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Linking Rural Road Infrastructure and Supply Chains: A Bibliometric Analysis and Thematic Interpretation

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Abstract: This study reviews how transport infrastructure, especially rural roads, improves supply chain performance and economic development in developing regions. The literature shows efficient systems cut logistics costs and time, streamline flows from production to markets, integrate rural areas into national and international markets, and expand access to services. Among six themes explored, supply chain management and sustainable transport infrastructure emerge as prominent research trends. Thus, the recommended future work is to develop multidimensional models, prioritize sustainable practices, and adopt advanced technologies, including recycled materials and smart transport systems, supported by multidisciplinary collaboration across engineering, environmental science, IT, economics, and public policy.

Keywords: Infrastructure; rural road; supply chain; sustainable development

1. Introduction

Transportation infrastructure, including roads, railways, and waterways, shapes the foundation for efficient supply chains, supporting the movement of goods and resources. Lin and Chen stated that infrastructure investments can reduce society's logistics costs and foster economic growth[1)]. Furthermore, transportation infrastructure drives the rapid movement of products from suppliers to consumers, enhancing supply chain reliability, reducing costs, and fostering regional economic development[2)]. The crucial role of infrastructure in supply chain performance is evident across sectors, from agriculture to manufacturing and services, where timely access to resources, transportation, and delivery is very important. Supply chains are dependent on transportation infrastructure. These chains comprise complex networks, encompassing the entire product lifecycle, from raw material to distribution. The performance of supply chains is linked to the quality and availability of transport routes. For example, studies conducted in Ghana and China have shown that robust transportation systems can reduce the ratio of national logistics costs to GDP, thereby increasing overall supply chain performance and competitiveness[3,4)]. In contrast, inadequate infrastructure leads to higher costs, delays, and reduced market access, particularly in Southeast Asian agricultural supply chains[5)]. Previous qualitative and quantitative studies have demonstrated the role of rural roads in specific areas. However, to our knowledge, no study has used bibliometric analysis to comprehensively map the knowledge structure of the field. Bibliometric analysis is a suitable method because it allows for the objective identification of major research clusters, influential authors and countries, as well as development trends of the field based on a large volume of scientific literature data, which is difficult to achieve in a traditional narrative review.

Rural roads, a critical component of transportation infrastructure, play a role in enhancing supply chain performance in developing countries. They are the main connecting route in rural and remote regions, influencing local economic and social activities. Development of roads can bring substantial benefits, including enhancing market access, reducing transport time and costs, and increasing household incomes[6,7)]. In agriculture, good rural road infrastructure enables farmers to transport products more efficiently, resulting in raising incomes and reduced post-harvest losses[8,9)]. Moreover, it can promote non-agricultural employment, encourage livelihood diversification, boost overall economic growth, and reduce poverty[10)].

Thus, the transportation infrastructure (i.e., rural roads) and supply chains are vital in shaping economic landscapes and development outcomes. Although the importance of rural transport infrastructure is widely acknowledged,

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existing research often focuses on specific cases in individual countries or regions. This results in a lack of a systematic overview of key research themes, trends and knowledge gaps in the field globally, especially in developing countries. The lack of such a comprehensive analysis makes it difficult for researchers and policy makers to identify priority directions for future research. Rural roads serve as a cornerstone for supply chain development. Investment in rural road infrastructure not only strengthens supply chain capacity but also advances socio-economic progress, underlining its importance for local and global development. To gain a better understanding of this research area, this study synthesizes research related to the three keywords, such as transportation infrastructure, supply chains, and rural roads, from developing nations. The study is expected to serve as a reference, regarding the role of transportation infrastructure, rural road improvement, in supply chain performance for researchers and practitioners. Against this backdrop, the specific objectives of this study are as follows:

- To synthesize and identify key research themes on the relationship between rural road infrastructure and supply chains in developing countries.
- To analyze the structure and linkages between research themes using bibliometric analysis.
- To identify recent prominent research trends and to suggest future research directions.

Despite extensive empirical work linking transport infrastructure to market access and development, evidence on rural roads and supply chain performance remains fragmented across disciplines and outcome definitions. Many studies emphasize localized settings or specific outcomes (e.g., travel time, prices, welfare), while fewer integrate supply-chain perspectives such as reliability, coordination, risk, and information flows. Our study addresses this fragmentation by applying bibliometric analysis to map the intellectual structure of the literature, synthesizing six major research clusters to clarify dominant directions and highlight gaps for future work in developing-country contexts.

2. Related Works

Infrastructure plays a significant role in enhancing the supply chains performance. By facilitating the smooth movement of goods, it reduces transportation time and inventory costs. Regarding resources, Peprah Adu, Dorasamy and Keelson mentioned that road infrastructure is critical for supply chain management, as it directly influences efficiency, reliability, and the costs of transporting goods[2]. It provides long-term competitive advantages and improving overall supply chain performance and supports regional economic development[2]. Lin and Chen mentioned that increasing investment in transportation infrastructure, such as railway and waterway systems, can reduce the logistics costs[1]. Gast, et al. mentioned that transportation infrastructure also affects supply chain resilience[11]. The effective use of infrastructure, including maintenance and upgrades, is essential for sustainable economic growth. For instance, Adu and Dorasamy in Ghana examined the impacts of improved road infrastructure on supply chain costs and concluded that the influence is positive[12]. Adu, Dorasamy and Keelson noted that traffic safety and environmental issues significantly affect supply chain performance[4]. It is necessary to plan to exploit transportation infrastructure in improving supply chain performance[13].

Rural road infrastructure plays a pivotal role in economic and social contexts. It significantly influences the accessibility and connectivity of rural areas, thus affecting livelihoods and community development. Studies across various areas have shown the multifaceted influence of rural road infrastructure. For example, in South Africa, poor road connectivity in regions such as Greater Tubatse increases transportation costs, hinder access to public transport, and hampers economic activities[14,15]. Similarly, in Ethiopia, poor road conditions limit agricultural productivity and market accessibility, emphasizing the importance of road infrastructure in income generation and economic opportunities (see Table 1)[7].

