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Transdisciplinary Innovations for a Complex World: Global Perspectives on Science, Policy, Engineering, and Societal Transformation

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Abstract
Contemporary global challenges—climate change, public health emergencies, digital disruption, and persistent inequality—manifest as interconnected crises that resist resolution through conventional disciplinary approaches. Despite growing recognition of this complexity, research, policy, and engineering communities continue to operate largely within institutional silos, producing fragmented knowledge that fails to translate into transformative societal outcomes. This review article examines transdisciplinary innovation models that systematically integrate science, engineering, public policy, and societal transformation pathways. Drawing on systems thinking, convergence research paradigms, and socio-technical transition theory, the article analyses conceptual frameworks that enable knowledge integration and translational impact. Key frameworks examined include the Multi-Level Perspective on socio-technical transitions, the Transformation Network's interepistemic convergence model, the Responsible Research and Innovation framework, and the Quadruple Helix innovation ecosystem model. The article explores global applications across climate transformation systems, smart infrastructure and digital public services, health systems integration and crisis response, and inclusive economic and technological development. Implementation mechanisms are evaluated through the lens of innovation lifecycle models, multi-level governance strategies, and societal impact assessment methodologies. Two comparative tables synthesise framework characteristics and implementation considerations. Synthesised findings indicate that successful transdisciplinary innovation requires not merely technical integration but institutional adaptability, epistemological pluralism, governance mechanisms that bridge global frameworks with local contexts, and sustained attention to equity, inclusion, and ethical governance. The article concludes that transdisciplinary innovation frameworks represent essential infrastructure for achieving systemic transformation and recommends institutional reforms to support convergence research, evidence-based policy translation, and cross-sectoral collaboration at scale.

Keywords: Transdisciplinary Innovation; Socio-Technical Systems; Science-Policy Integration; Sustainable Transformation; Systems Engineering Governance; Global Innovation Ecosystems; Convergence Research

1. Introduction

The defining characteristic of twenty-first-century global challenges is their interconnected, systemic nature. Climate change cannot be understood solely as an atmospheric phenomenon; it is simultaneously an engineering problem requiring technological innovation, a policy challenge demanding regulatory frameworks, an economic transition affecting livelihoods and industries, and a social justice issue with profound distributional consequences [2, 6]. Pandemic preparedness similarly spans virology, health systems engineering, digital surveillance infrastructure, behavioural science, economic policy, and global governance mechanisms [8].

Digital transformation touches every sector of society, raising questions that are simultaneously technical, ethical, institutional, and cultural [4, 10].

Yet the institutions through which knowledge is produced and translated into action remain stubbornly fragmented. Universities are organised into disciplinary departments that reward specialised publication. Research funding flows through thematic silos that discourage cross-cutting proposals. Government ministries address portfolios such as health, environment, industry, and education in isolation. Engineering education emphasises technical optimisation within well-defined problem frames rather than engagement with the social and political contexts that shape technological outcomes [1, 7]. This fragmentation produces what might be termed the 'translation gap'—the persistent inability to move from disciplinary knowledge to integrated solutions for complex societal challenges [3, 9].

The limitations of fragmented approaches have become increasingly evident. Climate adaptation strategies developed without community input fail to address local vulnerabilities and may exacerbate existing inequalities [2]. Smart city initiatives driven by technology companies without social science engagement reproduce urban inequalities and undermine democratic accountability [4]. Public health interventions designed without consideration of digital infrastructure cannot leverage real-time data for early warning and response [8]. These failures are not merely implementation shortcomings; they reflect deeper inadequacies in how knowledge is organised, how problems are framed, and how solutions are developed.

This article addresses the critical need for transdisciplinary innovation frameworks that systematically integrate science, advanced research systems, engineering and technological infrastructures, public policy and governance mechanisms, and societal transformation pathways. Transdisciplinary approaches go beyond interdisciplinary collaboration among academic disciplines to engage knowledge producers and knowledge users across academia, government, industry, and civil society in co-creating solutions to complex problems [2, 5, 7]. Such frameworks are not simply about bringing different perspectives into conversation; they require structured methodologies for integrating knowledge across epistemological differences, aligning innovation with policy processes, and translating research into transformative societal outcomes [3, 6].

