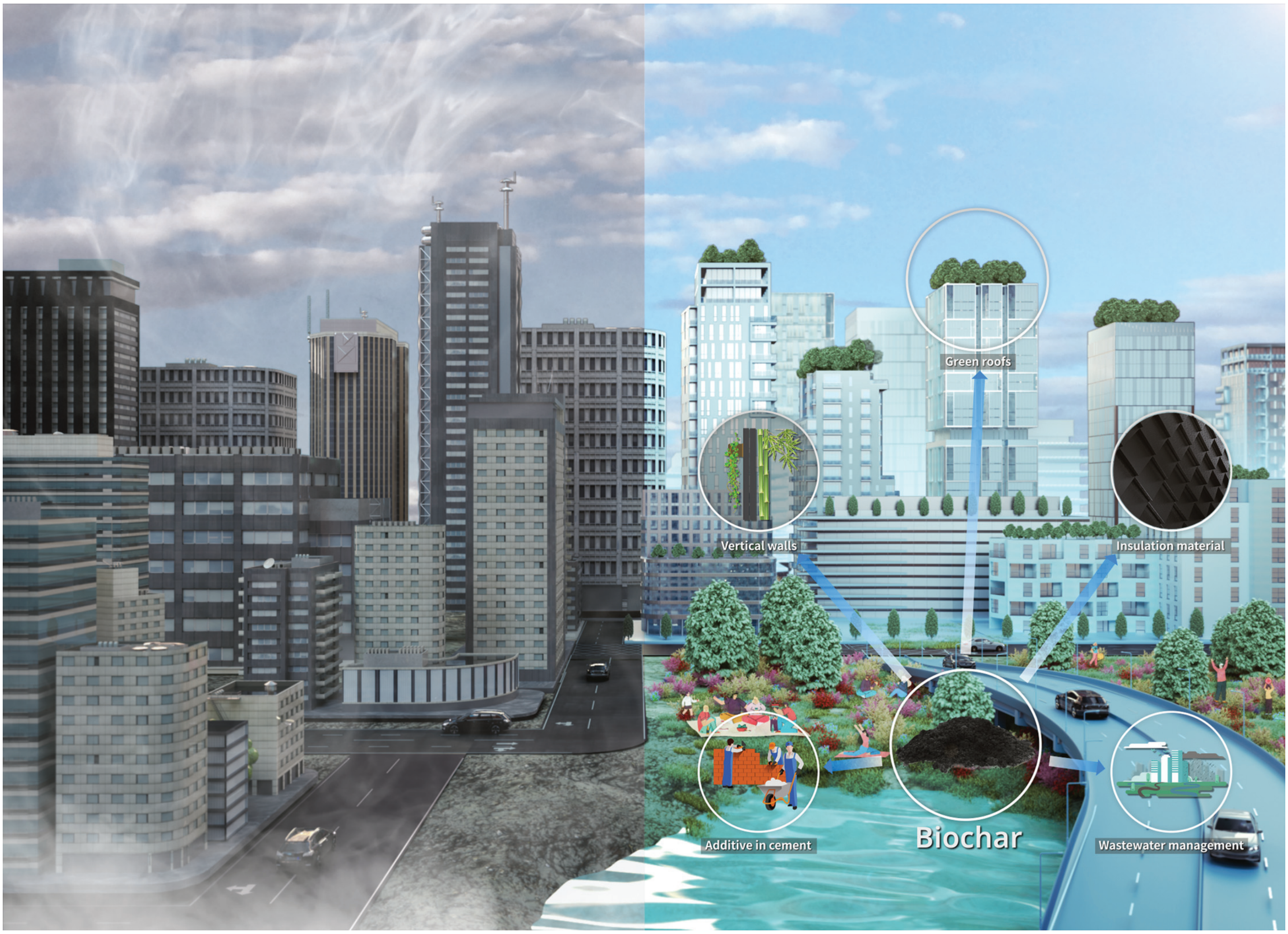

Showcasing research from Professor Yong Sik Ok *et al.* from Korea University, Republic of Korea.

Carbon negative biochar systems contribute to sustainable urban green infrastructure: a critical review

This article explores the innovative incorporation of biochar into various green infrastructure elements, including green roofs, vertical walls, stormwater management systems, application in cement mixtures and insulating materials demonstrating how biochar can help transition from traditional grey infrastructure to more environmentally resilient and sustainable green solutions.

