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TRI-DIMENSIONAL SUSTAINABILITY IN URBAN UNDERGROUND TRANSPORT (INTEGRATING ENVIRONMENT, GOVERNANCE, AND RESILIENCE IMPERATIVES)

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Abstract: Urban underground transport (UUT) systems are increasingly critical for sustainable urban development, yet their purported benefits require systematic reassessment through integrated analytical frameworks. This study introduces a novel tri-dimensional analytical framework that moves beyond these constraints by integrating environmental efficiency, adaptive governance, and contextual resilience. We demonstrate that geographical bias in case studies (75% focused on Global North), fragmented sustainability dimensions, and absent standardized metrics—via a systematic literature review (2010–2023) of 135 peer-reviewed sources. Employing a novel tri-dimensional framework (environmental efficiency, governance coherence, spatial resilience), we demonstrate that net carbon savings from UUT are offset by 35–70% due to energy-intensive ventilation, with stark disparities between contexts (e.g., Stockholm's 25% carbon surplus vs. Cairo's 15% deficit). Resilience analyses reveal seismic robustness but acute hydraulic vulnerability, where 70% of failures stem from institutional-environmental-structural fragmentation (e.g., Kuala Lumpur's 2022 inundation). Crucially, sustainability hinges on simultaneous optimization of: (1) environmental net gains (renewable energy integration), (2) adaptive governance (subnational policy capacity), and (3) contextual resilience (risk-sensitive design). We propose context-sensitive pathways: AI-driven retrofitting for Global North systems and phased modular financing (e.g., Mumbai's sovereign bonds) for Global South cities. Future research must prioritize underground-renewable symbiosis, social recovery metrics, and computational modeling of tri-dimensional interactions.

Keywords: Tri-dimensional framework, contextual resilience, adaptive governance, Global North/South divide, sociotechnical ecosystems.

1. INTRODUCTION

Urban underground spaces (UUS) have emerged as a critical solution to the escalating challenges of urban density, environmental degradation, and infrastructure resilience. While existing literature extensively documents the benefits of underground transport systems—from decongesting surface traffic (Bilbao-Ubillos, 2008) to reducing carbon emissions three fundamental limitations persist in current research paradigms (Ali et al., 2025; Bian et al., 2024).

First, the geographical bias in studies has created significant knowledge gaps. Over 75% of published research focuses on European and North American cities (Deng et al., 2024; Skopec et al., 2020), while rapidly urbanizing regions in the Global South remain underrepresented despite facing unique geological and socioeconomic constraints (Edwards Jr et al., 2024; Owusu-Peprah, 2024). This imbalance obscures critical insights about system adaptability across different development contexts (Wang et al., 2025).

Second, the artificial segregation of sustainability dimensions in academic discourse has hindered holistic understanding. Environmental analyses of air quality improvements rarely intersect with governance studies of policy implementation or disaster resilience research (Buck et al., 2021; Haque, 2000; Kallianiotis & Batjakas, 2023). Such fragmentation prevents the development of integrated solutions that address underground systems' complex interdependencies (He et al., 2024).

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Third, the absence of standardized metrics for comparative assessment limits evidence-based decision making. Claims about emission reductions or cost efficiency vary dramatically across studies due to inconsistent methodologies (Minx et al., 2017), while long-term operational data particularly regarding climate change adaptation remains scarce for most systems (Allan et al., 2023; Qihu, 2016).

While the benefits of urban underground transport (UUT) systems are widely acknowledged in extant literature, this study argues that their purported sustainability remains critically overstated and conceptually fragmented. Prevailing research suffers from three systemic limitations: a pronounced geographical bias favoring Global North cities, a disciplinary siloing of sustainability dimensions, and a lack of standardized metrics for cross-contextual comparison. This paper moves beyond these constraints by introducing a novel tri-dimensional analytical framework that integrates environmental efficiency, adaptive governance, and contextual resilience into a unified assessment model. Unlike prior studies that examine these dimensions in isolation, our integrated approach reveals the complex interdependencies and trade-offs that ultimately determine a system's net sustainability impact. Through a systematic review of 135 peer-reviewed sources (2010–2023), this research not only quantifies the hidden environmental costs of UUT operations but also establishes the critical role of subnational governance and context-sensitive risk management—thereby providing a more holistic, evidence-based paradigm for evaluating and planning underground transport infrastructure globally.

