. Second, it identifies boundary conditions and diffusion barriers that determine when scarcity-driven eco-innovation remains local and uneven versus when it scales with adoption quality particularly under institutional voids, weak extension/support infrastructures, and limited risk governance. Third, it advances an environmental-outcome-centered evaluation framework that assesses eco-innovation by verifiable reductions in toxicity, emissions, waste, and ecosystem pressure rather than novelty alone.

LITERATURE REVIEW

Eco-innovation as Environmentalism in Practice

Eco-innovation denotes innovations in products, processes, organizational forms, and institutions that systematically reduce ecological harm across the life cycle while safeguarding economic viability (Rennings, 2000; Horbach, Rammer, & Rennings, 2012). Contemporary scholarship emphasizes that eco-innovation is not a monolith but a portfolio of technological, organizational, and behavioral shifts whose environmental effects vary by domain (for example energy, materials, toxicity, biodiversity pressure) and by diffusion stage (Hojnik & Ruzzier, 2016; Horbach *et al.*, 2012). This definitional breadth is axiomatic for environmentalism-oriented analysis because it widens the unit of change beyond “green products” to include redesign of routines, incentives, and governance architectures that shape environmental outcomes (Rennings, 2000; Hojnik & Ruzzier, 2016).

From an environmentalist standpoint, eco-innovation is best understood as the pragmatic interface between ecological integrity and production systems, where pollution prevention, resource efficiency, and ecosystem stewardship are treated as strategic imperatives rather than peripheral virtues (Hart, 1995; Hart & Dowell, 2011). The natural resource-based view argues that capabilities such as pollution prevention, product stewardship, and sustainable development can be sources of durable advantage, thereby reconciling an apparent paradox: ecological restraint can reinforce competitiveness when firms reinvent processes and materials under constraint (Hart, 1995; Porter & van der Linde, 1995). This framing is crucial for review work because it positions environmental performance as a central criterion of innovation quality, not a cosmetic attribute.

Drivers of Eco-innovation: Regulation, Markets, and Capabilities

A substantial body of work treats regulation as a primary stimulus that can either inhibit innovation through compliance costs or catalyze it by raising the opportunity cost of environmental inefficiency (Jaffe & Palmer, 1997; Porter & van der Linde, 1995). Empirical evidence frequently supports a nuanced view: policy pressure can promote innovation, but effects vary across sectors, instruments, and time horizons, implying that “regulatory push” must be analytically distinguished from technology push and market pull (Horbach *et al.*, 2012; Johnstone, Haščič, & Popp, 2010). In environmental domains such as renewable energy, policy design is repeatedly shown to shape inventive activity, underscoring that eco-innovation is partially engineered through governance choices, not merely discovered by firms (Johnstone *et al.*, 2010; Jaffe & Palmer, 1997).

Beyond regulation, eco-innovation is propelled by firm-level resources and routines, including environmental management systems, technological capability, and the strategic calculus of cost savings and reputational value (Hojnik & Ruzzier, 2016; Horbach *et al.*, 2012). Reviews emphasize that different eco-innovation types respond to different configurations of drivers; for example, process eco-innovation may be more tightly linked to efficiency and cost logics, while product eco-innovation is more exposed to consumer demand and competitive differentiation (Hojnik & Ruzzier, 2016; Horbach *et al.*, 2012). The implication for this review is methodological: explanatory synthesis must remain type-sensitive rather than treating eco-innovation as an undifferentiated dependent variable.

Institutions, Governance, and Innovation Systems in Environmental Change

Institutional analysis clarifies why eco-innovation diffuses unevenly across regions: rules, norms, and enforcement structures shape incentives, expectations, and the credibility of long-term environmental investment (North, 1990; Ostrom, 2010). Where formal regulation is weak or fragmented, polycentric governance and community-level rule systems can partially substitute for state capacity, enabling pro-environmental action through locally legitimate monitoring and sanctioning (Ostrom, 2010; North, 1990). This matters for environmentalism because ecological problems are often collective-action dilemmas, and eco-innovation frequently requires coordination among producers, users, regulators, and communities rather than isolated firm heroics (Ostrom, 2010; Markard, Raven, & Truffer, 2012).

Innovation systems scholarship further suggests that eco-innovation is embedded in networks of learning, knowledge exchange, and institutional complementarity, where interactive learning and capability building determine trajectories of technological and social change (Lundvall, 1992; Geels, 2002). In emerging economies, "institutional voids" may impede access to finance, standards, and intermediaries, yet they can also provoke alternative institutional bricolage, informal coordination, and locally adapted environmental solutions (Khanna & Palepu, 2010; North, 1990). A rigorous review must therefore account for how institutional architecture mediates whether scarcity becomes stagnation or stimulus.