The urgency of this task is underscored by the accelerating pace of global change and the narrowing window for action on climate, biodiversity, and sustainable development. The Sustainable Development Goals explicitly recognise the interconnectedness of economic, social, and environmental objectives and call for integrated approaches to their achievement [2, 9]. Meeting these goals within the timeframe to which nations have committed requires innovation systems capable of operating across sectors and scales simultaneously.

The objectives of this article are threefold: first, to examine conceptual foundations of transdisciplinary innovation that have demonstrated utility in research and policy contexts; second, to analyse methodological and analytical frameworks that enable systematic integration across science, engineering, policy, and society; and third, to explore global applications where transdisciplinary approaches are producing measurable transformation outcomes. The article adopts a research-review hybrid methodology, drawing on recent scholarly literature and implementation case studies to develop a structured analysis of transdisciplinary innovation models and their translational potential.

2. Conceptual Foundations of Transdisciplinary Innovation

2.1. Systems Thinking and Socio-Technical Transformation Models

Systems thinking provides the foundational logic for transdisciplinary innovation. By conceptualising societal challenges as arising from complex systems with multiple interacting components, feedback loops, emergent properties, and path-dependent dynamics, systems approach inherently demand consideration of technical, social, institutional, and environmental dimensions simultaneously [1, 3]. The Multi-Level Perspective (MLP) on socio-technical transitions has emerged as one of the most influential frameworks for understanding how systemic transformation occurs [1, 6].

The MLP conceptualises socio-technical systems as operating across three analytical levels: niche innovations where radical new ideas emerge and develop; socio-technical regimes representing the established practices, rules, and institutions that stabilise existing systems; and the broader socio-technical landscape of exogenous trends and pressures [1, 6]. Transitions occur when niche innovations gain sufficient momentum to challenge and transform incumbent regimes, often catalysed by landscape-level pressures that destabilise existing arrangements. This framework has been extensively applied to understand transitions in energy, transport, agriculture, and water systems, providing insights into the conditions under which transformative innovation succeeds or fails [6].

What distinguishes the MLP from simpler innovation diffusion models is its attention to the co-evolutionary nature of socio-technical change. Technological innovation does not occur in isolation but interacts with user practices, cultural meanings, infrastructure, industry structures, policy frameworks, and scientific knowledge [1, 6]. Transformative outcomes require alignment across these multiple dimensions—a process that demands transdisciplinary engagement with the full range of actors and institutions that shape technological trajectories.

2.2. Convergence Research and Knowledge Integration Theories

Convergence research represents a distinct approach to knowledge integration that has gained prominence through initiatives such as the US National Science Foundation's Convergence Accelerator and the European Union's Horizon Europe framework [2, 7]. Convergence is defined as the deep integration of knowledge, tools, and ways of thinking from diverse fields to form a common framework for addressing scientific and societal challenges [2]. Unlike interdisciplinary research, which brings disciplines into conversation while maintaining their distinct identities, convergence aims to create new intellectual frameworks that transcend disciplinary boundaries.

The Transformation Network, a National Science Foundation-supported Sustainable Regional Systems Network, has developed an approach that explicitly integrates two schools of transdisciplinary thought: the metaphysical approach emphasising the emergence of new knowledge at the interfaces between disciplines, and the solution-focused approach prioritising stakeholder engagement and real-world problem-solving [2]. What distinguishes the Transformation Network's approach is its commitment to interepistemic and interontological engagement—building across different knowledge systems both within academia and among community partners, including Indigenous knowledge holders [2].

This interepistemic approach acknowledges that different knowledge systems represent valid and distinct ways of knowing that can enrich scientific understanding. Operationalising this approach requires sustained attention to community engagement, diversity, equity, inclusion, and justice—not as add-ons to technical research but as integral to the research process itself [2]. The practical application of this framework is evident in partnerships with Navajo Nation members to support community independence through sustainable off-grid food-energy-water systems, demonstrating how convergence research can produce solutions that are simultaneously technically sound, culturally appropriate, and community-owned [2].

2.3. Policy-Embedded Engineering Innovation Frameworks

Engineering innovation has traditionally focused on technical optimisation within well-defined problem frames, treating policy and social contexts as exogenous constraints rather than integral dimensions of design problems [1, 10]. The emerging field of policy-embedded engineering challenges this separation, recognising that engineering decisions shape policy options and that policy frameworks shape engineering possibilities in ways that require integrated consideration from the outset [4, 10].

