CARBON TRACKING IN THE BUILDING SECTOR: A ‘CABBAGE’ FRAMEWORK

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ABSTRACT: *The great challenge of global climate change urges world economies to reduce greenhouse gas emissions and promote sustainable development, where the building sector plays a vital role. Carbon tracking technology is one of the keys to capturing carbon emissions for sustainable construction such as net-zero buildings. This paper reviews five key carbon tracking technologies – life cycle assessment (LCA), energy modeling, building operation monitoring, carbon accounting software, and green certification and rating systems. With summarized advantages, beneficiaries, and limitations of the five technologies, we propose a Carbon Tracking ‘Cabbage’ (CTC) framework that incorporates all carbon tracking tools as inner technological layers for multiple stakeholders at multiple stages of construction management. The main contribution of this paper is the CTC framework that rationalizes the scopes and adoption strategies of carbon tracking technologies by collaborative stakeholders to achieve informed decision-making, implement effective carbon reduction strategies, and subsequently contribute to climate change mitigation actively.*

KEYWORDS: *Carbon tracking; Building sector; Carbon tracking cabbage framework; multi-stakeholder; Technology adoption*

1. INTRODUCTION

Global climate change poses an increasingly severe challenge to human society and ecosystem. Carbon emissions, as a major source of greenhouse gases, have been widely recognized as one of the primary drivers of climate change. In light of this, establishing a sustainable green economy through collective global efforts has become a pressing priority. The building sector plays a crucial role in global carbon emissions, accounting for a significant portion of the global greenhouse gas output (Khalili & Chua, 2013). As society strives to combat climate change and become carbon neutral, addressing the carbon footprints of buildings and adopting sustainable practices in the construction and operation of these structures has become a top priority.

Tracking and monitoring carbon emissions, particularly carbon dioxide (CO_2), reveal evidence and insights into the amount of carbon in the atmosphere, enabling targeted strategies to reduce emissions and mitigate the impacts of climate change (Liu et al., 2020). Carbon tracking, as an essential component of the broader carbon management strategy, has emerged as a powerful tool to measure, monitor, and mitigate the carbon impact of buildings (Liu et al., 2020). Additionally, carbon tracking provides crucial data for setting emission reduction goals, empowering governments, organizations, and industries to establish clear and achievable targets while monitoring progress. Through carbon tracking and reporting, businesses can measure the carbon footprint, identify improvement opportunities, transparently disclose environmental impacts to stakeholders, and showcase the social responsibility. Furthermore, standardized carbon tracking and reporting methods foster global cooperation, which enables international transparency, peer pressure, and collaboration in achieving shared climate goals (Kang et al., 2015). In summary, carbon tracking and reporting are essential tools in combating climate change, providing vital data to empower decision-makers, businesses, and individuals to take proactive action in creating a more sustainable and resilient future.

The significance of carbon tracking technologies in the building sector lies in measurability and interpretable evidence of comprehensive carbon emissions across the entire lifecycle of a building. From the production and transportation of construction materials to energy consumption during building operations and eventual demolition, these technologies offer valuable insights into the carbon impact of each stage, enabling informed decision-making and targeted carbon reduction strategies. Over the years, carbon tracking technologies in the building sector have undergone significant advancements and innovations (Xu et al., 2023). From traditional methodologies to cutting-

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edge digital solutions, these tools have played a pivotal role in quantifying the carbon footprint of buildings at different stages of their lifecycle. By providing a holistic assessment of carbon emissions, these technologies empower stakeholders, including architects, engineers, policymakers, and building owners, to make informed decisions that foster sustainable building practices.

However, current carbon tracking technologies fall short of encompassing the entire building lifecycle in the building sector. Although individual technology is advantageous, carbon tracking as a whole is always fragmented and incomplete. Subsequently, the fragmented and incomplete carbon tracking hinders holistic and effective carbon reduction strategies and leads to missed opportunities for emission mitigation and sustainable practices. Thus, there is a significant research gap in a comprehensive approach that spans carbon tracking to all stages of a building's lifecycle.