On the other hand, in Laos and Cambodia, road network improvements have enhanced market access, facilitated agricultural trade, and supported income diversification, although issues such as environmental impact and land disputes remain[9,16,17]. The development of rural roads has been associated with increased agricultural income, improved market access, and greater non-agricultural employment opportunities, contributing to poverty reduction in Vietnam[10,18]. In India's Jhunjhunu district, upgrading rural road infrastructure under programs of the Pradhan Mantri Gram Sadak Yojana (PMGSY) supports agricultural activities and encourages livelihood diversification[19]. However, these benefits depend on effective planning suitable for locations. Maloo, et al. conducted case studies in Maharashtra to propose a framework for a standardized baseline survey for roads and transportation in villages[20]. Zheng noted that China has steadily increased its investment in rural infrastructure and has introduced a range of policies aimed at supporting farmers and improving the well-being of the general population[21]. Aggarwal mentioned that rural road infrastructure is essential for healthcare access, helping timely delivery of medical supplies and patient transportation[22]. In Kenya, Greiner, Greven, and Klagge mentioned that rural roads have connected remote communities in sparsely populated areas to markets[6]. It also leads to socio-economic norms such as land disputes. Overall, previous studies from multiple countries demonstrate that rural road infrastructure is indispensable

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to socio-economic development. However, there is need for sustainable planning to fully take its benefits while minimizing negative impacts. Considering rural roads in supply chain strategies, it brings economic growth and promotes social welfare. Previous research utilizes a dual-track approach to link transportation with regional development. Quantitative econometrics, including 3SLS, panel data, and factor analysis are dominant because they address endogeneity, proving that infrastructure directly causes economic growth by reducing supply chain barriers. These models provide the statistical data needed to isolate how connectivity boosts incomes and market access. Furthermore, qualitative and mixed methods, such as case studies, are employed to capture complex socio-environmental trade-offs that data alone cannot measure. These methods reveal "hidden" impacts like land disputes or deforestation and explain how governance determines project success. Together, this methodological diversity balances statistical proof with contextual depth, ensuring a rigorous understanding of both the economic efficiency and social reality of rural development.

Table 1: Studies related to rural road infrastructure

No.	Country	Topic	Methodology	Finding Point	Reference
1	South Africa	Road connectivity, economic impact	Comparative analysis & Transport efficiency assessment	Emphasizes the negative impact of poor road connectivity on transport efficiency and the economy in Greater Tubatse.	Venter, Molomo and Mashiri [14]
2	India (Maharashtra)	Decentralized planning, road connectivity	Case studies & Decentralized planning surveys	Focuses on decentralized planning for rural transport through Gram Panchayats.	Maloo, et al. [20]
3	Laos	Road networks, socio-economic growth	Socio-economic growth & Infrastructure review	Improved road networks boost transport, agriculture, and trade.	Inthakesone and Kim [9]
4	Vietnam	Market access, rural infrastructure	Poverty reduction & Transaction cost analysis	Rural roads raise household income, increase non-farm employment, and support poverty reduction.	Nguyen, et al. [23]
5	Thailand & Vietnam	Rural roads, crop diversification	Panel data analysis & Regression models	Rural transport influences land use decisions and crop diversification.	Nguyen, et al.[10]
6	China	Economic benefits, rural connectivity	Policy review & Planning analysis	Economic benefits of rural road networks and challenges in planning.	Zheng[21]
7	India	Infrastructure improvement, sustainable development	Sustainable Livelihood Security Indicators (SLSI) & PCA	Assesses sustainability along India's West Coast and recommends policy interventions.	Krishna, et al. [24]
8	India	Rural roads, livelihood diversification	Econometric modeling & Fuzzy frameworks	Rural roads in Jhunjhunu affect livelihood diversification, emphasizing the need for broad economic policies.	Wagale, Singh and Sarkar [19]
9	Ethiopia	Road conditions, income generation	Household income & Market access analysis	Good rural transport improves market access and rural household income.	Wudad, Naser and Lameso [7]
10	Kenya (Baringo)	Economic opportunity, socio-economic transformation	Household surveys & Long-term ethnographic research	Roads enhance market access and contribute to socio-economic transformation.	Greiner, Greven and Klagge [6]
11	India	Road infrastructure, healthcare access	Impact evaluation of the PMGSY program	PMGSY improves healthcare access and socio-economic development, despite challenges.	Aggarwal [22]
12	Cambodia	Market access, economic resilience	Impact investigation & Economic resilience analysis	Reduces transport costs, improves market access, and diversifies work and income.	Takada, et al.[17]
13	Laos	Market access, environmental concerns	Literature synthesis & Field observations	Mountain rural roads drive economic integration but cause environmental concerns.	Castella and Phaipasith [16]

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14	Vietnam	Infrastructure, poverty alleviation	Three-stage least squares (3SLS) estimation	Enhancements in infrastructure and education reduce poverty and improve non-farm employment opportunities.	Do, et al[18)]
15	South Africa	Market access, infrastructure	Market efficiency & Cost-benefit analysis	Infrastructure improvements lower costs and market inefficiencies for livestock farmers.	Sehar and Oyekale[15)]

3. Materials and Methods

This study used a literature review method combined with bibliometric analysis. The literature review method was used to select relevant papers. Then, a bibliometric review design was followed. Bibliographic records were collected and screened using an inclusion/exclusion procedure. Keyword co-occurrence mapping and network-based clustering were conducted in VOSviewer to identify major thematic structures. Clusters were then synthesized through structured thematic interpretation of frequent keywords and representative papers, enabling cluster labeling, mechanism-oriented synthesis, and the identification of research gaps and implications. The process was carried out in the following steps, as illustrated in Figure 1:

Step 1: Literature review: Scopus scientific database was used as the main source to collect relevant academic articles. The search keywords were built based on the three main pillars of the study: transport infrastructure, supply chains and rural roads.

Step 2: Data Collection: Multiple detailed search strings were used to ensure the comprehensiveness of the collected documents. For example, the search string was: “(TITLE-ABS-KEY ("transport infrastructure") AND TITLE-ABS-KEY ("supply chains")) AND PUBYEAR > 2013 AND PUBYEAR < 2025”. The search focused on articles published within a ten-year period from 2014 to 2024 to capture recent research trends. These articles were then screened based on their titles and abstracts to eliminate studies that were not directly relevant to the context of developing countries or did not focus on the linkage between rural roads and supply chains. After screening, 138 articles were included in the analysis.

