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REVIEWPAPER

Green construction for low-carbon cities: a review

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Abstract

The construction industry is a major user of non-renewable energy and contributor to emission of greenhouse gases, thus requiring to achieve net-zero carbon emissions by 2050. Indeed, construction activities account for 36% of global energy consumption and 39% of global carbon dioxide emissions. Reducing carbon emissions requires adapted government policies, carbon emission analysis and calculation models, and sustainable materials. Here, we review green construction with focus on history, carbon emissions, policies, models, life cycle assessment, and sustainable materials such as biochar, bioplastic, agricultural waste, animal wool, fly ash and self-healing concrete. Analysis of carbon emissions over the building life cycle shows that the construction phase accounts for 20–50% of total carbon emissions. The average ratio of construction phase annual emissions to operation phase emissions is 0.62. We present national policy frameworks and technology roadmaps from the United States of America, Japan, China, and the European Union, highlighting plans to achieve carbon neutrality in the building sector.

Keywords Green construction · Zero-carbon building · Carbon emissions · Life cycle assessment · Sustainable materials · Net-zero carbon

Abbreviations

WorldGBC	World Green Building Council
NEDO	The New Energy and Industrial Technology Development Organization
CCUS	Carbon Capture, Utilization and Storage
NDRC	National Development and Reform Commission
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
BEAM	Building Environmental Assessment Method

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Introduction

Increasing global industrialization and urbanization have consumed a huge amount of non-renewable energy and released a significant amount of greenhouse gases, resulting in a rise in global temperature and causing numerous environmental degradation issues (Chen et al. 2022). Since pre-industrial times, from 1850 to 2022, the average carbon dioxide concentration in the Earth's atmosphere has increased dramatically from 285 to 417 ppm (Carbon Dioxide Daily 2022). Carbon dioxide is the most abundant greenhouse gas and has the most detrimental effect on the environment. The amount of carbon dioxide emitted by the use of non-renewable energy sources will increase by approximately 50% by 2050 (Rabaey and Ragauskas 2014). Suppose effective measures to control or reduce carbon dioxide emissions are not taken. In such a scenario, future climate change and its consequences will include a rise in global temperature, an increase in extreme weather, the destruction of marine and terrestrial ecosystems, a rise in sea level, the loss of biodiversity, and the extinction of some species (Mora et al. 2018; Wang et al. 2021). As a result, the construction industry, which is a major emitter of carbon dioxide, has focused more on green construction, sustainable materials, and carbon emission reduction over the building's life cycle in recent decades, and carbon intensity reduction has become one of the most common sustainable construction indicators. In addition, the most recent report of the Intergovernmental Panel on Climate Change affirms that limiting climate change to 1.5 degrees, committing to peak carbon dioxide emissions by 2030, and aiming for carbon neutrality by 2060 are all essential to achieving these goals (Intergovernmental Panel on Climate Change 2022; Yang et al. 2022a). Therefore, green construction in the building industry has become one of the most important research areas that can contribute to achieving this carbon neutrality objective.

The rapid growth of the construction industry stimulates global economic expansion while having a substantial impact on the natural and built environment. The construction industry consumes large quantities of energy, natural resources, and water while generating vast quantities of waste (Menegaki and Damigos 2018). As shown in Fig. 1, building construction activities account for 36% of global energy consumption and 39% of global carbon dioxide emissions (World Green Building Council 2017). By 2030, the global building sector will need to increase its energy intensity per square meter by an average of 30% to meet the global climate goal establishe by the Paris Agreement to limit the global average temperature increase to 2 degrees Celsius compared to pre-industrial levels (United Nations 2015). Currently, several nations have implemented diverse green construction policies in response to climate change concerns to promote early carbon peak and carbon neutrality in the construction industry (Adel et al. 2022). In addition, hybrid input–output analysis models and life cycle assessment methods for the construction industry are frequently used in green construction projects to reduce the carbon emissions and energy consumption of buildings over their lifetime (Zhang and Wang 2016) and achieve sustainable development goals. Using biochar and other sustainable materials are also methods and strategies for developing green construction (Fawzy et al. 2021; Osman et al. 2022a; Teng et al. 2019). Therefore, studying the advantages of implementing green construction and the obstacles it faces

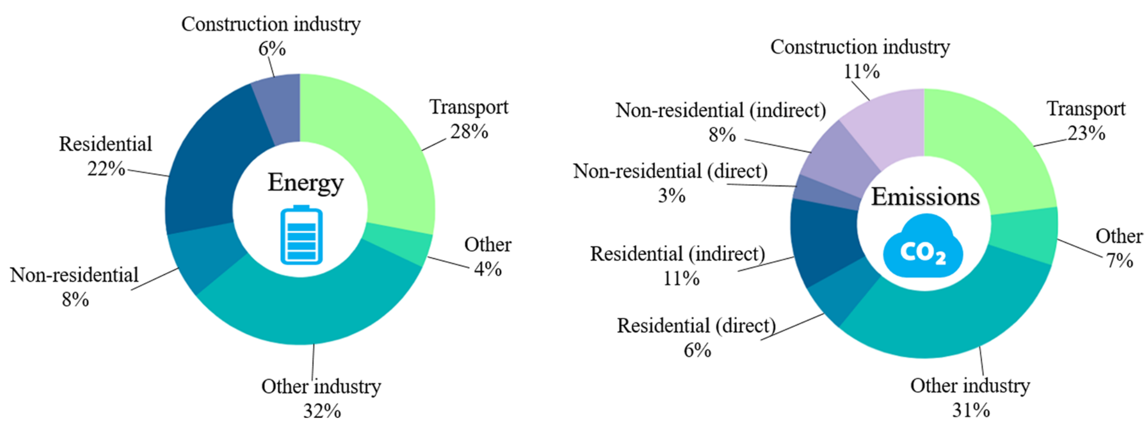


Fig. 1 Global share of buildings and construction's final energy use and emissions. This figure shows the share of energy consumption by industry, with the building industry accounting for 36% of energy consumption, including 6% for construction, 22% for residential, and 8% for non-residential. Moreover, the percentage of global carbon emissions is shown, with the building industry accounting for 39%. The construction industry is at 11%, non-residential (indirect) at 8%, non-residential (direct) at 3%, residential (indirect) at 11%, and residential (direct) at 6%. The goal of zero-carbon buildings can be achieved by reducing the energy consumption and carbon emissions of the building sector in the figure—data obtained from: (International Energy Agency 2019)

will help remove carbon dioxide from buildings through various environmental, economic, social, and technological measures, thereby facilitating the construction industry's early achievement of net-zero carbon emissions.

Herein, this literature review presents a systematic discussion of the factors influencing carbon emissions in the construction life cycle, focusing on the carbon emissions research boundaries of material consumption, on-site construction activities, transportation, on-site living, equipment operation, and on-site office on the construction phase. Furthermore, the review explores global green construction policies, primarily referring to the policies or measures developed by individual countries to promote the early achievement of net-zero carbon emissions in the construction industry. The review also presents a detailed investigation of various carbon emission analysis models or methods used in green construction and systematically discusses the application of life cycle assessment and its positive effect on achieving carbon neutrality in the construction industry. Moreover, the review proposes using sustainable materials such as biochar, bioplastic, agricultural waste, animal wool, fly ash, and self-healing concrete to analyze the positive impacts of green construction. Finally, the review provides relevant and up-to-date information, policies, and technologies for achieving carbon peak and carbon neutrality in the construction industry and helps relevant governments and personnel in different regions and countries to understand the environmental, economic, and social benefits of implementing green construction, as well as the challenges they face in the future.

History and definition of green construction

In the past few decades, the rise in global temperature, environmental degradation, and resource scarcity have brought green concepts to the attention of many industries (Yang et al. 2022a; Yang et al. 2022b). The expansive definition of "green" incorporates all cultures and activities created by humans to adapt to the environment and develop in harmony with it, guided by the fundamental theories of ecology and environmental science (Evenson and Gollin 2003). Environmental, sustainability, life cycle assessment, circular economy, sustainable materials, and waste recycling are the primary "green" aspects (Arif et al. 2009). Although we have been discussing green, different institutions, such as government and building departments, and individuals, such as researchers and construction companies, view green from different perspectives and use different sets of variables to determine a green course of action. In the life cycle of a construction project, the driving forces for each individual are distinct; therefore, understanding how to achieve carbon neutrality in the construction industry requires understanding the perceptions of these driving forces by various stakeholders (Liu et al. 2022).

In the twenty-first century, green building has become an important component of sustainable development (Ali and Al Nsairat 2009). Multiple nations have implemented this concept in the construction industry, and the term "green building" has multiple definitions. Kibert (2007) considers green buildings as healthy facilities designed and built resource-efficiently using ecologically based principles. In addition, green buildings are defined as those that reduce the impact of buildings on human health and the environment through better siting, design, construction, operation, and maintenance that improve the efficiency of energy, water, and material used in buildings and their sites (Kats 2003). Green buildings achieve the minimization or elimination of impacts on the environment, natural resources, and non-renewable energy through building construction activities in order to promote sustainability in the built environment and improve the health, well-being, and productivity of occupants and the community as a whole, and to foster a healthier and more productive society (Zuo and Zhao 2014).

Moreover, during the construction phase of a building, large quantities of energy, materials, water, and land are consumed, and greenhouse gases are released (Wu et al. 2019). The construction industry is responsible for a significant portion of both resource consumption and pollution emissions, as well as between 30 and 50% of the world's total carbon emissions. The construction industry's carbon emission intensity is greatest during the construction phase. Therefore, implementing sustainable building practices can reduce carbon emissions throughout the building's life cycle.

Green construction refers to the construction activities of engineering construction to maximize resource conservation and reduce the negative impact on the environment through scientific management and technological progress while ensuring the basic requirements of quality and safety to achieve the goals of energy saving, land saving, water saving, material saving and environmental protection, as shown in Fig. 2 (Shi et al. 2013). Green construction is an active application of the concept of sustainable development in the construction industry. Traditional construction projects ignore the environmental impact and only prioritize cost, quality and schedule as the primary objectives (Xu et al. 2019). Green construction, however, is an integrated construction method (e.g., life cycle assessment method) that focuses on the efficient use of resources, such as construction waste recycling, and environmental protection, such as the use of sustainable materials (Ortiz et al. 2009). In addition, the environmental impact of construction workers' activities and consumption has been evaluated. By implementing sustainability goals and executing green construction, construction workers and other stakeholders in the building

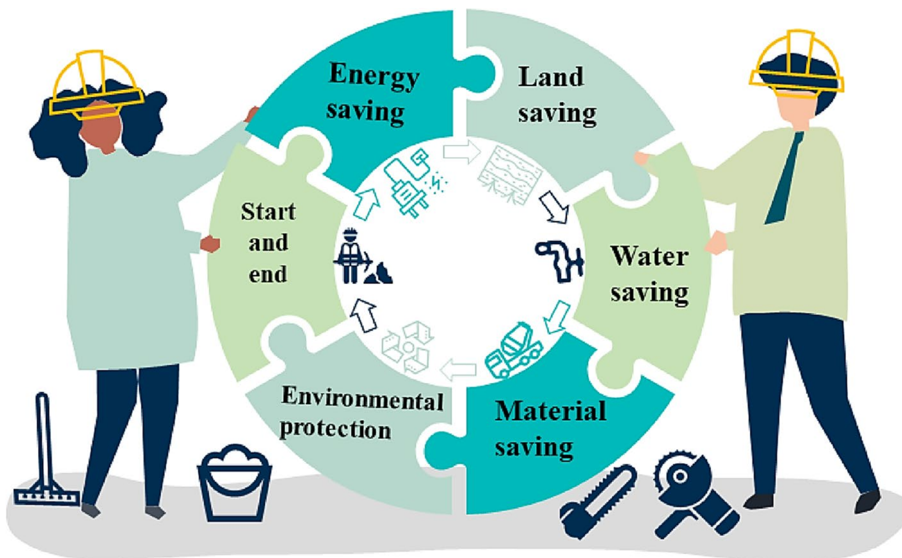


Fig. 2 Methodology and goals of the green construction process. This figure illustrates that the objective of green construction is to conserve energy, land, water, and materials. Moreover, the construction site environment should be safeguarded to the greatest extent possible. Green construction activities can be achieved through the measures and steps outlined in the figure. This figure also illustrates the need for construction crews to collaborate in order to complete green construction activities

construction process are required to reduce environmental impacts and promote carbon neutrality in the construction industry.

This section reviews the history and definition of green, green construction, and green building. It demonstrates the need to conserve energy, land, water, and materials to help the construction industry achieve net-zero carbon emissions as soon as possible and protect the environment.

