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TOWARDS LOW-CARBON TUNNEL ENGINEERING: A COMPREHENSIVE REVIEW OF EMISSION ESTIMATION AND FORECASTING TECHNIQUES

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Abstract: As global tunnel construction expands in scale, increasing attention is focused on carbon emissions. Life Cycle Assessment (LCA) has emerged as a prominent research focus and is widely applied for carbon accounting across sectors. However, LCA application within tunnel engineering specifically remains exploratory. This study traces the evolution of LCA from general carbon emission research to tunnel-specific carbon accounting. We comprehensively review existing literature on tunnel carbon emission estimation based on LCA principles and further examine relevant emission forecasting research. Finally, recommendations are provided to advance full life-cycle carbon research for tunnels, aiming to refine LCA methodologies and accelerate progress towards zero-carbon tunnels.

Keywords: Carbon emission, tunnel engineering, life cycle assessment, carbon emission estimation

1. INTRODUCTION

In recent years, the intensification of global warming and the frequent occurrence of extreme weather events have brought greenhouse gas (GHG) emissions to the forefront of international concerns (IPCC, 2021). According to data from the National Oceanic and Atmospheric Administration (NOAA), the global average temperature has risen by 1.1°C since the Industrial Revolution(Aboagye et al., 2023), with carbon dioxide (CO_2) — the primary anthropogenic GHG — contributing up to 80.1% of total emissions (Wang et al., 2015) Aligned with the Paris Agreement's goal of limiting global warming "well below 2°C" and pursuing efforts to limit it to 1.5°C, 137 countries have committed to carbon neutrality targets through legislative or policy frameworks (Liu et al., 2024). This global imperative necessitates systematic carbon emission research across industries to devise scientifically robust mitigation strategies.

Current academic research has extensively explored carbon emission accounting methods and reduction strategies. In the power sector, Li et al. (2024) comprehensively reviewed direct and indirect emission accounting systems and proposed directions for data integration optimization. Zheng et al. (2024) conducted bibliometric analyses in social sciences, elucidating the evolution and theoretical foundations of carbon accounting models. In urban planning, Chen et al. (2019) compared the strengths and limitations of inventory, modeling, and remote sensing inversion methods for emission estimation. Despite these interdisciplinary advancements, carbon emission research specific to tunnel engineering remains significantly understudied.

As a critical component of modern infrastructure, tunnels play an irreplaceable role in urban spatial expansion and transportation network development (Admiraal & Cornaro, 2016). With accelerating global urbanization,

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tunnel construction has expanded substantially: by the end of 2023, the total lengths of highway and railway tunnels in China exceeded 30,000 km and 20,000 km, respectively (Seo & Kim, 2013). However, environmental impact research in this field lags notably. Seo & Kim (2013) revealed that due to high-energy-consuming materials and complex construction processes, tunnel projects generate approximately four times the carbon emissions per unit area compared to surface roads. Moretti et al. (2016) further demonstrated that each linear meter of tunnel construction entails a full-life-cycle consumption of 2.3 tons of concrete, resulting in 1.8 tons of CO_2 equivalent emissions. These findings underscore the urgent need to explore carbon reduction potential in tunnel engineering.

This study focuses on carbon emissions across the entire life cycle of tunnels, aiming to address three key gaps: first, systematically reviewing the evolution of Life Cycle Assessment (LCA) applications in tunnel carbon accounting; second, developing a predictive model covering construction, operation, and decommissioning phases; third, proposing integrated carbon reduction strategies combining technological innovation and management optimization. The research outcomes will provide theoretical and practical guidance for low-carbon transformation in infrastructure construction in developing countries, facilitating the realization of carbon neutrality in the transportation sector.

2. BIBLIOMETRIC ANALYSIS

This section employs CiteSpace and the built-in bibliometric tools of the China National Knowledge Infrastructure (CNKI) database to analyze the body of literature related to carbon emission research in both China and the broader international context. The analysis focuses on the temporal distribution of carbon emission studies and examines how this body of research has gradually been applied to the field of tunnel engineering.

