



## Review Article

## Low-carbon efforts for underground space development in Singapore

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**Abstract**

Singapore, a land- and resource-scarce nation, serves as a global example of how low-carbon initiatives can drive the sustainable development of underground space in densely populated urban environments. This critical review highlights major low-carbon efforts from both academia and the industry over the past decade, along with supportive policies that integrate these efforts into governance and decision-making processes. These efforts, including cutting carbon emissions through material efficiency, shaping carbon emissions through digitalized construction, and tracking carbon emissions through sustainable operation, not only reflect the national efforts to carbon reduction across the full lifecycle of underground infrastructure but also offer valuable insights for similar urban settings worldwide. Furthermore, the review identifies the development of a well-defined framework for lifecycle carbon assessment as an overarching trend to promote carbon reduction in underground space development. However, significant challenges remain, such as the need for comprehensive data collection and integration, as well as a deeper understanding of how human behavior interacts with operational efficiency. Addressing these challenges requires interdisciplinary collaborations among government agencies, academic researchers, and industry practitioners to develop robust frameworks and dynamic models that more reliably capture the impact of low-carbon strategies on urban underground environments.

**Keywords:** Underground space development; Low-carbon efforts; Carbon emissions; Singapore

**1 Introduction**

Singapore stands as a global model in addressing the challenges and opportunities of low-carbon efforts for underground space development, demonstrating how emerging technologies can drive sustainable urban growth in a densely populated environment. As a land-scarce nation, Singapore has increasingly turned to underground solutions to accommodate its growing demands for infrastructure, utilities, and storage while optimizing land use. In 2019, the Urban Redevelopment Authority launched the Singapore Underground Masterplan to unlock the potential of underground space, showcasing how strategic urban planning can maximize land efficiency in a highly urbanized area. Low-carbon efforts play a crucial role in this vision,

aligning seamlessly with Singapore's Smart Nation Initiative, launched in 2014. This initiative harnesses cutting-edge technologies from the Fourth Industrial Revolution to enhance sustainability, efficiency, and resilience in urban development. Furthermore, Singapore's commitment to achieving net-zero carbon emissions by 2050 underscores the significance of adopting low-carbon efforts in infrastructure projects. To support this goal, the Building and Construction Authority (BCA) introduced the Singapore Green Building Masterplan, which targets 80% of green buildings, 80% of new developments to achieve super low energy status, and 80% of improvement in energy efficiency for best-in-class buildings. These efforts reinforce Singapore's position as a pioneer in integrating sustainability with urban development.

Over the decades, underground space development in Singapore has transitioned from labor-intensive manual work to advanced intelligent machinery. One example is

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the tunnel boring machine (TBM), which has revolutionized underground excavation by dramatically improving construction efficiency while minimizing geological risks. The automation of mechanized tunnelling, powered by artificial intelligence and machine learning, reduces reliance on human judgment by machine operators, enhancing precision and safety in complex underground environments (Mostafa et al., 2024). Additionally, the building information modeling (BIM) has become a mandatory standard for underground projects, facilitating seamless design coordination, risk assessment, and project management through highly detailed digital representations of underground structures (Ho & Rajabifard, 2016). Similarly, the digital twin technology has transformed underground engineering by creating real-time, data-driven digital replicas of construction projects. By integrating sensor data and monitoring systems, this technology enables predictive maintenance, enhances risk management, and improves project efficiency (Yan et al., 2019). Furthermore, robotic systems remarkably contribute to the inspection and maintenance of sewer systems, enhancing safety and efficiency by reducing human exposure to hazardous environments (Seet et al., 2018). These technological advancements not only signify a paradigm shift toward more sustainable and resilient underground space utilization but also contribute to urban planning and development (Bobylev et al., 2023; Wei et al., 2024).

This study presents a critical review of low-carbon efforts for underground space development in Singapore over the past decade. While global interest in low-carbon infrastructure is growing, systematic reviews specifically addressing underground space development remain limited. Particularly, cohesive frameworks are needed to tackle the unique challenges of densely populated environments like Singapore. These contexts require a well-integrated approach that balances material efficiency as well as underground design and construction to achieve carbon-neutral goals. To assess the effectiveness of Singapore's approach, this review adopts a thematic analysis focusing on three representative efforts, including cutting carbon emissions through material efficiency, shaping carbon emissions through digitalized construction, and tracking carbon emissions through sustainable operation. These efforts not only reflect major technological advancements globally

but also demonstrate Singapore's proactive approach in adopting and localizing engineering innovations for underground space development.

## 2 Cutting carbon emissions through material efficiency

### 2.1 Low-carbon materials

Low-carbon materials are becoming increasingly important in underground construction to reduce environmental impact and support urban sustainability. This is particularly vital for resource-scarce countries like Singapore, where reusing waste materials is crucial to ensuring a supplementary supply of construction resources and reducing dependency on imported raw materials. Table 1 lists representative low-carbon materials that have been used in engineering projects in Singapore. For example, supplementary cementitious materials, such as slag and fly ash, partially replace traditional Portland cement (Goh et al., 2003; Wu et al., 2010), not only decreasing the consumption of energy-intensive Portland cement but also lowering the associated carbon emissions. Geopolymer cement, produced from industrial by-products like rock powder and metakaolin, provides another low-carbon alternative to conventional concrete. These materials retain comparable strength and durability while reducing the environmental footprint of construction activities (Lahoti et al., 2017). Figure 1 illustrates the microstructures of different types of low-carbon concrete, highlighting the effectiveness of incorporating waste or low-carbon materials in improving pore structures and concrete performance. In addition to cement alternatives, the use of recycled aggregates, such as crushed concrete, plays a key role in sustainable construction by minimizing reliance on natural aggregates and reducing waste sent to landfills (Ho et al., 2013; Silva et al., 2019). Incorporating such aggregates supports resource efficiency and aligns with the principle of a circular economy, which prioritizes reuse and recycling to extend the lifecycles of construction materials.

The development of low-carbon materials not only reduces Singapore's dependence on imported raw materials but also strengthens the nation's commitment to addressing climate change. Innovative materials like bio-cement, produced through microbial-induced calcite precipitation,

Table 1  
Low-carbon materials and applications in construction works in Singapore.