Carbon emission in green construction

Regional governments worldwide have paid considerable attention to the deteriorating environment (Chau et al. 2015). Due to the construction industry's high energy consumption and proportion of carbon emissions, energy conservation and emission reduction are urgently required. The operation and maintenance phase accounts for approximately 55 to 60% of a building's total carbon emissions, according to an evaluation of carbon emissions over the entire life cycle (Zhang et al. 2021). However, the operation and maintenance of buildings span an extended period, which can reach up to several decades, and their carbon emissions are substantial due to a gradual accumulation process. In contrast, although the construction phase only accounts for 20–50% of the total carbon emissions (Buchanan and Honey 1994; Luo and Chen 2020), its density is the highest, and the construction phase's annual carbon emissions per square meter are much higher than those of the operation phase, so the development of green construction technologies is very urgent. In addition to playing an oriented role in achieving carbon neutrality, green construction technology can also aid in optimizing emission reduction during the building construction phase. Consequently, a precise analysis of the factors influencing carbon emissions in the building construction phase will aid in developing green construction technology, which can also serve as a basis for determining the direction of construction technology improvement and the corresponding measures. Table 1 examines the factors influencing carbon emissions during the building's life cycle.

It is commonly believed that the largest carbon dioxide emissions during the building life cycle occur during materials' production and operation phases. However, some studies have found that carbon emissions from the operation phase are only about 30% more than emissions from the construction phase (Kumanayake and Luo 2018; Peng 2016; Zhang and Wang 2015). According to a study conducted by several researchers, the ratio between annual construction phase emissions and annual operational emissions ranges from 0.39 to 1.30, with an average ratio of 0.62. This study indicates that the construction phase's carbon emissions are greater when viewed annually.

In addition, determining the system's boundary is essential for assessing carbon emissions accurately during the construction phase. Regarding the scope of carbon emission accounting throughout the life cycle of buildings, the majority of studies are nearly in agreement. However, the boundaries of construction phase carbon emission calculation studies are inconsistent. The central issue is whether building materials and equipment transport are included in the construction phase. For example, Guggemos Angela and Horvath (2006)) et al. argue that the transport of building materials and equipment should be included in the manufacturing phase, but some studies include them in the construction phase (Ji et al. 2018; Li and Chen 2017; Sandanayake et al. 2017). Based on the analysis of construction phase carbon emissions of eight construction projects in Table 1, we found that most studies used material consumption,

Table 1 Factors influencing carbon emissions from building construction

Project numbers	Research boundaries	Influencing factors	References
1	Material consumption On-site construction activities	Energy consumption Different energy sources Energy intensity The value per unit of output Machinery energy consumption Machinery efficiency Material usage	(Wu et al. 2019)
2	On-site construction activities On-site offices Transportation On-site living Equipment operation	Energy consumption Different energy sources Energy intensity The value per unit of output Floor area under construction	(Lin and Liu 2015)
3	Transportation Construction/installation on-site processes	Material usage Mechanical operation Waste deposit at the landfill	(Pacheco-Torres et al. 2014)
4	Transportation Construction activities	Operation of construction machines	(Fang et al. 2021)
5	Material consumption Construction activities	Material usage Mechanical operation Equipment operation Electricity usage Construction waste dispose	(Li et al. 2012)
6	Transportation Construction activities	Material usage Equipment operation	(Lu et al. 2016)
7	Material consumption Transportation	Regional material usage Transportation of construction material	(Onat et al. 2014)
8	Building material production and transportation On and offsite human activities Construction equipment use and transportation	Building type Floor area Structure	(Hong et al. 2015)

This table examines the factors that influence carbon emissions during the construction phase for various activities in various building projects, nations, and regions. The scope of the carbon emission study during the construction phase includes the consumption and transportation of materials, on-site construction activities, and operation of construction equipment. During the construction phase, energy consumption has a relatively large impact on carbon emissions

on-site construction activities, transportation, on-site living, equipment operation, and on-site offices as the boundary accounting, as shown in Fig. 3. Energy consumption, energy sources, energy intensity, the value per unit of output, machinery energy consumption, machinery efficiency, material usage, electricity usage, construction waste disposal, building type, area, and structure are the primary determinants of its carbon emissions.

During the construction phase, the use and transportation of construction materials, the operation of construction equipments, and the activities and lives of construction workers account for the majority of carbon emissions. Using sustainable materials during construction can reduce carbon emissions by up to 30% (González and García Navarro 2006). Carbon emissions can also be reduced by utilizing eco-friendly building practices.

This section examines the construction phase's scope and the factors influencing carbon emission accounting. The research indicates that carbon emissions from the construction phase are more significant when viewed annually. In the construction phase, carbon emissions accounting usually includes material consumption, on-site construction activities, transportation, on-site living, equipment operation, and on-site office space.

Global policies to support green construction and achieve carbon neutrality

The construction and building industry is highlighted as a major source of carbon emissions due to its extensive consumption of resources and energy and carbon emissions

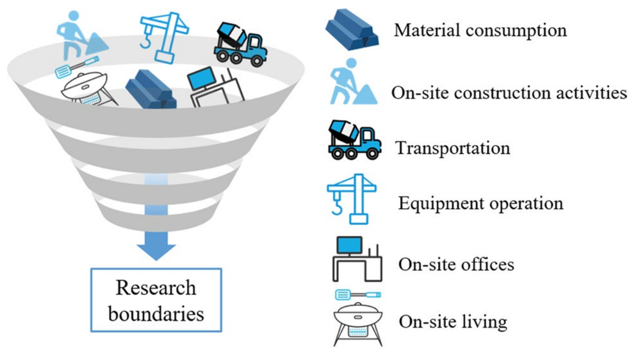


Fig. 3 Research boundaries of carbon emissions in the construction phase. The boundary accounting scope for carbon emissions during the construction phase is illustrated, which includes material consumption, on-site construction activities, transportation, on-site living, equipment operation, and on-site office. By calculating the carbon emissions from these construction activities, it is possible to derive the total amount of carbon dioxide produced during the construction phase of the entire project in order to develop green construction measures

throughout its entire life cycle (Osman et al. 2021a). The building sector and related construction activities currently account for 39% of energy-related carbon emissions globally, according to the World Green Building Council (WorldGBC). If we break this number into life cycles, the operational carbon emissions account for 28%, while embodied carbon emissions in the building materials account for 11%. Therefore, it is critical to realize carbon neutrality by implementing good policies in this sector (Qin et al. 2021; Too et al. 2022; Wu et al. 2022). The construction and building sector is clearly highlighted in the national policy framework and technologies roadmap in many countries, such as Japan (Figs. 4, 5), China (Figs. 6, 7), European Union, and the United States of America. Emerging initiatives to accelerate the transition to carbon neutrality include zero-emissions buildings and green construction (Galvin 2022; Karlsson et al. 2021; Luo 2022; Maierhofer et al. 2022; Ohene et al. 2022).

This section provides a summary of a common policy framework for the delivery of net-zero carbon buildings and identifies how green construction would contribute to their realization. The findings are listed in Table 2.

This section emphasizes green construction and net-zero building as essential components of carbon neutrality policies. Several key policy implications are proposed and illustrated in various aspects of green construction activities, such as green materials, carbon audit (particularly scope-3 emission accounting), future concerns on building management and certification system (particularly the new concept of net-zero building calls for new attention on how to incorporate life cycle assessment), and green materials (e.g., Japan highlights their focuses to the carbon absorbed in concrete and China highlights to carbon sink measures). New policy analytic tools, such as life cycle assessment and embodied carbon emission accounting, could help boost these choices.

Carbon emissions analysis in green construction

In 2022, the construction sector will be responsible for 39% of the world's total annual carbon emissions (World Economic Forum 2022). If no corresponding carbon reduction measures and methods are adopted, the construction sector is expected to account for 52% of the world's carbon emissions by 2050 (Houghton et al. 2001). Meggers et al. (2012) argue that reducing carbon emissions in the construction sector is central to transforming it into a more sustainable industry. Moreover, one of the essential green building technologies is reducing carbon emissions during the construction phase.

In order to implement measures to reduce carbon emissions during the construction phase, it is crucial to develop effective methods for assessing the environmental impact of the construction phase (Basbagill et al. 2013; Röck et al. 2020). Life cycle assessment is frequently used in the construction industry to evaluate environmental impact, with carbon emissions serving as its leading evaluation indicator (Rinne et al. 2022; Teh et al. 2017). In recent years, random forests and neural networks have also been used to calculate and predict carbon emissions in the construction industry, thanks to the continuous development of computer technology and big data technology (Fang et al. 2021; Ye et al. 2018). Various evaluation methods are utilized for various building types, structures, and regions, and the outcomes vary. Therefore, Table 3 provides statistics on studies of carbon emissions in construction conducted in various countries around the world using various methodologies.

A suitable carbon emission analysis method facilitates the identification and implementation of carbon dioxide reduction measures for each process and the reduction of carbon dioxide emissions from the construction site. Table 3 summarizes the carbon emission analysis of the construction phase of the building and the carbon emissions of five residential buildings, six office buildings, and one tower building. Among the studied cases, 50% of the buildings used life cycle assessment, which are office buildings and residential buildings from Korea, residential buildings from Finland, residential buildings from Spain, office buildings from the United States of America, and office buildings from Sweden, with carbon emissions of 4,420, 140,000, 291.7, 4,182.9, and 566 tonnes, respectively.

In addition, in the case study of Iran, the carbon footprint method was used to analyze the tower building's construction carbon emissions, totalling 13,076,390.2

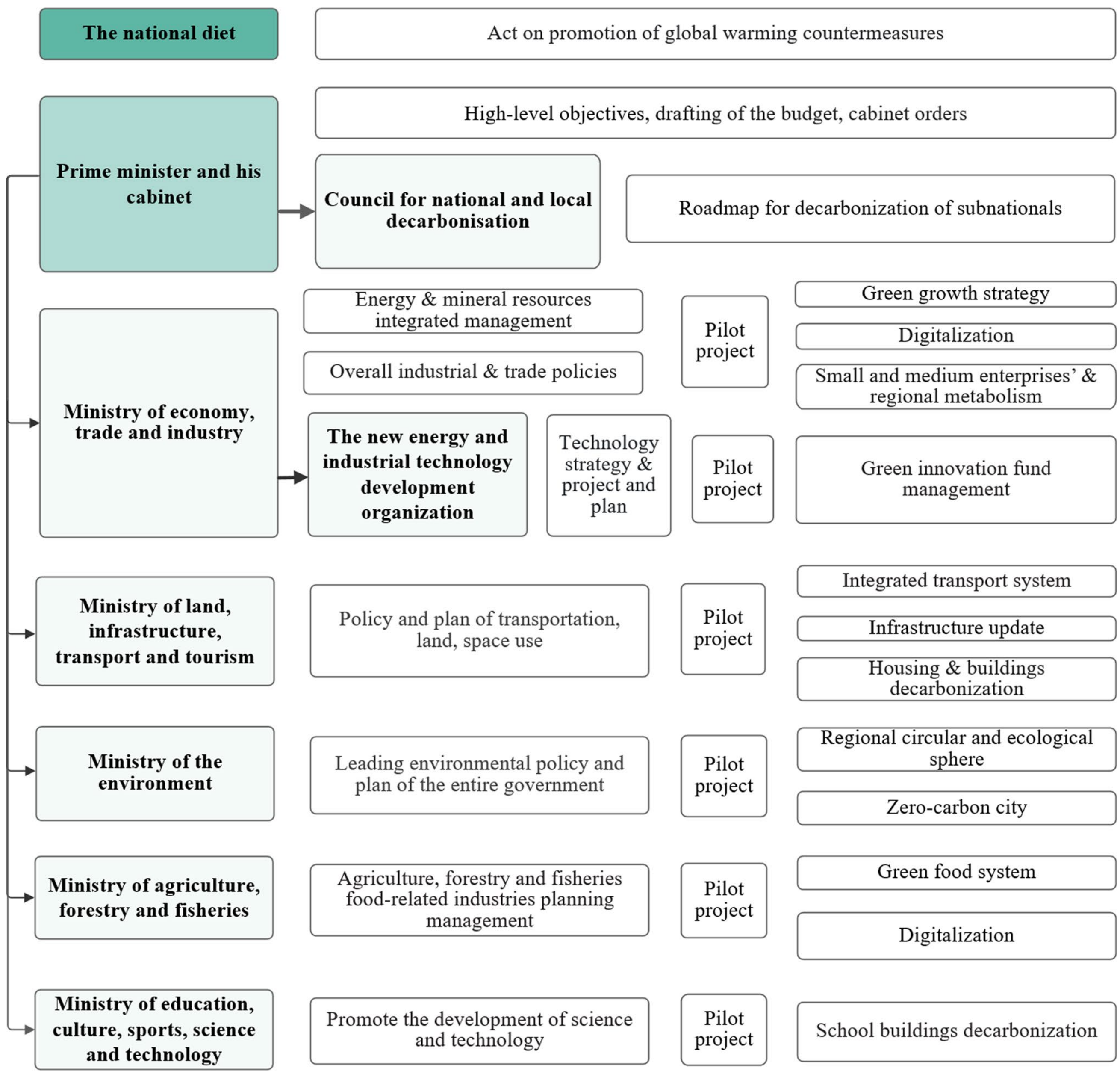


Fig. 4 Position of construction and building sector in national carbon neutrality strategy in Japan and the responsible ministry. The diagram illustrates Japan's national framework for promoting the carbon neutrality strategy in terms of the hierarchy of different policies. Each ministry prioritizes carbon neutrality initiatives and pilot projects differently. The ministry of land, infrastructure, transport, and tourism emphasizes the decarbonization of buildings among these

tonnes. In the case study of China, the construction carbon emissions of residential buildings were determined to be 8707 tonnes using the product carbon accounting method, and the construction phase carbon emissions were predicted for 38 cases using the random forest method. In the Korean case study, carbon emissions from office building construction were predicted using stochastic analysis. In the Japan case study, the input–output method was used to analyze the carbon emission during the construction phase of office buildings, which amounted to 1207.1 tonnes.