2.1. Carbon emissions

This section analyzes the temporal distribution of carbon emission research in China using the built-in bibliometric tools of the CNKI database, which was selected as the primary regional database for Chinese-language academic publications. The keyword used for the literature search was “carbon emissions” with the source type limited to peer-reviewed academic journals and the publication period restricted to 2005–2025. After an initial screening of the search results, a total of 11,831 relevant research articles were identified. Among these, 7,733 were published in journals indexed by the PKU Core (Peking University Core Journals), and 4,098 appeared in journals indexed by the Chinese Social Sciences Citation Index (CSSCI).

The temporal distribution of the two categories of publications is illustrated in Figure 1. As shown in the figure, carbon emissions began to attract attention in China around 2009. Since then, the annual number of publications has gradually increased. However, research activity declined around 2017 before regaining momentum in 2021, with the number of publications continuing to rise and reaching approximately 400 per year. This trend may be related to the signing of the Paris Agreement. Overall, these changes reflect the growing national emphasis on carbon emissions and the increasing attention the topic has received within the research community.

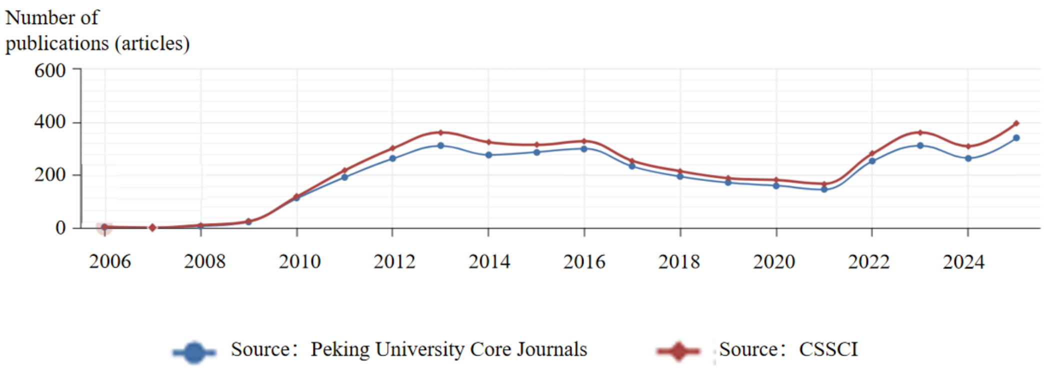

Figure 1. *Temporal Distribution of Research Publications on Carbon Emissions in China*

To explore the key aspects of carbon emission research, this study utilizes the Web of Science (WOS) Core Collection as the bibliometric database. A precise search was conducted using the keyword “carbon emission,” with the document type restricted to articles and the time span set from 2005 to 2025. The search yielded over 200,000 publications. After relevance screening, 483 representative articles were selected for keyword co-occurrence analysis using the CiteSpace tool. Keywords with a frequency greater than 40 occurrences were identified as key thematic labels. As shown in Figure 2, carbon emission research spans a wide range of fields, including industry, agriculture, and climate, and covers diverse perspectives such as policy frameworks, environmental impacts, and carbon dioxide equivalent (CO_2e) calculations. Among these, the keyword "carbon emission calculation" appeared most frequently, over 70 times, highlighting it as a major research hotspot. Therefore, it is essential to conduct a focused review of existing research findings and practical experiences within this specific domain.