Low-carbon material	Application	Reference
Supplementary cementitious material	Municipal fly ash to partially replace traditional Portland cement	Goh et al. (2003)
Geopolymer cement	Rock power to densify geopolymer binder	Lahoti et al. (2017)
Bio-cement	Bio-grouting for soil and rock reinforcement	Pan et al. (2020)
3D printed concrete	3D concrete printing with steam and CO <sub>2</sub> injection	Tay et al. (2024)
Carbon-sequestering additive	Biochar to sequester CO <sub>2</sub> in cement mortar	Gupta et al. (2018)
Recycled aggregate	Concrete production using recycled aggregates	Shan et al. (2017)

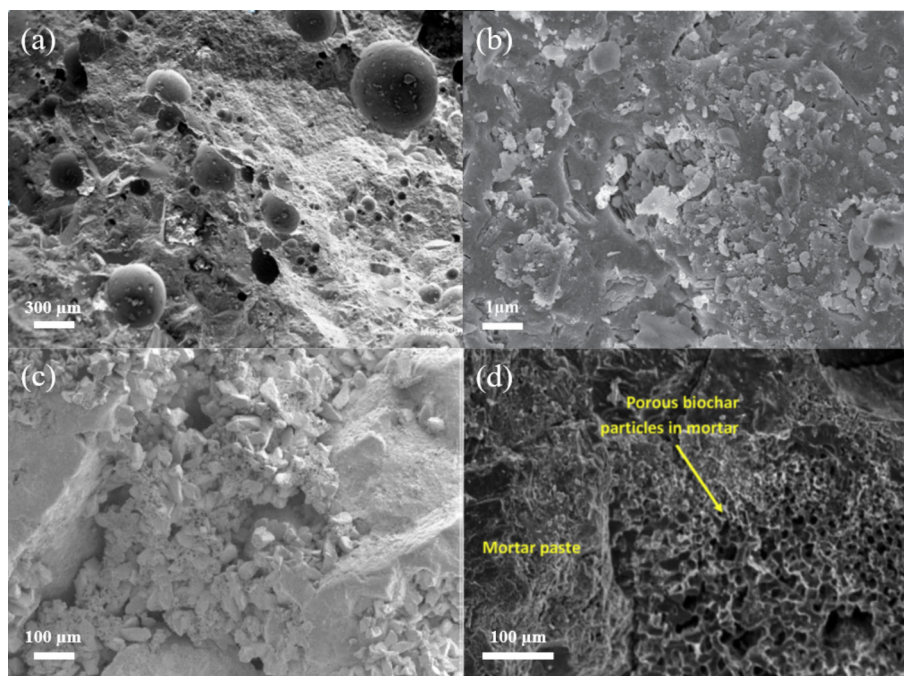


Fig. 1. (a) Copper slag-reinforced concrete, (b) rock power-densified geopolymer, (c) bio-cemented sands, and (d) biochar-hardened mortar paste (Wu et al. (2010), Lahoti et al. (2017), and Gupta et al. (2018); reproduced with permission, courtesy of Elsevier. Pan et al. (2020); reproduced with permission, courtesy of Jian Chu).

are paving the way for more sustainable construction practices. By facilitating carbon sequestration, bio-cement significantly contributes to climate change mitigation (Pan et al., 2020; Wu et al., 2019). The powered form of bio-cement demonstrates excellent flowability when mixed with water, making it an ideal material for grouting applications. It is particularly effective in sealing porous soils and fractured rocks. Additionally, advanced carbon technologies, such as carbon capture and mineralization, present a promising solution for tackling carbon emissions from flue gases generated from incineration plants. This process captures  $\text{CO}_2$  and converts it into solid carbonates or sands, which can then be repurposed for land reclamation (Khoo et al., 2011). However, improving the energy efficiency and carbon abatement potential of this process remains a key challenge. Incorporating innovations, like recycling waste heat from other industries, and leveraging renewable energy, like utilizing geothermal energy, could

substantially reduce the energy demands of carbon capture systems (Muhd Nor et al., 2016; Khoo et al., 2021).

## 2.2 Rock-breaking technologies

Unlike underground excavation in soil formation, the fracturing and fragmentation of hard rocks are among the most energy-intensive processes in underground engineering. These processes often require a large amount of energy and cause significant environmental impacts, such as noise, vibration, and dust pollution. Significant efforts have been devoted to advancing rock-breaking technologies to reduce energy consumption while minimizing environmental impact. Table 2 summarizes a range of rock-breaking technologies, including recently developed technologies as well as innovative enhancements of existing technologies.

Table 2  
Emerging rock-breaking technologies in rock mechanics research.

Rock-breaking technology	Application	Reference
Microwave heating	Microwave heating before mechanical breakage	Ma et al. (2022)
Flame jet-water cooling	Thermal spalling due to rapid heating and cooling	Li et al. (2024)
Abrasive water jet	High-pressure water combined with abrasive particles	Li et al. (2022)
High-voltage electric pulse	Shock wave through expansion of a plasma channel	Kang et al. (2025)
High-energy laser pulse	Thermal cracking through melting and vaporization of rock materials	Rui and Zhao (2021)
Expansive mortar	Dynamic amplification of expansion pressure	Wang et al. (2022)
Acid treatment and quartz abrasion	Energy-efficient rock abrasion inspired by bivalve burrowing	Guo and Wu (2025)

In Singapore, competent rocks, such as Bukit Timah granite and deep Jurong sedimentary rocks, are of high quality and well-suited for tunnel and cavern construction. However, traditional drill-and-blast methods often generate high levels of vibration and noise, which can disturb nearby residents and, in some cases, exceed regulatory limits. These disturbances pose considerable risks to surrounding infrastructure, underscoring the urgent need for alternative rock-breaking solutions. Recognizing the need for more sustainable and efficient approaches to rock excavation, Singapore's academic and industrial sectors have shown strong interest in developing and implementing novel rock-breaking technologies, such as expansive mortar and microwave fracturing.

Expansive mortar, originally developed as a soundless demolition agent for concrete removal, has recently been adapted for deep rock excavation due to its ability to fracture rock with minimal noise and vibration. However, the expansive pressure generated by calcium oxide hydration is often insufficient to overcome the high strength of confined rocks. To address this challenge, recent studies have explored the dynamic amplification of expansive pressure to enhance rock failure. When the expansive mortar is introduced into rock voids or joints, it generates internal pressure that partially weakens the rock structure. Under dynamic loading, the expansive pressure is further intensified, accelerating the fracturing process and promoting rock failure (Wang et al., 2022). Figure 2(a) highlights the underlying mechanism of the dynamic amplification of expansive pressure. The horizontal and vertical axes, i.e., brittleness indices  $K_1 = \frac{M_p - E_u}{M_p}$  and  $K_2 = \frac{E_u}{M_p}$ , quantify the post-peak rupture energy relative to withdrawn elastic energy and the released elastic energy relative to withdrawn elastic energy, respectively, where  $E_u$  is the unloading elastic modulus, and  $M_p$  is the post-peak modulus. While the intact and hollow granite discs typically exhibit brittle failure under dynamic loading, the discs filled with the expansive mortar demonstrate a transition to ductile failure, generating dense cracks and small fragments. The experimental results indicate that expansive mortar combined with dynamic loading enhances the efficiency of rock fracturing and fragmentation.