In general, according to the analysis in Table 3, we can find that the carbon emission analysis in different buildings during their construction phase is usually performed using a life cycle assessment, as shown in Fig. 8. The life cycle assessment procedure is being used more and more frequently as a formal and comprehensive analysis

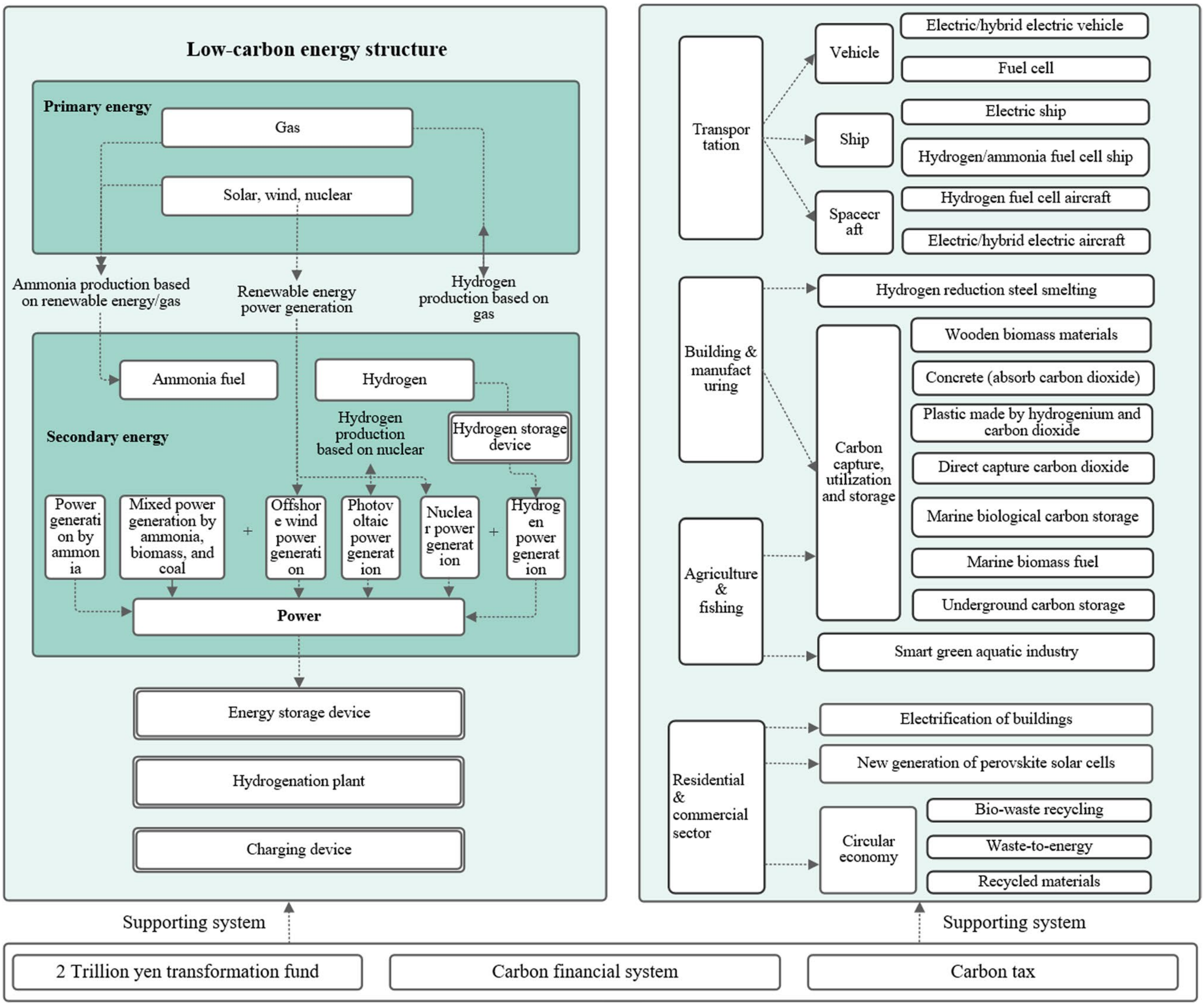


Fig. 5 Position of construction and building sector in national carbon neutrality technology roadmap in Japan. The figure depicts Japan's national technology roadmap for promoting the carbon neutrality strategy, with a focus on various sectors and key technologies, including promoting renewable energy and hydrogen technologies in the power sector, promoting energy-efficient technologies, low-carbon materials, and carbon capture and storage technologies in the industrial sector, and promoting a solar photovoltaic application in the residential sector. The bottom of the graph also highlights the financial and regulatory support for the development of carbon–neutral technologies, including the transformation fund and the carbon financial system. Among them, the construction industry is highlighted as a key sector, with a focus on the application of wood biomass-based materials and carbon mitigation effects in concrete, among others

method widely used to assess the life cycle environmental impacts of products in other industrial sectors. Many studies have been conducted in the construction industry on the life cycle assessment approach to carbon accounting (Li et al. 2012). In the construction phase, life cycle assessment can calculate the carbon emissions of each construction procedure, such as material use, transportation, construction activities, and construction processes, for which effective measures, such as the use of sustainable materials, can be implemented to reduce carbon emissions at the construction site. In addition, random forest, neural network, and stochastic analysis can be used to predict the carbon emissions during the construction phase in order to predict the steps that will generate high carbon emissions and take the corresponding carbon reduction measures. Consequently, effective carbon analysis methods are required to achieve carbon neutrality during construction.

This section examines carbon emissions analysis methods for construction projects in ten different countries. The results of the study indicate that their standard method is life cycle analysis, which accounts for the carbon emissions of each construction phase procedure and develops carbon reduction measures accordingly.

Life cycle assessment and green construction

Life cycle assessment is a mature technique used to investigate the environmental impacts of a product or service at various stages of the product's life cycle, including raw material extraction, material production, consumption, end-use, and end-of-life (cradle-to-grave) (Li et al. 2018; Pamu et al. 2022; Tseng et al. 2018; Zhang et al. 2019). As a prevalent environmental management tool, life cycle assessment is typically used to evaluate the environmental impacts of a product or service and its associated activities by investigating and quantifying resource & energy consumption, waste disposal, and treatment. In addition, it provides an impact assessment methodology to convert these values into scores or values of environmental impacts in various categories, such as global warming potential, which typically illustrate the effects of greenhouse gas emission (Chàfer et al. 2021; Lakho et al. 2022; Qiao et al. 2022; Shafique et al. 2020; Wang et al. 2020b; Yılmaz and Seyis 2021).

A typical life cycle assessment approach is carried out in four steps (ISO 14040, 14044), illustrated in Fig. 9 (Pamu et al. 2022; Qiao et al. 2022).

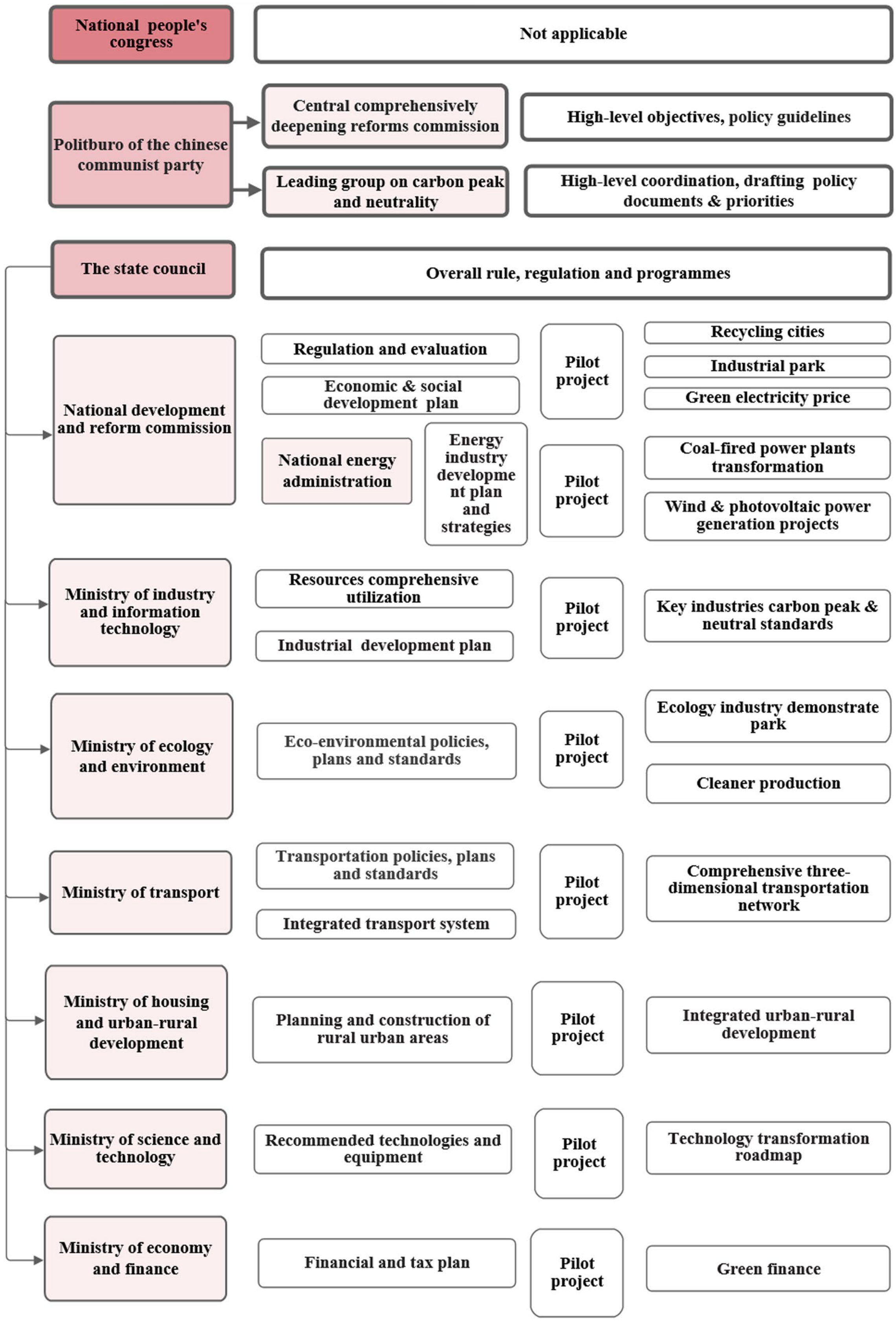
- *Step-1* Goal definition and scope. In this step, we identify the life cycle assessment study purpose, the targeted products, and the related boundaries (the processes we include in the analysis).
- *Step-2* Life cycle inventory analysis. The inventory consists of the inputs and outputs for each process in the life cycle. In this step, we analyze and quantify these flows, which serves as the basis for the subsequent impact assessment.
- *Step-3* Impact assessment. Depending on the characteristics of various emissions, they will contribute to various impacts to varying degrees. Based on the inventory analysis, this step categorizes the effects on human health and the environment. The general method will convert the value derived from the number of emissions and the coefficient to an impact value.
- *Step-4* Reporting and interpretation. This step will analyze and interpret the results and, based on these findings, investigate opportunities to reduce consumption and emissions at each life cycle stage.