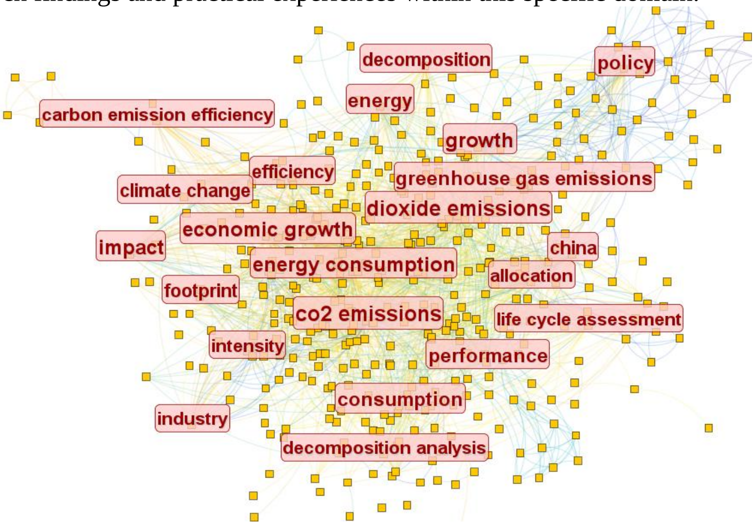

Figure 2. *Keyword Co-Occurrence Network of Carbon Emission Research*

2.2. Carbon emissions in civil engineering

As illustrated in Figure 2, the application of carbon emission research within the field of civil engineering has emerged as a significant hotspot. To further analyze the key research areas of carbon emissions across various branches of civil engineering, an additional thematic search using the term "civil engineering project" was conducted within the previously identified dataset of 200,000 publications. After manual screening, 318 articles directly related to carbon emissions in civil engineering were identified. These selected articles were then subjected to visual analysis using CiteSpace, and the resulting keyword co-occurrence network is presented in Figure 3.

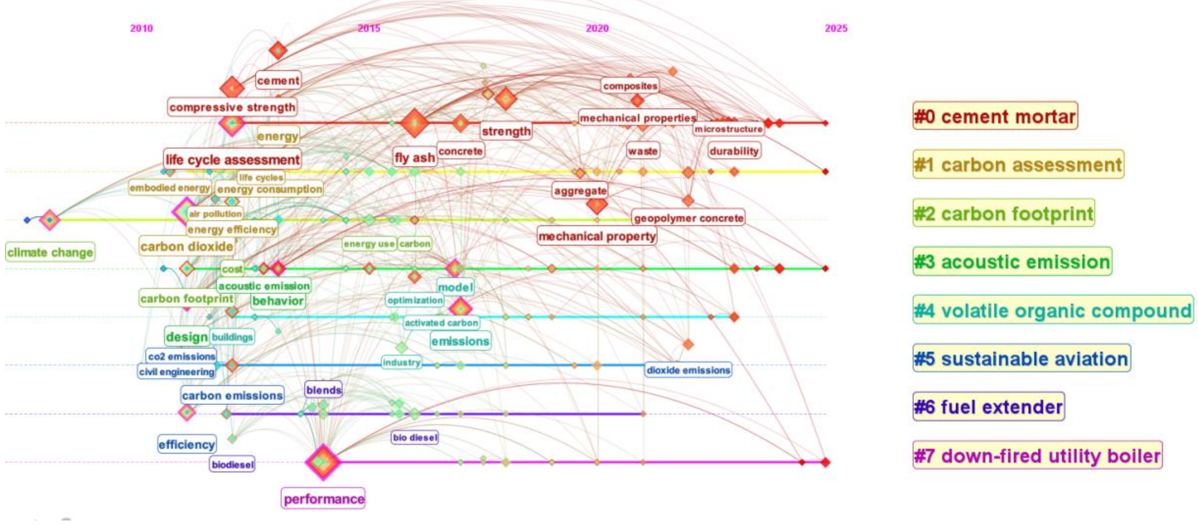

Figure 3. *Cluster Timeline Analysis of Keywords in Articles Related to Carbon Emission*