This paper embarks on a novel framework that rationalizes the full-lifecycle carbon tracking based on an in-depth exploration of all the carbon tracking technologies in the building sector. By reviewing historical milestones, technological breakthroughs, and real-world applications, we aim to present a comprehensive overview of the evolution of these technologies and their impact on the industry's sustainability efforts. The primary objectives of this study are:

- To provide an in-depth analysis of the historical evolution of carbon tracking technologies in the building sector, highlighting key milestones and breakthroughs that have shaped their current state;
- To examine the existing carbon tracking technology models, methodologies, and tools deployed in the building industry, assessing their effectiveness, limitations, and potential for future enhancements; and
- To explore real-world case studies and successful implementations of carbon tracking strategies, showcasing how these technologies have contributed to carbon reduction goals and sustainable building practices.

2. LITERATURE REVIEW

2.1 Existing carbon tracking technologies

As shown in Fig. 1, there are five main categories of carbon tracking techniques. They are LCA, energy modeling, building operation monitoring, carbon accounting software, and green certifications and rating systems. The associated phases and key technologies are sketched along the of a curved arrow of a typical construction project course in Fig. 1.

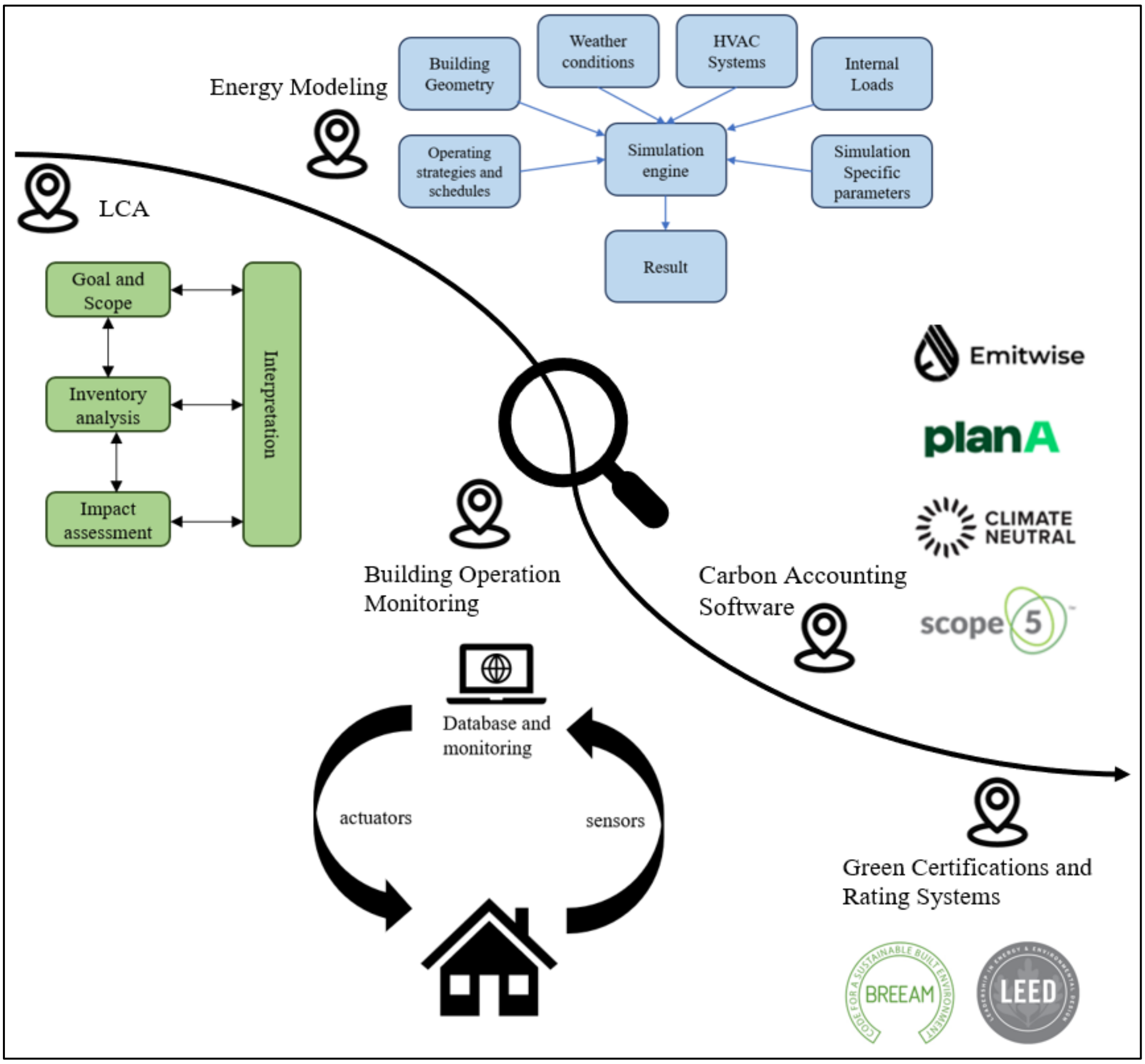

Fig. 1: Conceptual map of existing carbon tracking technologies.

LCA. LCA is a systematic method used to assess the carbon emissions generated throughout the entire lifecycle of a building, including raw material procurement, construction, operation, and demolition (Dodoo et al., 2014). By comprehensively regarding the environmental impacts at each stage, LCA provides comprehensive carbon emission data, guiding design and material selection to achieve sustainable and low-carbon building solutions. The strength of LCA lies in its comprehensiveness, such as material production, transportation, construction, and dismantling, beyond the building's use phase. Thus, LCA offers a more holistic evaluation of the building's environmental impact.