As life cycle assessment can quantify not only the manufacturing process consumption and emissions but also those of upstream processes and end-of-life, life cycle assessment will provide a powerful tool to support better green construction management from a broader perspective, such as the material production stage for construction activities (Braulio-Gonzalo et al. 2022; Desai and Bheemrao 2022; Dong et al. 2018; Monteiro and Soares 2022; Shafique et al. 2020; Wang et al. 2020b). Fig. 10 depicts the entire construction and building life cycle. To reduce the life cycle energy & resource consumption, as well as waste disposal & pollutants, it is essential to employ a good design that considers not only the structure but also the management and use of materials. For instance, the low embodied energy of renewable materials presents a new opportunity for promoting net-zero buildings. Emerging research has highlighted the benefits of using renewable materials in green construction, such as timber, bamboo, and others, to reduce life cycle emissions and consumptions (Amoruso and Schuetze 2022; Figueiredo et al. 2021; Lakho et al. 2022; Qiao et al. 2022; Scolaro and Ghisi 2022; Zhang et al. 2019). Another widely applied green construction & building management approach enlightened by life cycle assessment is a green roof, which could generate embodied benefits like eco-system service as a typical nature-based solution by applying green materials and well design. From a life cycle perspective, a nature-based solution could generate additional benefits such as climate risk mitigation, upstream water and energy savings, among others (Busker et al. 2022; Cascone 2022; Jacobs et al. 2022; Koroxenidis and Theodosiou 2021; Twohig et al. 2022).

From the standpoint of carbon neutrality, life cycle assessment supports the reduction of "embodied carbon emissions". In the past, the "in-use" stage, which includes technologies and facilities efficiency, indoor building management, and the "construction and renovation" stage, received a great deal of attention regarding building carbon emission life cycle analysis. Simultaneously, less emphasis has been placed on the "material" stage. According to the results and characteristics of the life cycle assessment, renewable materials could contribute to carbon–neutral effects from the perspective of carbon sequestration and reduce embodied carbon emissions (Amoruso and Schuetze 2022; Desai and Bheemrao 2022; Dong et al. 2021; Liang et al. 2014; Liu et al. 2017b; Qiao et al. 2022).

Based on the above review and illustration of how life cycle assessment could support decision-making on green construction, a policy package is proposed based on life cycles on green construction & building management (Table 4).

This section highlights the importance of life cycle assessment as a decision-support tool for green and low-carbon building assessment and management. Based on the concept of life cycle assessment, we analyze the detailed life cycles for construction activities and qualitatively investigate


National people's congress
Not applicable
Politburo of the chinese communist party
Central comprehensively deepening reforms commission
High-level objectives, policy guidelines
Leading group on carbon peak and neutrality
High-level coordination, drafting policy documents & priorities
The state council
Overall rule, regulation and programmes
National development and reform commission
Regulation and evaluation
Economic & social development plan
Pilot project
Recycling cities
Industrial park
Green electricity price
National energy administration
Energy industry developme nt plan and strategies
Pilot project
Coal-fired power plants transformation
Wind & photovoltaic power generation projects
Ministry of industry and information technology
Resources comprehensive utilization
Industrial development plan
Pilot project
Key industries carbon peak & neutral standards
Ministry of ecology and environment
Eco-environmental policies, plans and standards
Pilot project
Ecology industry demonstrate park
Cleaner production
Ministry of transport
Transportation policies, plans and standards
Integrated transport system
Pilot project
Comprehensive three-dimensional transportation network
Ministry of housing and urban-rural development
Planning and construction of rural urban areas
Pilot project
Integrated urban-rural development
Ministry of science and technology
Recommended technologies and equipment
Pilot project
Technology transformation roadmap
Ministry of economy and finance
Financial and tax plan
Pilot project
Green finance

◂**Fig. 6** Position of construction and building sector in national carbon neutrality strategy in China and the responsible ministry. The figure shows China's national framework for promoting the carbon neutrality strategy in different policies hierarchy. Each ministry has different focuses on carbon neutrality initiatives & pilot projects. Among them, the decarbonization of buildings is incorporated into the integrated development of urban–rural areas, promoted by the ministry of housing and urban–rural development

the specific carbon emissions impacts and characteristics for each life cycle. On this basis, policy packages for each life cycle of green construction activities are proposed. These findings are essential for addressing the policy challenges outlined in Sect. 4, such as accounting for scope-3 emissions, designing and rating new certification systems based on life cycle assessment, and evaluating low embodied carbon materials based on life cycle assessment.

Impact of using sustainable materials in green construction

Changes in the performance of green construction due to the use of sustainable building materials can improve environmental friendliness and economic viability. Sustainable materials are an integral part of green construction, and their lower polluting properties and greater efficacy sustainably motivate green construction development. The primary direction for sustainable materials is bio-innovative substances and recyclable waste. Green sustainable construction materials such as biochar, bioplastics, agricultural waste, animal wool, fly ash, and self-healing concrete are widely used in the construction of green buildings. Fig. 11 illustrates the effect of applying six sustainable materials to green construction.

Biochar

Biochar is a material distinguished by its high porosity, light weight, and high specific surface area. Biochar is produced by thermochemically converting a variety of plant and wood biomass at moderately lower temperatures (lower than 700 or 800 degrees) and in an oxygen-free environment (Legan et al. 2022). Biochar is commonly produced industrially using gasification, roasting, and pyrolysis processes (Tripathi et al. 2016).

Biochar improves the mechanical properties of concrete used in construction materials (Restuccia et al. 2020). Asadi Zeidabadi et al. (2018) used bagasse and rice husk biochar to replace conventional concrete material. The specific surface area and amorphous silica content of the biochar increased the tensile strength of the concrete. In particular, it was found that 5% bagasse biochar by the pretreatment process increased the compressive strength by 54.8% and the tensile strength by 78% in comparison with conventional concrete. Biochar is biodegradable and does not react with cement, so it can be utilized as a cement filler to reduce cement's porosity and significantly enhance concrete's durability (Cosentino et al. 2019). In addition, adding biochar enables carbon sequestration while enhancing the hydration for cement mortars (Wang et al. 2020a), thereby enhancing the composites' fire resistance and thermal stability.

Cao et al. (2014) demonstrated that biochar has a high water retention capacity in green roof substrates, extending permanent wilting of the roof substrate by 2 days. The water retention capacity of biochar is reflected in the green roofs stormwater management, which greatly optimizes the reduction in stormwater outflow and the extension of outflow time, enhancing the green roof's characteristics of minimizing urban flooding (Gan et al. 2021). Besides, biochar has a remarkable protective effect on the green roof substrate. Applying biochar at an appropriate rate can significantly increase the substrate moisture in the green roof, adjust the substrate temperature, change the microbial community structure and increase plant growth (Chen et al. 2018). Moreover, biochar retains many nutrients in green roofs washed by rainwater because of biochar's surface area, pore size, and cation exchange capacity.

Based on these properties, the modification of biochar at the bottom of the substrate optimizes the efficiency of water and nutrient retention during the green roof installation (Kuoppamäki et al. 2016). It is worth mentioning the additional higher stability in highly aromatic biochar soils (Vercruysse et al. 2021). The biochar amendment improved the green roof soil, significantly reducing soil weight (7.6%) while expanding soil porosity (8.4%), which is essential for enhancing soil carbon sequestration and mitigating greenhouse gas emissions (Omondi et al. 2016).

In conclusion, biochar can enhance the mechanical properties and hydration of concrete and cement mortar. Additionally, biochar improves the water retention of building materials, which helps stabilize soil and reduce carbon emissions.

Bioplastic

Bioplastics are innovative bio-based plastic polymers (Farghali et al. 2022). Bioplastics are divided into three main types, (1) biodegradable and bio-based materials represented by starch-based polymers; (2) biodegradable and petroleum-derived materials; (3) non-biodegradable bio-based materials (Abraham et al. 2021). Bioplastics can be used to make materials such as compostable geotextiles or natural membrane facades (Friedrich 2022). After steel and cement, the construction industry is the third largest supplier of bioplastics. Using bioplastics as a novel construction material will

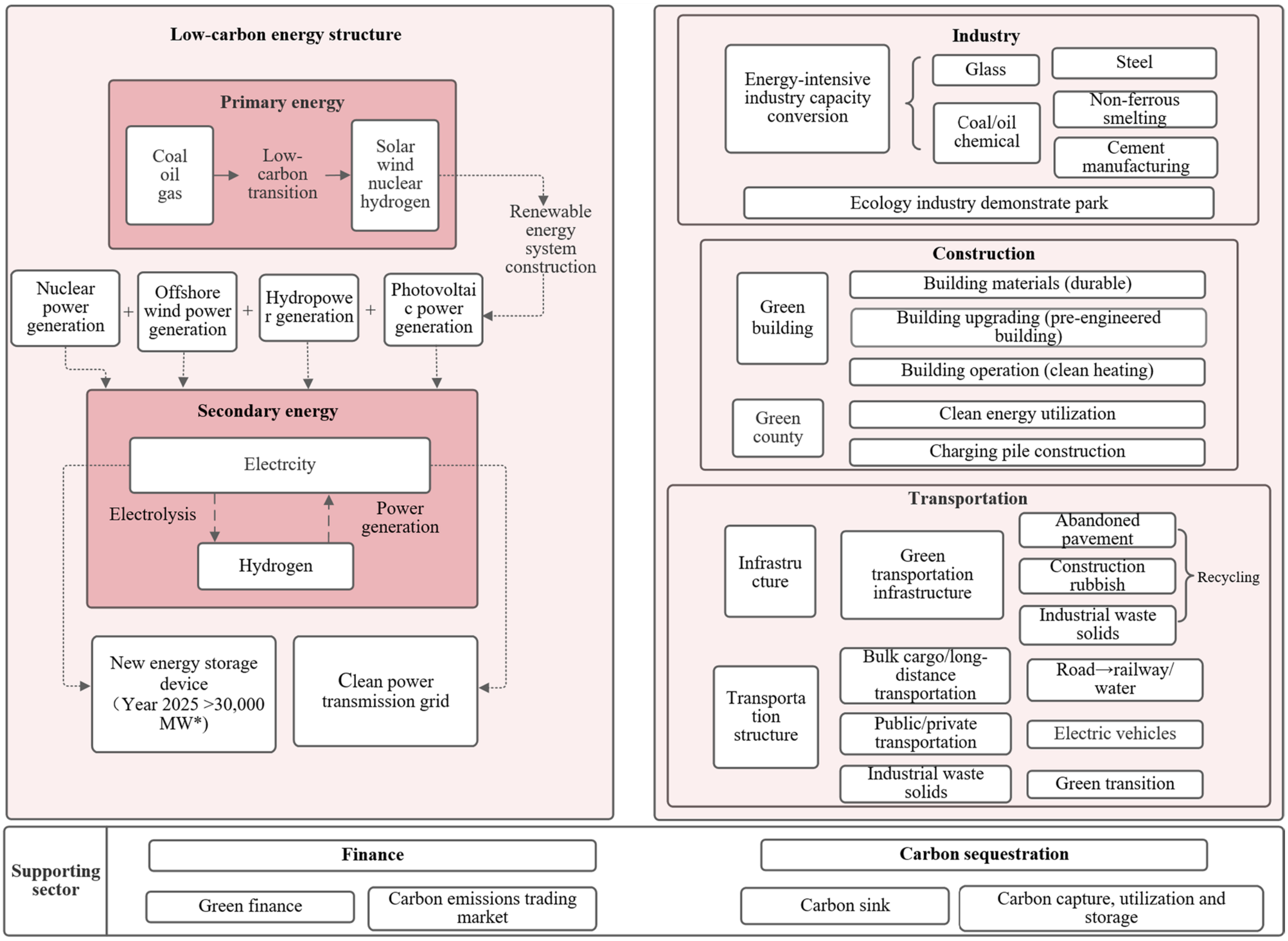


Fig. 7 Position of construction and building sector in national carbon neutrality technology roadmap in China. The figure shows China's national technology roadmap for promoting the carbon neutrality strategy, with a focus on different sectors and key technologies such as promoting renewable energy and energy storage technologies in the power sector, promoting energy-efficient technologies in key industrial sectors which are energy intensive such as cement, glass, and steel, and promoting low carbon transports in the transportation sector. The bottom of the figure also highlights the financial & regulatory support for developing carbon–neutral technologies and focuses on carbon sink measures. Among them, the building sector is highlighted as one key sector, focusing on green building promotion, considering the significant carbon mitigation potential in this sector. "MW" refers to megawatt

enable the production of resource-efficient components, and this sustainable building material has superior durability compared to green building materials like wood. It can be customized to meet user needs in various colours (Köhler-Hammer et al. 2016).