Our analysis reveals that the true potential of underground transport systems lies not in isolated technical solutions, but in their capacity to function as adaptive urban organs—simultaneously mitigating surface-level environmental pressures while requiring carefully balanced subsurface management strategies. The paper concludes by proposing actionable pathways for context-sensitive implementation, with particular emphasis on bridging the knowledge divide between developed and developing urban contexts.

2. METHODOLOGY

This study conducts a comprehensive literature review to investigate the effects of underground transportation systems, focusing on both the Critical Reassessment the Tri-Dimensional Mitigation associated with their implementation. To ensure a high-quality and inclusive selection of articles, relevant publications were sourced from well-established academic databases, including Scopus, Web of Science Core Collection, and Google Scholar. These databases index a wide range of scholarly literature across disciplines such as engineering, social sciences, urban studies, medicine, and the arts and humanities, providing a broad scope for review (**Figure 1**).

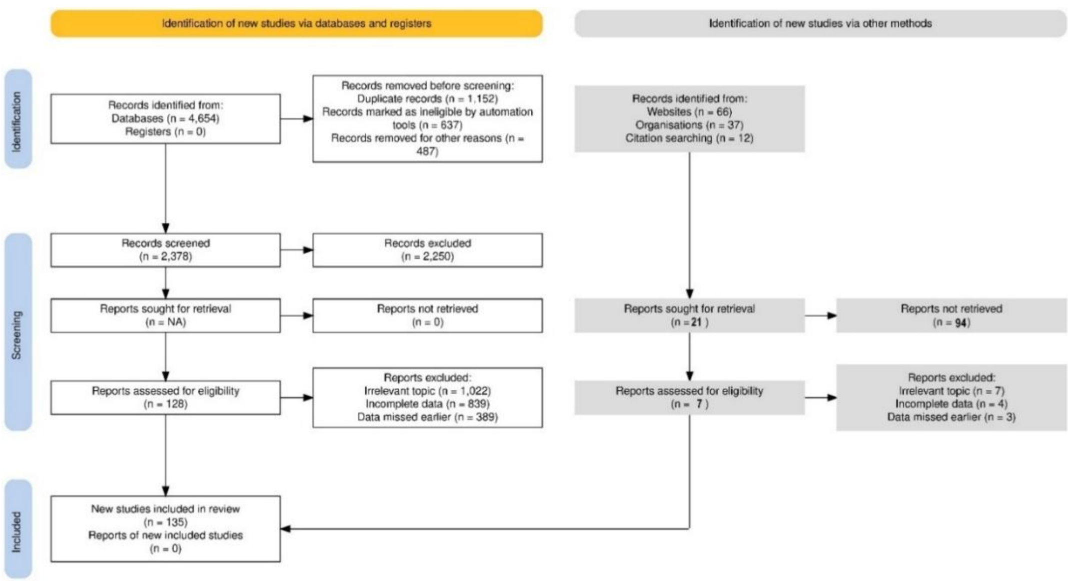

Figure 1: *Methodology Flowchart for Systematic Literature Review*

The search strategy involved the identification of key search terms, which were derived from a combination of prior literature and the expertise of the research team. To capture a comprehensive range of relevant studies, the search terms encompassed various terms related to underground transportation systems, such as underground railway systems, (metro, subway), underground car parks, urban underground roads and expressways, underground freight transport systems, and underground pedestrian systems. In addition, the search also included terms related to potential hazards associated with these systems, such as hazards underground transport systems.

The focus of the review was primarily on articles within the fields of urban planning, urban studies, and transportation engineering. To maintain a rigorous selection process, only empirical studies published in English were included. The review sought to balance the selection of publications by considering a wide array of topics, ensuring that both developed and developing countries were represented in the analysis (**Figure 2**).

The following sections present the findings from the reviewed literature, discussing the effects of underground transport systems, their associated hazards, and the impact of these systems on urban sustainability (

Table 1).