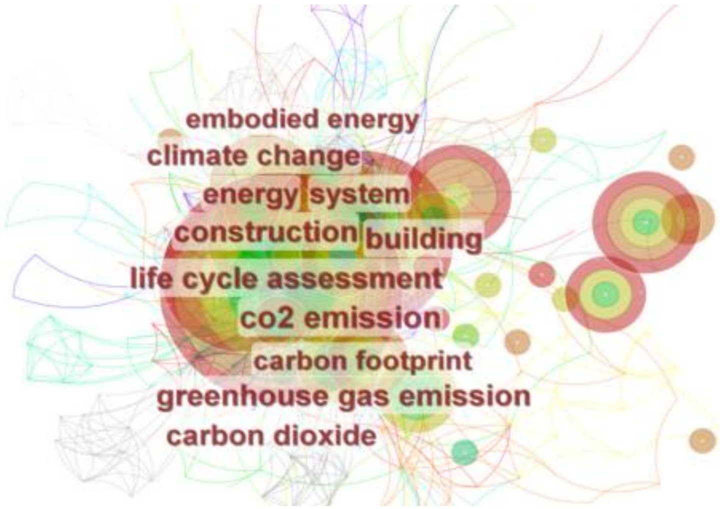

Figure 4. *Keywords Clustering with Frequency More than 30 Times*

The keyword visualizations are presented in Figures 3 and 4. As shown in Figure 3, carbon emission calculation is a primary focus within the civil engineering domain. Among material-related terms, "cement mortar" appears with the highest frequency. Over time, the central themes of carbon emission research have shifted—from early focuses on CO_2 quantification and air pollution impacts to broader concerns such as sustainable development, tunnel construction, and micro-scale infrastructure. Figure 4 presents a cluster analysis of keywords with a frequency exceeding 30 occurrences. The analysis reveals a concentration of research on systems, structures, and life cycle assessment (LCA), while studies specifically addressing carbon emission calculations in tunnel engineering remain relatively limited. Dou et al. (2024) pointed out that the life-cycle research on low-carbon tunnels has yet to form a complete and coherent life-cycle framework, with studies at various stages remaining rather general and fragmented.

3. TUNNEL CARBON EMISSION CALCULATION BASED ON LCA

To obtain the latest research on carbon emission calculation throughout the entire life cycle of tunnels, this study defined two sets of keywords—"carbon emission" and either "tunnel" or "tunneling"—and combined them into a single search string. The Web of Science Core Collection was selected as the database, with citation indexes limited to SCI and SSCI, resulting in 1,526 publications. After manual screening, 31 articles were identified as highly relevant to the topic of carbon emission calculations across the tunnel life cycle. Currently, the widely accepted tunnel life cycle framework divides carbon emissions into four stages: the survey and design stage, the construction stage, the operation and maintenance stage, and the demolition and recycling stage. Given the relatively limited research focused on the survey and design stage, this paper organizes and reviews the literature based on the remaining three stages—construction, operation and maintenance, and demolition and recycling—as summarized in Tables 1, 2, and 3, along with relevant analysis and discussion.

Table 1. *Carbon Emission Calculation during the Tunnel Construction Phase*

Reference	Method	Metric	Conclusion	Further work
Tabrizikahou & Nowotarski, 2021	VSM JIT technique TPM techniques	CO_2	This facilitates construction engineers and project managers in acquiring building designs and planning strategies oriented toward minimizing energy consumption.	The outcomes of the proposed approach are subject to the influence of region-specific practices and conditions.
Zhao et al., 2022	emission coefficient	CO_2	Carbon dioxide emissions were quantified for each phase of slurry shield tunnel construction. Notable disparities were identified among different	

			construction rings, with the highest CO_2 emission being more than three times greater than the lowest.	
Song, Zhu, Shen, Yan, et al., 2024	Emission-Factor Approach (EFA)	CO_2-eq	The carbon emissions of a highway tunnel in Jiangxi Province were calculated, with the material production phase accounting for the largest proportion at 91.5%. Concrete and steel had the highest carbon emissions, and Concrete in portals, linings, and waterproofing had the highest emissions	
Seo & Kim, 2013	Emission-Factor Approach (EFA)	CO_2-eq		Carbon emissions are represented in terms of carbon dioxide (CO_2) emissions rather than carbon dioxide equivalents (CO_2e), with a primary focus on CO_2 generated during material production.
Pritchard & Preston, 2018	Estimation based on existing research data	CO_2-eq	The embodied CO_2 emissions of three tunnels were estimated. The increased embodied energy and emissions from wider tunnels can be offset by reduced operational emissions.	Further research is needed to better quantify the relationship between operational energy emissions and actual tunnel diameter. The calculation method will depend on train type, service type, and expected operational lifespan.
Zou et al., 2024	Emission-Factor Approach (EFA)	CO_2-eq	A carbon emission calculation model for the construction process was established based on the new prefabricated invert technology, incorporating constraints of cyclic advancement on material transportation. The calculation revealed that carbon emissions during prefabricated invert construction were reduced by over 15% compared to cast-in-place construction, with reduced cement and steel consumption contributing the most to emission reduction.	The carbon accounting model can be further optimized by incorporating cycle-induced constraints on material transportation and accounting for on-site transport conditions.