Step 3: Data Analysis and Visualization: VOSviewer software was used to perform keyword co-occurrence analysis. After setting the minimum keyword threshold to three occurrences and making further adjustments, a network of 78 main keywords was generated. Based on this network, research topic clusters were identified and visualized. Based on the results, discussions and conclusions are presented in Step 4.

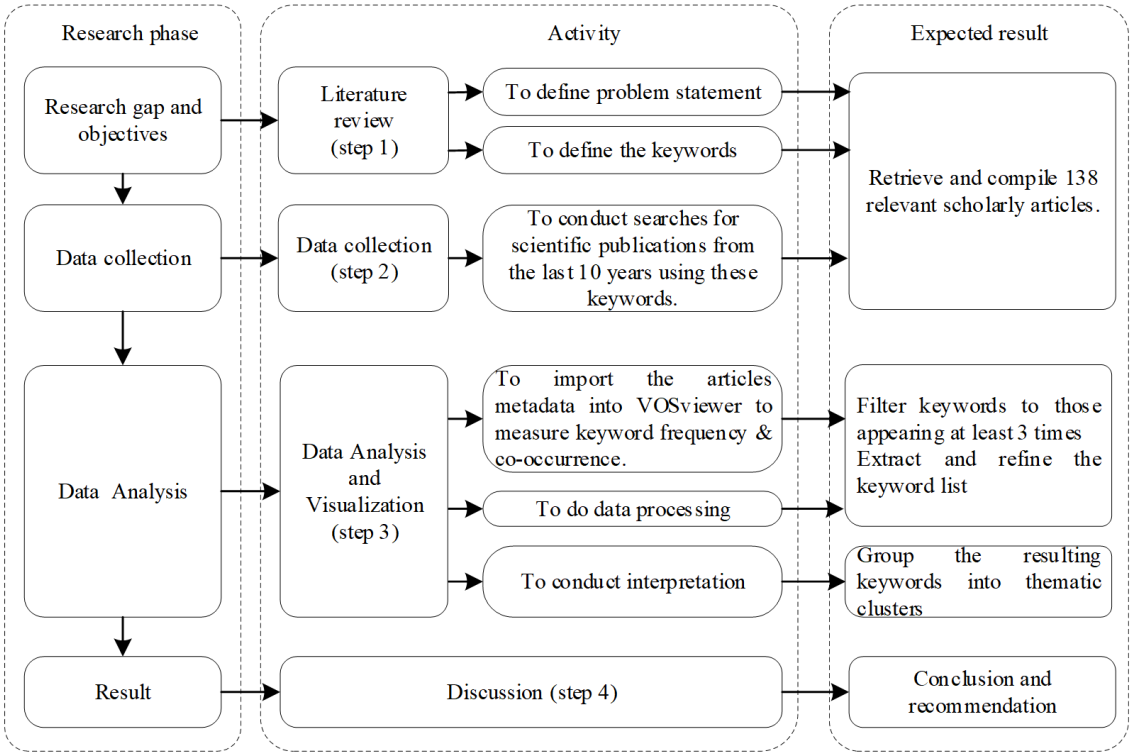


Fig. 1: Analysis framework

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4. Results

Keywords were grouped into related clusters (see Figure 2 and Table 2).

a) Cluster 1: This cluster focuses on investigating the relationship between infrastructure improvement and socio-economic development. Research explores the enhancement of accessibility and market access through road infrastructure and public transportation, examining their impact on economic growth and household incomes.

b) Cluster 2: This cluster focuses on the optimization and resilience of the transportation system in the face of disasters (e.g., earthquakes, floods, storms, and other disasters). This cluster includes risk management strategies such as cost-benefit analysis and resilience evaluation. Studies emphasizes economic impacts and decision-making processes related to management and transport.

c) Cluster 3: This cluster focuses on economic growth with infrastructure investment, especially considering environmental sustainability and economic development. Studies used cost analysis in logistics and infrastructure projects, highlighting the role of investment in promoting transportation and economics.

d) Cluster 4: This cluster focuses on features the integration of information systems with transport policy to enhance efficiency. Research focuses on how the design, construction, and management of information affect policy development and competitiveness for railways and supply chains. It provides insights into new technologies and their role in the policy planning process.

e) Cluster 5: This cluster focuses on the intersection of climate change mitigation and infrastructure adaptation strategies. Research explores adaptation measures in infrastructure and agriculture, conducts case studies, and assesses impacts on international trade. Policy interventions for climate change adaptation and related risks are topics.

f) Cluster 6: This cluster focuses on environmental impacts in industry. It addresses emissions from the cement and construction industries. Studies utilize supply chain analysis to assess energy use and greenhouse gas emissions, sustainability practices.

These research clusters not only exist independently but are also closely related to each other, reflecting the multidimensionality of the field. For example, Cluster 1 (red) on socio-economic development is a direct consequence of investments in Cluster 3 (blue) on supply chain management and infrastructure. Meanwhile, Cluster