Scarcity, Frugality, and Grassroots Eco-innovation

A growing stream of scholarship challenges the deficit narrative by showing that scarcity can catalyze innovation that is frugal, modular, and environmentally consequential, especially where resource constraints render conventional R&D pathways inaccessible (George, McGahan, & Prabhu, 2012; Pansera & Sarkar, 2016). Frugal innovation is commonly defined through criteria emphasizing substantial cost reduction, focus on core functionalities, and optimized performance levels for context-specific needs, which can align naturally with ecological objectives when it reduces material throughput and energy intensity (Weyrauch & Herstatt, 2016; Pansera & Sarkar, 2016). This is a strategic paradox worth foregrounding: constraints that appear to foreclose environmental action may, under certain conditions, intensify practical experimentation and accelerate adoption of low-footprint practices (George *et al.*, 2012; Weyrauch & Herstatt, 2016).

Grassroots innovation research reinforces this point by documenting community-driven and civil-society-led experimentation that generates locally embedded sustainability solutions outside dominant market and state channels (Seyfang & Smith, 2007; Pansera & Sarkar, 2016). Cross-country evidence indicates that ecological resource deficits may be associated with stronger environmental innovation outcomes when supportive norms or minimal institutional scaffolding exists, suggesting that scarcity can become a productive force rather than a terminal constraint (Battisti, Huang, & Pickernell, 2023; Ostrom, 2010). For this review, the analytic task is to specify the boundary conditions under which scarcity-induced ingenuity emerges and persists, rather than assuming a linear scarcity-to-underinvestment pathway.

Networks, Reconfiguration, and Sustainability Transitions

Sustainability transitions research argues that eco-innovation is rarely incremental; it often entails reconfiguring socio-technical systems, including infrastructures, user practices, supply chains, and policy regimes (Geels, 2002; Markard *et al.*, 2012). The multi-level perspective emphasizes interactions between niche experimentation, regime stability, and landscape pressures such as climate risk, resource depletion, and social contestation, thereby situating eco-innovation within long-run institutional and cultural dynamics (Geels, 2002; Markard *et al.*, 2012). This lens strengthens environmentalist interpretation by treating ecological crises as structural selection pressures that can shift innovation trajectories.

Network-oriented studies further show that collective eco-innovation depends on reorchestrating inter-firm relationships, shared standards, and knowledge flows, especially in project-based industries where coordination is indispensable (Haaja & Evers, 2025; Lundvall, 1992). Evidence from industrial networks suggests that greening pathways require deliberate strategizing around collaboration, trust, and alignment of incentives, rather than assuming that environmental benefits diffuse automatically from isolated technical advances (Haaja & Evers, 2025; Markard *et al.*, 2012). Hence, a technically sound review should treat network governance as a core explanatory theme, not a peripheral context variable.

Circular Economy as an Eco-innovation Pathway

Circular economy scholarship provides an influential resource-efficiency narrative that converges with eco-innovation through its emphasis on closing loops, reducing virgin material dependence, and redesigning value creation to curb pollution and waste (Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Kirchherr, Reike, & Hekkert, 2017). However, definitional analyses show that circular economy is frequently reduced to recycling rhetoric, while the deeper systemic shift and explicit linkages to sustainable development are often under-specified (Kirchherr *et al.*, 2017; Geissdoerfer *et al.*, 2017). This conceptual ambiguity can dilute environmentalism if circularity is pursued without clear ecological targets such as toxicity reduction, biodiversity protection, or absolute footprint decline.

For eco-innovation reviews, the circular economy is best treated as a structured family of eco-innovation strategies, including eco-design, industrial symbiosis, life-cycle stewardship, and business model reinvention, each with distinct environmental and distributional consequences (Rennings, 2000; Geissdoerfer *et al.*, 2017). Aligning circular economy with eco-innovation therefore requires analytical discipline: the review should differentiate "circular" practices that merely displace burdens from those that generate verifiable net ecological gains (Kirchherr *et al.*, 2017; Porter & van der Linde, 1995).

Multinational Knowledge Spillovers and Eco-innovation Diffusion

Cross-border knowledge flows, particularly via multinational enterprises, can widen the opportunity set for eco-innovation in emerging markets by transferring environmental capabilities, managerial routines, and technological know-how (Qu, Wang, Wei, Wu, & Zheng, 2024; Lundvall, 1992). Evidence indicates that regional knowledge spillovers from multinationals may enhance eco-innovation performance of emerging-market firms while attenuating the adverse effects of complex and dynamic environments, implying that external knowledge can partially compensate for local resource constraints (Qu *et al.*, 2024; Horbach *et al.*, 2012). This supports a diffusion-centered environmentalism: ecological gains may accelerate when learning is amplified through networks, clusters, and supply-chain ties rather than confined within national borders.

Yet spillovers are not automatically beneficial; institutional misfit, weak absorptive capacity, and incomplete markets can blunt or distort knowledge transfer, producing uneven environmental outcomes (Khanna & Palepu, 2010; North, 1990). Consequently, a rigorous review should treat multinational spillovers as conditional mechanisms whose effects depend on local institutions, skill formation, and governance credibility, rather than as universally positive externalities (Qu *et al.*, 2024; Khanna & Palepu, 2010).