Insulating walls and partitions, as well as non-structural (interior) elements, such as partition walls and partitions in temporary buildings, can be fabricated from polyhydroxyalkanoates-containing bioplastic foams (Ivanov et al. 2015). The production of bioplastics for eco-friendly building materials is also reflected in the enhanced durability and corrosion resistance of building windows and doors. Shaik et al. (2022) evaluated that bioplastic materials developed from eggshell and walnut shell powders as filler materials exhibited higher ductility and good mechanical properties for widespread applications in fences and door frames. Excellent thermal and acoustic insulation properties of bioplastics allow green buildings to reduce heat and noise gain, thereby reducing negative energy impacts on the environment and enhancing other energy performance metrics (De Corato 2021). Bioplastics are more environmentally friendly, low-integrated-energy, and energy-efficient to produce and use in the building sector (Ivanov and Stabnikov 2017). Moreover, compared to petrochemical plastics, poly-3-hydroxybutyrate bioplastic emits 0.18 kilogram carbon dioxide equivalent/kilogram of greenhouse gases and 40 mega joule/kilograms of non-renewable energy. This shows that the novel bioplastic replaces the traditional commonly used petrochemical plastic, which is beneficial to reducing carbon dioxide emissions from buildings, meeting environmental standards for green construction, and solving the problem

Table 2 Global policy framework for the delivery of carbon–neutral buildings through green construction

Aspects of net-zero carbon buildings	Policies	Examples
Green building management & certification	Developing a certificating system to guide the application of green materials with low emissions and building energy efficiency approaches	Leadership in energy and environmental design: The United States of America Building research establishment environmental assessment method: The United Kingdom Comprehensive assessment system for building environmental efficiency: Japan Green mark: Singapore Building environmental assessment method plus: Hong Kong SAR High-quality environmental standard: France
"Advancing Net-Zero" is World Green Building Council's global project	Calls for stakeholders and authorities in business, organizations, cities, and countries & regions to realize net-zero operating emissions by 2030 and for all buildings to be net zero in operation by 2050	European Union, The United States of America, Hong Kong SAR, Singapore
Green construction materials	Establish recommended material inventory, which is low embodied emissions	British Standards Institution label for Construction products
Procure high-quality carbon offsets	Applied nature-based solutions to increase carbon sequestration effects and offset embodied carbon emissions	The green roofs for healthy cities: North America Nature-based-solutions: European Union
Reduce Scope 3 emissions	Initiatives and information disclosure for construction companies to report their scope 3 emissions (in supply) and actions to reduce climate risk	Climate-related information disclosure guidance by the financial stability board and its task force on climate-related financial disclosures since 2017 and updated in 2021

The table displays the policies that support the promotion of next-generation net-zero buildings, including management and certificate systems for green building management, an initiative on promoting net-zero buildings, low-carbon building materials, carbon offset measures, and supply chain mitigation measures (so-called scope-3 emissions). Examples are provided to illustrate the implementation of the policy. "SAR" indicates special administration region

of excessive greenhouse gas emissions (Ivanov and Christopher 2016).

Because some bioplastics are biodegradable, they are left in the soil for in situ biodegradation following the demolition of construction materials. After demolition, bioplastic structures require less landfill space, which reduces the cost of construction waste disposal (Stabnikov and Ivanov 2016). When landfilled and composted, these biological materials significantly reduce construction-related environmental pollution.

However, compared to petroleum-based plastics, bioplastics have higher production costs and are more difficult to recycle, which is not conducive to the development and improvement of green construction (Thakur et al. 2018). In recent years, numerous innovative production technologies have been developed in order to reduce the cost of producing bioplastics by reusing waste. Developing biotechnology for bioplastics using microalgae and other microbial wastes as raw materials, for instance, has received significant societal interest (López Rocha et al. 2020).

In conclusion, bioplastics are utilized as eco-friendly materials, enhance the durability of materials, and have exceptional insulating properties. This contributes to reducing greenhouse gas emissions and improving energy efficiency, resulting in lower energy costs.

Agricultural waste

Agricultural waste is the term for biomass generated by the agriculture industry (Osman et al. 2021b). It is high in fiber and has high concentrations of minerals, including phosphate and nitrogen, as well as organic carbon and pesticide byproducts (Speight 2020). Agricultural waste is classified according to its structure into straw crops such as crushed rye or rice and fibrous materials such as flax and cotton (Gaspar et al. 2020). Agricultural waste has been shown to significantly improve the performance of concrete, making it a sustainable resource for the construction industry. Manan et al. (2021) added agricultural waste banana peel as an auxiliary ingredient to conventional concrete to improve the strength of oxide and non-oxide elements, which can

Table 3 Carbon emissions analysis model in different studies and countries during construction

Studies	Country	Method	Building type	Structure	Building area (m^2)	t-carbon dioxide
Seo et al. (2016)	 Korea	Korea life cycle inventory database information network	Office building and Residential	Steel structure and reinforce concrete	5,555.6	4,420
Heinonen et al. (2011)	 Finland	Life cycle assessment and input–output	Residential	–	70,000	140,000
Jafary Nasab et al. (2020)	 Iran	Carbon footprint	Tower	Steel–concrete structure	30,000	13,076,390.2
Hong et al. (2015)	 China	Product carbon accounting	Residential	Reinforced concrete	11,508	8,707
Pacheco-Torres et al. (2014)	 Spain	Life cycle assessment	Residential	Steel	757.6	291.7
Scheuer et al. (2003)	 The United States of America	Life cycle assessment	Office building	Steel columns and girders	7,300	4,182.9
Fang et al. (2021)	 China	A random forest-based model	Office building and Residential	–	–	–
Lee et al. (2019)	 Korea	Stochastic analysis	Office building	Reinforced concrete	33,521	–
Wallhagen et al. (2011)	 Sweden	Life cycle assessment	Office building	Reinforced concrete	3,537	566
Suzuki and Oka (1998)	 Japan	Input–output analysis	Office building	–	1,857	1,207.1

This table indicates that other countries have studied carbon emissions from the building sector using different evaluation methods, and the results are also influenced by the structure, size, and type of buildings. The total amount of carbon emissions vary greatly by building type, structure, and size. The table also shows that most of the studies use either a life cycle assessment approach or a combination of life cycle and other methods to calculate carbon emissions during the construction phase. "m^2" refers to square meters, "t" refers to tonnes, and "–" indicates not mentioned

increase the flexural strength and compressive resistance of concrete materials. The underlying reason is that agricultural waste provides a large number of elements, such as potassium and sodium, that prevent the concrete from degrading. Concrete's flexural and tensile characteristics are greatly enhanced by applying nano cementitious additives developed by Lim et al. (2018) from rice husk ash and palm oil fuel ash.

Moreover, ceiling tiles made from agricultural waste using rice husks, grape pruning residues, cork, and prickly pear can act as sound-absorbing panels with a coefficient of sound absorption of 0.80 (Maderuelo-Sanz et al. 2022). The novel eco-efficient ceiling tiles can be used with lower energy and cost losses and still exhibit good thermal, acoustic, and mechanical properties after reuse. Bagasse waste fibers exhibit excellent acoustic properties due to their inherent surface roughness, and the average sound absorption and noise reduction coefficients evaluated were maintained between 0.26–0.64 and 0.27–0.62, respectively (Mehrzad et al. 2022). In addition, bagasse waste is also effective in insulating buildings, reducing operational energy requirements, and improving building thermal comfort. The

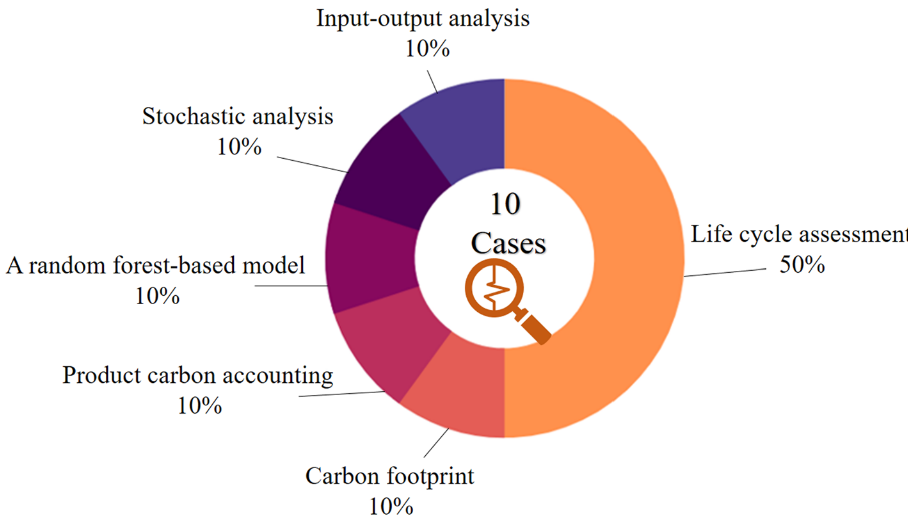


Fig. 8 Ten cases of carbon emission analysis methods during the construction phase. Life cycle assessment, input–output analysis, stochastic analysis, random forest model, product carbon accounting, and carbon footprint are some of the carbon emission analysis techniques utilized during the construction phase of the study. Life cycle methods make up 50% of all cases. Input–output model, stochastic, random forest model, product carbon accounting, and carbon footprint each account for 10%. Diverse carbon emission calculations or prediction methods will result in greater precision

development of novel insulation materials facilitates the attenuation of the negative effects of buildings on the environment and enhances the user experience. The mechanical properties of agricultural waste insulation materials are influenced by the size and structure of the raw material. The composite board structure made of rye and flax straw has a low moisture absorption alternative to polystyrene, glass, and rock wool traditionally used for building insulation, which can save much energy in the production process and thus reduce heating costs (Bakatovich et al. 2018).

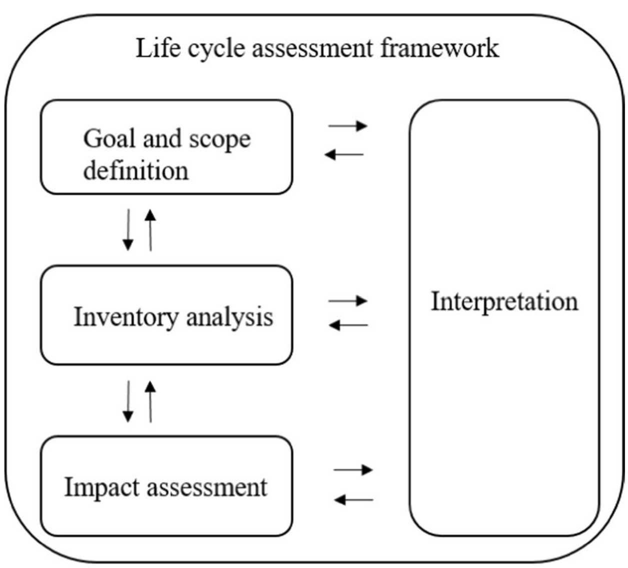


Fig. 9 Life cycle assessment framework. This figure illustrates the four general steps required to conduct a life cycle assessment on a particular product or service. The first step is the objective's definition and scope. The second step is to conduct a life cycle inventory analysis. The third step is to conduct an impact analysis. In conclusion, the evaluation report is interpreted

Moreover, the pores in the composite board structure are reduced to the maximum extent, reducing thermal conductivity to increase by a 4–5 degrees magnitude. Furthermore, the moisture absorption of the plate material is 15–24% compared to rye straw waste, which reduces the absorption of moisture in the air by the heat insulation layer, which reflects the promising direction provided by the high heat retention of agricultural waste in the heat insulation of construction materials. Agricultural waste can reinforce the earthen soil at the base of the building and mitigate damage to the building due to environmental weather variations of disasters. Straw and jute coir is used as fibers to improve the elasticity of the earth's structure and thus resist flood damage. The significance of this feature is to contribute to the sustainable development of green construction in the ecological environment.

Therefore, agricultural waste has high insulating properties, and adding it to concrete improves the strength of concrete and increases the soil's resistance to flooding. Agricultural waste not only demonstrates the economic value of avoiding additional energy costs but also reduces noise pollution.