The Responsible Research and Innovation (RRI) framework provides structured guidance for integrating policy and societal considerations into engineering and research processes [5, 7]. RRI emphasises four key dimensions: anticipation of potential impacts and implications; reflection on purposes, motivations, and assumptions; inclusion of diverse stakeholders in deliberation and decision-making; and responsiveness to emerging knowledge and perspectives [5]. These dimensions are not sequential steps but ongoing practices that should be embedded throughout innovation processes.

The RRI framework has been operationalised in diverse contexts, from nanotechnology and synthetic biology to artificial intelligence and smart infrastructure [5, 7]. In each case, the framework provides mechanisms for engaging policy-makers, civil society, and affected communities in shaping innovation trajectories, rather than treating societal engagement as an afterthought once technical decisions have been made. This anticipatory governance approach is particularly important for emerging technologies where uncertainties are high and potential impacts are poorly understood.

2.4. Data-Driven Governance and Digital Transformation Platforms

The digital transformation of governance has created unprecedented opportunities for transdisciplinary integration. Integrated digital platforms now enable the collection, analysis, and visualisation of data across sectors, supporting evidence-based policy formation and real-time monitoring of societal outcomes [8, 9, 10]. The Climate-Smart Public Health framework exemplifies this integration, leveraging data science and artificial intelligence to integrate climate, environmental, and health monitoring systems for early warning and adaptive response [8].

Applied in Madagascar—a region highly vulnerable to climate impacts—this framework incorporates surveillance, risk assessment, early warning systems, and resilient health-care infrastructure [8]. By integrating health data from more than 2770 public clinics with climate and environmental exposure data, the system enables rapid health research, prediction, and public health planning. Early data analysis has demonstrated strong climate sensitivity in diseases such as malaria and diarrhoea, enabling more efficient targeting of preparedness efforts [8].

The Quadruple Helix innovation model provides a complementary framework for understanding how data-driven governance can support transdisciplinary collaboration [4, 9]. Extending the traditional Triple Helix of university-industry-government relations, the Quadruple Helix adds civil society as a fourth actor whose engagement is essential for responsible innovation. Digital platforms can facilitate this engagement by making data accessible, enabling participatory monitoring, and supporting deliberative processes around innovation priorities and outcomes [4, 9].

3. Methodological and Analytical Frameworks

3.1. Cross-Sector Research Design Models

Translating transdisciplinary principles into practice requires structured research designs that enable integration across sectors and knowledge systems. The Transformation Network's approach to convergence research emphasises systems thinking, systems dynamics modelling, and sustained attention to community engagement as core methodological commitments [2]. This is not a one-size-fits-all methodology but a flexible framework that can be adapted to different contexts and challenges.

Participatory action research (PAR) has emerged as a particularly important methodology for transdisciplinary innovation [2, 5]. PAR explicitly positions community members as co-researchers rather than research subjects, engaging them in problem definition, data collection, analysis, and action planning. This approach is essential for ensuring that research addresses problems that communities themselves identify as priorities, and that solutions are appropriate to local contexts and capabilities. The Transformation Network's work with Navajo Nation partners exemplifies how PAR can support both rigorous research and community empowerment [2].

Design-based research (DBR) offers another methodological approach particularly suited to engineering-intensive transdisciplinary innovation [1, 10]. DBR involves iterative cycles of design, implementation, analysis, and redesign in real-world contexts, enabling simultaneous development of practical solutions and theoretical understanding. This approach is widely used in learning sciences, human-computer interaction, and socio-technical systems design, and has significant potential for broader application in transdisciplinary innovation.

3.2. Multi-Level Governance Integration Strategies

Transdisciplinary innovation cannot succeed without effective integration across governance levels. The Multi-Level Perspective on socio-technical transitions explicitly recognises that innovation occurs within multi-level governance systems where local, national, and international actors and institutions interact in complex ways [1, 6]. Effective transdisciplinary frameworks must navigate these multi-level dynamics, aligning innovation efforts across scales.

The European Union's Missions approach represents an ambitious attempt to operationalise multi-level governance for transdisciplinary innovation [7, 9]. Each EU Mission—on climate adaptation, cancer, healthy oceans, climate-neutral cities, and soil health—operates as a portfolio of research and innovation actions spanning multiple sectors and governance levels, coordinated through dedicated governance structures that bring together diverse stakeholders. This portfolio approach enables experimentation and learning while maintaining strategic coherence, addressing a persistent tension in transdisciplinary innovation between local adaptation and coordinated action [7].