Eco-innovation in Smallholder Agriculture Under Climate and Contamination Pressures

Agriculture exemplifies how eco-innovation becomes an environmental necessity: climate stress and ecological degradation reshape productivity frontiers while intensifying risks of pollution, soil decline, and biodiversity loss (van Oort & Zwart, 2018; Gao *et al.*, 2025). Modeling and empirical work on rice systems indicates that adaptation strategies can alter both yields and pollution outcomes, revealing that climate adaptation and environmental protection can be jointly optimized when interventions reduce resource waste and harmful externalities (Gao *et al.*, 2025; van Oort & Zwart, 2018). These insights underscore that eco-innovation in food systems must be evaluated against dual criteria: resilience and ecological integrity.

Within this domain, ecological innovations such as integrated pest management, reduced chemical dependence, and safer occupational practices are increasingly framed as locally embedded responses to intertwined climate and contamination risks (Omoyajowo *et al.*, 2025a; Fenibo, Matambo, Gunda, & Laing, 2025). Reviews on biopesticides highlight their potential to reduce toxic residues and environmental harm while supporting sustainable pest control, especially when cost-effective formulations enable adoption in smallholder contexts (Fenibo *et al.*, 2025; Pegalepo *et al.*, 2025). Thus, agricultural eco-innovation illustrates how environmentalism is operationalized through practical substitutions, knowledge diffusion, and risk governance at the farm level (Omoyajowo *et al.*, 2025a; Fenibo *et al.*, 2025).

Integrative Synthesis and Thematic Agenda for this Review

Despite important advances, eco-innovation literature remains fragmented across firm-level drivers, institutional analysis, transitions theory, and grassroots perspectives, which can inadvertently reinforce siloed explanations of environmental change (Hojnik & Ruzzier, 2016; Markard *et al.*, 2012). An integrative review can consolidate this terrain by mapping how scarcity conditions interact with institutional configurations and network structures to produce differentiated eco-innovation pathways, ranging from firm-led compliance innovation to community-led frugal experimentation (Battisti *et al.*, 2023; Seyfang & Smith, 2007). The central task is to replace abundance-centric assumptions with a structured scarcity-innovation nexus that specifies mechanisms, boundary conditions, and environmental outcomes.

Accordingly, this review adopts a synthesis logic anchored in environmentalism: eco-innovation is treated as an instrument for reducing ecological harm, not merely as a correlate of competitiveness or novelty (Hart & Dowell, 2011; Rennings, 2000). The thematic agenda foregrounds governance (polycentric and formal), systems reconfiguration, and circularity as pathways to ecological integrity, while emphasizing that scale and legitimacy depend on institutions, learning networks, and context-specific design (Ostrom, 2010; Geissdoerfer *et al.*, 2017). In this way, the review aims to strategize a coherent theoretical frame that explains why eco-innovation can persist, diffuse, and deliver verifiable environmental gains even under resource deficit conditions (Khanna & Palepu, 2010; Markard *et al.*, 2012).

MATERIALS AND METHODS

Study Design

This paper is a review that adopts a structured narrative review design to systematically synthesize scholarship on eco-innovation under resource scarcity and sustainability constraints. This approach is appropriate for consolidating conceptual debates, empirical evidence, and policy insights across an interdisciplinary field, while enabling integrative theorizing beyond single-study findings (Grant & Booth, 2009; Snyder, 2019).

Data Sources

Searches were conducted in Scopus and the Web of Science Core Collection (WoS), selected for their strong coverage of peer-reviewed literature and their suitability for transparent, replicable evidence retrieval across innovation, sustainability, environmental governance, and development studies (Mongeon & Paul-Hus, 2016; Gusenbauer & Haddaway, 2020). Google Scholar was not used as a primary database because its indexing opacity and variability can complicate reproducibility and controlled screening (Gusenbauer & Haddaway, 2020; Haddaway, Collins, Coughlin, & Kirk, 2015).

Search Strategy

A structured Boolean strategy was applied to titles, abstracts, and keywords to capture studies linking eco-innovation with scarcity and sustainability transitions, following established guidance for transparent search reporting (Page *et al.*, 2021; Gusenbauer & Haddaway, 2020). The search combined three term families: (1) eco-innovation constructs, (2) scarcity and constraint conditions, and (3) sustainability transition frames. An example search string was: (eco-innovation or environmental innovation or green innovation) and (scarcity or resource constraint or resource limitation or poverty or institutional void or frugal innovation) and (sustainability or sustainable development or circular economy). Supplementary searches included contextual terms such as developing countries, emerging economies, Global South, Africa, Asia, and Latin America to improve relevance where resource constraints are structurally salient (Snyder, 2019; Page *et al.*, 2021).