Animal wool

Wool is one of the most widely used natural animal protein fibers. Curled wool fibers produce millions of tiny air

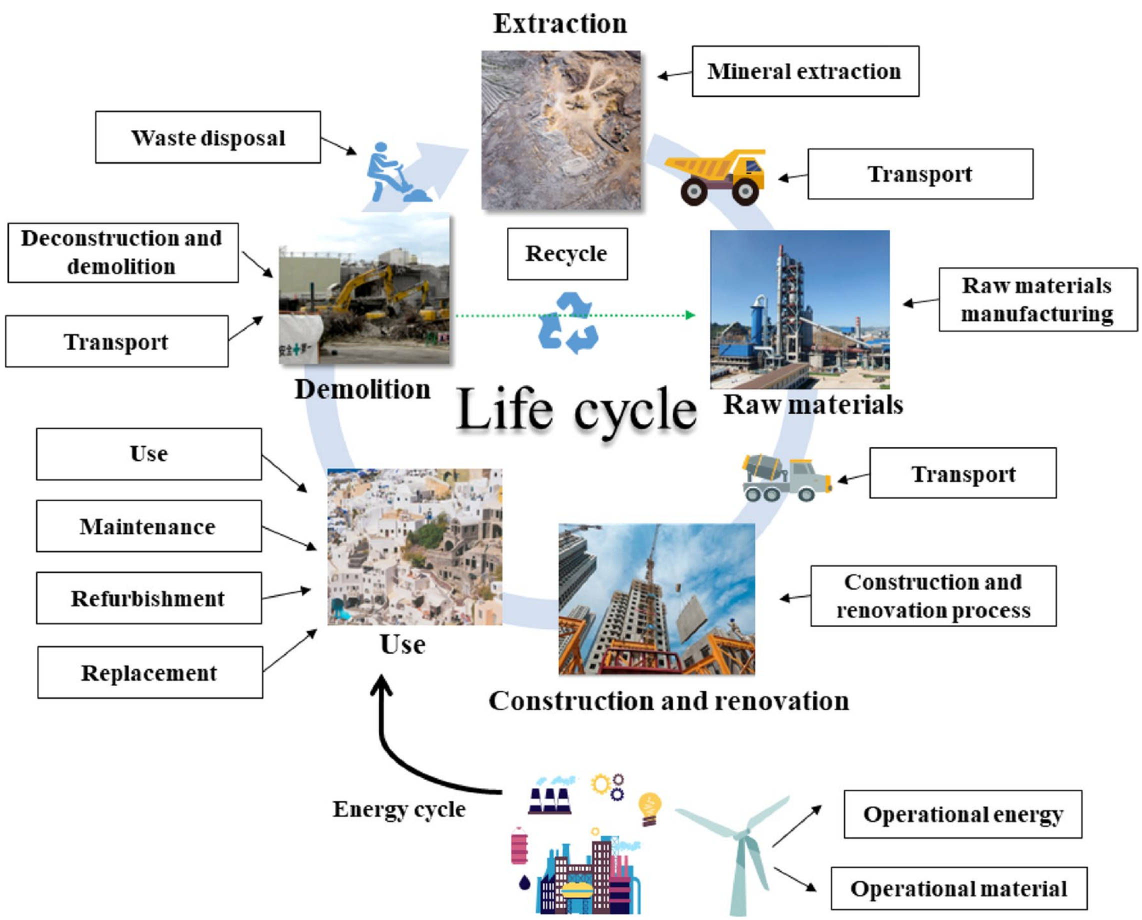


Fig. 10 Life cycles of construction and building management. This figure describes the detailed life cycles of construction activities, beginning with resource extraction and concluding with waste disposal and treatment. Initially, the raw materials are extracted and transported to the material processing plant. These materials are then transported to the construction site for a series of construction operations. After the construction project has been completed, it will be operated, maintained, and then demolished. Some construction waste is recycled for use in new construction projects

pockets that act as heat barriers and effective insulators (Tiza et al. 2021). Cotton wool is the most common animal wool applied to green building materials. Sheep's wool meets the criteria for green building materials because it is an eco-friendly, renewable, and completely recyclable material. Wool possesses exceptional thermal and acoustic properties (Ilangovan et al. 2022). Renewable and environmentally friendly wool fiber waste has a bacterial load and has the potential to enhance the thermal efficiency of buildings. Furthermore, the low thermal conductivity of 0.05 Watt/(meter-Kelvin) and the high moisture diffusivity of 1.1×10^{-6} to 1.2×10^{-5} of cotton wool have proven their compatibility with conventional building components for sustainable building renovation and maintenance (Jerman et al. 2019).

The introduction of wool improved the ductility of cement mortars, and Fantilli et al. (2017) substituted atmospheric plasma-treated wool for mortar cement, increasing flexural strength by 23% and flexural fracture toughness by 300%. Fiber-reinforced wool is used to reinforce mortar; however, wool is limited by an alkaline environment, and the tendency of alkaline enhancement makes wool tend to dissolve, so how to overcome cement alkalinity becomes the key to the wool application (Fantilli and Jóźwiak-Niedźwiedzka 2021). Among them are fiber pretreatment to modify the fiber surface to enhance its alkali resistance (Parlato and Porto 2020); cement matrix modification using gel material to reduce the alkalinity of concrete (Alyousef et al. 2020). Pretreatment and modification of waste sheep wool fibers to make the wool fibers more adhesive to the cement matrix and maintain the compressive strength of the concrete (Alyousef et al. 2022). As a result, cotton wool has been identified as an eco-friendly, sustainable concrete additive material that is highly valued in terms of green building materials.

Also, animal wool is currently a strong contributor to the sound insulation of concrete wall materials. High sound absorption coefficients indicate better sound insulation capacity of concrete (Ghermezgoli et al. 2021). The sound absorption coefficient of 2.5% wool fiber composite concrete

Table 4 Policy recommendations based on life cycles of construction activities

Life cycle stages	Impacts on carbon emission and environmental pollution	Policy recommendations
Raw materials manufacturing	The carbon emissions of building materials throughout their life cycle are mainly concentrated in the material extraction & production stage. The carbon emission factors of different building materials are quite different	Mining and promoting low-carbon building materials, alleviating the shortage of building resources and carbon emissions in the process of material processing
Transport	Carbon emissions mainly come from gasoline and diesel consumed by traditional trucking	Promote using new energy vehicles for transportation, such as electricity and biodiesel
Construction & renovation process	Building construction methods, architectural styles, and others will affect the demand for building materials and energy consumption	Realize green construction in the whole project construction process, use new technologies to achieve refined design and construction, vigorously develop prefabricated buildings, and focus on promoting the construction of steel structure prefabricated houses
Use	Carbon emissions mainly come from the energy (electricity) consumed during the use of buildings	Establish new energy consumption standards and install solar panels on buildings' top and side facades to replace traditional electricity. Continue to promote waste classification, reduction, and recycling, and promote the reduction of domestic waste at the source
Maintenance	The renovation of the building and the interior decoration will consume the corresponding building materials	Advocate green decoration and encourage the selection of green building materials, furniture, and home appliances
Refurbishment	Improve the phenomenon of large demolition and construction in many areas, and many buildings are forced to be demolished before reaching their life cycle, resulting in a waste of resources	Promote the green transformation of existing buildings, encourage the transformation of old urban communities and dilapidated rural houses
Replacement		
Deconstruction & demolition	The longer the building life cycle, the smaller the environmental impact per unit of time. Compared with Europe, the United States of America, and other countries, the average service life of buildings in my country is generally short, only 20–30 years	Extend the life of the building and prolong the use time of building materials
Waste disposal	The recycling and reuse of construction waste can effectively reduce the consumption of primary construction resources and the carbon emission in the production stage of building materials, and there is still much room for improvement in the recycling efficiency of building materials in my country (such as steel, 50%)	Improve the recycling efficiency of building materials, strengthen the recycling of building materials, and promote the reduction of construction waste Shift the traditional landfill treatment method into circular economy-based solutions, e.g., construction demolishes waste reuse & recycle, biomass materials (bamboo and timber) used for electricity generation
Recycle		

Based on the features of each life cycle in construction and building management, which are illustrated in Fig. 10, this table analyzes the main impacts on carbon emission for each life cycle and proposes & discusses key policies implications as countermeasures in each life cycle to promote the carbon neutrality in the construction sector

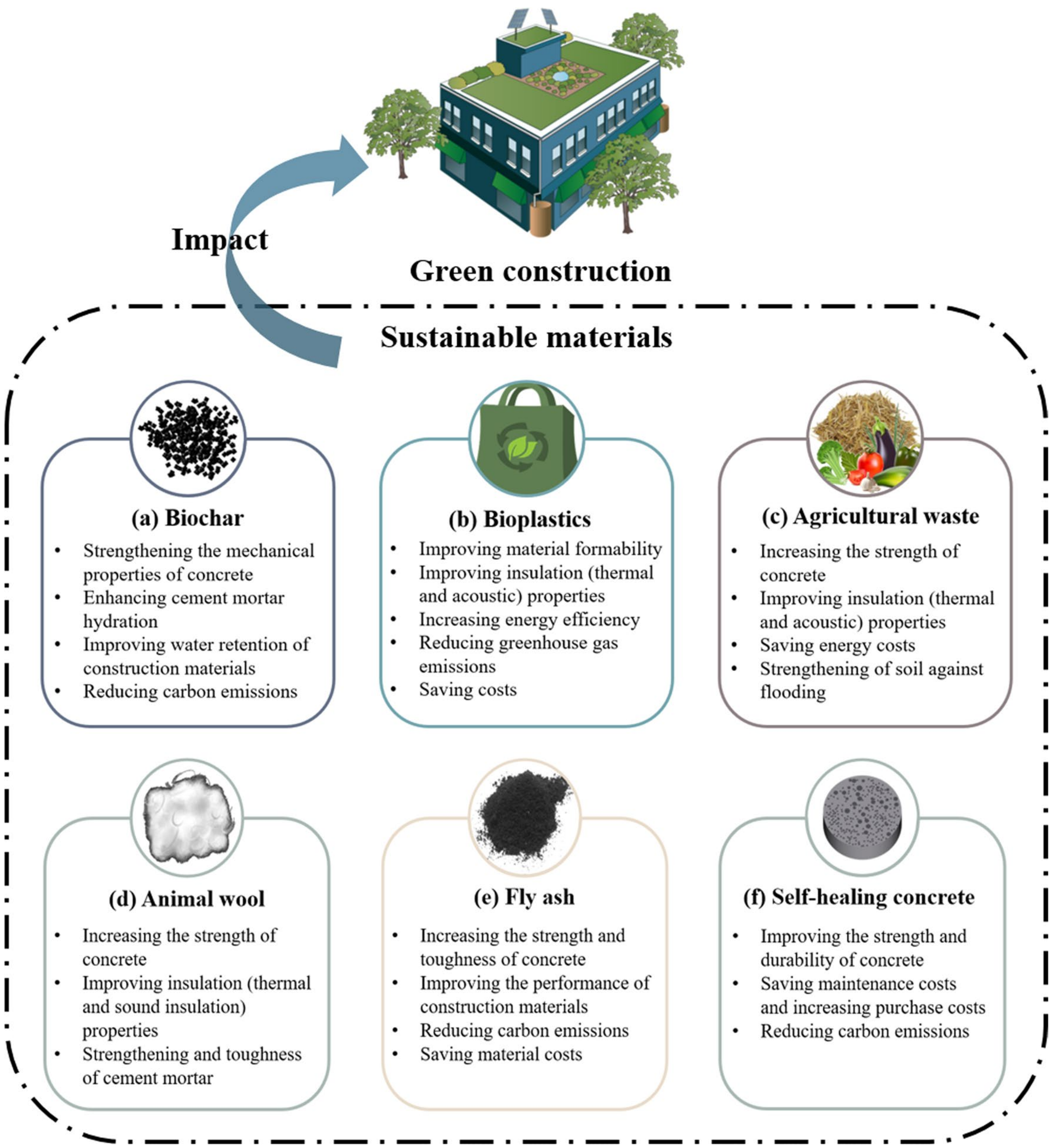


Fig. 11 Impact of six sustainable materials on green constructions. Sustainable materials influence the performance of green construction, with each of the six sustainable materials positively impacting green construction by improving performance. In addition, six sustainable materials can reduce greenhouse gas pollution. These six sustainable materials could be indicated to improve the environmental benefits of green construction and enhance construction efficiency

reaches 0.66 at 2000 Hertz, which undoubtedly improves the overall acoustic quality and provides a good noise reduction function (Alyousef 2022).

In conclusion, animal wool enhances the insulating qualities of green buildings and reinforces concrete and cement mortar. And due to the noise-reducing properties of animal wool, animal wool is more socially and environmentally sustainable.

Fly ash

Fly ash is a common auxiliary cementitious material with potential volcanic ash reactivity (Tian et al. 2020). Fly ash is typically gray, abrasive, alkaline, and fire-resistant refractory material with a high alumina and silica content. Fly ash is the fine residue produced when pulverized coal is burned in coal-fired and steam power plants (Amran et al. 2020). Fly ash is, therefore, one of the primary by-products of the gasification or incineration of municipal solid waste.