Energy Modeling. Energy modeling is a method that involves simulating a building's energy consumption using specialized software, thereby estimating carbon emissions. These models integrate factors such as building design, energy systems, and climate conditions, providing architects and energy experts with optimized strategies to enhance energy efficiency and reduce carbon emissions (Wang et al., 2021). Energy modeling allows decision-makers to predict a building's energy performance under different conditions during the design phase, facilitating environmentally friendly and energy-efficient choices. Additionally, it enables continuous monitoring and optimization of energy usage during the subsequent operational phase.

Building Operation Monitoring. Building operation monitoring entails the installation of sensors and monitoring systems to collect real-time data on energy consumption and emissions. These monitoring systems help building managers gain better insights into energy usage, promptly identify potential energy waste, and implement measures to reduce carbon emissions (Bilec et al., 2010). Continuous monitoring enables building managers to track energy performance and make timely adjustments and improvements to achieve sustained carbon reduction.

Carbon accounting software. Carbon accounting software is a specialized tool used to track and record carbon emission data for building projects and companies. These software solutions typically offer data collection, analysis, and reporting functionalities, facilitating the formulation of carbon reduction strategies and supporting the realization of carbon neutrality and emission reduction goals (Liu et al., 2019). Carbon accounting software empowers the building industry to efficiently collect and manage carbon emission data, providing support for achieving carbon neutrality and emission reduction objectives.

Green certifications and rating systems. Some countries and regions have introduced green building certification and rating systems, such as LEED, BREEAM, and Green Building Labels. These systems comprehensively assess a building's environmental performance, including carbon emissions, thus encouraging the adoption of more environmentally friendly design and operational practices in the construction industry. Participation in green certifications and ratings allows building projects to gain recognized environmental recognition, enhance market competitiveness, and contribute to sustainable development (Wang, Teng, et al., 2021). These green certification systems provide a clear goal for the building industry, driving the sector towards a more environmentally friendly and low-carbon direction (Chang et al., 2016). By comprehensively applying these carbon tracking technologies and practices, the building industry can play a proactive role in addressing global climate change and collectively create a more sustainable and greener future.