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Carbon negative biochar systems contribute to sustainable urban green infrastructure: a critical review†

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Biochar from biomass and waste is a valuable component of various urban green infrastructures, including green roofs, permeable pavements, green walls, and green parking lots. Incorporating biochar into substrate mixtures offers numerous benefits, including improved water retention, nutrient availability, plant growth, and carbon sequestration. Moreover, biochar plays a crucial role in stormwater management by effectively retaining and filtering stormwater, reducing runoff, mitigating urban flooding, and improving surface water quality. This study conducted a comprehensive bibliometric analysis and synthesis of the literature to provide a broad perspective of the current understanding of biochar use in green infrastructure projects, focusing on the impact of biochar on soil and environmental quality, water retention, pollutant removal and the overall performance and sustainability of green infrastructure systems. This review also provides a comprehensive synthesis of the potential of biochar in enhancing green infrastructure systems and guiding future research and implementation strategies. The insights provided in this review can guide corporate stakeholders in understanding the benefits, challenges, and applications of biochar in urban green infrastructure management, empowering them to make informed decisions and contribute to the development of sustainable and resilient urban environments aligned with the principles of the UN SDGs and ESG considerations.

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1. Introduction

Rapid urbanization has resulted in many environmental problems worldwide, notably the loss of natural green spaces.[1] This reduction in green land has negative consequences for ecosystems, biodiversity, air quality, and the overall well-being of urban residents by disrupting the ecological balance, intensifying the urban heat island effect, and diminishing cities' aesthetic appeal. Green infrastructure is recognized as one of the key adaptation measures to address these challenges.[2,3] In an urban environment, green infrastructure refers to a combined network of urban greenery, such as parks, gardens, green roofs, street trees, and local rainwater management systems.[4] Suitable substrates of green infrastructure are crucial for healthy and resilient urban greenery.[5] High water retention, porosity for root growth, nutrient availability, and structural stability are the key conditions that need to be fulfilled by the substrates.[6] Many biomaterials (*i.e.*, cellulosic fibers, such as jute, hemp, coir *etc.*) have been suggested for mitigating soil erosion, but they are susceptible to degradation due to microbial decomposition. Hence, to uphold soil quality and productivity, the recent recommendation involves the utilization of biochar, which has emerged as a promising solution for controlling soil erosion.[7] Biochar's durability surpasses geo-environmental infrastructure's design period, making it a reliable and long-lasting option for erosion prevention.[8–12] Its resistance to degradation ensures sustained effectiveness in minimizing soil erosion and contributes to the long-term stability of engineered structures.[13]

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Various methods exist for producing biochar, including technologies such as slow pyrolysis, fast pyrolysis, torrefaction, microwave treatment, gasification, flash carbonization, and hydrothermal carbonization.[14] Depending on the specific process parameters and techniques employed, these methods vary significantly in terms of yield and quality of biochar production (as well as other co-products such as bio-oil and syngas).[15] Biochar is receiving increasing attention because it is a promising, crucial functional element in substrates used in green infrastructure due to its unique physical and chemical properties.[16–18] Biochar primarily consists of carbon, hydrogen, and oxygen, with smaller quantities of nitrogen and sulfur. It may also contain microelements like calcium, zinc, potassium, and magnesium. Raising pyrolysis temperature in biochar production boosts the carbon content of biochar by removing volatile components. However, it reduces the biochar yield.[19] Tan *et al.* showed that pyrolysis temperature also altered the pore structure, distribution, order, compactness, and porosity of biochar.[20] Moreover, the physicochemical properties of biochar, including elemental composition, surface area, stability, and functional groups, are influenced by pyrolysis temperature.[21–24] The type of feedstock used for biochar production affects its properties, such as pore size and volume, water holding capacity, surface area, pore distribution, and cation exchange capacity.[25,26]

Typical applications of biochar include soil amendment in agriculture,[27–29] building material,[30,31] pollutant removal,[32–35] air purification,[36,37] catalyst in biofuel production,[38,39] biogas upgrade,[40–42] and electrical energy storage in supercapacitors and batteries.[43] Moreover, IPCC (2018) acknowledged biochar as a negative emission technology, recognizing its capacity to remove CO_2 from the atmosphere.[44] In 2022, the IPCC report on "Climate Change 2022: Mitigation of Climate Change" emphasizes that biochar holds significant worldwide promise in potentially eliminating 2.6 billion tons of CO_2 annually.[45]

Within the biochar sector, numerous industries and manufacturers, such as Pacific Biochar, Phoenix Energy, Novocarbo, Pyreg, Silicate, Skanska, Bionero, Carbonex, InPlanet, Biochar Supreme, Airex Energy, Swiss Biochar, Arsta Eco, Earth Systems, Guangdong Dazhong Agricultural Science and Technology, Rainbow Bee Eater, and Pacific Pyrolysis, are actively involved in carbon abatement projects.[46] For example, Pacific Biochar, a US-based company, targets to sell 1500 metric tons of CO_2 credits to Microsoft in 2022 and achieve 21% Carbon Dioxide Removal (CDR) in 2023.[47] Rainbow Bee Eater, an Australian company, is also dedicated to similar initiatives. These manufacturers primarily source feedstock from forestry residues, agricultural by-products, wood waste from construction, and crop leftovers. They market biochar as a fertilizer and/or animal feed while leveraging the energy generated during production. For instance, Carbofex, produces up to 140 kg of biochar per hour from 500 kg of spruce wood chips. It has gained recognition as a Top 60 finalist in the Carbon XPRIZE's $100 million carbon removal competition, which started in April 2021. Shopify and Microsoft have each made purchases from Carbofex for their sustainability initiatives. Ecoera, Sweden's pioneering large-scale biochar producer, is engaged in a project aimed at establishing a climate-positive agricultural system. Similarly, Carbon Cycle, a German-based manufacturer, specializes in producing high-quality biochar from woodchips, catering to farming sectors across Europe. Many of these manufacturers have secured carbon credit sales to climate-conscious corporations including Shopify and Microsoft.[48]