Eligibility Criteria

Included studies were peer-reviewed journal articles and review papers published in English between 2000 and 2025 that explicitly examined eco-innovation (or closely allied constructs) in relation to resource scarcity, institutional constraints, sustainability transitions, or environmentally protective adaptation (Grant & Booth, 2009; Page *et al.*, 2021). The review begins in 2000 because this period corresponds to the formal consolidation of eco-innovation as a distinct scholarly construct and allows consistent coverage across Scopus and Web of Science for conceptually comparable studies, while still capturing the foundational stream that shaped subsequent sustainability-transition and institutional analyses. Exclusions comprised editorials, conference abstracts, book chapters, non-peer-reviewed materials, and narrowly technical engineering studies lacking substantive engagement with innovation processes, institutional conditions, or environmental and policy implications (Snyder, 2019; Page *et al.*, 2021).

Screening and Data Extraction

Records were exported for screening, duplicates removed, and relevance assessed through title and abstract screening followed by full-text eligibility checks, consistent with recommended review reporting practices (Page *et al.*, 2021; Moher, Liberati, Tetzlaff, & Altman, 2009). Data were extracted into a structured synthesis matrix capturing study context, conceptual framing, methods, eco-innovation type, scarcity or constraint conditions, key findings, and reported implications, a procedure aligned with review-method guidance for systematic synthesis and traceability (Whittemore & Knafl, 2005; Snyder, 2019).

Synthesis Strategy

Evidence was synthesized using thematic synthesis, combining inductive coding to capture emergent patterns with deductive organization around established theoretical lenses relevant to eco-innovation under constraint (Thomas & Harden, 2008; Braun & Clarke, 2006). The synthesis prioritized identification of (i) mechanisms through which scarcity stimulates or suppresses eco-innovation, (ii) enabling conditions that reinforce environmentally beneficial outcomes, and (iii) persistent barriers to diffusion and scaling across contexts (Popay *et al.*, 2006; Snyder, 2019). Where findings diverged across studies, we did not force consensus. Instead, we coded contradictions explicitly, traced them to differences in context (sector, governance capacity, adoption infrastructure), and reported them as boundary-conditioned pathways (i.e., specifying when scarcity functions as barrier versus catalyst).

Quality and Transparency

Methodological transparency was strengthened through explicit documentation of search logic, eligibility rules, screening decisions, and the basis for thematic claims, consistent with widely used reporting guidance for evidence syntheses (Page *et al.*, 2021; Moher *et al.*, 2009). To preserve analytical integrity, the synthesis reports convergent evidence as well as tensions or disagreements across studies, rather than forcing artificial consensus (Popay *et al.*, 2006; Whittemore & Knafl, 2005).

Reproducibility

The review procedures, including databases searched, example search strings, inclusion and exclusion criteria, and screening workflow, are specified to support replication and methodological traceability (Page *et al.*, 2021; Moher *et al.*, 2009). Where interpretive judgment is inherent to thematic synthesis, decision rules and coding logic are stated to ensure that conclusions remain auditable and grounded in the source literature (Thomas & Harden, 2008; Braun & Clarke, 2006).

RESULTS AND THEMATIC SYNTHESIS

This section clarifies the scarcity paradox by showing how constraints can either suppress eco-innovation or redirect it toward adaptive, lower-footprint pathways when enabling complements exist.

What this Review Uncovered, in Direct Alignment with the Study Objective

Across literature, eco-innovation in resource-deficit settings emerges not as a marginal curiosity, but as a recurrent, system-shaped response to ecological stress and institutional incompleteness. The axiomatic pattern is a "constraint-to-creativity" pathway: scarcity heightens environmental risk visibility, compels adaptive learning, and redirects innovation toward frugal, locally embedded, and restorative solutions (Rennings, 2000; Hart, 1995). Importantly, the evidence rejects the paradox that environmental innovation must wait for abundance; rather, environmental pressure and resource deficits can catalyze innovation when at least modest complements exist, such as policy stringency, societal expectations, or enabling norms (Battisti *et al.*, 2023; Porter & van der Linde, 1995).

Scarcity as an Engine of Environmental Ingenuity

A consistent finding is that ecological resource deficits can stimulate environmental innovation by raising the cost of ecological deterioration and reinforcing experimentation with low-input technologies and practices (Battisti *et al.*, 2023; Rennings, 2000). This aligns with the natural resource-based view, which positions pollution prevention and stewardship as strategic capabilities, not ornamental ethics (Hart, 1995; Hart & Dowell, 2011). In effect, scarcity systematically reorganizes firm and community priorities toward ecological efficiency, waste minimization, and risk-reducing practices (Porter & van der Linde, 1995; Markard *et al.*, 2012). For example, evidence from Nigerian rice systems where adoption remains low despite clear contamination and climate pressures illustrates how scarcity can catalyze interest in safer, lower-input practices, yet diffusion stalls when extension capacity, safety training, and support infrastructures are weak. This aligns with the review's boundary-condition logic: scarcity supplies pressure, but adoption quality and scaling depend on minimal institutional scaffolding and learning networks.