2.2 Advantages, beneficiaries and limitations of carbon tracking

This subsection provides an in-depth examination of the advantages and limitations of different carbon tracking technologies used in the building sector. The technologies discussed include LCA, Energy Modeling, Building Operation Monitoring, Carbon Accounting Software, and Green Certifications and Rating Systems. Each technology's advantages and limitations are summarized for comparison. The beneficiaries are also analyzed to gain a comprehensive understanding of the benefits in sustainable and low-carbon building practices.

Table 1: Advantages, beneficiaries, and limitations of carbon tracking technologies.

Carbon tracking tech.	Advantages	Beneficiaries	Limitations
LCA	• Comprehensive and holistic approach • Enables optimized design and material selection	• Building owners and developers • Government agencies and regulatory authorities • Environmental organizations and NGOs	• Data-intensive and time-consuming • Dependent on data quality and availability
Energy Modeling	• Virtual simulations for energy efficiency • Allows iterative design improvements	• Architects and engineers • Energy managers	• Relies on input assumptions and model accuracy • Real-world performance may differ from predictions
Building Operation Monitoring	• Provides real-time data on energy consumption • Identifies energy wastage and reduction potential	• Building owners and developers • Energy managers	• Requires infrastructure of sensors and data systems • Interpretation may need specialized expertise
Carbon Accounting Software	• Streamlines data collection and analysis • Supports progress tracking and mitigation strategies	• Building owners and developers • Government agencies and regulatory authorities	• Choosing appropriate software can be challenging • Reliability depends on data accuracy and completeness
Green Certifications and Rating Systems	• Offers standardized benchmarks for sustainability • Incentivizes eco-friendly design and practices	• Building owners and developers • Environmental organizations and NGOs	• Time-consuming and resource-intensive certification • Potential gap between predicted and realized outcomes

LCA's strength lies in the comprehensive assessment capability, which takes into account the environmental impact of the life cycle stages of the building. LCA provides comprehensive carbon emission data and other environmental indicators and helps decision makers to fully understand the environmental performance of the building. Through LCA, builders can compare the environmental performances of different design and material options to make more informed choices, optimize building design and material choices, reduce carbon emissions and environmental impact, and achieve sustainability goals (Hong et al., 2015). However, LCA also has some challenges and drawbacks. Its complexity is a significant problem. The implementation of LCA is complex and costly, because it requires a large amount of data collection, analysis and calculation, and has high technical and professional requirements. In addition, the reliability of LCA depends on the quality of the data and the reliability of data source. Therefore, incomplete or missing data can lead to uncertainty in the results and misled decisions. At the same time, conducting LCA also requires a significant investment of time and resources, which may become impractical or difficult to apply to complex construction projects.

Energy modeling can provide architects and energy experts with comprehensive data and information to gain insights into a building's energy use. With the simulation results of a building's energy consumption under different conditions, decision makers can predict a building's energy performance and make environmentally friendly and energy efficient decisions at the early design stage. Secondly, energy modeling integrates factors such as building design, energy system and climate conditions to provide solutions for building projects to optimize energy efficiency and reduce carbon emissions. Therefore, energy modeling can reduce energy costs and environmental impact throughout the life cycle (Li & Chen, 2017). However, energy modeling's reliability depends on the accuracies of both input data and the building model. Inaccurate data or modeling can lead to biased results and ineffective decisions. Secondly, energy modeling requires a high level of technology and expertise, and there may be barriers to learning and application for some builders. In addition, energy modeling also requires a certain amount of time and resource investment, especially for complex construction projects, which may increase the difficulty and cost of implementation.