The Regions2030 pilot project, developing a common indicator framework for SDG monitoring at the regional level across the EU while allowing for integrative indicators, illustrates how multi-level governance can be operationalised through shared metrics and reporting frameworks [9]. Such frameworks enable comparison and learning across contexts while respecting the specificity of local conditions—essential for transdisciplinary innovation that must be simultaneously globally informed and locally adapted.

3.3. Evaluation Metrics for Societal and Sustainability Impact

Evaluating transdisciplinary innovation requires metrics that capture outcomes across multiple dimensions and timescales. Traditional research evaluation focuses on academic outputs such as publications and citations, while engineering evaluation emphasises technical performance within defined specifications. Neither adequately captures the societal and sustainability outcomes that are the ultimate rationale for transdisciplinary innovation [3, 5, 8].

The Global Impact Analytics Framework (GIAF) provides structured methodologies for evaluating implementation research across multiple sectors [3]. Developed at the University of Canberra, the GIAF includes a taxonomy, glossary, and associated measurement tools for impact analysis at different implementation phases: pre-implementation (initiation), early implementation (maturity), or later implementation (evolution). The framework's application to mental health and wellbeing projects for veterans and first responders across seven countries demonstrates its utility for cross-sectoral evaluation [3].

The adaptation of Technology Readiness Levels for implementation science represents another significant methodological advance [3]. The TRL-IS checklist adapts the well-established technology readiness framework for impact assessment in implementation sciences, providing structured guidance for evaluating the maturity of implementation projects. This enables more systematic comparison across projects and sectors, supporting evidence accumulation about what works in different contexts.

Sustainability impact assessment (SIA) frameworks provide complementary approaches for evaluating environmental, social, and economic outcomes of transdisciplinary innovation [8, 9]. SIA emphasises participatory processes that engage stakeholders in defining assessment criteria and interpreting findings, aligning with the inclusive principles of transdisciplinary research. Integration of SIA with GIAF and TRL-IS approaches could provide comprehensive evaluation covering both implementation processes and sustainability outcomes.

3.4. Innovation Lifecycle Models from Research to Societal Adoption

Understanding how transdisciplinary innovation moves from research to societal adoption requires lifecycle models that capture the full trajectory from knowledge creation to transformative impact. The innovation lifecycle concept, widely used in business and technology management, can be adapted to the distinctive characteristics of transdisciplinary innovation aimed at societal challenges [1, 6, 10].

Early-stage transdisciplinary innovation involves problem framing and knowledge integration across diverse perspectives [2]. This phase requires mechanisms for eliciting and negotiating different understandings of the problem, identifying relevant knowledge from multiple sources, and developing shared conceptual frameworks. Methods such as knowledge co-production workshops, concept mapping, and scenario development are valuable at this stage.

Mid-stage innovation involves prototyping and testing integrated solutions in real-world contexts [1, 10]. This phase requires design methodologies that can accommodate multiple objectives and constraints, engagement with diverse stakeholders who will use or be affected by the innovation, and iterative refinement based on feedback. Living labs, testbeds, and pilot projects provide infrastructure for this phase.

Late-stage innovation involves scaling and diffusion of successful solutions [6, 7]. This phase requires attention to the institutional, policy, and market conditions that enable or constrain adoption, strategies for building coalitions of support, and mechanisms for adapting solutions to new contexts. Transition management and strategic niche management provide frameworks for navigating this phase.

Table 1: Comparative Overview of Major Transdisciplinary Innovation Frameworks and Their Global Application Domains

Framework Name	Core Components	Sectoral Integration Level	Implementation Scale	Evaluation Methodology	Societal Impact Indicators
Multi-Level Perspective [1, 6]	Niche-regime-landscape dynamics; co-evolutionary change	Socio-technical systems (energy, transport, agriculture)	Multi-level (local to global)	Historical case analysis; transition mapping	System transformation; regime shift
Transformation Network [2]	Interepistemic engagement; systems dynamics; community DEIJ	Regional sustainable systems	Regional/community	Reflexive assessment; community feedback	Cultural appropriateness; community empowerment
Responsible Research & Innovation [5, 7]	Anticipation; reflection; inclusion; responsiveness	Emerging technologies; research systems	Project to programme	Process evaluation; stakeholder deliberation	Ethical governance; public trust
Quadruple Helix [4, 9]	University-industry-government-civil society collaboration	Innovation ecosystems	Regional/national	Ecosystem mapping; network analysis	Inclusive innovation; civic engagement
Climate-Smart Public Health [8]	Surveillance; risk assessment; early warning; resilient infrastructure	Climate-health-digital	National/health system	Integrated data analytics; predictive modelling	Health outcomes; climate adaptation

4. Global Applications and Implementation Pathways

4.1. Climate and Environmental Transformation Systems

Climate transformation requires fundamental changes in energy, transport, food, and industrial systems—changes that cannot be achieved through technological innovation alone but demand simultaneous transformation of policies, business models, user practices, and cultural meanings [1, 6, 8]. The Multi-Level Perspective has been extensively applied to understand and enable such transformations.