Microwave fracturing has emerged as a promising and viable alternative for rock breaking. Microwave energy generates thermal stress within rock structures, leading to controlled fracturing and eliminating the need for traditional mechanical methods. Recent advancements have focused on optimizing the design of dielectric-loaded converging waveguide antennas (Fig. 2(b)), which improve the effectiveness of microwave fracturing by fine-tuning maximum temperature, high-temperature volume, and effective working distance (Ma et al., 2022). The efficiency of rock fracturing is also influenced by the optimal selection of antennas based on both the rock fracturability index and the total microwave power (Ma et al., 2024). Despite these advancements, further development is needed

to adapt microwave fracturing for industrial-scale applications, particularly for breaking abrasive and massive rocks.

Besides rock-breaking technologies, the utilization of excavated materials effectively reduces carbon emissions during underground construction. The reuse of excavated rocks and soils as backfill or raw materials not only minimizes waste generation but also reduces the environmental footprint associated with sourcing and transporting new materials. In Singapore, on-site recycling systems have been adopted to process and repurpose construction waste. For instance, bentonite recovery systems allow the cleaning and reuse of bentonite slurry used in tunnelling operations, significantly reducing the consumption of new bentonite and associated disposal costs (Marotta, 2010). Similarly, water recycling systems integrated into pipe jacking operations recover and purify water used during underground excavation, enabling its continuous reuse and minimizing water wastage (Woo et al., 2023).

### 3 Shaping carbon emissions through digitalized construction

#### 3.1 3D geological modelling

3D geological modelling is critical to advancing low-carbon initiatives in underground engineering by providing a comprehensive understanding of subsurface conditions. This technology enables the detailed visualization and analysis of geological features, allowing engineers to identify geological anomalies, such as faults and cavities. By detecting these anomalies early in the planning phase, construction risks can be effectively mitigated, along with minimizing project delays, reducing material waste, and lowering carbon emissions. A 3D geological model of Singapore has recently been established using a combination of borehole data, 2D geological maps, digital elevation models, and archival geological descriptions (Fig. 3(a)). First, over 60 000 boreholes from across Singapore are collected and processed, with data verification to ensure the selection of accurate, relevant, and consistent geological information (Pan et al., 2020). Second, the cross-section lines are generated based on the borehole data and used to create a fence diagram, taking the east coast region of Singapore as an example (Fig. 3(b) upper). Next, the geological units are plotted in layers and assigned different colors (Fig. 3(b) middle). Finally, the 3D geological model is constructed by integrating these geological units with the expertise of experienced geologists (Fig. 3(b) lower). The resulting geological model, incorporating various geological formations in Singapore (Fig. 3(c)), supports a wide range of geological and geotechnical applications, such as the interpretation of ancient river distribution (Pan et al., 2019) and the facilitation of subway construction (Wu et al., 2022).

The 3D geological model is further developed by incorporating data management and integrating geophysical data to improve its accuracy and usability. A web-based

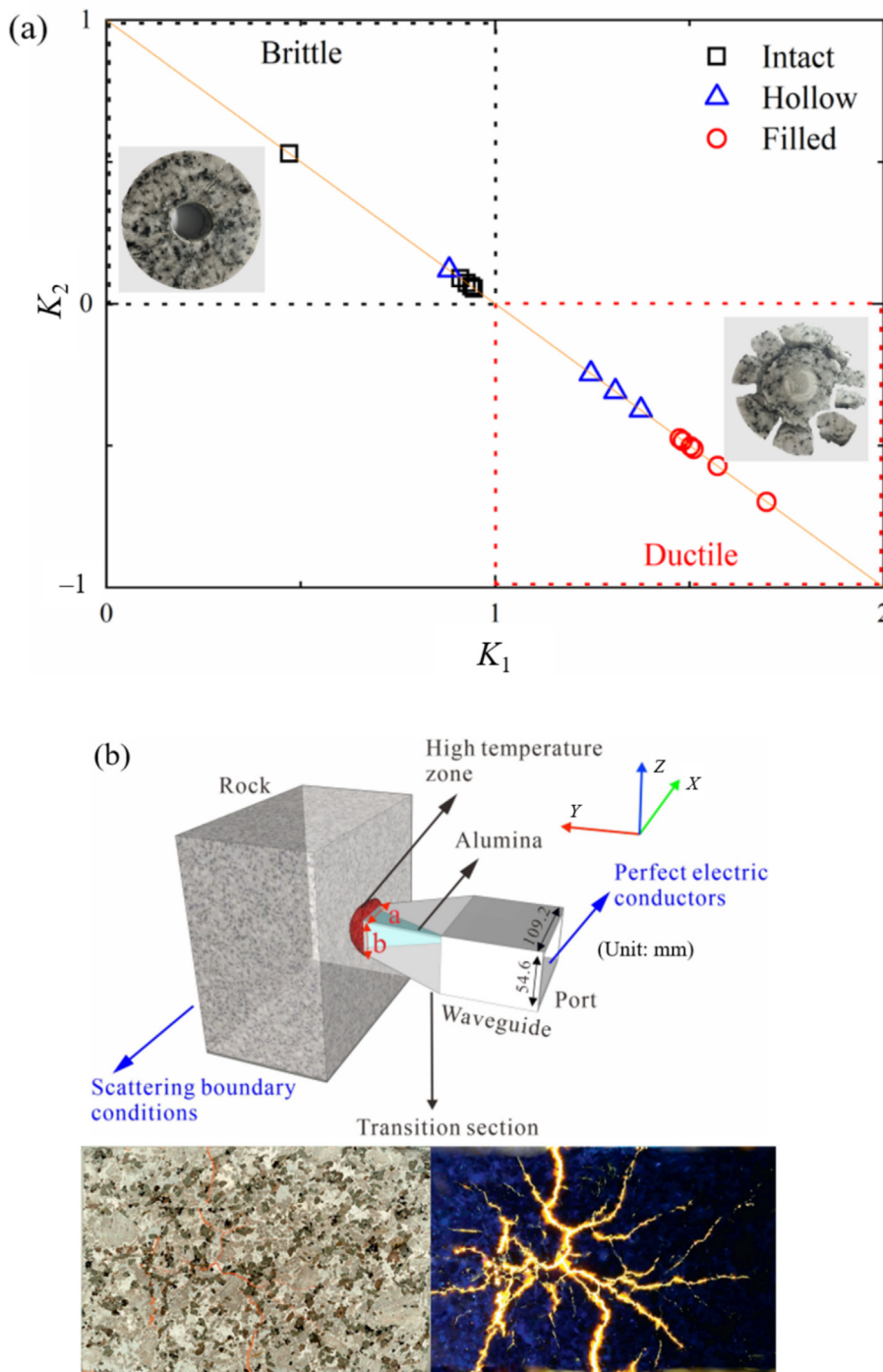


Fig. 2. Rock-breaking technologies with (a) expansive mortar, and (b) microwave heating (Wang et al. (2022) and Ma et al. (2024); reproduced with permission, courtesy of Elsevier).