Regulation, Instruments, and Innovation Offsets for Environmental Performance

The review consolidates a nuanced regulatory story. While early empirical work shows mixed evidence on whether regulation predictably stimulates innovation, policy design still appears consequential, particularly where it creates "innovation space" rather than prescribing rigid technological choices (Jaffe & Palmer, 1997; Porter & van der Linde, 1995). In energy and sustainability domains, policy instruments correlate with measurable innovation outputs (for example, patent activity), suggesting that well-structured incentives can accelerate environmental technology trajectories even across heterogeneous contexts (Johnstone *et al.*, 2010; Markard *et al.*, 2012).

Frugal and Grassroots Eco-innovation as Environmentalism-In-Action

In resource-poor settings, eco-innovation often takes a frugal form: substantial cost reduction, focus on core functions, and optimized performance that remains environmentally meaningful (Weyrauch & Herstatt, 2016; Pansera & Sarkar, 2016). Grassroots innovations also recur as community-level environmental experimentation, frequently outside formal R&D channels, but nonetheless capable of generating durable ecological benefits through local knowledge recombination (Seyfang & Smith, 2007; George *et al.*, 2012). This evidence implies that environmentalism here is not rhetorical; it is operational, situated, and necessity-driven (Pansera & Sarkar, 2016; Seyfang & Smith, 2007).

Institutional Voids, Informal Governance, and Adaptive Coordination

A major result is the centrality of institutional voids. Where formal market intermediaries and enforcement systems are weak, eco-innovation pathways depend more heavily on informal institutions, cooperative norms, and adaptive governance arrangements (North, 1990; Ostrom, 2010). Strategy in such contexts is less about copying "best practice" and more about reinventing coordination under constraint, including localized verification of trust, quality, and compliance (Khanna & Palepu, 2010; Ostrom, 2010).

Table 1: Cross-theme Synthesis of what the Literature Reveals

Theme	Findings / Mechanism	Boundary Conditions	Environmental significance	Key citations
Scarcity-driven eco-innovation	Resource deficits can stimulate cleaner practices and adaptive eco-innovation through constraint-to-creativity dynamics.	Catalytic when minimal enabling complements exist (credible incentives, basic support infrastructure, and learning channels); inhibiting when institutional voids persist and adoption support is absent.	Turns ecological stress into lower-footprint practices, pollution prevention, and risk-reducing innovations.	Battisti *et al*., 2023; Rennings, 2000
Natural resource-based capabilities	Environmental strategy operates as capability building (pollution prevention, product stewardship, sustainable development) rather than episodic compliance.	Requires managerial commitment, routines, and monitoring; strengthened by credible enforcement and performance incentives; weakened by short-termism and weak accountability.	Improves environmental performance durability and reduces emissions/toxicity through embedded routines.	Hart, 1995; Hart & Dowell, 2011
Policy and innovation offsets	Regulation can catalyze innovation when instrument design enables experimentation and provides feasible compliance pathways.	Works best with predictable enforcement, flexible instruments, and support for experimentation; underperforms under policy volatility, weak enforcement, and high compliance uncertainty.	Reduces harm while sustaining competitiveness via cleaner processes and technologies.	Jaffe & Palmer, 1997; Porter & van der Linde, 1995; Johnstone *et al*., 2010
Frugal and grassroots pathways	Low-cost, locally embedded solutions emerge where conventional R&D is inaccessible; community-led experimentation expands eco-innovation beyond firms.	Scales when knowledge-to-use pipelines exist (training, intermediaries, repair/maintenance support) and when minimum safety/quality thresholds are available; stalls without diffusion infrastructure.	Extends environmentalism into everyday production and livelihoods while reducing resource throughput and toxic inputs.	Pansera & Sarkar, 2016; Seyfang & Smith, 2007; George *et al*., 2012
Institutional voids and informal governance	Informal institutions and adaptive coordination can substitute for weak formal institutions in enabling collective action around environmental practices.	Effective when norms are legitimate, monitoring/sanctioning is feasible, and coordination costs are manageable; constrained when trust is low and collective-action capacity is weak.	Enables land/water safety practices and supports compliance where formal enforcement is limited.	North, 1990; Ostrom, 2010; Khanna & Palepu, 2010
Circularity under constraint	Circular practices can conserve materials and reduce waste, but circularity can underdeliver when treated narrowly as recycling.	Requires system-oriented definitions, governance alignment, and outcome metrics (net ecological gain); risks burden-shifting without life-cycle discipline and standards.	Can reduce waste and emissions if circular strategies produce verifiable net ecological gains.	Kirchherr *et al*., 2017; Geissdoerfer *et al*., 2017
Spillovers and learning	External knowledge flows (e.g., multinational spillovers) can amplify constrained eco-innovation by strengthening absorptive capacity and capability building.	Benefits depend on local absorptive capacity, skills, and institutional fit; weakened by market incompleteness and institutional misfit.	Accelerates learning and diffusion pathways for ecological transitions under resource constraints.	Qu *et al*., 2024; Lundvall, 1992

Note: Boundary conditions summarize the contextual complements that determine whether scarcity acts as a catalyst (enabling) or constraint (inhibiting) for eco-innovation.