The German Energiewende (energy transition) illustrates both the potential and the challenges of transdisciplinary innovation for climate transformation [1, 6]. The transition has involved not only deployment of renewable energy technologies but also fundamental restructuring of electricity markets, grid infrastructure, ownership models (including significant citizen ownership), and political governance. This multi-dimensional transformation has been enabled by sustained engagement across research, policy, industry, and civil society, with feed-in tariffs, citizen energy cooperatives, and regulatory reforms co-evolving with technological innovation [6].

Implementation mechanisms for climate transformation include policy mixes that combine technology-push (research funding, demonstration support) and demand-pull (feed-in tariffs, carbon pricing) instruments; stakeholder engagement processes that build consensus and manage conflict; and monitoring and evaluation systems that track progress and enable adaptive management [6, 8]. Stakeholder alignment requires attention to distributional impacts—who benefits and who bears costs—and mechanisms for addressing equity concerns. Policy integration across levels of government and sectors is essential, as climate transformation touches energy, transport, housing, industry, and agriculture simultaneously.

Outcome assessment models for climate transformation are increasingly sophisticated, combining energy system modelling with socio-technical transition analysis and sustainability impact assessment [6, 8]. The Climate-Smart Public Health framework's application to climate-sensitive diseases in Madagascar demonstrates how climate transformation outcomes can be assessed through integrated health and environmental data [8].

4.2. Smart Infrastructure and Digital Public Services

Smart infrastructure and digital public services represent domains where transdisciplinary innovation is essential for realising potential benefits while managing risks [4, 9, 10]. Early smart city initiatives often emphasised technological sophistication while neglecting social equity, democratic accountability, and sustainability outcomes [4]. More recent approaches position digital infrastructure within broader innovation ecosystems, where technologies such as artificial intelligence, big data analytics, the Internet of Things, blockchain, and digital twins are evaluated not for their technical novelty but for their contribution to public value [4, 10].

The Sustainable Public Innovation Ecosystem framework positions public administration as a coordinating hub where technological innovation and sustainability interact through governance mechanisms and collaborative processes [4]. Within this ecosystem perspective, public administrations assume the role of orchestrators rather than sole decision-makers. They design governance frameworks, regulatory conditions, and digital infrastructures that enable collaboration and knowledge sharing across universities, firms, and citizens [4].

Implementation mechanisms for smart infrastructure include procurement policies that incentivise sustainability and inclusion; regulatory sandboxes that enable experimentation while managing risks; and participatory design processes that engage diverse users in shaping digital services [4, 10]. Stakeholder alignment requires attention to digital divides and mechanisms for ensuring that marginalised groups are not excluded from digital transformation benefits. Policy integration across digital, infrastructure, social, and environmental domains is essential, as smart infrastructure decisions shape outcomes across all these areas.

Outcome assessment models for smart infrastructure are evolving from narrow efficiency metrics toward multi-dimensional public value frameworks that capture social, environmental, and democratic outcomes alongside economic and technical performance [4, 10]. The Quadruple Helix model provides a framework for assessing whether innovation ecosystems are delivering inclusive and sustainable outcomes [4].

4.3. Health Systems Integration and Crisis Response

Health systems are increasingly recognised as complex adaptive systems requiring transdisciplinary approaches for effective integration and crisis response [3, 8]. The COVID-19 pandemic exposed both the strengths and weaknesses of health systems worldwide, demonstrating the critical importance of integration across surveillance, clinical care, public health, and broader social and economic systems [8].

The Climate-Smart Public Health framework's application to pandemic preparedness illustrates how transdisciplinary integration can enhance crisis response [8]. By integrating health data with climate, environmental, and demographic data, the framework enables early warning of disease outbreaks, predictive modelling of disease spread, and targeting of interventions to populations most at risk. This integration requires collaboration across health, climate, data science, and social science disciplines, as well as engagement with communities and health system actors.