data management system has been created to enable 2D map and 3D model views, interactive queries, and borehole search. To keep the model current and accurate, new borehole data are evaluated using voxel-based and spatial-based geological interface learning models to determine whether new interface data can be added to the model or

whether additional intervention from experienced geologists is required (Yang et al., 2025). Additionally, virtual boreholes generated from geophysical data are integrated into the 3D geological model to refine and enhance the interface data previously derived from widely spaced boreholes (S. Wu et al., 2023).

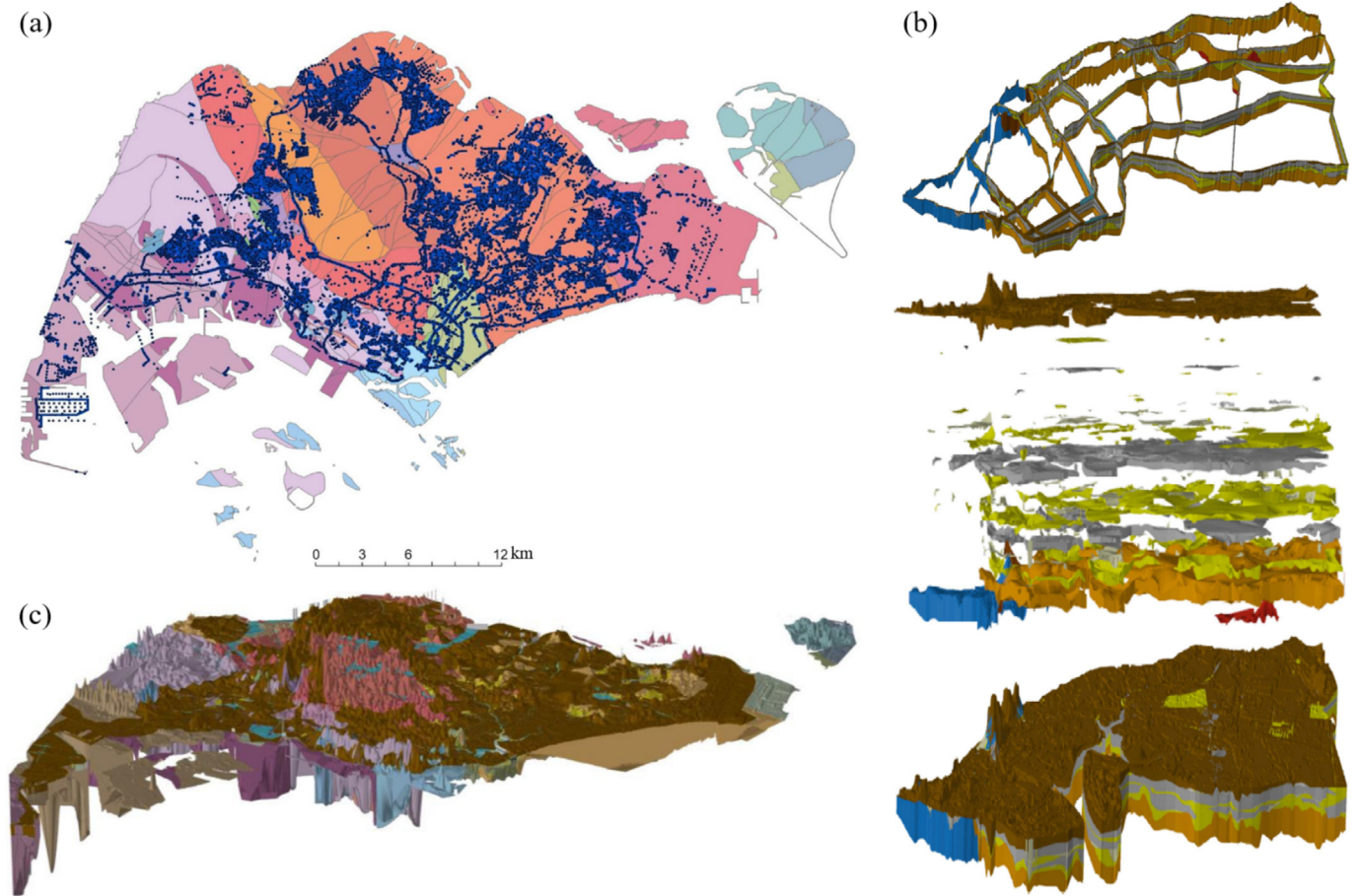


Fig. 3. 3D geological model of Singapore. (a) Geological map of Singapore and borehole distribution, (b) construction procedure for east coast region, including fence diagram (upper), layered model (middle), and combined model (lower), and (c) completed geological model (Pan et al. (2018) and Yang et al. (2025) reproduced with permission, courtesy of Jian Chu).

### 3.2 Underground BIM

Singapore has mandated the use of BIM in the construction industry since 2013. The BCA has developed a construction productivity roadmap, with BIM submission as a key regulation, and issued the Singapore BIM Guide, which provides a detailed framework outlining the requirements for BIM implementation, including deliverables, workflows, and professional roles at different stages of construction projects. Notably, underground utilities are required as architectural, civil, pumping, and sanitary BIM elements (BCA, 2013). These efforts enable the construction industry to harness digital technologies, paving the way for smarter and more resilient development of subsurface infrastructure. For instance, in a tunnel project, the BIM technology was utilized to assess preliminary designs and refine detailed plans, fostering a forward-thinking and data-driven methodology (Fig. 4(a)). In this project, the model also supported the development of numerous and complex cross-disciplinary designs for a fire station, identifying potential errors and enhancing project efficiency (Fig. 4(b)). Another notable example is the implementation of BIM technology in the design and construction of an

underground electrical substation in a densely populated area. This substation required meticulous planning due to the presence of over 11 000 interconnected underground cables forming a dense, web-like network (Fig. 4(c)). By employing the BIM technology, engineers were able to optimize the layout of underground piping, cabling, and other critical utilities with high precision, ensuring a seamless integration of subsurface infrastructure (Hyundai, 2024).