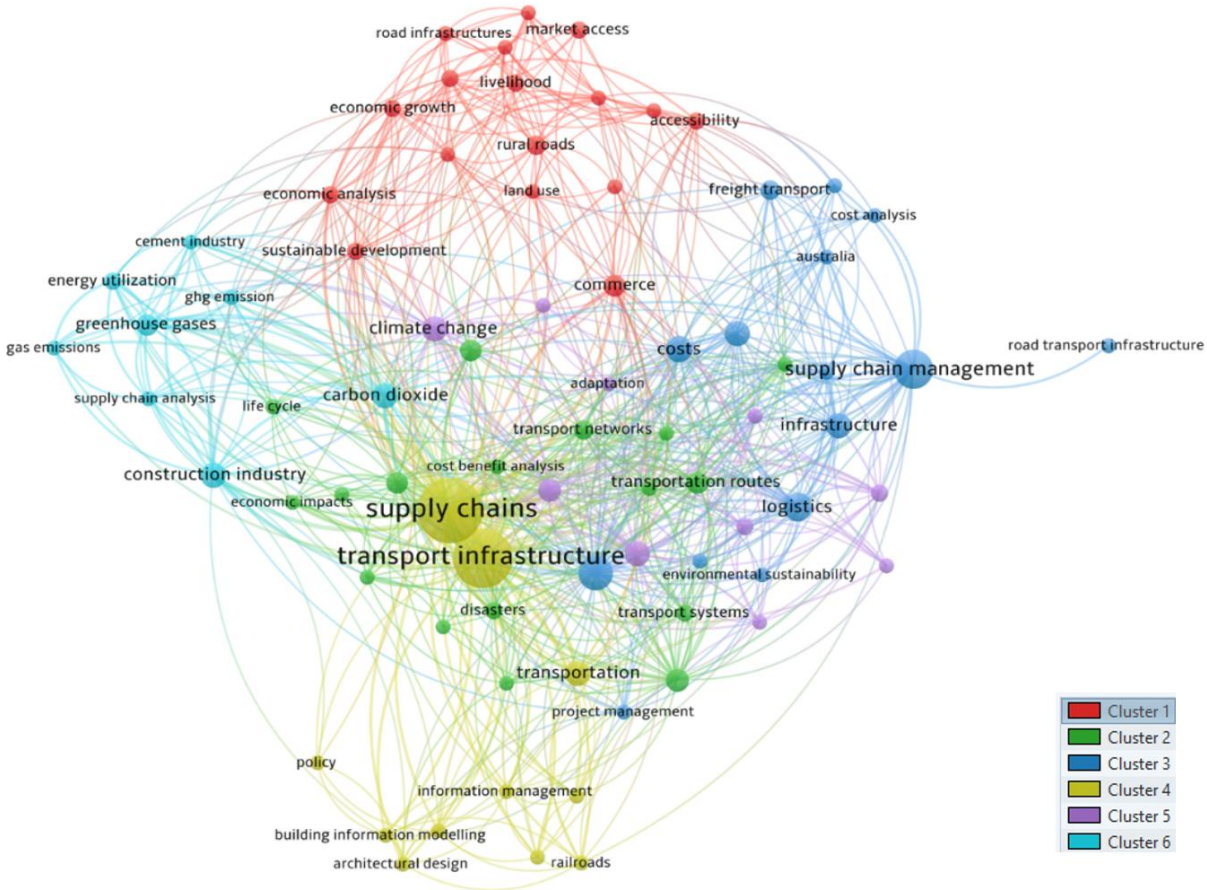


Fig. 2: Keyword Co-occurrence Network

Table 2: Analysis results by cluster

Cluster (Color)	Research Direction	Keyword
1 (red)	Socio-economic development and infrastructure	Trade, Economic analysis, Economic growth, Household income, Land use, Livelihood, Market access, Road infrastructure, Rural roads, Sustainability…
2 (green)	Risk management	Cost-benefit analysis, Decision-making, Disaster, Earthquake, Socio-economic efficiency, Economic impact, Freight transport, Highway management…
3 (blue)	Supply chain management and transport infrastructure	Cost analysis, Costs, Economic development, Environmental sustainability, Freight transport, Infrastructure, Investment, Logistics…
4 (yellow)	Information systems and transport policies	Building information management, Competition, Information management, Information systems, Policy, Railway, Supply chain, Transport infrastructure…
5 (purple)	Climate change adaptation and infrastructure	Adaptation, Agriculture, Case study, Climate change, Infrastructure adaptation, Infrastructure investment, International trade, …
6 (cyan)	Environmental impact and industrial emissions	CO_2, Cement, Construction sector, Energy use, Gas emission, GHG emission, Greenhouse gases, Supply chain analysis

2 (green) on risk management shows that infrastructure development cannot be separated from uncertain factors such as natural disasters, and this directly affects the economic efficiency mentioned in Cluster 1. Cluster 4 (yellow) on information systems and policies acts as a tool to support, connect and optimize activities in both Cluster 1 and Cluster 3. Finally, Cluster 5 (purple) and Cluster 6 (cyan) emphasize that all infrastructure development and supply chain activities face challenges of climate change and environmental impacts, requiring a sustainable approach.

4.1. Cluster 1

Efficient and resilient transport infrastructure serves as the bedrock for socio-economic development by enhancing accessibility and market access. Robust road networks influence logistics firm locations, overcoming time–distance constraints[25] and driving performance in manufacturing sectors[4,13]. At the macro level, large-scale investments boost GDP and comparative advantages in global value chains[26,27], facilitated by strategic links like the Eurasian rail system[28]. Regionally, dense logistics networks and port growth stimulate employment and economic benefits, though they necessitate managing externalities like congestion and pollution[29–31], especially as market concentration exposes supply chain vulnerabilities[32].

Beyond growth, infrastructure resilience is vital for food security and ensuring continuous access to essential services during disruptions[33,34], as availability directly dictates firms' long-term stability[35]. Furthermore, the transition toward socio-economic prosperity is increasingly linked to sustainability; green logistics, carbon-neutral construction, and carbon-capture chains mitigate environmental damages while supporting social outcomes[36–39]. Ultimately, optimizing infrastructure configurations—from hydrogen transport costs[40] to institutional upgrades and innovation policies[41,42], remains central to fostering inclusive economic growth and improving household welfare.

This cluster highlights transport infrastructure as a macro-level productivity enabler, improving accessibility, shaping firm location, and strengthening market integration to support industrial performance and economic growth. At regional scales, logistics densification is linked with employment and competitiveness . At the same time, expansion generates trade-offs, including congestion, pollution, and systemic risks from market concentration. Divergences across studies reflect scale and context, with national corridor analyses emphasizing comparative advantage, while urban and regional work stresses externalities and distributional effects. What remains unresolved is the mechanism from infrastructure investment to supply chain performance and household welfare, particularly in rural networks with limited maintenance.

4.2. Cluster 2

Research within this cluster emphasizes the integration of resilience and risk management into supply chain infrastructure. Studies demonstrate that redundant inventory and infrastructure are essential for managing post-disaster disruptions[43], while user-centric and multilayer network models help identify critical road segments and seismic-vulnerable tunnels to prioritize investment[34,44,45]. Disruptions—ranging from localized floods and storms to global pandemics—illustrate how network failures create non-linear economic losses and delay cascades, necessitating robust resilience strategies beyond physical hardening to include sourcing and inventory flexibility[32,33,46].