Siliceous fly ash is used as an additive for green concrete in building structures, which is a waste disposal method for fly ash and also reduces the consumption of cement and improves the compressive strength and fracture toughness of concrete (Golewski 2018). Golewski (2017) utilized 20% coal fly ash added into concrete to achieve the highest fracture toughness, which is important for developing concrete mechanical parameters. Fly ash is a lower-cost volcanic ash material and is the most common solid waste material in the brick-making industry. The compressive strength of green fly ash bricks exceeds 20 megapascals, 25% higher than traditional load-bearing fired clay bricks. The water absorption rate of nearly 9% or so also reflects better durability and reduced water penetration (Hwang et al. 2016). Fly ash has contributed in terms of green building materials. Because hazardous heavy metals, chlorides, and sulfates are significantly stabilized in mortars, carbonate fly ash is considered a green and sustainable additional cementitious ingredient (Bui Viet et al. 2020). This combination of traditional construction materials in the form of additives strengthens the mechanical properties of construction materials like concrete and bricks, improves the efficiency of construction activities, and prevents increased maintenance and operation costs due to structural instability.

Utilizing fly ash waste reduces pollution and other negative environmental effects significantly. In the construction industry, concrete is considered a raw material with high carbon dioxide emissions. Optimized replacement materials for concrete can significantly reduce greenhouse gas emissions. Coal fly ash can replace cement to achieve carbon neutrality by relying on its carbon dioxide sequestration capacity. Coal fly ash replacing 10% cement can reduce 41.9 kilograms of carbon dioxide equivalent/Gigawatt-hour (Ebrahimi et al. 2017). The combination of waste glass and fly ash, however, strengthens the mortar and increases compressive strength while delaying the hydration of cement (Bui Viet et al. 2020; Ebert et al. 2021). Sandanayake et al. (2020) examined fly ash geopolymer concrete applied in the Melbourne region and achieved 3.63–41.57% carbon dioxide emission reduction and material production cost savings (23.80–30.25%) for construction projects compared to conventional concrete. Green construction is implemented with the main objective of reducing environmental pollution and incorporating fly ash waste to achieve efficient and economically sustainable management of ecological waste, thus reducing the greenhouse gas effect of construction activities.

Thus, fly ash improves the performance of construction materials by increasing the strength and toughness of concrete. In addition, fly ash positively impacts carbon emissions reduction and material cost savings.

Self-healing concrete

Innovative self-healing technology for concrete cracks self-repair technology has been extensively researched and implemented (Huseien et al. 2019). Self-healing concrete is produced by distributing a substance containing a repair solution, such as capsules or fibers, into the concrete mixture so that when a crack occurs, the liquid that flows from the capsules or fibers spreads immediately to heal the crack in the presence of moisture and without tensile stress (Amran et al. 2022; Rose et al. 2018). The materials for self-healing concrete are readily available, and the amount of reinforcement is reduced, thereby reducing the carbon footprint of building construction. Also, self-healing concrete is highly adaptable to different environments and can be used as wall panels in construction.

Additionally, when combining fractured concrete with a calcium nutrition supply and bacterium-based self-healing concrete, the bacteria precipitate calcium carbonate to repair the fissures (Vijay et al. 2017). This replacement of chemical sealers with microorganisms has solved its limitations, such as instability and low heat resistance, making it a new generation of commonly used self-healing concrete. Consequently, bio-concrete is another name for this self-healing concrete.

By decreasing diffusion, permeability, and absorption, self-healing properties extend the durability of concrete. The type of healing agent (bacterial type) influences self-healing concrete and further improves the material's compressive and flexural strength. In addition, natural fibers have proven to be suitable carriers, protecting the alkaline medium in the concrete mixture and boosting the compressive strength by up to 42% (Rauf et al. 2020). The crystalline admixture is a mixture of healing agents with hydrophilic reduced permeability. The mechanical characteristics of self-healing concrete that had been cured for 28 days with the addition of this healing agent were assessed by Chandra Sekhara Reddy and Ravitheja (2019). The compressive strength increased by 11.457%, while the splitting tensile strength increased by 35%. This demonstrates that good self-healing properties repair pores and pre-cracks in concrete as much as possible, strengthen the mechanical properties of concrete materials, and delay hydration and carbonation. Moreover, the greatest advantage of self-healing concrete lies in the solid self-restoration ability. According to Wang et al. (2014), the maximum width of the repaired fissures increased by a factor of four as a consequence of the examination of the addition of bacteria to concrete. Self-healing concrete will have a higher toughness compared to traditional concrete due to the addition of bacteria and healing agents that increase the threshold to withstand the forces that cause fractures, which can reduce the likelihood of damage and fractures in building walls and reduce maintenance expenses (Rao et al. 2017). This results from the concrete infrastructure's decreased rate of deterioration, increased lifespan, decreased frequency, and lower maintenance costs during its lifetime. However, a present disadvantage is that self-healing concrete is more expensive than regular concrete.

Carbon reduction and energy savings are the results of self-healing concrete. Indirectly, it reduces greenhouse gas emissions by reducing the possibility of concrete cracking, thereby decreasing the amount of cement loss that must be replaced (Su et al. 2021). Additionally, Van Belleghem et al. (2017) found that self-healing concrete performs self-repair of cracks forming a barrier that prevents chloride penetration into the concrete, capable of reducing the chloride concentration by up to 75%. The green properties applied to large buildings will greatly reduce the pollution caused to the atmosphere and reduce the carbon footprint, which is an eco-friendly and environmentally sustainable technology.

Overall, self-healing concrete improves the strength and durability of concrete in green construction, reduces maintenance expenses, and has a positive impact on lowering carbon emissions.

This section provides an overview of the impact of six sustainable materials on green buildings. Sustainable materials improve the building's ability to eliminate carbon dioxide emissions, the economic benefits of construction projects, and the energy efficiency of building structures, thereby reducing energy consumption.

Benefits of green construction implementation

Environmental, economic, and social benefits categorize green construction's advantages through special green technologies and materials. Environmental benefits can reflect the role of green construction in the ecological environment to resist pollution; intuitive cost-saving expenditures are to achieve economic benefits; social benefits are to expand the benefits brought by green construction to the entire society and give satisfaction to the human senses. Table 5 shows the benefits embodied in the green construction cases.

This table provides quantitative data on the environmental, economic, and social aspects of green construction to illustrate its superior performance. Green construction significantly reduces carbon dioxide emissions from buildings, reduces energy consumption, saves on investment costs, and provides comfort for occupants. All of this demonstrates the numerous advantages of green building.

Environmental benefit

Implementing green construction practices is regarded as a significant carbon dioxide reduction strategy. Green buildings may use renewable energy sources such as solar, wind, and geothermal energy to meet the needs of their residents while reducing their energy consumption and carbon footprint to zero (Osman et al. 2022b). The optimal building design for green materials contributes to the structure's environmental sustainability. Oh et al. (2019) developed an ideal design strategy for reinforced concrete two-way slabs used in green buildings that are used for big structures and reflect a specific carbon emission reduction performance (residential: 4.94%; office buildings: 11.40%; commercial buildings: 19.96%). In addition to capturing and storing air pollutants, green roofs may also directly sequester carbon in the soil, plants, and other media. According to Luo et al. (2015) a green roof has a greater carbon storage capacity of 13.15 kilograms/square centimetres using a 1:1 mixed substrate of sewage sludge and local natural soil, which is a good illustration of the environmentally friendly nature of green construction, as the rapid growth of plants on the green roof greatly increases the carbon sequestration rate of its soil.

In addition, the combustion of fossil fuels and the use of electricity accelerate the process of urbanization while generating polluting byproducts that exert enormous pressure on the ecological environment. The effect of a green roof on a building's energy consumption and, consequently, its consumption of fossil fuels over the long term is to reduce the building's energy consumption. By reducing the energy consumption of equipments and materials during operation, green construction significantly impacts carbon emissions. Increasing industrialization accelerates urban warming and creates urban heat islands. Tehran's green roofs reduce the surrounding air temperature, thereby increasing the relative humidity above the roof by 11.94%, thereby reducing the heat exchange within the building and achieving sustainability (Moghbel and Erfanian Salim 2017). Therefore, green construction has high environmental benefits.

Economical benefit

Quantifying the costs and benefits of green building can inform decisions on multiple levels (Gabay et al. 2014). The Malaysian government has actively promoted the construction of environmentally friendly homes. Solar radiation sensible heat gain obtained through windows, the installation of double-glazed walls on the interior and exterior, and green walls conserve energy in terms of cooling needs. To the report, green residential buildings using green envelope components will improve the annual cooling load by 18–25% and lighting load by 5%, saving 13–171 dollars per

Table 5 Green construction case based on environmental, economic, and social benefits

Green construction or components	Benefits			References
	Environmental	Economical	Social	
Green construction of reinforced concrete two-way slabs	Carbon emission reduction: residential: 4.94%; office buildings: 11.40%; commercial buildings: 19.96%	Concrete cost reduction: residential: 11.88%; office building: 21.52%; commercial building: 26.50%	–	(Oh et al. 2019)
Green roof	Carbon emission reduction: mixed sewage sludge substrate:13.15 kg/cm^2; local natural soil:8.58 kg/cm^2 Increase urban greening rate	–	–	(Luo et al. 2015)
Green envelope component housing in Malaysia	–	Energy savings: cooling load: 18–25%, lighting load: 5% Reduction in household electricity costs: \$13–\$171	–	(Azis 2021)
Green construction in Kuwait	Carbon emission reduction: 65,893 kg/year	Water saving: 46% Energy savings: cooling load: 25%; lighting load: 86% Energy cost savings: 54%	Good interior air quality is provided by efficient heating, ventilation, and air conditioning systems; appropriate acoustic materials are used to enhance the ambience	(Alsulaili et al. 2020)
Green-certified office building in Indonesia	–	Water and energy saving: 58.65% Cost saving: 41.74%/m	–	(Miraj et al. 2021)
Green Construction in Chongqing	Pollutant load reduction in stormwater runoff: total suspended solids: 46.62 mg/L Neutralize pH: 5.61 to 6.84	–	Effectively reduce stormwater runoff and flooding	Zhang et al. (2015)
Climbing the Green Wall	–	–	Noise reduction: 5.7–12.4 dB	(Tang et al. 2021)
Paving green wall	–	–	Noise reduction: 7.0–15.6 dB	
Green energy office in Kuala Lumpur	–	Energy savings: 412,533 kWh/year Cost savings: \$41,327/year (70.8%)	–	(Dwaikat and Ali 2018)
Seven green office buildings in the Greater Tokyo area	Carbon emission reduction: 6305 t/year (14.6%)	Average energy savings: 157,336 kWh/year (11.4%) Cost savings: 116 million yen	Higher thermal comfort, more natural lighting, and better ambient air quality contribute to a healthier interior environment	(Balaban and Puppim de Oliveira 2017)
Green Schools in Israel	–	Energy saving: 41,000 kWh/year (41%) Water savings: 1039 m^3/year (24%) Operating cost savings: 24%	Healthy environment: well-ventilated and sunny, free from toxic substances	(Meron and Meir 2017)
Green roof in Tehran	Increase relative humidity: 11.94% Reduce air carbon dioxide concentration: 27.98 ppm	–	–	(Moghbel and Erfanian Salim, 2017)

The green building or component cases and data on environmental, economic, and social benefits are briefly described. The environmental aspects of green construction are reflected in carbon emission reduction, and the economic benefits are reflected in cost savings. The social aspects of green construction refer to the impact on human society, such as noise reduction, environmental experience. "–" indicates not mentioned. "kg/cm^2" refers to kilograms per square centimeter. "kg/year" refers to kilograms per year. "mg/L" refers to milligrams per liter. "dB" refers to decibels. "kWh/year" refers to kilowatt hours per year. "t/year" refers to tonnes per year. "ppm" refers to parts per million household (Azis 2021), as this highly solar-absorbing material saves money spent on cooling.

Although green construction requires more expensive construction costs due to its high-strength green materials, resulting in an additional 9.22% of the investment, maintenance, and renewal costs for green-certified office buildings in Indonesia, the energy savings from green performance results in a 41.74% cost savings compared to buildings built traditionally (Miraj et al. 2021). The high performance of most green constructions in the operation process saves energy input and water use, resulting in economic benefits. The Kuala Lumpur green energy office can reduce electricity expenditure by 412,533 kilowatt-hour (41,327 dollars) per year, equivalent to a 70.8% reduction in the expenditure of a conventional office (Dwaikat and Ali 2018). In a study of the economic benefits of green schools in Israel, the reduction in consumption of green schools saves water (1039 cubic metres/year) and energy (41,000 kilowatt-hour/year) for the infrastructure, enabling sustainable economic construction and saving 24% of school operating expenses Meron and Meir (2017). Therefore, it is worth the reduction in green building operating costs compared to the increase in upfront investment from a long-term perspective. Therefore, the economic benefits of green construction are worthy of recognition.