The BIM technology is increasingly being integrated with other advanced technologies, such as the Internet-of-Things (IoT), machine learning, and digital twin, to promote low-carbon efforts in underground engineering. This integration fosters more efficient planning, design, construction, and management of underground projects by leveraging real-time data, predictive analytics, and smart monitoring systems. In smart water grid operations, digital twin assists to detect and pinpoint anomalies, improving operational efficiency and sustainability (Z. Wu et al., 2023). Despite the contributions of BIM implementation to Singapore's industrial productivity, non-value-adding practices remain a topic of debate, such as "design models do not fit for intended downstream uses" "design changes

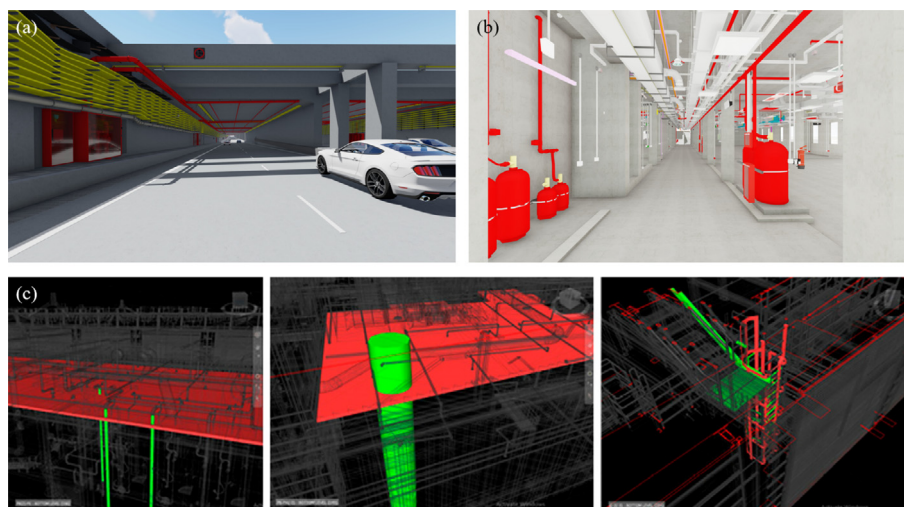


Fig. 4. Applications of underground BIM in Singapore. (a) A road tunnel, (b) a fire station, and (c) an underground subway station with piping, cables, and other facilities (reproduced with permission, courtesy of Hyundai).

are expensive once fabrication has commenced” “lacking construction input in design”, and “lacking skilled BIM experts to engage” (Liao et al., 2021). Currently, the BIM technology primarily supports low-carbon goals through its technical capabilities. For example, the BIM technology enables 3D modeling of underground structures, facilitates carbon emission simulations, enhances construction sequencing and logistics, and supports carbon tracking through structural lifecycles (Chapman et al., 2020; Dou et al., 2024; Huang et al., 2023). However, there is still significant potential for improving the operational dimensions, such as enhancing collaboration and coordination among various disciplines, strengthening long-term management throughout the project lifecycles, etc.

#### 4 Tracking carbon emissions through sustainable operation

##### 4.1 Intelligent detection of underground anomalies

Non-intrusive geophysical surveys are indispensable in modern underground construction, offering a broad range of essential functions that enhance both operational efficiency and environmental sustainability. These geophysical surveys are highly effective in detecting underground

anomalies, monitoring subsurface infrastructure, and providing data-driven insights to support planning and decision-making processes. The non-intrusive surveys are also capable of reducing the need for invasive drilling and extensive fieldwork, thereby significantly lowering the carbon footprint associated with traditional surveys. Academic institutions and industry professionals in Singapore collaborate to implement a diverse array of geophysical surveys to mitigate engineering risks (Table 3), such as ground penetrating radar, distributed optical fiber, microtremor array, and infrared thermography. Furthermore, geophysical surveys are often integrated with geotechnical and geochemical investigations, enabling multi-disciplinary validation for reliable imaging of underground structures (Liu et al., 2023; Z. Zhang et al., 2024).

Recent advances in artificial intelligence and machine learning have greatly improved geophysical data analysis and interpretation. Both unsupervised and supervised machine learning techniques are applied to extract energy-concentrated signals scattered by underground anomalies, which are then used to determine the geometrical and physical features of these anomalies (C. Zhang et al., 2024). This method leverages high-frequency waves to capture anomaly features at submeter scales and

Table 3  
Geophysical surveys and their applications in detection of underground anomalies.

Geophysical survey	Application	Reference
Ground penetrating radar	2D mapping underground utilities and reconstructing 3D tree root systems	van Son et al. (2019); Luo et al. (2024)
Distributed optical fiber	Monitoring bolted-concrete tunnel linings and underground gas distribution networks	Mohamad et al. (2012); Campanella et al. (2016)
Passive seismic	Velocity structure mapping ahead of TBM cutter head	Nilot et al. (2024)
Seismic scattering	Detecting underground anomalies with P-wave velocities differing from surrounding strata	Meng et al. (2024); C. Zhang et al. (2024)
Microtremor array	Identifying soil and rock interfaces using S-wave velocities	Ku et al. (2021)
Infrared thermography	Imaging of sewer pipes and diagnosing lining defects	Sham et al. (2019)
Hybrid gravimetry	Measuring relative gravity to absolute value	Shettell et al. (2024)

requires neither geophysical expertise nor human intervention for data analysis. Figure 5 illustrates an example of a convolutional neural network (CNN) model, which generates a probability distribution ranging from 0 (without anomalies) to 1 (with anomalies), providing a quantitative measure of anomaly likelihood. High-probability and low-probability values correspond to underground openings and surrounding disturbed zones, respectively (Meng et al., 2024). Field measurements taken after ground excavation closely align with the prediction results, demonstrating its high accuracy in detecting underground anomalies. The machine learning-driven technology improves the accuracy and reliability of anomaly detection, streamlining underground exploration and risk assessment.