From an economic perspective, infrastructure reliability and accessibility remain primary determinants of logistics firm locations and investment decisions[25,35]. Optimization

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models for inland waterways and hydrogen or CO_2 transport corridors identify critical cost thresholds and demand-dependent modal choices (e.g., pipelines vs. trucks) to guide decarbonization and corridor planning[39,40]. Furthermore, benchmarking city logistics and ranking transport risks using advanced fuzzy decision-making tools (e.g., PIPRECIA) allow for more robust strategic planning under ambiguity[30,47,48].

Finally, the cluster explores the governance of technological innovation. While IoT-based smart mobility and eco-friendly innovations (e.g., recycled materials, AI monitoring) offer significant environmental benefits, they face barriers such as high upfront costs and regulatory gaps[49,50]. Effective implementation requires technological integration, supportive government policies, and balanced procurement choices by public clients, ensuring that growth remains compatible with climate goals and logistics performance[36,37,42,51]. Together, these studies converge on a framework for transport systems that harmonize economic efficiency with disaster resilience.

This cluster underscores that resilience is essential: disruptions cause non-linear losses and cascading delays, making redundancy in links, facilities, or inventory buffers a decisive factor for continuity and recovery. Most studies employ network-based methods to identify critical segments and vulnerable assets for investment prioritization. Divergence arises over which resilience strategy is most cost-effective—some emphasize physical robustness and asset hardening, while others highlight operational flexibility in sourcing, inventory, and routing, with differences explained by hazard type, redundancy, and data resolution. A key gap remains the absence of standardized resilience metrics linking infrastructure states to supply chain outcomes, particularly in rural road systems of developing contexts where redundancy is low, disruptions frequent, and decision tools must operate with sparse data.

4.3. Cluster 3

Transport infrastructure design, location, and governance serve as fundamental determinants of supply chain reliability and long-run economic development. Infrastructure availability and logistics performance directly shape regional economic attractiveness; for instance, reduced availability in key modes like inland waterways significantly raises logistics costs, triggering facility relocation and modal shifts[35]. This economic geography is further reinforced by the tendency of logistics firms to cluster near major highways and suburban hubs to capitalize on accessibility[25]. At the urban level, tailoring logistics measures through investment in intermodal terminals and smart regulations can effectively mitigate congestion and CO_2 emissions while enhancing freight efficiency[30].

A critical component of infrastructure investment is the enhancement of system resilience to prevent non-linear economic losses. Research highlights that redundant transport links and distribution facilities are vital for managing disaster-induced disruptions, particularly when inventory redundancy is used to compensate for limited freight flexibility[43,44]. By mapping critical road segments and analyzing potential network delay cascades, policymakers can prioritize adaptation investments in vulnerable assets such as bridges, tunnels, and seismic-prone links[33,34,45,46]. From a risk management perspective, prioritizing infrastructure and customs efficiency over traditional cargo-loss risks remains essential for economic supply chain management[48]. Furthermore, while the corporatization of global maritime networks has expanded capacity, it has also necessitated a strategic re-evaluation of buffer capacity versus lean efficiency in the post-pandemic era[32].

Environmental sustainability has become an inseparable pillar of infrastructure-led growth. Structural investments—such as infrastructure-led FDI and green logistics operations—have been shown to lower carbon emissions through energy conservation while simultaneously expanding trade opportunities[36]. Although technology-enhanced logistics can initially reduce carbon damages, sustainable growth requires a continuous commitment to fuel-efficient technologies and eco-friendly road innovations like recycled materials and energy-harvesting pavements[37,49,51]. Recent cost optimizations for carbon-capture supply chains and hydrogen transport corridors (ranging from 0.3 to 3.44 €/kg) further illustrate how demand-dependent infrastructure choices dictate the economic viability of the energy transition[39,40].

Ultimately, the successful delivery of these projects depends on robust governance and innovative planning tools. Public procurement choices, such as mandating Building Information Modeling (BIM), crucially shape delivery efficiency despite potential internal supply chain tensions[42]. Moreover, advanced methodological tools—including interval-valued intuitionistic fuzzy matrix games and IoT-based smart mobility metrics—offer robust frameworks for strategic planning under ambiguity, ensuring that future transport technologies remain aligned with evolving supply and demand patterns[47,50].

This cluster shows that infrastructure availability and accessibility shape logistics geography: firms cluster near major corridors and hubs, while reduced modal options raise costs and trigger relocation or modal shifts. Targeted investments such as intermodal nodes or freight regulations can improve efficiency and reduce congestion and emissions. Divergence arises around supply chain design—buffer versus lean—where post-pandemic insights highlight tensions between centralized efficiency and the need for slack capacity. Governance assumptions also matter, as procurement and delivery requirements may

enhance efficiency and standardization. Unresolved questions concern how these relationships generalize to rural road investments, particularly sequencing choices and bottleneck removal strategies.

4.4. Cluster 4

The convergence of information systems, data, and digital technologies is now a cornerstone of transport policy, aimed at enhancing efficiency, resilience, sustainability, and global competitiveness. Rather than being mere tools, these technologies act as strategic drivers in the policy planning process. For instance, data-driven segmentation and city-logistics indicators provide the evidence base needed to tailor urban freight policies that reduce congestion and CO_2 emissions[30]. Furthermore, the integration of IoT and real-time information allows policy levels to transition toward sustainable, smart-mobility solutions[50], while global "intelligent logistics" frameworks use technological indicators to mitigate carbon damage without sacrificing economic growth[37].

Digital innovation and governance play a critical role in the design and construction phases of transport infrastructure. Rapid progress in ITS, AI, and machine learning necessitates evolving regulatory frameworks to enable predictive maintenance and traffic management[49]. The effectiveness of these environmental policies is often mediated by lean supply chain management and collaborative information sharing[51]. A prime example is the use of Building Information Modeling (BIM) as a policy instrument. In Sweden, digital requirements are leveraged to push innovation within construction supply chains, although policymakers must balance prescriptive BIM requirements with the need for supplier-led solutions[42].

For railways and broader supply chains, information management is vital for resilience analytics. Agent-based models and multilayer network methods use detailed economic and network data to identify critical links, allowing planners to embed redundancy and efficiency into infrastructure strengthening policies[33,44]. These user-centric accessibility models, utilizing open data and disaster scenarios, directly support risk-management policies in vulnerable regions[34]. Specifically, for underground transport links and rail networks, life-cycle resilience indices and cascading failure analysis of high-resolution data provide the necessary evidence for long-term adaptation and investment prioritization[45,46].