Building operations monitoring provides real-time and accurate energy consumption data to help building managers get a complete picture of a building's energy use. Through continuous monitoring, managers can immediately grasp the energy consumption of the building, find potential energy waste and problems in time, and provide a basis for taking targeted measures. Secondly, operational monitoring can help optimize a building's energy use and operational strategies to achieve ongoing carbon reduction and energy conservation goals. By aligning operations with actual data, builders can reduce carbon emissions and energy costs and improve operational efficiency (Geng et al., 2022). However, the installation and maintenance of building monitoring systems may require certain inputs and costs. The selection, installation and commissioning of sensors and monitoring equipment require specialized technical support. Secondly, the processing and analysis of large amounts of real-time data may also require certain technical and management capabilities (Geng et al., 2022). For some builders, it may be necessary to train and improve the data analysis and operations management skills of relevant personnel. In addition, the building monitoring system also faces the problem of data security and privacy protection, and it is necessary to establish a reasonable data management and protection mechanism to ensure data security and compliance.

Carbon accounting software enables efficient data collection and management. By automating data acquisition and processing, manual operation and time cost can be greatly reduced, and the accuracy and reliability of data can be improved. Secondly, carbon accounting software provides powerful data analysis and reporting capabilities, capable of turning complex carbon emissions data into intuitive charts and reports to provide clear insight and guidance for decision-makers (Long et al., 2018). This helps to develop carbon reduction strategies and track progress, driving the construction industry in a lower carbon direction. However, choosing the right carbon accounting software for your needs requires consideration of a number of factors, including the software's functionality, compatibility, price, and user-friendliness. Different software may be suitable for different sizes and types of construction projects, so careful evaluation and selection are required. Secondly, it is necessary to ensure the accuracy and integrity of the data during the use of the software, otherwise, it may lead to errors and inaccurate analysis of the results. Therefore, the construction industry needs to establish a reasonable data collection and verification mechanism to ensure that the software output data is reliable and usable.

The Green certification and rating system provides the construction industry with clear environmental standards and targets, driving the construction industry to adopt more environmentally friendly and sustainable design and operation practices. By participating in certification and rating, construction projects can receive recognized environmental recognition, improve their market competitiveness, and attract more environmentally conscious customers and investors. Secondly, the green certification and rating system takes into account the environmental performance of the building, including carbon emissions, energy efficiency, material use and indoor environmental quality, so as to achieve comprehensive environmental benefits and sustainable development (Ma et al., 2020).

However, some rating systems may be too complex and cumbersome, requiring large amounts of data and proof to meet certification standards, increasing costs and burdens for builders. Secondly, the certification and rating process can be time-consuming, affecting the schedule and operation of the project. In addition, sometimes the rating results may only reflect the design and planning stages of the building and do not actually take into account the actual operation and use of the building, and therefore may be biased from the actual environmental performance.

3. THE PROPOSED CARBON TRACKING 'CABBAGE' FRAMEWORK

Fig. 2 presents the proposed Carbon Tracking 'Cabbage' (CTC) framework. The architecture of CTC framework represents the characteristics and beneficiaries of all the five technologies. The integrated framework can enable builders and all stakeholders to get a comprehensive picture of the carbon emissions of buildings. The quantitative carbon tracking results also enables carbon reduction strategies and plans in a data-driven manner, driving the construction industry towards a greener and low-carbon direction in the digital era. Incorporating a multi-stakeholder engagement approach, the CTC framework fosters collaboration among diverse participants, including architects, engineers, policymakers, and environmental experts, creating a synergistic effort to address carbon emissions and advance sustainability within the construction industry. With integrated carbon tracking technologies and evidenced-based multi-stakeholder practices, the construction industry can play an active role in contributing to the global response to climate change and co-creating a more sustainable and green future.

Fig. 2: The proposed Carbon Tracking 'Cabbage' framework in this paper.