#### 4.2 Underground CO<sub>2</sub> monitoring and control

Underground CO<sub>2</sub> monitoring and control are vital for assessing and reducing carbon emissions in the confined environment. Effective monitoring not only improves the understanding of emission sources but also aids in exploring mitigation measures. In Singapore, an integrated CO<sub>2</sub> monitoring and control system has been implemented in the underground structures with twin tunnels and surrounding utilities (Fig. 6). This advanced system continuously tracks key factors, including air conditioning efficiency, mechanical ventilation performance, lighting conditions, and the overall building energy consumption. These factors are quantified and converted into an equivalent CO<sub>2</sub> footprint, providing a comprehensive assessment

of carbon emissions in underground space. The system then compares the monitoring results against government regulations and environmental standards. If discrepancies are identified, such as excessive CO<sub>2</sub> levels or inefficiencies in energy usage, the system offers automated feedback and suggests corrective actions, including optimizing ventilation efficiency, adjusting lighting schedules, or implementing energy conservation measures. By integrating real-time monitoring with intelligent control mechanisms, this system enhances the sustainability of underground infrastructure while ensuring compliance with environmental regulations.

A dynamic evaluation framework for low carbon capacity and carbon emission capacity is developed to quantify the low-carbon effect on underground space development (Bian et al., 2024). The low carbon capacity refers to the potential of underground systems to reduce the carbon footprint through innovative and sustainable approaches, such as implementing energy-efficient designs to minimize energy use and harnessing geothermal energy to reduce dependence on fossil fuels. The carbon emission capacity assesses the sources and intensity of carbon emissions associated with underground construction, such as understanding carbon emissions during material production and construction processes and quantifying carbon emissions from transporting and managing excavated materials. The goal of evaluating both low carbon and carbon emission capacities is to achieve net-zero carbon emissions, requiring not only technological advancements but also a holistic consideration of social, economic, and environ-

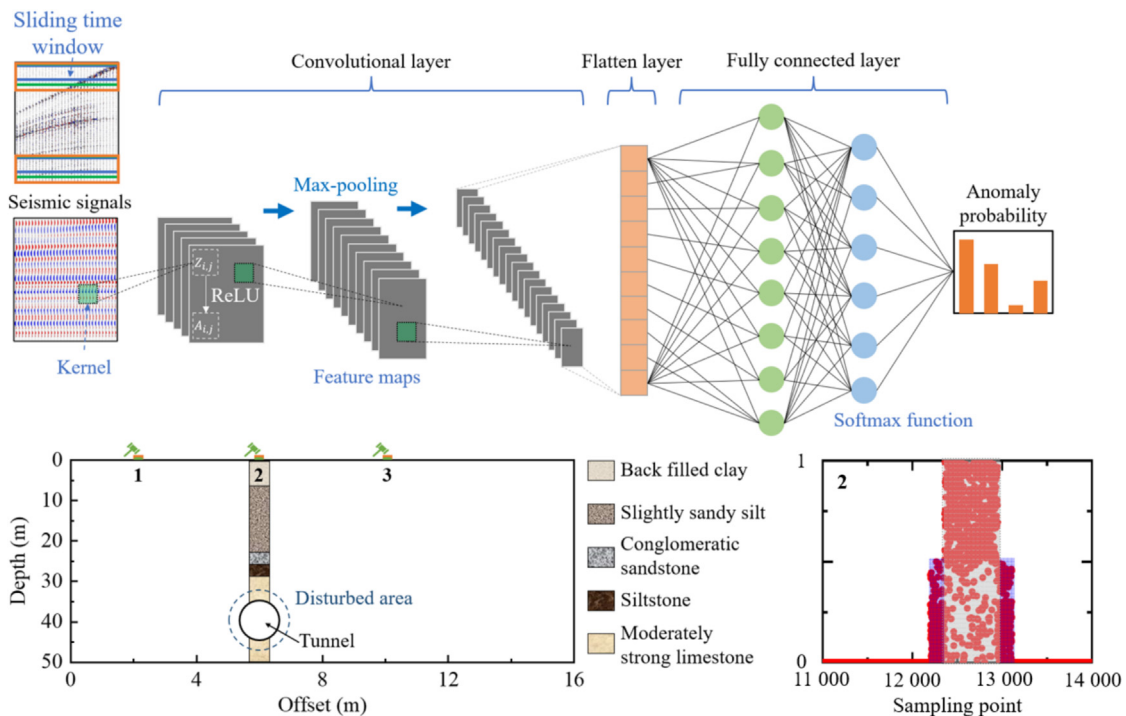


Fig. 5. Intelligent detection of underground tunnel and surrounding disturbed zones using seismic scattering and CNN methods (Meng et al. (2024); reproduced with permission, courtesy of Elsevier).