Implementation mechanisms for health systems integration include digital health platforms that enable data sharing across providers and sectors; governance frameworks that address data privacy, security, and sovereignty; and workforce development strategies that build capacity for transdisciplinary practice [3, 8]. Stakeholder alignment requires attention to the diverse interests and perspectives of patients, providers, payers, policymakers, and communities. Policy integration across health, social, and environmental domains is essential, as health outcomes are shaped by factors far beyond the health system.

Outcome assessment models for health systems integration are increasingly sophisticated, with frameworks such as GIAF enabling systematic evaluation of implementation processes and impacts [3]. The TRL-IS checklist provides structured guidance for assessing the maturity of health implementation projects, supporting evidence accumulation about what works in different contexts [3].

4.4. Inclusive Economic and Technological Development

Inclusive economic and technological development requires transdisciplinary approaches that address the distributional consequences of innovation and ensure that benefits reach marginalised groups [2, 9]. Too often, technological innovation has exacerbated rather than reduced inequality, creating new forms of exclusion and concentrating benefits among already-advantaged groups.

The Transformation Network's work with Navajo Nation partners on sustainable off-grid food-energy-water systems illustrates how transdisciplinary innovation can support inclusive development [2]. By engaging community members as co-researchers and prioritising culturally appropriate solutions, the project aims to support community independence while building local capacity and ownership. This approach contrasts with conventional development models that impose external solutions without regard for local contexts and capabilities.

Implementation mechanisms for inclusive development include participatory design processes that engage marginalised groups in shaping innovations; targeted support for entrepreneurship and innovation in underserved communities; and regulatory frameworks that prevent exclusionary outcomes [2, 9]. Stakeholder alignment requires attention to power imbalances and mechanisms for amplifying voices that are typically excluded from innovation processes. Policy integration across economic, social, and technological domains is essential for ensuring that innovation policy supports rather than undermines inclusion.

Outcome assessment models for inclusive development must go beyond aggregate metrics to capture distributional outcomes and impacts on specific groups [2, 9]. Disaggregated data, participatory evaluation methods, and attention to process outcomes (such as participation and empowerment) alongside material outcomes are essential for assessing whether development is truly inclusive.

Table 2: Advantages, Limitations, and Implementation Characteristics of Transdisciplinary Approaches in Science–Policy–Engineering Integration

Approach Type	Strengths	Technical Requirements	Institutional Prerequisites	Policy Implications	Measurable Sustainability Outcomes
Socio-Technical Transitions [1, 6]	Addresses systemic change; captures co-evolution; identifies leverage points	Systems modelling; historical analysis; stakeholder engagement	Long-term policy commitment; adaptive governance	Enables transformative policy design; supports mission-oriented innovation	System decarbonisation; resource efficiency; regime shift
Convergence Research [2, 7]	Integrates diverse knowledge; creates new frameworks; community-engaged	Knowledge integration methods; partnership infrastructure	Flexible funding; interdisciplinary capacity; community trust	Supports evidence-based policy; enables culturally appropriate solutions	Community wellbeing; knowledge co-production; solution appropriateness
Responsible Innovation [5, 7]	Anticipates impacts; includes diverse voices; supports ethical governance	Stakeholder engagement; ethics expertise; foresight methods	Ethical review capacity; inclusive governance structures	Builds public trust; supports anticipatory governance	Ethical outcomes; public acceptance; risk reduction
Digital Integration Platforms [4, 8, 10]	Enables data integration; supports real-time monitoring; scales across contexts	Digital infrastructure; data governance; analytics capacity	Technical capacity; data sharing agreements; regulatory frameworks	Supports evidence-based policy; enables performance monitoring	Health outcomes; service access; resource efficiency

5. Barriers, Ethical Considerations, and Future Directions

Despite significant advances in transdisciplinary innovation frameworks, substantial barriers impede their widespread adoption. Institutional resistance and structural silos remain formidable: universities organised into disciplinary departments, promotion and tenure systems that reward disciplinary publication, funding streams that follow disciplinary boundaries, and government ministries organised into policy silos [1, 2, 7]. These structures create powerful disincentives for the time-intensive work of building cross-disciplinary relationships, developing shared vocabularies, and negotiating epistemological differences.