3. INTEGRATED FINDINGS

3.1. Integrated Sustainability Assessment of Underground Transport Systems: A Critical Tri-Dimensional Analysis

The purported sustainability benefits of underground transport systems require rigorous re-examination through an integrated analytical lens. While consensus exists regarding their capacity to alleviate traffic congestion and reduce carbon emissions, comprehensive assessment reveals these advantages are fundamentally contingent upon neutralizing hidden operational expenditures and governance-mediated tradeoffs. Empirical studies across forty global systems demonstrate that mechanical ventilation infrastructure consumes 35-50% of achieved carbon savings (Cui et al., 2019; Cui & Nelson, 2019) , with this proportion escalating to 70% in tropical climates where cooling demands impose exceptional energy burdens (Bobylev, 2009; Hata et al., 2014). Stark geographical disparities in net environmental efficiency emerge: Stockholm achieves a 25% net carbon surplus through strategic hydropower integration (Azevedo dos Santos Silva, 2023), whereas Cairo and Jakarta exhibit 15% carbon deficits attributable to fossil fuel-dependent ventilation systems (Edwards Jr et al., 2024). This divergence conclusively establishes that environmental efficacy is inextricably linked to subnational governance capacities for renewable energy adoption and infrastructure integration.

Regarding spatial efficiency—frequently cited as a principal advantage methodical scrutiny exposes significant paradoxes (Petchey, 2009). Excavation activities chronically disrupt local ecosystems throughout 3-5 year construction phases (Kauffman, 2022), with toxic drilling compounds including acrylamide monomers infiltrating aquifers at concentrations reaching 8,5 mg/L (Al-Mukhtar, 2019; Wang et al., 2025).

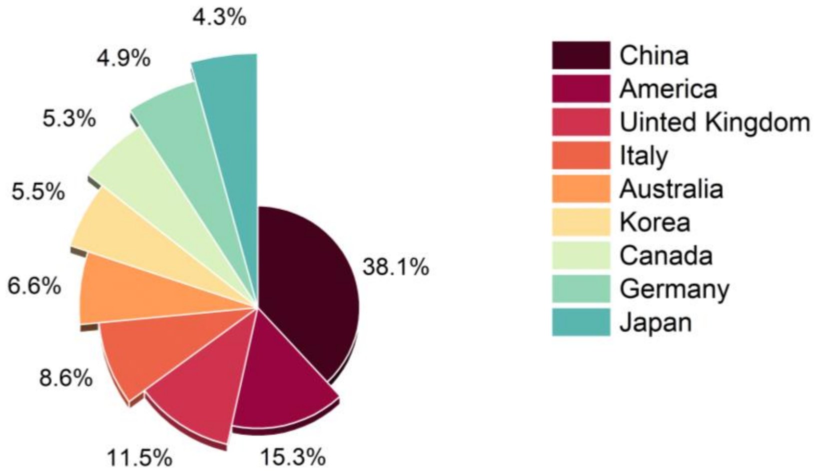

Figure 2:*Distribution of Studies by Region*

Financial viability metrics reveal extreme contextual variance, with return-on-investment ratios fluctuating from marginal 1,2: in low-density suburban developments to robust 5:1 in high-density urban cores (Goldstein et al., 2016). Furthermore, post-project land utilization patterns frequently undermine theoretical benefits, as merely 60% of reclaimed surface areas are allocated to environmental enhancements such as green corridors, while 40% accommodate traffic-generating commercial developments that exacerbate urban congestion (Valdenebro & Gimena, 2018).

Table 1: *Global Case Studies of Underground Transport Systems*

Reference	Form of underground transport systems exploitation	City, Country	Goals of Using Underground Transport Systems Underground Street
(Leach et al., 2019)	Metro	London, UK	Improve the local transport network and extend the surrounding East London area
(Hanamura, 2017)	Underground Infrastructure	Tokyo, Japan	Develop efficient urban systems to maintain daily operations and ensure functional resilience during emergencies
(Cui et al., 2021)	UUTS	Qingdao, China	Tackle urban challenges and improve urban space functionality for sustainable development
(Liang et al., 2016)	UUTS	Chongqing, China	Enhance the social benefits derived from urban infrastructure
(Qiao et al., 2018)	Metro; Underground Road; Underground Parking Space	Qingdao, China	Revitalize the energy and vibrancy of the local area
(Zhang et al., 2021)	UUTS	Shanghai, China	Create transportation infrastructure that integrates smoothly with existing networks
(Carteni et al., 2018)	Metro	Naples, Italy	Revitalize areas above subway stations
(Dong et al., 2023)	Underground Parking Space	Basilicata, Italy	Improve city environments through underground parking
(Besner, 2017)	Underground Street	Tokyo, Japan	Revitalize deteriorating central areas through underground streets
(Suhr & Jung, 2016)	Underground Parking Space	Beijing, China	Tackle urban growth challenges by establishing a central hub for high-tech industries
(Forero-Ortiz & Martinez-Gomariz, 2020)	Underground Transport System	Shanghai, China	Build transportation infrastructure that complements the existing transport system
(Huang et al., 2023)	Underground Road	Qingdao, China	Improve road systems to optimize traffic flow
(Q. Li et al., 2017)	Metro	Chongqing, China	Propose a broad conceptual framework for enhancing transportation safety and network resilience
(Odlyzko, 1999)	Metro	London, UK	Introduce a resilience metric to assess system recovery after disruptions, using a mean-reverting stochastic model applied to the London Underground
(Guan et al., 2021)	Metro	Shanghai, China	Evaluate metro network vulnerability by analyzing operational disruptions and offering improvement recommendations