Rafael Dami´ & Clara I. Zamorano, 2011	CML-IA baseline	CO_2	The environmental impact assessment revealed that support structures, linings, and infrastructure works accounted for at least 70% of the total environmental burden across all considered impact categories for the five RMR classes in railway tunnel construction.	Due to limited operational data for railway tunnels and the fact that tunnel maintenance is primarily condition-based, the maintenance and operational phases were not considered in this study. Since tunnel decommissioning rarely occurs, the end-of-life recycling phase was also excluded from consideration.
Wang et al., 2023	Input-output methods and process analysis methods	CO_2-eq	The modified process analysis method was employed to calculate CO_2 emissions during shield tunnel construction. The results indicate that the reinforced concrete precast segments contribute the most to carbon emissions	The combined use of traditional calculation methods and neural network models enables comprehensive and accurate analysis of carbon emissions in the construction industry.
Liu et al., 2024	process-based project inventory analysis method	CO_2-eq	The embodied carbon per meter of tunnel varies between 7.97-24.27 t depending on surrounding rock conditions, with significantly increased emissions observed as rock quality deteriorates. In highway tunnels, the material production phase contributes the highest proportion (79%-87%) of embodied carbon, while the transportation phase accounts for the lowest share. In the material production phase, concrete and steel are the primary carbon emission contributors, with concrete accounting for the largest share at approximately 50%-80%.	Digital models can leverage their visual capabilities to compare different design schemes or material types, ultimately reducing project carbon emissions.
Guo et al., 2025	Emission-Factor Approach (EFA)	CO_2-eq	During the case project's construction phase, building material production was the primary emission source, contributing 78.65% of total emissions, while construction machinery energy consumption and transportation accounted for 18.87% and 2.48% respectively	

			The greenhouse gas emissions from building material production showed a highly significant positive correlation (Pearson's *r* = 0.999, *p* = 0.000 < 0.001) with the total building emissions） The construction of support structures—particularly pipe splicing, initial lining, and secondary lining works—represents the primary emission-intensive activities in metro tunnel construction phases.	
Shi et al., 2024	Process-based hybrid life cycle assessment model		Using the hybrid method, GHG emissions from auxiliary materials were identified. Under severe data gaps, the hybrid method complements missing data and effectively improves data quality.	Due to insufficient upstream material and energy data, emissions related to upstream fuel were not considered. This study focuses on carbon emissions during the construction phase, which represents only a small portion of the life cycle. Future research should consider the impact of upstream fuel emissions.
Mao et al., 2013	Emission-Factor Approach (EFA)	CO_2-eq	Differences in construction methods affect carbon emissions; semi-prefabricated structures emit slightly less than traditional ones.	Future research will examine more cases to explore the link between prefabrication and emissions.
Chen et al., 2024	BIM and EN 15978 life cycle modules	CO_2-eq	Summarized embodied carbon calculation methods, considering geotechnical conditions and quantifying emissions from transport and construction stages.	Advocates integrating carbon assessment into geotechnical analysis to evaluate life-cycle economic benefits from a holistic perspective, enriching future research and practice in tunnel construction decarbonization
Kamari et al., 2022	BIM	CO_2-eq	Concrete-based materials contribute most to the embodied carbon emissions of buildings. Wooden elements can reduce the model's carbon emissions.	Data provided by BIM is insufficient for direct use in LCA.

				LCA-related methods vary significantly, including boundary conditions, calculation methods, and impact categories. Supplementary indicators may be added in the future for comprehensive project evaluation.
Wang et al., 2015	Emission-Factor Approach (EFA)	CO_2	An empirical method for estimating CO_2 emissions was proposed based on four highway construction projects in Southwest China. CO_2 emissions mainly occurred during material production, followed by on-site construction, with transportation contributing the least.	Future work could include developing specific construction guidelines (e.g., equipment selection, green construction technologies).
Guo et al., 2019	Database analysis and calculation (Source: China Life Cycle Database (CLCD))	CO_2	Considered different rock mass classifications and identified the dependency of LCA on rock mass types.	Future studies will consider the carbon emissions from the demolition and recycling phases.
Yang et al., 2018	BIM	CO_2-eq	BIM-based life cycle assessment (LCA) models can comprehensively evaluate the environmental performance of buildings throughout their life cycle.	The integration of LCA and BIM is hindered by software compatibility issues.
Han et al., 2012	I-O LCA	CO_2-eq	A model was proposed to assess carbon emissions during the construction phase.	Analyzing the cost and schedule of construction methods will aid in selecting more environmentally friendly and cost-effective approaches in future studies.
Huang et al., 2020	the ReCiPe Midpoint (E) V1.06 method		Explored the environmental impacts of D&B construction for Norwegian standard highway tunnels. Compared the environmental impacts of D&B construction across tunnels of different sizes and lengths.	Carbon emissions from tunnel operation, maintenance, and demolition phases have not yet been considered.