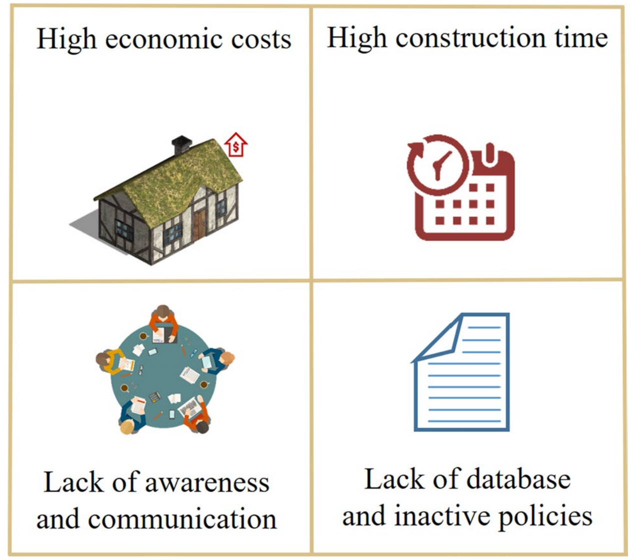


Fig. 12 Four different aspects of the implementation challenge of green construction, where green construction implementation faces obstacles and restrictions. The figure provides the direction for the development of green construction. Green construction is more expensive and requires longer construction times. Additionally, there is a lack of staff awareness and communication regarding green construction, as well as an absence of a comprehensive database and policy support

Social benefit

Green construction improves urban residents' health and living conditions. In hot regions, green walls and green roofs can significantly reduce the cooling demand of residential buildings while also enhancing the comfort of their occupants. Green housing in Kuwait has a significant social impact, with efficient heating systems ensuring a comfortable living environment and ventilation and air conditioning systems reducing harmful emissions to improve indoor air quality (Alsulaili et al. 2020). Additionally, good acoustic insulation enhances the residents' experience. In addition, green office buildings in Japan have typically improved the comfort of their occupants by enhancing indoor and outdoor air quality, thermal comfort, and natural indoor lighting (Balaban and Puppim de Oliveira 2017).

The green wall of plant growth acts as a protective film, and the plant leaf orientation and pore structure limit sound transmission. Tang et al. (2021) confirmed that paved green walls had better noise reduction than climbing green walls, reducing noise pollution by 7.0–15.6 decibel. Green roofs rely on vegetation and substrate to retain large amounts of rainwater, and the ability of green roofs in Chongqing, China, to retain an average of 77.2% of runoff demonstrates the high rainwater retention capacity of green roofs (Zhang et al. 2015). The effective control of precipitation runoff by green construction helps to reduce the occurrence of urban flood disasters (Liu et al. 2017a). Green construction directly benefits human life through environmental and economic benefits quantified and amplified to society to achieve social benefits.

This section examines the advantages of three aspects of green building. Environmental, economic, and social benefits are extremely important evaluation indicators for identifying the low carbon emission, low-cost, and high-comfort characteristics of green construction.

Challenges of green construction implementation

The implementation of green construction practices is a more significant social movement for environmental sustainability. Therefore, it is essential to identify the obstacles to implementing green construction in order to find solutions that will enhance green development. As shown in Fig. 12, the obstacles to implementing green construction have been classified as economic cost, time, educational awareness, and policy system.

The cost has been identified as a significant and sensitive barrier to green construction implementation in the construction industry. Chegut et al. (2019) evaluated and determined the marginal cost of green construction for 336 Building Research Establishment Environvmental Assessment

Method (BREEAM)-certified buildings and found that green construction design costs were 32% higher than conventional construction design costs. On average, renovation and fit-out costs were 32% and 28% higher, respectively. Additionally, the extended building cycle for green construction lengthens the cost of construction financing and lowers the developer's return on equity investment. Uğur and Leblebici (2018) calculated an increase of 7.43% (Gold certification) and 9.43% (Platinum certification) in the new construction costs of two Leadership in Energy and Environmental Design (LEED)-certified green buildings in Turkey. While approaches to reducing green construction costs can offset the increased upfront costs of green buildings by reducing long-term operation and maintenance costs through efficient use of energy and water, it still does not fully address the high costs of upfront design and construction. The cost factor affects the scale of green construction capital investment and increases the difficulty of implementation feasibility (Tam et al. 2017). Agyekum et al. (2020) analyzed the factors affecting the financing of projects in implementing green policies in Ghanaian building projects. Inadequate knowledge and a lack of reliable information about green construction led to the inability to finance the projects and an increase in expenses. One of the major future research directions is the reduction of the cost of green construction materials and technologies, and the promotion of green construction must consider a life cycle assessment approach (Shi et al. 2013).

Green construction techniques are more expensive and take longer than traditional techniques, of which the time impact of implementing green construction in Gauteng, South Africa, can be verified (Masia et al. 2020). Because it slows the project, the extra time needed to comply with green criteria is an inescapable roadblock to decision-making for contractors, clients, consultants, and subcontractors (Darko et al. 2017), and there is time pressure to deliver projects. Workers may be inclined to abandon time-consuming sustainable practices. The time-consuming phenomenon of green construction technology is also evident in the Nigerian public hospital green building project (Ebekozien et al. 2021). Furthermore, green construction material review requirements are high, requiring additional time to obtain approval (El-Sayegh et al. 2021).

Green construction technology is more complicated than conventional technology and is not widely known among professionals. Due to the more stringent requirements of green construction implementation, the lack of training and experience of construction personnel, the lack of awareness of green construction, and the inability to obtain government support will make it difficult to promote green construction implementation (Nguyen et al. 2017). In addition, this new green technology is often not welcomed by the public, and the lack of awareness of it has not gained enough social trust (Liu et al. 2018). The low awareness of green construction among the implementing agencies and their inability to coordinate well affect the progress of the construction process and confuse in implementation (Balaban and Puppim de Oliveira 2017). The efficacy and acceptance of green buildings in Malaysia are constrained by the customers' and investors' lack of technical knowledge and experience. By increasing knowledge and skills connected to green technology, information, and good practices, methods to generate knowledge and capacity are also created to improve awareness and motivation (Mustaffa et al. 2021).

The adoption of green certification systems is hampered by a lack of data and awareness about green construction certification methods (Agyekum et al. 2019). The database containing detailed information on green construction materials facilitates the rating of the certification system, which helps institutions to quickly and accurately assess the sustainability of green construction. The current database applied to green construction in Kazakhstan is not appropriate and user-friendly, raising the difficulty of investigating contacts (Assylbekov et al. 2021). In Nigeria, there are less operating laws for the construction industry, and there are not enough proposed construction codes for green-rated projects that have not been incorporated into formal regulations, thus reducing the popularity of green construction (Abisuga and Okuntade 2020). Therefore, it is necessary to stimulate political will and encourage and facilitate the implementation of green and construction policies.

This section describes the challenges encountered in implementing green construction, such as higher economic costs, lengthy construction times, a lack of awareness and work coordination among construction staff, a lack of database information, and unsupportive policies. These obstacles limit the viability of green construction and increase the complexity of the building. Consequently, addressing these obstacles facilitates the implementation of green construction and promotes the construction industry's sustainability.

Conclusion

This comprehensive literature review examines the development of green construction to achieve net-zero carbon emissions in support of global sustainability objectives. It begins with a systematic review of the definition of green construction to illustrate how different stakeholders perceive the drivers of carbon reduction and comprehend how carbon–neutral green can be achieved in the construction industry. Concurrently, the study examines the broad definition of "green" and highlights the fact that different institutions, such as the government and the building industry, and different individuals, such as researchers and builders, view green from different perspectives and use different sets of variables to determine a green path. In addition, this study examines the definition of green construction and demonstrates that green construction has become an essential component of sustainable development in the twenty-first century. Green construction refers to practices that maximize resource conservation and reduce negative environmental impacts through scientific management and technological advances while adhering to basic quality and safety standards in order to achieve energy, land, water, and material savings and environmental protection. Therefore, green construction can reduce carbon emissions throughout the life cycle and speed up the construction industry's transition to net-zero carbon emissions.

In addition, this study provides a comprehensive analysis of carbon emissions over the life cycle of a building. According to the research, the construction phase accounts for 20–50% of total carbon emissions. Although buildings have a long operation and maintenance period, which can last decades, and their carbon emissions are significant and accumulate slowly, the construction phase has the highest carbon emission density, with significantly higher annual carbon emissions per square meter than the operation phase. In the meantime, based on the findings of some researchers regarding the ratio of annual emissions from the construction phase to annual emissions from the operation phase, we determined that this ratio averages 0.62. This result indicates that annual carbon emissions per square meter are significantly higher than those during the operation phase. The survey also reveals that the majority of previous studies have considered material consumption, on-site construction activities, transportation, on-site living, equipment operation, and on-site office as construction carbon emission boundaries, whose primary carbon emission influencing factors are energy consumption, various energy sources, energy intensity, unit output value, machinery energy consumption, machinery efficiency, material use, and electricity use. To develop more effective and targeted carbon reduction measures for buildings, it is crucial for decision-makers to identify precisely which accounting boundaries and influencing factors to prioritize.

In addition, the assessment investigates the policies developed by various nations to achieve carbon–neutral building programs. It begins by introducing green building management & certification, the development of certification systems to guide the use of green materials, and building energy efficiency techniques. Second, the global project "Advancing Net Zero Emissions" of the World Green Building Council (WorldGBC) is examined for its call to companies, organizations, cities, national and regional stakeholders, and authorities to achieve net-zero emissions in operation by 2030 and net-zero emissions in operation in all buildings by 2050. In the meantime, it is proposed to establish a list of recommended materials with low embodied emissions. In addition, procuring high-quality carbon offsets and implementing nature-based solutions to enhance carbon sequestration and offset embodied carbon emissions. Lastly, initiatives and disclosures are proposed to require construction firms to report their scope three emissions (supply side) and actions to mitigate climate risk.

In the context of carbon emission analysis modeling for the construction industry, it is essential to develop effective methods for assessing the environmental impact of the construction phase in order to implement decarbonization measures whose life cycle assessment is required. We discussed various methods for evaluating the construction phase's environmental impact in depth. We found that life cycle assessment is frequently used in the construction industry to assess environmental impact, with carbon emissions as the leading assessment indicator. In recent years, random forests and neural networks have also been used to calculate and predict the construction industry's carbon emissions, thanks to the continuous development of computer technology and big data technology. We summarized the carbon emission analysis of the construction phase of buildings of five residential buildings, six office buildings, and one tower building, of which about 50% of the buildings used life cycle assessment, namely office and residential buildings in Korea, residential buildings in Finland, residential buildings in Spain, office buildings in the United States of America and office buildings in Sweden, with carbon emissions of 4,420, 140,000, 291.7, 4,182.9, and 566 tonnes, respectively. During the construction phase, the life cycle assessment can calculate the carbon emissions of each construction procedure, such as material use, transportation, construction activities, and construction process. Therefore, the assessment also details the life cycle assessment methodology and explains four key steps to support accurate calculations and the development of corresponding measures to reduce carbon emissions in the construction industry.

In addition, the use of sustainable materials such as biochar, bioplastics, agricultural waste, animal wool, fly ash, and self-healing concrete can reduce the carbon footprint of a construction process. We present an in-depth analysis of the environmental, economic, and social benefits of green construction implementation. Concurrently, the current challenges of implementing green construction are presented. The cost of implementing green construction in the construction industry has been identified as a significant and delicate obstacle. In addition, there is a lack of reliable information and a low level of knowledge regarding green construction, which leads to the failure of financing projects and increases the financial burden. In some countries, there is also a lack of government policy support, and there are not enough proposed building codes for green-rated projects that have been incorporated into formal regulations, thereby diminishing the popularity of green buildings.

In addition, green building technologies are more costly and require more time to implement than conventional technologies. To fully promote the system-wide carbon neutrality of the construction industry, the future application of life cycle analysis in green construction should be enhanced in order to develop robust measures and policies and to increase knowledge of green building for universal access. Promoting net-zero carbon emissions from green construction can be beneficial for the environment, society, and economy, thereby contributing to global sustainable development and aiming for a global average temperature rise significantly below 2 degrees from pre-industrial levels and toward 1.5 degrees.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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