On a global scale, information-rich "green logistics" and the corporatization of terminal networks demonstrate how digital integration influences market structure and trade reliability[32,36]. The "logistics revolution," fueled by Internet-based systems, has transformed firm location strategies, reinforcing the weight of transport policy in national competitiveness[25]. Ultimately, transport policy must address both physical and digital risks, utilizing advanced decision-support tools like fuzzy matrix games to navigate deep uncertainty in strategic planning[47].

This cluster highlights digital technologies—IoT, real-time data, and analytics—as policy tools to improve freight efficiency, sustainability, and resilience. Evidence converges on the role of data systems in planning, monitoring, and resilience analytics by identifying critical links and vulnerabilities. Divergence arises around governance: some view digital mandates as innovation drivers, while others warn of misalignment with supplier capacity. Environmental impacts also vary, as benefits depend on complementary practices like lean management and collaboration. A key gap concerns rural and developing contexts, where the challenge is not technology availability but the institutional and data conditions needed for scalability under limited resources and fragmented governance

4.5. Cluster 5

Research within this cluster converges on the critical necessity of developing transport and trade-related infrastructure that is resilient, low-carbon, and reliable in the face of climate-induced shocks. A primary focus is the adaptation of maritime and inland ports, which are vital nodes in global trade yet highly vulnerable to sea-level rise and extreme weather. The PIANC guidelines provide a structured framework for climate-risk assessment and adaptation planning, offering both structural and non-structural toolboxes for existing and new infrastructure, as evidenced by practical applications in the Port of Gladstone[52].

Furthermore, the resilience and recovery of transport networks are examined through the lens of post-disaster logistics and regional vulnerability. Insights from the 2016 Kaikōura earthquake highlight how constraints in material supply chains and regulatory limits can prolong disruption, necessitating integrated recovery policies[53]. To address these risks, reliability-oriented routing algorithms for multimodal transport have been developed to maintain functionality during epidemics or natural disasters, providing essential decision support for infrastructure investment[54]. In rural contexts, such as Bangladesh, the sustainability of infrastructure depends heavily on managing supply-chain risks and project delays to protect climate-vulnerable populations[55].

The cluster also emphasizes infrastructure decarbonization as a dual strategy for mitigation and risk reduction. Large-scale roadmaps, such as those from Sweden, demonstrate that transitioning to material efficiency, electrification, and CCS can reduce infrastructure construction emissions by over 90% by 2045, thereby lowering long-term physical climate risks[38]. This is complemented by integrated models for renewable-fuel supply chains in Europe, which optimize pipeline and storage infrastructure to support a climate-neutral transport sector[56].

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Finally, the research explores the impact on international trade and the development of green corridors. Improved logistics performance and tracking systems are shown to align with Sustainable Development Goals (SDGs) across Europe and Central Asia[57]. For instance, optimizing rail and port infrastructure for soybean exports from Brazil to China illustrates how "green corridors" can simultaneously reduce CO_2 emissions and transport costs[58]. Supporting these advancements are institutional innovations and monitoring technologies, such as vehicle-dynamics-based pavement assessment[59] and adaptive governance models like New South Wales' Asset Standards Authority, which bridge the gap between academia and industry to manage assets under future climate pressures[60].

This cluster shows that climate shocks are reshaping infrastructure priorities, making reliability and adaptation central to ports and multimodal corridors, with risk assessment and adaptation planning increasingly guiding action. Divergence arises between structural upgrades versus operational and governance approaches, and between mitigation and adaptation sequencing. "Green topic" studies emphasize CO_2 and cost reduction through optimized routing, while governance-focused work highlights institutional arrangements and monitoring systems. A key gap is translating these insights to rural road systems, where climate vulnerability interacts with weak maintenance, limited redundancy, and high welfare stakes, underscoring the need for resilience metrics that link infrastructure to supply chain continuity in rural contexts.

4.6. Cluster 6

This research cluster provides a comprehensive analysis of how industrial systems, particularly the cement and construction sectors, can mitigate their environmental footprint through optimized supply chains and governance. By examining energy use and greenhouse gas (GHG) emissions, these studies offer a roadmap for transitioning heavy industry toward a climate-neutral future. A central focus is the decarbonization of industrial materials; for instance, a Swedish supply-chain roadmap highlights that the construction of buildings and transport infrastructure consumes approximately 32 TWh of energy annually, but through aggressive sustainability practices—including material efficiency, the adoption of alternative binders to address cement-related emissions, electrification, and the use of low-CO_2 materials—emissions could be reduced by 50% by 2030 and up to 90–94% by 2045[61]. Complementing this is an integrated optimization model for European renewable fuel supply chains, which manages seasonal resource variability to support a climate-neutral transport sectorw[56].

At a macro scale, the link between industrial efficiency and environmental quality is evident, as seen in an analysis of 47 European and Central Asian countries where superior logistics performance in customs and tracking is associated with higher environmental quality, whereas uncontrolled industrialization often leads to degradation[57]. This is further exemplified by the use of linear programming in Brazil to identify "green corridors" for soybean exports that minimize both costs and CO_2 emissions through port optimization and the use of Capesize vessels[58]. Furthermore, large-scale sectoral tools like Australia's TraNSIT allow for the optimization of millions of trips across agriculture and forestry, providing the evidence base for regulatory changes that reduce the environmental impact of these industrial activities[62–64].

The implementation of these green industrial practices depends heavily on governance and project delivery models. While Germany's traditional sequential delivery is criticized for poor planning and risk allocation that can derail environmental targets[65], the Asset Standards Authority in New South Wales promotes a "whole of life" governance model that builds capability across the supply chain to ensure sustainable outcomes[60]. Resilience also acts as a sustainability driver, as structured adaptation guidelines for ports[52] and reliability-oriented routing algorithms[54] prevent the "emissions spikes" associated with infrastructure failure and inefficient reconstruction. This is particularly vital in uncertain environments like the Arctic, where subsystem redundancy is a core requirement[66].