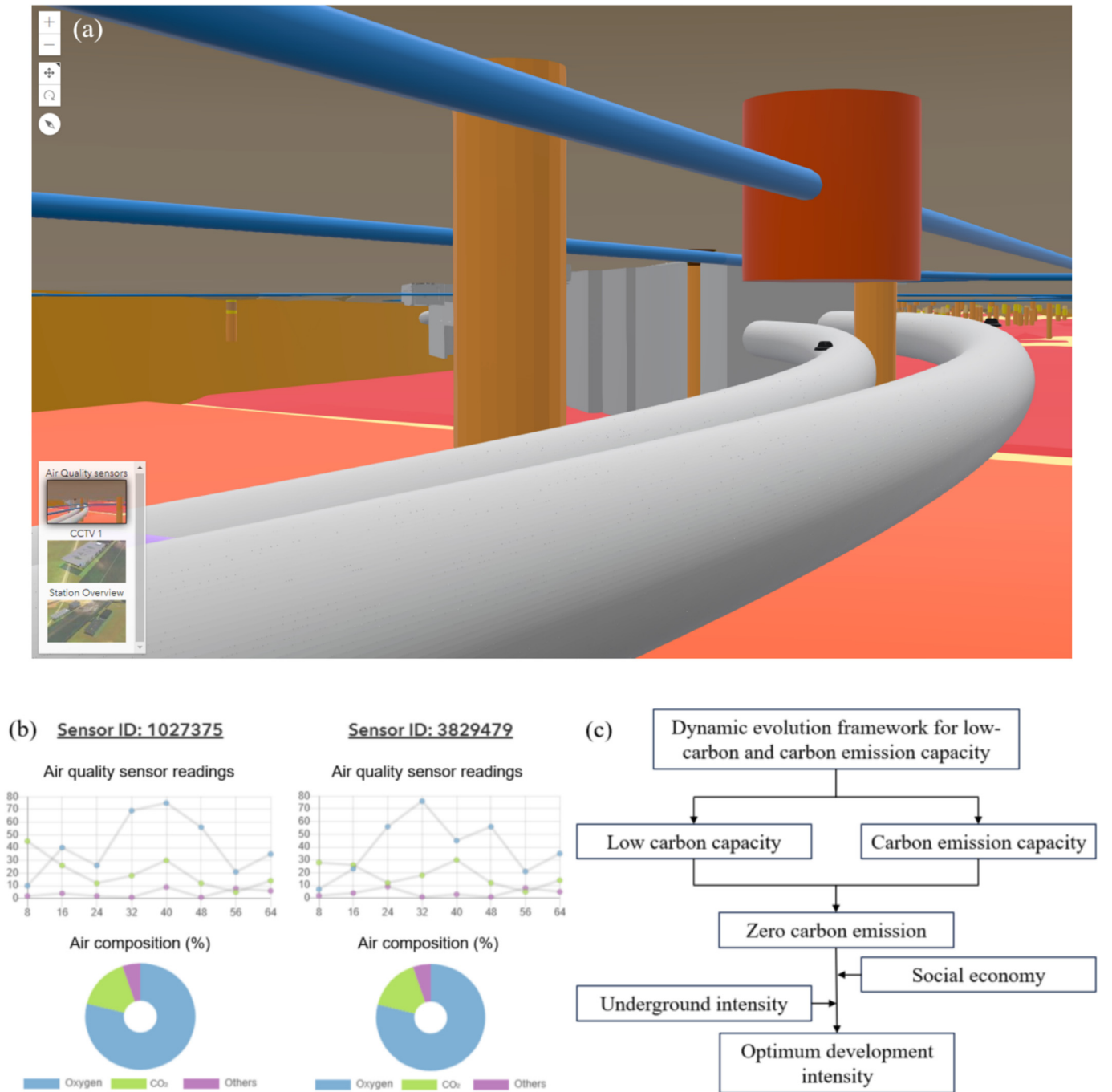


Fig. 6. (a) Integrated CO<sub>2</sub> monitoring and control system, (b) air quality sensor readings, and (c) a dynamic evaluation framework for low carbon capacity and carbon emission capacity (Bian et al. (2024); reproduced with permission, courtesy of Elsevier).

mental factors. In this context, underground CO<sub>2</sub> monitoring plays a critical role by offering real-time feedback on the performance of the dynamic evaluation framework. Such feedback is essential for identifying areas for improvement and implementing timely control measures that enhance the low-carbon efficiency of underground projects.

Assessing carbon emissions is crucial for evaluating the effectiveness of lower-carbon efforts in underground engineering. Various assessment methods have been developed

to analyze the carbon footprint across different construction stages. For example, carbon emissions during conventional tunnel construction are assessed based on four primary energy contributors, such as tunnel excavation, waste removal, auxiliary services, and material production for support and lining (Rodríguez & Pérez, 2021). In highway tunnel construction, material production (e.g., steel and concrete) and power supply machinery are identified as the major contributors (Xia et al., 2023). For TBM construction, the contribution of TBM to carbon emissions

(10.4%) is significant but lower than auxiliary services (11.1%) and material production for support and lining (73.3%) (Rodríguez et al., 2024). Material prefabrication is also identified as the major contributor in the construction of a subway station (Liu et al., 2019). Despite using different methods and parameters, these carbon emission assessment methods consistently highlight material prefabrication as a key factor in reducing carbon emissions during underground construction.

## 5 Discussion

Based on our review above, an overarching trend in efforts to reduce the carbon footprint of underground space development is the establishment of a well-defined framework for lifecycle carbon assessment, along with supportive policies that integrate carbon considerations into governance and decision-making processes. Singapore's BCA Green Mark 2021 encourages the industry professionals to develop green and sustainable building solutions (BCA, 2021; D. Zhang et al., 2024). As an internationally recognized certification framework, it offers comprehensive assessment criteria across the entire building lifecycle. Notably, the Whole Life Carbon section evaluates both operational and embodied carbon emissions, as well as potential carbon benefits beyond the end-of-life phase. While the Green Mark 2021 has advanced environmental sustainability in above-ground developments, underground projects remain a significant source of carbon emissions due to energy- and material-intensive activities, such as deep excavation, ground reinforcement, continuous ventilation, and material transportation. Therefore, understanding and mitigating the carbon footprint of underground space development is crucial for achieving sustainable urban development. Based on this review, particularly in relation to material efficiency, digitalized construction, and sustainable operation, future research directions can be identified, such as reducing embodied carbon in construction materials without compromising performance, optimizing carbon outputs by leveraging digital twin and emission simulation, and minimizing post-construction emissions from ventilation, lighting, and temperature control systems. Beyond these directions, important gaps remain, such as the need for comprehensive data collection from various industry and government sectors, and a better understanding of the interaction between human behavior and operational efficiency.

Developing an effective assessment framework requires access to reliable, localized data and a comprehensive methodology for evaluating lifecycle carbon emissions throughout the stages of underground construction. The proposed framework, illustrated in Fig. 7, outlines various key stages of underground construction for tunnels and caverns, such as material prefabrication, underground excavation, maintenance and renovation, and end of life. These stages are aligned with the three topics reviewed above, as highlighted in Fig. 7, and provide a structured

methodology for evaluating the effectiveness of low-carbon efforts. However, a major challenge for researchers lies in data collection and integration from various industry and government sectors. For example, materials prefabrication involves multiple sectors across the value chain, including raw material extraction, manufacturing, transportation, and waste disposal. Carbon emission data from these sectors are often fragmented, inconsistently reported, or not directly traceable. This lack of standardized and integrated data makes it difficult to accurately assess the carbon footprint and hinders effective benchmarking and policy development. For practitioners, a more practical direction could involve focusing on a specific project to gather detailed data, serving as a pilot to refine the framework, and enabling the development of scalable methods for broader applications. Furthermore, from a governance perspective, managing underground space within a low-carbon framework requires underground activities aligning with national climate goals by incorporating lifecycle emission targets (Wang et al., 2025), integrated energy systems (Qin et al., 2024), and performance-driven designs (Zhou & Leng, 2023). Institutional coordination across urban planning, construction activities, and environmental assessments is essential to avoid regulatory fragmentation and ensure policy implementation (Wang & Chang, 2014; Zhao et al., 2019). Robust policy mechanisms, such as carbon pricing, carbon audits, and incentive schemes, should be embedded into regulatory frameworks to drive low-carbon innovation and promote accountability in underground space development (Qiao et al., 2019).