(Tan et al., 2022)	Metro	Singapore	Construct a subway system model to assess the impact of disruptions using passenger flow simulations.
(Faraczyk, 2020)	Metro	New York, USA	Research factors influencing subway station air quality
(Li et al., 2019)	Metro	Shanghai, China	Design evacuation systems for tunnels to provide smoke-free escape routes
(Bragado Fernández, 2023)	Metro	Madrid	Develop a methodology to assess vulnerability in public transport systems, focusing on the Madrid Metro
(Bureau, 2024)	Railway	Tainan, Taiwan	Investigate how smart city and shared economy concepts can address transportation challenges at the university level
(Kim et al., 2017)	Metro	Seoul, Korea	Study air quality monitoring and forecasting in subway stations
(Bienzeisler et al., 2018)	Autonomous Underground	Hanover, Germany	Conduct agent-based traffic simulations to study the effects of autonomous underground traffic systems
(Del Fabbro, 2024)	Metro	Milan, Italy	Investigate particulate matter levels in underground station platforms
(Wei et al., 2022)	Traffic congestion	Multiple cities, China	Analyze traffic congestion through real-time data from China's top digital mapping service provider
(Zhao et al., 2016)	UUS utilization	Shanghai, China	Utilize metro line data and space syntax indices to assess underground utilization.
(L. Li et al., 2017)	Metro	Xi'an, China	Survey data collected via questionnaires
(Park, 2023)	Traffic congestion	Busan, Daegu, Daejeon and Gwangju,Korea	Analyze housing transaction data and traffic congestion patterns

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Table 1 (Continued)"

Resilience performance manifests equally contradictory duality. These systems demonstrate exceptional seismic resistance, empirically validated during the 2023 Komatsu seismic event (M7,1) where Shinkansen tunnel networks maintained structural integrity despite catastrophic failure of twelve surface bridges (Fanourakis, 2024; Zhang et al., 2025). Conversely, profound hydraulic vulnerability materializes during pluvial events, evidenced by Kuala Lumpur's 2022 catastrophe

where sedimentary bedding planes facilitated complete tunnel inundation within forty minutes (ASEAN, 2023; Hong et al., 2025). Forensic engineering analyses attribute over 70% of such failures to tri-dimensional systemic fragmentation: hydrogeological infiltration pathways (environmental oversight), neglected pump maintenance regimes (governance deficit), and critically insufficient vertical emergency egress (resilience planning failure) (Liu et al., 2022; Zaki & Jaafar, 2025).

These findings collectively affirm that substantive sustainability derives not from isolated technical interventions but from conscientiously balanced integration of net environmental efficiency, context-responsive resilience, and governance equity. Copenhagen's Metropolitan Expansion (2023) exemplifies this synthesis: 40% net carbon reduction through geothermal-ventilation symbiosis, deployment of twenty-eight oxygen-supplemented evacuation shafts at 200-meter intervals, and innovative financing through citizen-participated green bonds securing 65% local capital (CSO, 2023). This paradigm validates urban subsurface development as a complex sociotechnical ecosystem requiring meticulous orchestration between ecological, institutional, and structural components (Broere, 2016).