Technological integration, including AI, IoT, and Blockchain, further supports these goals by facilitating real-time traffic management and predictive maintenance, such as Kalman-filter-based pavement diagnosis which extends infrastructure life and reduces the emissions linked to premature replacement[59,67]. However, the transition to sustainable industry remains constrained by local socio-economic factors; for example, infrastructure investments in Vietnam favor international economic linkages [68], while in Kenya, poor transport and stringent regulations on cold supply chains limit the delivery of vital industrial-biological products[69]. Finally, post-disaster recovery research from the Kaikōura earthquake and rural road projects in Bangladesh underscores how coordination in material supply chains is essential to maintaining the long-term sustainability of existing infrastructure systems[53,55].

This cluster shows that deep decarbonization in construction and infrastructure is increasingly pursued through supply chain redesign, including material efficiency, alternative binders, electrification, and low-CO_2 materials. Macro-level analyses link stronger logistics performance with better environmental outcomes, while uncontrolled industrialization aligns with deterioration. Divergence arises in governance models: sequential delivery and risk allocation can undermine sustainability, whereas whole-of-life approaches emphasize capability-building across supply chains.

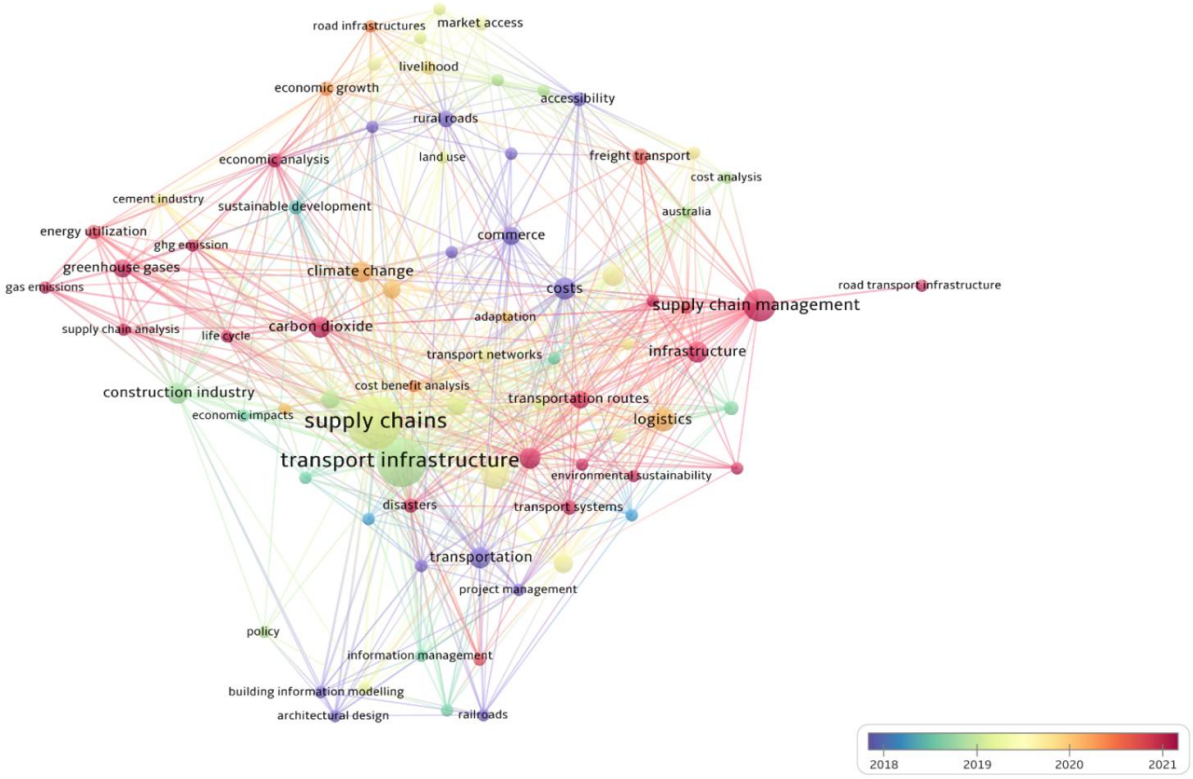


Fig. 3: Keyword co-occurrence network by year

Optimization studies stress system efficiency, while policy analyses highlight enforceability and coordination. A key gap is translating these insights to rural infrastructure in developing contexts, where weaker procurement, monitoring, and data systems limit implementation.

Across the six clusters, three cross-cutting themes recur: (i) a persistent efficiency–resilience trade-off, (ii) the enabling role of data and governance in turning investments into reliable service outcomes, and (iii) the coupling of infrastructure planning with decarbonization and climate adaptation objectives. However, the co-occurrence structure also indicates that rural-road specific evidence, especially in developing-country supply chains.

The above research clusters demonstrate the multifaceted nature of research directions, each examining crucial aspects of infrastructure, transportation, and their socio-economic and environmental impacts. Furthermore, analyzing keywords by year of publication helps to identify emerging focuses. Figure 3 presents the network of keywords by publication year. The analysis shows prominent research on supply chain management and sustainable transport infrastructure development (considering environmental impacts, natural disaster effects, and economic efficiency), in which road transport infrastructure remains a core subject of interest.

5. Discussion

The analysis of the key phrases reveals a comprehensive picture of the research field, in which socio-economic development is inseparable from effective supply chain management and risk reduction. The strong association between keywords such as “economic growth”, “market access” (Cluster 1), and “logistics” (Cluster 3) shows that research often focuses on measuring the economic efficiency of infrastructure investment projects. However, the emergence of the clusters on “risk management” (Cluster 2) and “climate change” (Cluster 5) shows a shift in the perception of scientists: development is not only about growth, but also about sustainability and resilience. The relationship between these clusters implies that future policies need to take an integrated approach, focusing not only on road construction but also incorporating strategies for disaster risk management, climate change adaptation and environmental protection.