Huang et al., 2015	ILCD 2011 Midpoint V1.03 method		Explored the environmental impacts of rock support on 24 highway tunnels with varying sizes and rock mass classifications. All environmental impacts showed higher sensitivity to rock mass classification than to tunnel size.	Technical improvements should focus on reducing rebound and optimizing the design of shotcrete additives and binders.

Table 2. *Carbon Emission Calculation during the Tunnel Operation and Maintenance Phase*

Reference	Method	Metric	Conclusion	Further work
Brimblecombe et al., 2015	Sen's slope LSR regression	CO_2-eq	Integrated hourly traffic volume and derived carbon emission factors for diesel and gasoline/LPG fleets inside the tunnel using bivariate regression.	Variations in road gradient between tunnels and traffic speed may affect the accuracy of multiple regression analysis. Further research can focus on specific tunnels with long-term measurement series, including changes in traffic composition, to minimize uncertainty.
Zou et al., 2024	Emission-Factor Approach (EFA)	CO_2-eq	Incorporate carbon emissions generated during the early tunnel operation phase into the assessment system, considering the indirect impact of significantly improved construction efficiency on emissions.	
Song, Zhu, Shen, & Feng, 2024	Emission-Factor Approach (EFA)	CO_2-eq	Tunnel lighting carbon emissions are significantly higher than those from ventilation.	Carbon emission calculations for the demolition and recycling phase require further refinement.
Weingartner et al., 1997	Measurement and Calculation Method	CO_2-eq	During tunnel operation, carbon emission factors for diesel engines were calculated based on aerosol emission measurements, revealing that the majority (63%) of diesel vehicles were heavy-duty.	High diesel engine emissions prevented the assessment of gasoline engine contributions using statistical models.
Guo et al., 2025	Database analysis and calculations (Source: China Life Cycle	CO_2-eq	A 4-km, four-lane highway tunnel in China emits approximately 375,500 tons of CO_2 equivalent. Over half of the greenhouse gas emissions during the	Energy-saving technologies for tunnel ventilation and lighting will effectively promote carbon

	Database, CLCD)		operation phase come from tunnel ventilation and lighting.	reduction in Chinese tunnels.
Raposo et al., 2019	BIM	CO_2-eq	Evaluated the cost and environmental impacts of seismic retrofitting and demolition of prefabricated components using an integrated LCA and BIM approach.	The integration of LCA and BIM is influenced by the databases used.
Audi et al., 2020	CML method EDIP method	CO_2-eq	Calculated carbon emissions from bus traffic inside the tunnel during operation, power consumption of tunnel ventilation and lighting, and power consumption of roadway lighting.	LCA cannot cover all aspects, mainly socioeconomic factors, but it still provides a robust set of midpoint indicators.

Table 3. *Carbon Emission Calculation during the Tunnel Deconstruction and Material Recovery Phase*

Reference	Method	Conclusion	Further work
Wu et al., 2024	Emission-Factor Approach (EFA)	Carbon emissions from the demolition and recycling phase contribute only 4.9% of the total life cycle emissions, much lower than the operation and maintenance phase.	Life cycle assessment (LCA) of carbon emissions for cross-sea transport infrastructure is still an emerging field, with detailed baseline data for practical analysis difficult to obtain.
Xie et al., 2020	Hybrid analysis method	Embodied carbon accounts for 0.15% of life cycle energy consumption at end-of-use. Recycling and reuse of building materials after use help minimize life cycle emissions (LCE).	
Akbar Nezhad & Nadoushani, 2014	BIM	Assessed the cost, energy consumption, and carbon emission impacts of demolition and recycling phase strategies.	
Yahya et al., 2016	Impact Pathway Approach (IPA)	The ecological impact of metal waste treatment in the construction industry mainly arises from fuel consumption by machinery. The disposal of rebar waste incurs the highest total ecological cost, followed by sorting facilities and recycling strategies, ranked second and third respectively.	Future research should focus on integrating ecological indicators into BIM-based project development strategies.