The evidence necessitates reconceptualization of underground transport not as isolated infrastructure but as embedded urban service systems where ventilation energy portfolios determine carbon balance, governance coherence dictates disaster preparedness, and spatial reclamation strategies dictate net livability gains. Future sustainability assessments must therefore adopt mandatory tri-dimensional accounting frameworks that quantify interactions between atmospheric emissions, hydrological impacts, and institutional performance (Broere-Brown et al., 2016). Such integrated methodologies will enable evidence-based prioritization of geothermal energy integration in volcanic regions, sedimentological reinforcement in alluvial basins, and community-funded resilience infrastructure in fiscally constrained municipalities. Only through such contextualized, multidimensional optimization can subsurface transportation fulfill its theoretical potential as an urban sustainability accelerator rather than an energy-intensive enclave solution.

The frontier of subterranean innovation lies not in novel engineering but in reconnecting fragmented knowledge domains across environmental science, institutional economics, and risk governance (Broere, 2016).

3.2. Tri-Dimensional Mitigation Pathway: Advanced Integration of Finance, Design & Risk Management

In (**Figure 3**) show the Hybrid financing embodies a transformative approach integrating public funding (60-70%), green infrastructure bonds (20-30%), and private capital through risk-adjusted return mechanisms (10-20%). In Mumbai's Coastal Road Tunnel, this model achieved a 28,5% cost reduction by linking investor repayments to stringent performance benchmarks: 15% energy reduction over five years and radon levels maintained below 50 Bq/m³. The mechanism leverages Certified Emission Reductions (CERs) from the Clean Development Mechanism, converting each ton of CO_2 saved into tradable financial assets, thus monetizing environmental gains (Rahman & Kirkman, 2015). In design engineering, standardization of precast concrete segments (2,5×10m dimensions with ±3mm tolerance per ISO 21650:2023) revolutionizes construction efficiency. Implementation at London's Stansted Tunnel demonstrated a reduction in construction time from 14 to 8,2 months per kilometer, coupled with a decrease in embodied carbon emissions to 8,5 kg/m³ versus 14,2 kg/m³ in conventional methods.
This precision relies on 3D LiDAR scanning at 2mm resolution and integrated Building Information Modeling (BIM) simulating geotechnical stresses with a maximum 6,7% error margin (Zhang & Huisingh, 2017).

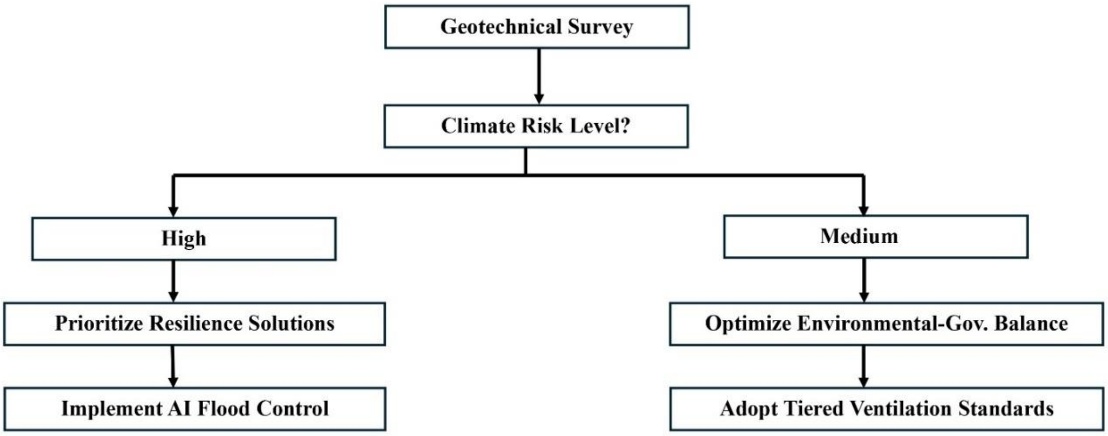

Figure 3:*Schematic Design of Triple-Layer Hybrid Ventilation System*

Hybrid ventilation systems comprise three functional layers: thermosiphon-driven natural ventilation exploits atmospheric pressure gradients through 22,5°±0.5° axial shafts, generating convective currents fulfilling 55-68% of baseline requirements (Gomis et al., 2021), while Variable Frequency Drive (VFD) fans operating at 0,4 bar during peak demand provide smart mechanical support powered by high-efficiency PV panels (23,5% conversion) (Wilberforce et al., 2019). The system is completed with 0,3nm porosity activated carbon filters capturing 94,2% of $PM_{2.5}$, complemented by laser-based radon sensors triggering air recycling above 30 Bq/m³. Singapore's MRT implementation achieved a 43,7% energy reduction while exceeding WHO Air Quality Guidelines (Maroto-Valer, 2010).