Although considerable research has been conducted on rural roads and supply chains, there are still important gaps. The literature has limited studies on the changes in socio-economic impacts of transport infrastructure improvements over time (e.g., system dynamic modeling) and their impact on regional, national, and international supply chains. For example, Filassi, et al. developed 03 strategies that could enhance the performance of agricultural systems and policies for rural development[70]. Kumar, et al. mentioned that rural road density has a positive influence on crop diversification, resulting in livelihood and farm-level output improvement[71]. Furthermore, the complexities of policy implementation and management, which can significantly influence the

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successful integration of rural transport infrastructure into available infrastructure and the development and maintenance of them should be considered. For example, facing to earthquake, Liu, et al. mentioned that there are supply problems for the repair and rebuilding of transport facilities[53]. It is proposed that the post-earthquake recovery policies and material supply chain operation strategies are needed to recover transport networks. Stokeld, et al. studied the responsiveness of stakeholders to cross-border climate risk for the supply chain of soybeans[72]. This study concluded that some responses can reduce risk of impacts across the supply chain by improving transport infrastructure. This suggests a need for more comprehensive analytical research that can capture these multidimensional perspectives. The opportunities still exist for new materials, emerging digital technologies and interdisciplinary management (e.g., construction, IT, logistics, and finance, etc.) frameworks for future studies, requiring research approaches that address technical, ecological and socio-economic issues in rural road development. For example, Aboul-Atta and El-Lebody studied factors affecting successful logistic zones of 38 logistic zones in several countries of the world[73]. This study concluded that the requirement of successful logistic zones includes the integration of factors, such as transport, IT, laws, and finance. Toymentseva, et al. mentioned that transport companies can use digital technologies to optimize flow processes in supply chains, resulting in increasing the profitability[74].

Future research endeavors should focus on creating models that take into account the nature of policies and governance issues in order to better incorporate rural infrastructure with supply chains efficiently. In studies, on sustainability practices, for rural roads construction and design should focus on using recycled materials and eco-friendly technologies to reduce impact and boost economic advantages[49,75,76]. Using cutting-edge technologies could be consider like analysis and intelligent transportation systems to improve the development and maintenance of transportation infrastructure[50,67]. Promoting teamwork, across fields such as engineering, environmental science, IT, economics and public policy is crucial, for tackling the complex issues involved in improving rural roads. Exploring collaboration approaches, like private partnerships in research, is crucial to enhance resource distribution and draw investments for rural infrastructure improvement efforts effectively and sustainably. There are several collaboration approaches, as follows:

5.1. Policy Frameworks & Governance Models

Research finds that robust policy frameworks, emphasizing institutional innovation, diversified investment (government funding plus social capital), urban-rural integration mechanisms, and adaptive governance, are critical for sustainable rural revitalization[77–79]. Studies highlight the need for tailored approaches that consider local contexts while promoting cross-sectoral coordination between government agencies, private sector actors, NGOs, and communities[80–82].

5.2. Sustainable Practices & Eco-Friendly Technologies

The adoption of recycled materials in road construction is shown to reduce environmental impact but faces challenges related to performance prediction and contractual arrangements[83]. Green finance initiatives support sustainable infrastructure by incentivizing innovation in green technology and aligning development with global sustainability standards[84]. Intelligent transportation systems (ITS) are increasingly applied to enhance efficiency, safety, data-driven planning, and environmental outcomes in both urban and rural settings[85,86].

5.3. Digital Solutions & Supply Chain Integration

Digital platforms facilitate value chain integration by enabling full-lifecycle participation among stakeholders—improving transparency, data sharing, monitoring of farm operations (via AI/blockchain), logistics optimization (RFID/GPS), and decision support[77,87,88]. These tools help overcome fragmentation in infrastructure delivery while supporting resilient supply chains capable of adapting to disruptions such as pandemics or climate shocks[89,90](Karmaker et al., 2020; Setyadi et al., 2025).

5.4. Interdisciplinary Collaboration & Public-Private Partnerships

Interdisciplinary collaboration is essential for addressing technical complexity in project-based supply chains; combining contractual (formal) with relational (collaborative) governance improves project performance[91]. PPPs are widely recognized as effective mechanisms for mobilizing resources but require clear roles/accountability structures to ensure equitable risk-sharing and sustainability outcomes[92–94]. Table 3 presents the studies that used integrated approaches from 2022 to 2025.

Based on the results, a research agenda is proposed that prioritizes (i) the use of digital technologies and information systems to enhance supply-chain visibility and coordination under rural connectivity constraints, (ii) sustainability assessments that jointly consider logistics performance, emissions, and land-use trade-offs, and (iii) interdisciplinary designs integrating transport planning, supply-chain operations, and development outcomes. To strengthen comparability and policy relevance, clearer performance metrics should be adopted, and infrastructure quality and maintenance should be explicitly considered, rather than road presence or distance.

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Table 3: Timeline showing evolution of integrated models/policies/technologies for sustainable rural infrastructure

Year	Number of paper	Authors
2025	3	[81,86,95] (Wu & Fang, 2025; Uphoff & Cruz-Miranda, 2025; Cao & Tao, 2025)
2024	4	[80,84,85,96] (Mahmood et al., 2024; Elassy et al., 2024; Awokuse et al., 2024; Yu et al., 2024)
2023	4	[51,88,91,97] (Fan et al., 2023; Eriksson & Pesämaa, 2023; Gebresenbet et al., 2023; Hussain et al., 2023)
2022	3	[98–100] (Kaiser & Barstow, 2022; Qin et al., 2022; Gutiérrez-Vélez et al., 2022)

6. Conclusion

Rural road development plays a key role in strengthening supply chain networks, especially in developing regions where infrastructure is often lacking. By facilitating the efficient movement of goods from production to market, rural roads help to optimize supply chains, making them more cost-effective and responsive to market demands. Improved connectivity between rural and urban areas simplifies logistics, reduces transportation costs and times, and allows producers in remote areas to integrate into broader economic systems, ensuring that products reach consumers more efficiently.

Investing in rural road infrastructure has significant long-term economic and social benefits, including poverty reduction and job creation. Improved roads increase access to health care and education, thereby improving the quality of life and promoting human capital development. Furthermore, better transport networks can stimulate non-agricultural employment opportunities, encourage economic diversification, and attract businesses through improved infrastructure. These improvements can also help reduce rural-urban migration by improving living conditions in rural areas. Future research should aim to build on existing findings by developing comprehensive models that capture the multidimensional interactions between infrastructure improvements and supply chain dynamics, while also considering other social factors such as local community support. Emphasizing sustainable practices and technological innovations, such as the use of recycled materials and intelligent transport systems, can lead to breakthroughs in infrastructure development. Furthermore, interdisciplinary collaboration between engineering, environmental science, information technology, economics, and public policy is needed to create comprehensive and innovative solutions. New cooperation models, including public-private partnerships, will also be needed to efficiently allocate resources and promote investment in rural infrastructure projects.

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