While the focus above highlights low-carbon efforts in underground construction, Singapore is also actively developing and planning a range of energy and resource projects as part of its broader low-carbon strategy. For example, the deep tunnel sewerage system (DTSS) utilizes gravity to transport used water to the centralized treatment facilities for purification and discharge (Fig. 8(a)). This system enhances energy efficiency by reducing the need for pumping stations, thereby lowering both operational costs and carbon emissions (Kua et al., 2022). Singapore has long been recognized for its geothermal potential, as reflected by the region's geological characteristics (Poh et al., 2025) and the presence of Sembawang hot spring (Fig. 8(b)). Recent geothermal exploration has confirmed the presence of viable geothermal resource, which could be harnessed by future renewable energy systems (Lu & Wu, 2024). The subsea oil storage facility, the Jurong Rock Caverns, has been in operation for nearly 10 years (Fig. 8(c)). This underground facility was developed to meet the growing demand for secure and efficient storage of liquid hydrocarbons, particularly crude oil and petroleum products (Zhao et al., 1999). A large-scale underground electricity substation was constructed and integrated with a 34-storey commercial tower (Fig. 8(d)), which not only optimizes land use but also exemplifies the seamless integration of aboveground and underground structures. Singapore is well-positioned to lead in sustainable underground space

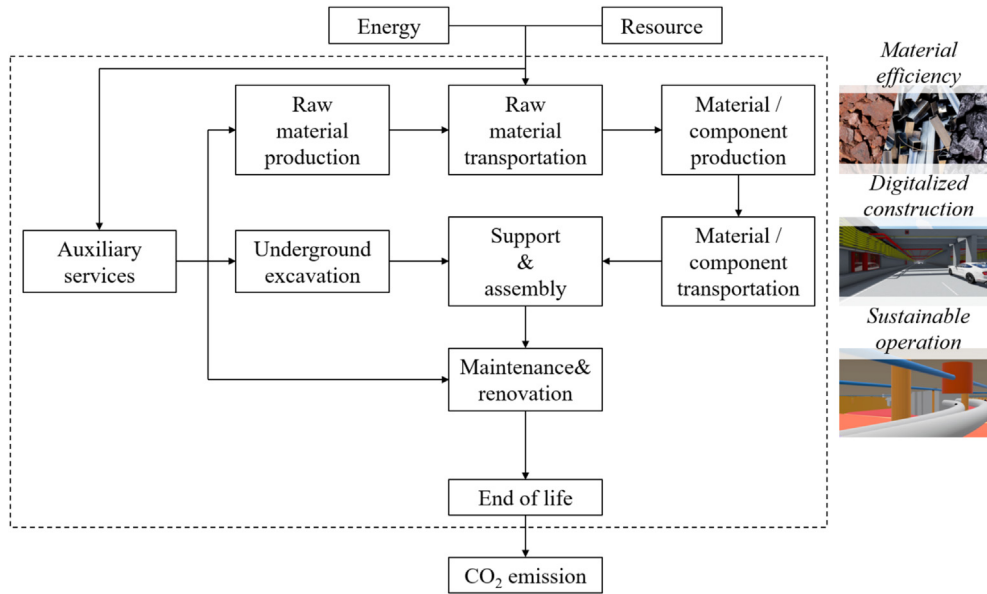


Fig. 7. Proposed workflow for assessment of lifecycle carbon emission of underground structures.

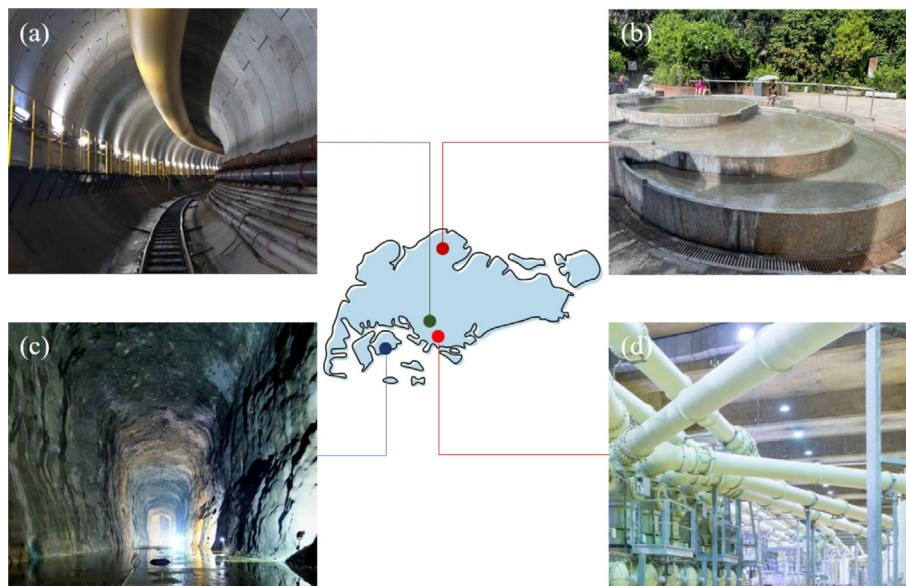


Fig. 8. (a) DTSS for water recycling (Courtesy of Public Utilities Board, Singapore), (b) Sembawang hot spring, (c) Jurong Rock Caverns for oil storage (Courtesy of Jurong Town Corporation, Singapore), and (d) underground electricity substation (Courtesy of Energy Market Authority, Singapore).

development. By incorporating carbon-conscious design and construction into numerous underground projects, it can serve as a model for high-density urban environments worldwide.

**6 Conclusions**

The critical review examines how low-carbon efforts contribute to the sustainable development of underground space, particularly in highly urbanized environments. As

global urbanization continues to intensify, the demand for innovative solutions to optimize land use and reduce carbon footprints has never been more pressing. Drawing on significant achievements and data availability from Singapore, this study explores three key areas, such as cutting carbon emissions through material efficiency, shaping carbon emissions through digitalized construction, and tracking carbon emissions through sustainable operation. These topics not only highlight Singapore’s efforts to carbon reductions across the full lifecycle of underground infras-

structure but also contribute to the development of a structured framework for lifecycle carbon assessment. The review further underscores that a major overarching trend in low-carbon underground development is the integration of lifecycle assessment frameworks with supportive policies that incorporate carbon considerations into governance and decision-making processes. For remaining challenges, interdisciplinary collaborations among government agencies, academic researchers, and industry practitioners provide opportunities to develop robust frameworks and dynamic models capable of reliably managing lifecycle carbon emissions in underground space development.

### Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### CRedit authorship contribution statement

**Tong Jiao:** Funding acquisition, Conceptualization, Resources, Data curation. **Pei Peng:** Validation, Data curation, Resources. **Shixiang Li:** Data curation. **Wei Wu:** Project administration, Conceptualization, Writing – review & editing, Funding acquisition.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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