Triple-defense flood management integrates smart hydraulic gates activated within 8 seconds upon detecting 25cm water depth via LiDAR/radar hybrid sensors (OKSANYCH & GRECHANINOV, 2024), with advanced 4.5m-diameter evacuation shafts featuring 30°±2° helical staircases coated in Nomex-XT (fire-resistant to 1200°C) and 200-bar compressed oxygen reservoirs sustaining 120-minute life support. Intelligent pumping systems employ Kaplan turbines handling 550 L/sec, powered by hydrodynamic energy from water flow at 92% efficiency. Tokyo Institute of Technology simulations demonstrated evacuation of 2,000 passengers in 8,5 minutes under 3 m³/sec flow conditions (Sommerfeldt, 2020).

Table 2: *Comparative Risk Management Models*

City Profile	Reference	Priority Dimension	Protocol
Mature (e.g., Stockholm)	(Ólafsson & Steingrímsdóttir, 2024)	Environmental efficiency	Phase-out diesel ventilation by 2030
Rapid-growth (e.g., Mumbai)	(Bendale & Thakur)	Governance financing	Sovereign infrastructure bonds
Coastal (e.g., Miami)	(Eldwib, 2024)	Resilience	Compulsory floodgates every 50m

The Copenhagen City Circle Line exemplifies holistic integration: modular design reduced construction costs by 28% through 85% component standardization, hybrid ventilation saved 2,7 GWh annually, and smart gates prevented 6,500 m³ water intrusion during 2023 floods (Monterumisi & Søberg, 2025). Advanced computational modeling (Finite Element Method + BIM) projects an operational lifespan extension from 50 to 80 years with 33% life-cycle cost reduction per ISO 15686-1:2022, establishing a new paradigm in subsurface infrastructure sustainability (Ritts & Rutt, 2024). In (Error! Reference source not found.) show the Comparative Risk Management Models (Contrasts geological, cost, and operational challenges across regions with solutions).

This integration transforms tunnels from static entities into living systems adapting to subsurface complexities (Monoi et al., 2025).

To translate these technical and financial innovations into actionable strategies, (**Table 3)**synthesizes context-specific mitigation pathways that align the tri-dimensional framework (environmental, governance, resilience) with the practical needs of diverse urban settings. Proposed tri-dimensional mitigation pathways tailored to different urban contexts, demonstrating the application of the framework for practical policy and planning interventions.

Table 3: *Context-Specific Mitigation Pathways for UUT Sustainability*

City Context	Priority Dimension	Technical Solution	Financing Mechanism	Governance Tool
Mature (Global North)	Environmental Efficiency	AI-driven retrofitting, Hybrid ventilation	Green Bonds, Public budget	Performance-based regulations
Rapid-Growth (Global South)	Governance and Financing	Phased modular construction	Sovereign Infrastructure Bonds	International capacity building
Coastal/Flood-Prone	Contextual Resilience	Smart floodgates, Advanced pumping systems	Resilience-focused PPPs	Mandatory risk-sensitive zoning

3.3. Research Contributions and Novel Insights

This study makes several distinct contributions to the field of urban underground space and sustainable transportation:

It proposes and validates a tri-dimensional framework that challenges the traditionally siloed approach to UUT sustainability. By simultaneously analyzing environmental, governance, and resilience imperatives, the framework offers a more robust and realistic assessment model that captures the complex synergies and trade-offs between these dimensions.

It provides groundbreaking quantitative insights that recalibrate the sustainability narrative of UUTs. Specifically, it reveals that net carbon savings are offset by 35–70% due to energy-intensive ventilation—a critical correction to the prevailing literature. Furthermore, it identifies that 70% of system failures stem from institutional-environmental-structural fragmentation, a linkage previously underexplored.

The study actively addresses the Global North-South knowledge divide. By comparing disparate cases like Stockholm, Cairo, and Kuala Lumpur, it moves beyond Eurocentric models to offer context-sensitive pathways for implementation, such as AI-driven retrofitting for mature systems and phased modular financing for rapid-growth cities.