Based on the number of studies and research content summarized in Tables 1, 2, and 3, it is evident that current research on tunnel carbon emissions using LCA theory remains limited both domestically and internationally, with a notable lack of unified standardized methodologies. Compared to the construction sector, tunnel carbon emission studies still lack comprehensive quantitative analysis methods. Different researchers consider varying indicators and employ diverse approaches when calculating tunnel carbon emissions. The most commonly used methods are the carbon emission factor method and the direct calculation method based on available data. The carbon emission factor method requires defining the calculation boundaries according to the different life cycle stages of the tunnel to accurately quantify carbon emissions. However, limitations arise due to differences in database types and the varying scope of data collected across databases. Consequently, using databases to calculate tunnel carbon emissions often faces issues such as incomplete data and limited coverage of certain tunnel life cycle phases.

A comparison of the number of publications in Tables 1, 2, and 3 indicates that current research on tunnel carbon emissions predominantly focuses on the construction phase. During this stage, emissions are typically quantified based on factors such as geological conditions, excavation methods, material production, and transportation processes. Tunnels are generally designed for long service lives, and the operation phase accounts for the largest proportion of total life cycle carbon emissions. However, studies addressing emissions during the operation and maintenance phase remain limited compared to those focused on construction. Tunnel lighting, in particular, contributes significantly to carbon emissions during this phase and is commonly assessed using database-driven direct calculation methods. Research on the deconstruction and recovery phase of tunnels is even more scarce, likely because most tunnels are still in operation and have not yet reached the end of their service lives. Existing studies in this area primarily examine the impact of recycling strategies on carbon emissions and their associated economic benefits.

In summary, while continuing to advance research on carbon emissions during the construction phase, future efforts should place greater emphasis on investigating emissions during the operation, maintenance, and decommissioning phases to achieve a more comprehensive understanding of the full life-cycle carbon footprint of tunnels.

4. TUNNEL CARBON EMISSION PREDICTION BASED ON LCA

Carbon emissions during the operation and maintenance phase of tunnels account for more than 80% of the total emissions over the tunnel's life cycle (Opher et al., 2021). Conducting predictive studies is therefore essential for quantifying the full carbon footprint, identifying high-emission components, and enabling timely, dynamic adjustments. Such efforts can effectively support the adoption of low-carbon materials and construction technologies. At present, research on the prediction of tunnel carbon emissions remains relatively limited. A search of the WoS database using the keywords "tunnel" and "prediction" yielded a small number of relevant publications. After performing a relevance-based screening and analysis, the findings are summarized in Table 4.

Table 4. *Research on Carbon Emission Prediction for Tunnels*

Reference	Models/Software	Method	Parameter	Conclusion	Further work
Zhao et al., 2022	SSA-SVR	Random forest (RF) Support vector regression （SVR） sparrow search algorithm (SSA) Grey wolf optimizer and genetic algorithm （GWO）	cohesiveness of the soil, internal friction angle, penetration resistance, earth pressure, buried depth, advancing speed, torque, total thrust force, advancing time, mud inflow rate，mud density	CO_2 emissions during material production, material transportation, and prefabrication of structural components show little variation. Carbon dioxide emissions vary greatly among different stages of shield tunneling. Torque is the most significant factor affecting CO_2 emissions, while slurry inflow has the least impact.	The prediction model targets CO_2 emissions during different stages of slurry shield tunnel construction, but further consideration is needed for emissions during operation, maintenance, and other construction methods.
Xu et al., 2019	IBM SPSS Statistics 20.0 （IBM）	Linear regression analysis	Rock mass classification, Overburden depth, Rock mass quality, Excavation method for inter-pipe clearance, Tunnel alignment deviation	Two theoretical models were proposed to predict greenhouse gas emissions from tunnel construction, providing emission references during the design phase. The influencing factors, ranked from greatest to least, are total material quantity, excavation area, excavation method, rock mass classification, and overburden depth, with a significant correlation between rock mass classification and excavation method.	The prediction accuracy partially depends on local upstream material and energy emission levels as well as geological conditions. The model may not be applicable to other regions.