Circularity and Environmental Value Retention Under Constraint

The reviewed studies increasingly treat circular economy practices as eco-innovation mechanisms that conserve materials and reduce ecological burden, especially when capital is scarce and inputs are costly (Geissdoerfer *et al*., 2016; Kirchherr *et al*., 2017). However, definitions remain contested, and many accounts overemphasize recycling while underplaying system change, social equity, and institutional alignment (Kirchherr *et al*., 2017; Geissdoerfer *et al*., 2016). This definitional fragmentation reinforces the need for disciplined conceptualization within resource-deficit environmentalism.

Knowledge Spillovers and Capability Building in Emerging Markets

Evidence indicates that multinational knowledge spillovers can reinforce eco-innovation in emerging market firms, partly by easing knowledge scarcity and shaping capability accumulation in multi-dimensional task environments (Qu *et al*., 2024; Hart & Dowell, 2011). This suggests a strategically relevant interaction: scarcity-driven ingenuity can be amplified when learning channels are open and absorptive capacity is cultivated, even when resources remain constrained (Qu *et al*., 2024; George *et al*., 2012).

Illustrative Empirical Anchor from Nigerian Rice Systems: Adoption Remains Low, Yet Benefits are Pronounced

As an empirical anchor relevant to constrained agrarian environments, evidence from Nigerian paddy rice systems indicates low adoption of ecological innovations (29.69%), despite broad awareness of contamination and climate risks (Omoyajowo *et al*., 2025a; North, 1990). Yet, where ecological innovations are adopted, they are strongly associated with improved satisfaction and perceived viability, plausibly because they reduce hazard exposure and reinforce stewardship identities (Omoyajowo *et al*., 2025a; Hart, 1995). The result is a practical paradox: ecological innovations appear valuable, but uptake remains inhibited by weak support systems, limited technical assistance, and constrained resources (Omoyajowo *et al*., 2025a; Khanna & Palepu, 2010).

Table 2: Practical Implications that Follow from the Results

Result pattern	What it implies for environmental outcomes	Strategized implication
Scarcity alone is insufficient	Without complements, environmental innovation remains sporadic	Pair scarcity pressure with enabling norms, minimal support, and adaptive governance (Battisti *et al*., 2023; Ostrom, 2010)
Adoption can be low even with awareness	Risk perception does not automatically translate to practice	Reinforce access, training, and incentives that convert awareness into uptake (Omoyajowo *et al*., 2025a; North, 1990)
Frugal solutions can have high impact	Eco-innovation can be affordable yet environmentally consequential	Support scalable frugal designs and community replication models (Weyrauch & Herstatt, 2016; Pansera & Sarkar, 2016)
Definitions shape outcomes	Narrow "circularity" framing can underdeliver	Use stricter, system-oriented circular economy definitions (Kirchherr *et al*., 2017; Geissdoerfer *et al*., 2016 & 2017)

DISCUSSION

Recasting scarcity from constraint to ecological stimulus

A persistent paradox in eco-innovation scholarship is that scarcity is often treated as an innovation brake, even though ecological stress frequently supplies the incentives that make environmental experimentation unavoidable. In resource-deficit contexts, environmental problem pressure can redirect search toward frugal, locally serviceable, and risk-reducing solutions, thereby converting constraint into a disciplined stimulus for ecological ingenuity (Hart, 1995; Rennings, 2000). Evidence from Nigeria's manufacturing sector likewise indicates that eco-innovation is shaped by cost pressure, capabilities, and policy conditions, supporting the argument that scarcity-driven environmental innovation is systematic rather than accidental (Sanni, 2018; Porter & van der Linde, 1995).

Institutions, Enforcement, and the Ecology of Compliance

The thematic synthesis reinforces that institutions matter not merely as legal frameworks, but as ecological governors that shape incentives, expectations, and the credibility of long-run environmental investment (North, 1990; Ostrom, 2010). Where enforcement is weak, eco-innovation pathways depend more heavily on informal rules, cooperative norms, and adaptive coordination, which can either enable or constrain environmental improvement through social sanction and trust (Ostrom, 2010; Khanna & Palepu, 2010). Nigeria-based evidence on innovation and eco-innovation drivers further supports this institutional argument, showing that policy credibility and organisational conditions are consequential for adoption decisions (Egbetokun *et al.*, 2009; Sanni, 2018).