Data governance and ethical challenges become increasingly complex as integration deepens. The Climate-Smart Public Health framework's attention to data use agreements, Institutional Review Board oversight, and data anonymisation reflects the ethical sensitivity required when integrating health, environmental, and social data [8]. Questions of data sovereignty—particularly when working with Indigenous communities—add additional layers of complexity [2]. As artificial intelligence becomes more central to transdisciplinary innovation, questions of algorithmic bias, accountability, transparency, and fairness demand sustained attention [4, 10].

Financing and innovation ecosystem limitations constrain the scale and sustainability of transdisciplinary innovation. The Transformation Network's support through the National Science Foundation's Sustainable Regional Systems programme [2], the European Union's Missions framework [7, 9], and dedicated interdisciplinary initiatives demonstrate that dedicated funding mechanisms are essential. However, sustainable financing requires demonstrating value for money, which in turn depends on robust evaluation frameworks that can capture the full range of transdisciplinary impacts. Current funding models often favour short-term, predictable outcomes over the long-term, uncertain, and systemic outcomes that transdisciplinary innovation aims to produce [1, 6].

Capacity building for global transformation remains a critical challenge. Transdisciplinary competencies—including systems thinking, stakeholder engagement, knowledge integration, and reflexivity—are not systematically developed in most educational programmes [5, 7]. Building these competencies at scale requires curriculum reform, experiential learning opportunities, and career pathways that support transdisciplinary practice.

Future trajectories in transdisciplinary research should focus on several priorities. First, further development and validation of evaluation frameworks capable of capturing transdisciplinary impacts across different sectors and scales [3, 8]. Second, comparative research on institutional mechanisms that successfully support transdisciplinary collaboration across different national and cultural contexts [2, 7]. Third, investigation of how digital technologies can support rather than undermine epistemological pluralism and community engagement [4, 8, 10]. Fourth, longitudinal studies tracking the translation of transdisciplinary research into policy outcomes and sustainability impacts over extended timeframes [1, 6]. Fifth, exploration of how transdisciplinary approaches can support transformation in the Global South, where contexts differ significantly from the European and North American settings where many frameworks have been developed [2, 9].

6. Conclusion

This article has examined transdisciplinary innovation frameworks that systematically integrate science, engineering, public policy, and societal transformation pathways. The frameworks analysed—Multi-Level Perspective, Transformation Network convergence research, Responsible Research and Innovation, Quadruple Helix, and Climate-Smart Public Health—represent diverse yet complementary approaches to integration across knowledge systems, sectors, and governance levels. Across these frameworks, several common themes emerge.

First, successful transdisciplinary innovation requires attention not only to technical integration but to epistemological pluralism. Acknowledging that different disciplines, knowledge systems, and communities may legitimately understand problems differently is essential for genuine collaboration [2, 8]. The Transformation Network's interepistemic approach exemplifies this principle in practice.

Second, institutional structures matter profoundly. The persistence of disciplinary and sectoral silos systematically undermines integration efforts. Dedicated programmes, missions, and institutional mechanisms that create space for transdisciplinary work are essential for countering these tendencies [2, 7, 9].

Third, governance frameworks must evolve to support transdisciplinary innovation. This includes anticipatory governance that engages diverse stakeholders in shaping innovation trajectories [5, 7], multi-level governance that aligns action across scales [1, 6], and data governance that addresses privacy, sovereignty, and equity concerns [4, 8, 10].

Fourth, evaluation methodologies must capture the full range of transdisciplinary outcomes. Frameworks such as GIAF and TRL-IS represent important advances, enabling systematic comparison and evidence accumulation across heterogeneous projects and contexts [3].

Fifth, equity and inclusion must be central to transdisciplinary innovation. Innovation that exacerbates inequality or excludes marginalised groups cannot be considered successful, regardless of technical achievements [2, 4, 9].

The strategic importance of transdisciplinary innovation for global challenges cannot be overstated. Climate change, pandemic preparedness, digital transformation, and sustainable development all require integrated approaches that transcend disciplinary and sectoral boundaries. The frameworks examined in this article provide conceptual resources, methodological tools, and practical guidance for this work.

Looking forward, future transdisciplinary research agendas must prioritise the institutional and governance dimensions of integration alongside technical and methodological advances. Policy and institutional transformation—in universities, funding agencies, government ministries, and international organisations—is essential for creating the conditions under which transdisciplinary innovation can flourish and translate into transformative societal outcomes. The urgency of global challenges demands nothing less.

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