Wang et al., 2023	neural network models	CNN-LSTM and BPNN	Cohesion Internal friction angle Penetration resistance Earth pressure Overburden depth Advance rate Cutter torque Shield thrust Shield cutter operating time	A relatively accurate estimate of carbon emissions during shield tunnel construction can be obtained, applicable to carbon emission prediction and control in similar tunnel projects.	
Seyrfar et al., 2021	Python	BPNN RF and XGBoost	City of Chicago Energy Benchmark Database	Assessed energy consumption of multi-family residential buildings in Chicago and evaluated the impact of various variables on building energy use.	Most building energy benchmark data are self-reported, so data accuracy remains a concern in these studies.
Huang et al., 2015	ReCiPe Midpoint (E) V1.06/World ReCiPe E method		Excavation area Cross-sectional area Tunnel length	Improving transportation efficiency and increasing biofuel blending in regular diesel are potential policies for reducing GWP emissions. Explosives production and blasting are the main contributors to HTP, but truck transportation also plays a significant role in mitigating HTP impacts.	Selected six categories as impact indicators： climate change (GWP), human toxicity (HTP), photochemical oxidant formation (POFP), particulate matter formation (PMFP), terrestrial acidification (TAP), terrestrial eco-toxicity (TETP)
Zhao et al., 2022	QAP model	SSA-LSTM	Population Per capita GDP Industrial structure Energy intensity Urbanization rate	The influence of various factors on carbon emissions in the Yellow River Basin varies across different periods. Significant provincial differences exist in total carbon emissions.	Inter-provincial differences should be fully considered when formulating emission reduction policies.

Based on Table 4, current research on tunnel carbon emission prediction still holds substantial potential for development. The primary prediction methods can be broadly categorized into two types: mechanism-driven models and data-driven models. The former is grounded in physical equations and engineering principles, using established calculation formulas in combination with various databases to simulate and predict trends in tunnel carbon emissions. The latter rely on machine learning or statistical techniques—such as linear regression, support vector machines (SVM), and random forests—to analyze existing data and predict carbon emissions.

As indicated in the table, existing predictive algorithms predominantly focus on estimating carbon emissions during tunnel construction. However, a significant research gap exists concerning the temporal nonlinearity of emissions during the operation phase—a critical period due to its dominant contribution to the tunnel's overall life cycle emissions.

Limited research has addressed regional variability, revealing substantial differences in total emissions across regions. These disparities stem from factors like economic structure, energy mix, industrial distribution, climate, and population density. Furthermore, variations in renewable energy adoption, transportation modes, and urbanization levels further exacerbate the spatial heterogeneity of emissions.

Future research on tunnel carbon emission prediction should prioritize developing integrated models that combine mechanism-driven and data-driven approaches to enhance accuracy and robustness. While current efforts concentrate on construction, expanding the scope to encompass operation, maintenance, and end-of-life phases is essential for enabling holistic low-carbon optimization throughout the entire life cycle. Additionally, establishing localized, spatiotemporally dynamic carbon emission factor databases is recommended. This would reduce reliance on generic or foreign datasets and better reflect local conditions.

5. CONCLUSION

This study focuses on the application of LCA in tunnel engineering to carbon emissions in tunnel engineering, systematically reviewing and analyzing the current methodologies for carbon emission calculation, prediction models, and carbon reduction/sequestration measures. The aim is to clarify research progress, identify key challenges, and provide references for future studies. Based on the literature review and problem analysis, the following two main conclusions are drawn:

(1) Tunnel carbon emission calculations primarily concentrate on the construction phase, with insufficient coverage of the entire life cycle. Existing research largely focuses on accounting for carbon emissions during construction, emphasizing the carbon footprints of materials such as concrete and steel, energy consumption and emissions from construction equipment, and indirect emissions during transportation. Considerations for carbon emissions in the design, operation, maintenance, and decommissioning phases remain inadequate, and a comprehensive full life cycle carbon accounting system has yet to be established.

(2) Carbon emission prediction models are continuously evolving, but accuracy and adaptability require further enhancement. Current prediction methods include statistical regression, machine learning, and BIM-LCA integration techniques, achieving some progress in improving prediction efficiency and dynamic responsiveness. However, many models still suffer from high dependency on input data, parameter uncertainties, and difficulties in covering complex construction scenarios, limiting their broad practical application in engineering projects.

In summary, although tunnel carbon emission research has made preliminary progress in the construction phase, challenges remain in full life cycle coverage and prediction accuracy. Future efforts should accelerate the systematic development of carbon accounting methods, promote the deep integration of intelligent prediction and carbon reduction technologies, and establish a systematic, sustainable low-carbon tunnel development model aligned with the “dual carbon” goals, thereby supporting the high-quality transformation of green infrastructure.

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