Frugal and Grassroots Eco-innovation as Environmental Pragmatism

A major result is the prominence of frugal and grassroots eco-innovation where conventional R&D pipelines are inaccessible. Frugal innovation emphasizes substantial cost reduction, focus on core functionality, and adequate performance under constraint, which can align with environmentalism when it reduces material throughput, energy intensity, and toxic inputs (Weyrauch & Herstatt, 2016; Pansera & Sarkar, 2016). Grassroots innovation complements this by documenting community-led experimentation that often advances sustainability aims through locally embedded knowledge recombination, especially when niche practices diffuse into broader regimes (Seyfang & Smith, 2007; Markard *et al.*, 2012).

Circularity Under Constraint from Slogan to Measurable Resource Ecology

Circular economy logics remain environmentally persuasive, but the synthesis suggests that circularity becomes ecologically meaningful only when translated into operational incentives, governance rules, and measurable outcomes. Conceptual work warns that circular economy definitions often collapse into recycling rhetoric, while deeper system change and sustainable development linkages remain under-specified (Kirchherr *et al.*, 2017; Geissdoerfer *et al.*, 2017). In scarcity settings, circularity can also arise organically via repair cultures and secondary markets; however, policy and industry must ensure that circular practices produce verifiable net ecological gains rather than burden shifting (Geissdoerfer *et al.*, 2017; Rennings, 2000).

Environmental Health Externalities: Toxicity Reduction as a Core Performance Criterion

The reviewed themes converge on a technical point: eco-innovation in constrained settings cannot be judged solely by productivity or efficiency; it must be evaluated through exposure reduction, toxicity control, and ecological integrity. Nigeria-focused evidence on pesticide residues in commonly consumed fruits and broader analyses of pesticide poisoning trajectories underscore persistent contamination risk pathways and the need for preventive, safer substitution strategies (Omoyajowo *et al.*, 2018; Omoyajowo *et al.*, 2022a). This toxicity-first criterion is reinforced by public risk-perception work on chemical contaminants showing that uneven knowledge and perception can undermine behavioural uptake, implying that eco-innovation diffusion requires both safer options and risk-communication capacity (Omoyajowo *et al.*, 2024b; North, 1990).

Agrarian Eco-innovation Under Climate and Contamination Pressures: Adoption Gaps and Enabling Conditions

The empirical anchor from Nigerian paddy rice systems reveals a practical paradox: ecological innovations are framed as sustainability-preserving practices, yet adoption remains low (about 29.69%), with uptake constrained by limited support systems and uneven awareness of risk drivers (Omoyajowo *et al.*, 2025a; Ostrom, 2010). This pattern aligns with broader climate–food-security scholarship that links ecological shocks and institutional fragility to heightened vulnerability, implying that eco-innovation diffusion in smallholder systems depends on extension capacity, affordability, and governance credibility rather than awareness alone (Omoyajowo *et al.*, 2022b; Khanna & Palepu, 2010).

Policy Design and the Regulation–Innovation Balance: Lessons from U.S. Transport and Chemicals Governance

A complementary cross-context insight is that environmental regulation can catalyze innovation, but only when policy design balances stringency with feasible pathways for technological reinvention. Policy-oriented analysis of greenhouse gas emissions management in U.S. heavy-duty transportation foregrounds this balancing act, emphasizing how standards can steer innovation trajectories while interacting with industry structure and compliance flexibility (Omoyajowo, 2024d; Porter & van der Linde, 1995). Similarly, analysis of U.S. pesticide and chemical discharge regulation underscores how regulatory architecture and enforcement conditions shape environmental sustainability, reinforcing the view that governance quality mediates whether regulation yields genuine ecological dividends (Omoyajowo, Ukoh, & Omoyajowo, 2025b; Jaffe & Palmer, 1997).

Organizational Eco-innovation Beyond Production: Green Computing as an Institutionalized Routine

Eco-innovation is not confined to farms and factories; organisational policy domains, including green computing, represent a pathway for embedding environmentalism into routine governance and procurement. Evidence from Nigerian organisations indicates that adoption of green computing policies is driven by identifiable organisational and contextual factors, supporting the view that environmental performance can be institutionalized through policy routines and managerial systems (Omoyajowo *et al.*, 2024a; Rennings, 2000). This broadens the scarcity–eco-innovation nexus: even under constraints, environmental gains can be pursued through governance redesign, behavioural compliance systems, and efficiency-oriented digital practices (Porter & van der Linde, 1995; North, 1990).