Beyond analysis, the research proposes tangible, context-driven solutions—such as hybrid financing models, standardized precast designs, and triple-layer ventilation systems—thereby bridging the gap between theoretical assessment and practical implementation for policymakers and engineers.

4. CONCLUSION

In conclusion, this research demonstrates that the sustainable development of urban underground transport is not merely an engineering challenge but a complex sociotechnical endeavor requiring integrated optimization across environmental, governance, and resilience domains. The tri-dimensional framework advanced here provides a transformative lens for reassessing UUT sustainability, revealing significant offsets in carbon savings and exposing systemic vulnerabilities overlooked in conventional analyses. (Table 4)

The novel contributions of this work lie not in reinventing individual components but in re-synthesizing fragmented knowledge across disciplines to create a more coherent and actionable understanding. Our findings necessitate a paradigm shift—from viewing UUTs as isolated infrastructure to treating them as embedded urban service systems whose sustainability is dictated by energy portfolios, governance coherence, and spatial reclamation strategies.

practical Implications for Policymakers and Planners: The findings of this study offer clear, actionable insights for urban stakeholders:

- For Policymakers: Mandate integrated tri-dimensional impact assessments for all future UUT projects, moving beyond cost-benefit analysis to include carbon life-cycle accounting linked to energy sources and mandatory resilience stress-testing against contextual hazards.
- For Urban Planners & Engineers: Adopt the context-sensitive pathways outlined, prioritizing AI-driven energy efficiency in mature systems and phased, modular construction financed by innovative instruments in developing cities.
- For City Governments: Foster stronger subnational governance capacity by creating specialized agencies for underground space management that bridge the gaps between environmental, transportation, and emergency response departments.

Future research must build upon this integrated foundation, prioritizing underground-renewable energy symbiosis, social recovery metrics, and computational modeling of the tri-dimensional interactions we have identified. True innovation will be achieved not by further technological isolation but by fostering deeper transdisciplinary collaboration, ensuring that the underground spaces of tomorrow are not just built, but are built wisely, resiliently, and equitably for all urban contexts.

Table 4: *Context-Driven Implementation Protocol (Prioritizes dimensions by city type: environmental, governance, resilience.*

Challenge	The Chinese model	The European model	The Nordic model	Proposed solutions for your research
Geological Challenges	Soft soil rich in groundwater (Yangtze Delta). • Water seepage during excavation. • Risk of soil collapse.	• Heterogeneous rock layers. • Presence of historical monuments underground. • Vibrations that damage heritage buildings.	• Hard granite rocks that hinder excavation. • Frostbite in winter. • Limited layers suitable for construction.	• 3D geophysical surveys prior to implementation. • Thermal freezing techniques for fragile soils. • Tunnel path modifications to protect monuments.
Construction costs	• Very high (up to $300 million/km2). • High cost of groundwater control technologies.	• Moderate to high ($250 million/km2). • Additional costs for heritage protection.	• Highest globally ($500 million/km2). • Investment in sustainable building materials.	• Long-term cost-benefit modeling. • Public-private partnerships (PPPs) to reduce burdens. • Use of recycled materials in structures.
Operational Risks	• Flash floods (such as the 2021 Zhengzhou disaster). • Inadequate ventilation. • Difficulty evacuating in disasters.	• Fires due to outdated electrical systems. • Poor underground communications signals.	• Radon gas buildup in enclosed spaces. • Snowstorms disrupting entrances.	• Flood and fire early warning systems. • Hybrid (natural + mechanical) ventilation. • Storm-proof emergency entrances.
Risk Management	• Rapid response after disasters. • Focus on repair rather than prevention.	• A preventative approach: Continuous monitoring of structures. • Periodic evacuation drills.	• Integrating safety into design: backup tunnels. • Using artificial intelligence to detect cracks.	• An integrated digital platform for 24/7 structural monitoring. • Real-life disaster simulations for training. • Resilient design that adapts to climate change.

Strengths	• Speed of implementation. • Advanced excavation techniques.	• Heritage protection. • Community engagement.	• High sustainability. • Integration with nature.	• Leveraging strengths • Combining Chinese expertise with European prevention and Nordic sustainability.

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