3.1 Rationale

Carbon tracking and management becomes distinctly robust and strategic based on the CTC framework. This comprehensive approach stems from the imperative to synergize diverse data streams, resulting in a panoramic understanding of an organization's carbon footprint and the cultivation of a holistic strategy for sustainable practices. By seamlessly integrating techniques like LCA, Energy Modeling, Building Operation Monitoring, Carbon Accounting Software, and Green Certifications and Rating Systems, stakeholders attain a multifaceted perspective on their carbon emissions, uncovering insights that span the entire spectrum of product lifecycles.

Energy modeling serves as a vital supplement to this perspective, shedding light on emissions linked to energy usage, while real-time operational data from building operation monitoring introduces an agile layer of information. Carbon accounting software meticulously quantifies emissions, and green certifications provide benchmarks for measuring sustainability performance. The true power of integration lies in its ability to provide a nuanced analysis of emissions' sources and potential reduction avenues. This comprehensive comprehension empowers organizations to precisely identify processes or lifecycle stages that contribute significantly to the carbon footprint, facilitating the strategic alignment of reduction efforts with broader sustainability objectives.

Furthermore, the incorporation of real-time monitoring and reporting, seamlessly facilitated by building operation monitoring and carbon accounting software, bestows organizations with the nimbleness to make swift, well-informed decisions. The trajectory towards carbon reduction objectives can be closely monitored, enabling agile adjustments in real-time that optimize the efficiency of sustainability initiatives. The integration of esteemed green certifications and rating systems augments the credibility of these endeavors, ingraining transparency and accountability within the organizational approach to sustainability. In essence, this fusion of techniques underscores a sagacious and pragmatic approach to surmounting the intricate challenges of carbon reduction, laying the essential groundwork for a verdant and more sustainable future, fortified by data-driven insights and strategic harmony.

3.2 Adoption strategies

The CTC framework provides actionable strategies for stakeholders to adopt in order to achieve their carbon reduction goals. By facilitating data integration and collaboration across departments, organizations can ensure a seamless flow of information from technologies such as LCA, energy modeling, building operations monitoring, carbon accounting, and green certification. This collaborative approach promotes a comprehensive understanding of carbon emissions, enabling informed decision-making and targeted mitigation efforts. The implementation of advanced technology solutions has become a key strategy. By investing in carbon accounting software, energy management systems, and IoT devices for real-time monitoring of building operations, organizations can improve their ability to accurately quantify emissions and optimize energy use in a timely manner. A continuous improvement cycle is essential, where real-time monitoring data informs regular review and analysis to identify trends and areas for improvement. Over time, this iterative process enhances carbon reduction strategies and optimizes operations.

Transparently communicating efforts to reduce carbon emissions to stakeholders demonstrates a commitment to sustainability, while incentive programs and recognition boost employee motivation and morale. Long-term strategic planning ensures that organizations remain adaptable and resilient in their carbon reduction initiatives. Overall, the CTC framework serves as the foundation for implementing these strategies, guiding organizations toward a more sustainable and environmentally responsible future.

3.3 Application scenarios of the CTC framework

The CTC framework can guide sustainable construction management in different phases of a construction. For example, the framework integrates LCA and energy modeling, enabling design teams to assess the environmental impact of different design options. This enables the selection of materials, systems and technologies that meet carbon reduction targets, creating a solid foundation for sustainable projects. As the construction phase begins, the CTC framework maintains its importance. The integration of real-time monitoring and data-driven insights gives construction teams the means to track energy consumption and emissions in real time. During construction, rapid interventions can be implemented to optimize energy use and reduce carbon emissions, reflecting the immediate utility of the framework.