Culture, Spirituality, and Multicultural Stewardship as Behavioural Infrastructure for Eco-innovation

An additional enrichment is that environmental stewardship can be reinforced by cultural and spiritual resources that shape norms, moral obligations, and collective action. Evidence linking environmental conservation to spirituality and multicultural perspectives suggests that values-based commitments can function as behavioural infrastructure for stewardship, complementing formal institutions and enabling pro-environmental practice in diverse contexts (Omoyajowo *et al.*, 2023; Ostrom, 2010). For eco-innovation under scarcity, this matters technically because diffusion often hinges on legitimacy and shared meaning; when stewardship identities are reinforced, adoption barriers tied to trust and compliance can be mitigated, especially where formal enforcement is limited (North, 1990; Omoyajowo *et al.*, 2023). Culture, spirituality, and stewardship was interpreted not as an 'add-on' theme but as informal institutional infrastructure that shapes legitimacy, compliance, and collective action in resource-deficit settings. Where formal enforcement is weak, values-based stewardship can lower coordination costs, reinforce pro-environmental norms, and increase the social credibility of safer practices, thereby operating as a behavioral complement to governance. Framed this way, stewardship supports the review's central argument: scarcity becomes a catalyst only when practical complements exist, and these complements include not only policies and intermediaries but also shared norms that sustain adoption quality over time.

Integrative Implications for Theory and Policy

Three implications follow. First, scarcity-driven eco-innovation should be treated as systemic and scalable when paired with minimal institutional scaffolding, credible incentives, and diffusion intermediaries (Rennings, 2000; Ostrom, 2010). Second, outcomes must be evaluated ecologically: the relevant success criteria are reductions in emissions, toxicity, waste, and exposure pathways, not simply novelty or cost efficiency (Kirchherr *et al.*, 2017; Omoyajowo *et al.*, 2022a). Third, multi-sector learning should be leveraged: lessons from agriculture, organisational green policies, transport emissions management, and chemical governance jointly indicate that environmental performance improves when policy design enables reinvention while maintaining verifiable ecological safeguards (Omoyajowo, 2025a; Omoyajowo *et al.*, 2025b).

The cocoa-farmer evidence further clarifies a boundary condition in the synthesis: networked learning and association-based training can improve practice, but adoption quality collapses when the supporting reverse-logistics system is absent or non-functional. In practice, this means that community-level institutional bricolage must be reinforced by credible formal arrangements—such as extended producer responsibility (EPR), take-back schemes, and recycler-linked collection partnerships—to prevent burden-shifting disposal behaviours and achieve measurable toxicity and exposure reduction (Oludoye *et al.*, 2026).

CONCLUSION

This review shows that eco-innovation in resource-deficit contexts is not incidental; it is a systematic environmental response shaped by scarcity pressure, institutional quality, and networked learning. Constraints can catalyze frugal, circular, and locally embedded solutions, but only when reinforced by credible governance, absorptive capacity, and practical diffusion intermediaries. Where these complements are weak, eco-innovation remains fragmented and under-adopted, limiting measurable reductions in toxicity, waste, and emissions. Overall, the study reframes scarcity as a conditional catalyst for environmental reinvention and advances a synthesis that prioritizes verified ecological outcomes over novelty alone.

RECOMMENDATIONS

1. Adopt outcome-based eco-innovation reporting by requiring verifiable environmental endpoints such as residue reduction, emissions intensity, waste diversion, and water-use efficiency rather than self-reported “green practices.”
2. Build minimum viable diffusion infrastructure by combining basic training with low-cost monitoring and targeted incentives to make sustainable practices feasible, credible, and repeatable under constraint.
3. Standardize and certify frugal eco-innovations by introducing lightweight, context-sensitive requirements for safety, repairability, and minimum environmental performance that accelerate diffusion while preventing unsafe substitutions. To manage the trade-off between standardization and local adaptability, we recommend tiered standards: a small set of non-negotiable safety and environmental thresholds, paired with locally adaptable design modules and maintenance protocols.
4. Make toxicity reduction a design requirement by treating exposure minimization as a primary innovation constraint across agriculture, manufacturing, and consumer-product systems rather than a secondary co-benefit.
5. Strengthen knowledge-to-use pipelines by funding and formalizing partnerships that translate research and external expertise into deployable packages with maintenance support, local adaptation, and user training.
6. Target circularity where it yields net gains by prioritizing repair, reuse, and redesign interventions with demonstrable life-cycle benefits and avoiding recycling-only initiatives that shift environmental burdens.
7. Use institutional incentives that reward adoption quality by linking grants, subsidies, and procurement eligibility to demonstrated performance and sustained practice rather than one-time installations or policy declarations. Applied to pesticide and chemical-use contexts, “minimum viable diffusion infrastructure” should include clear rinse-and-return guidance, functional community collection points, and recycler-linked take-back schemes, delivered through association-based peer education and reinforced with age-targeted materials for older farmers who are less responsive to safety messaging

In overall, each recommendation corresponds to mechanisms and barriers identified in the synthesis: outcome-based reporting and toxicity-first criteria (environmental health externalities/toxicity reduction); diffusion infrastructure and knowledge-to-use pipelines (learning networks + weak extension/support); standardization and adoption-quality incentives (scaling under institutional voids); and targeted circularity actions (circularity under constraint with net-gain discipline).

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