During the operational phase, the framework facilitates continuous monitoring and ensures the continuous and efficient operation of construction projects. Building operation monitoring ensures sustainable performance, while carbon accounting software tracks ongoing emissions. In addition, a recognized green certification and rating system is used to validate and communicate the sustainable achievements of the project to stakeholders, promoting transparency and accountability. Finally, during the retrofit and retrofit phases, the CTC framework guides informed decision-making by assessing the carbon emissions impact of retrofit choices. By seamlessly integrating LCA and energy modeling, retrofit teams can strategically upgrade systems, materials, and technologies to achieve the best carbon reduction outcomes.

All in all, the CTC framework serves as a comprehensive and adaptable tool for effective and sustainable construction management at all stages of a construction project. By leveraging its integrated technology, stakeholders are able to make informed, data-driven decisions that align with carbon reduction targets, advance environmentally responsible building practices, and contribute to a greener future.

4. DISCUSSION

As carbon emissions continue to be the primary driver of climate change, tracking and mitigating carbon emissions has become a top priority for governments, organizations and industries around the world. The construction sector's significant contribution to global carbon emissions underscores the need to focus on reducing the carbon footprint of buildings throughout their life cycle. Carbon tracking becomes a powerful tool for measuring, monitoring and mitigating the carbon impact of buildings. By tracking and monitoring carbon emissions, policymakers gain valuable insights into the amount of carbon in the atmosphere, enabling targeted mitigation and climate change strategies. Carbon tracking also helps to set clear and achievable emission reduction targets and promotes global cooperation and transparency to achieve common climate goals.

In addition, it is important to standardize carbon tracking and reporting methods to ensure consistency and comparability in international Settings. These technologies enable businesses to measure their carbon footprint, identify opportunities for improvement, and demonstrate to stakeholders their commitment to environmental responsibility. In the construction sector, carbon tracking technology provides a comprehensive understanding of the carbon emissions of buildings throughout their life cycle. From construction through operation to final demolition, these tools provide insights for informed decision-making and promoting sustainable building practices. Throughout the inquiry, the focus remained on the development and advancement of carbon tracking technology. From traditional methods to cutting-edge digital solutions, these technologies continue to improve our ability to quantify and understand carbon emissions, making them indispensable in our fight against climate change.

Overall, carbon tracking technologies enable stakeholders to make informed choices, assess the environmental impact of their actions, and work together to build a more sustainable and resilient future. By providing valuable data and insights, these technologies are transforming the construction industry and moving us closer to a carbon-neutral and healthier planet.

5. CONCLUSION

In summary, this comprehensive review highlights the significance of carbon tracking technologies in the building sector for combating climate change and promoting sustainable practices. The five key technologies—LCA, Energy Modeling, Building Operation Monitoring, Carbon Accounting Software, and Green Certifications and Rating Systems—each play essential roles in understanding, monitoring, and reducing carbon emissions in buildings. LCA provides a comprehensive view of a building's carbon footprint across its entire life cycle, guiding sustainable design and material choices. Energy Modeling allows for energy consumption simulation and optimization during the operational phase, enabling the early implementation of energy-efficient strategies. Building Operation Monitoring offers real-time data collection to understand and reduce energy wastage. Carbon Accounting Software tracks emissions and sets reduction goals, while Green Certifications and Rating Systems incentivize sustainable practices.

A proposed Carbon Tracking 'Cabbage' (CTC) framework integrates all the technologies and empowered stakeholders for data-driven decision-making, carbon reduction strategies, and sustainability initiatives. Collaboration among researchers, policymakers, and industry professionals, as sketched in the CTC framework, is crucial for implementing this framework and achieving a greener and more sustainable future. By embracing carbon tracking technologies under the CTC framework, the building sector can actively contribute to mitigating climate change and creating a resilient and environmentally responsible world.

However, the CTC framework in this paper is conceptual. We require a system platform and pilots in the industry to realize and validate the effectiveness of the CTC framework. Furthermore, the arguments and discussion only flows at the surface of general cases. Fine adjustments are necessary for each construction 'niche' industry to meet construction industrial standards, supply chains, and cultures for carbon tracking of the whole life cycles of buildings.

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