2. The role of biochar in green infrastructure

Biochar's unique properties make it a valuable component for use as a substrate in green infrastructure systems. When mixed with soil, biochar can enhance soil aggregate stability, soil fertility, nutrient availability, contaminants immobilization,[49,50] water retention,[51,52] and address the greenhouse effect through carbon sequestration and contaminant adsorption.[53,54] Implementing green infrastructure elements into urban planning or development (such as green roofs and green walls) can effectively reduce the temperature in buildings during the summer. These vegetated surfaces provide insulation and shade, reducing solar heat gain and the need for building cooling, mitigating urban heat islands, and enhancing city microclimates for more comfortable, energy-efficient environments.[55–57] For example, field case studies have been conducted to analyze the hydrothermal properties of green roofs, as highlighted by Yang *et al.*[58] and Jin *et al.*[59] The incorporation of biochar will enhance the absorption and retention of rainwater, allowing it to infiltrate into the soil or slowly release it back into the environment. Moreover, biochar in green infrastructure helps to alleviate the burden on traditional stormwater management systems and reduces the risk of urban waterlogging and sewer overflows. It promotes natural water filtration and recharge of groundwater while enhancing water quality by reducing the amounts of pollutants that enter water bodies through runoff.[60–63]

Biochar can be mixed into the substrate medium of various urban green infrastructure systems such as green roofs, cement mixtures, green parking lots, and green walls, thus enhancing the properties of substrates.[64] Moreover, studies demonstrate that incorporating biochar into engineered infrastructures, such as in green infrastructure, including slopes and landfill covers, is gaining importance due to its environmentally friendly and economically beneficial characteristics.[65,66] Building green roofs to manage rainwater is considered economical, particularly in urban areas where land scarcity poses challenges. Green roofs offer multiple benefits, including water management, thermal regulation, and environmental sustainability. Recently, various countries have introduced incentives to promote the large-scale manufacturing of biochar for commercial use in green infrastructure projects. These incentives aim to support the achievement of carbon reduction goals by 2030 and encourage the adoption of sustainable practices.[1]

Scientific research on biochar has advanced significantly in the past a few years. However, gaps in our understanding require further exploration and investigation, such as the lack of a decision tool to identify the most suitable biochar for specific soils, materials, and environmental constraints. Hence, we conducted a bibliometric analysis (Fig. S1†) to gain a comprehensive understanding of the current knowledge and findings in this field. The number of papers on the application of biochar in infrastructure development has significantly increased over the years. Starting with only one paper in 2007, the number of publications on this topic reached 435 in 2022. This exponential rise indicates a surge of interest in utilizing biochar in various infrastructure and urban planning applications. Additionally, this rise is consistent with the biochar gaining wide recognition as a potential solution in addressing challenges in urban infrastructure development and has become a prominent area of research in recent years (Fig. 1).

Moreover, experimentation at the implementation scale may need to address relevant knowledge gaps, notably about the life cycle evaluation of environmental impact, economic evaluation, and production technology. Hence, a comprehensive summary of the research is essential to provide clear guidance and shape future development directions.[74] The application of biochar in green infrastructure lacks comprehensive and systematic studies and understanding. This review aims to fill the gap by providing insights into the current state of the field and identifying areas where further investigation and advancements are needed. Specifically, this review focuses on analyzing existing research concerning the utilization of biochar in green infrastructure applications *via* a bibliometric analysis and aims to provide a comprehensive understanding of the current knowledge and findings in this field. Based on the analysis in this review, the interactions between biochar in green infrastructure were investigated as follows: (1) biochar as an additive in cementitious mixtures; (2) biochar for vertical greenery systems; (3) biochar application in green roofs; (4) biochar as an insulating material for walls and (5) use of biochar in stormwater management. This review will guide future developments and implementations of biochar in green infrastructure (Fig. 2). Suggestions for effective implementation and long-term sustainability will also be discussed, together with an investigation of the social aspects-how communities perceive and engage with biochar-infused green infrastructure.

3. Biochar in green infrastructure

3.1. Biochar as an additive in cementitious mixtures

Every stage of the construction process, from the preparation of raw materials to cement production, contributes to carbon dioxide (CO_2) emissions. It is a well-established fact that the production of Portland cement, widely recognized as the primary construction material, is a major contributor to the emission of CO_2, accounting for approximately 8% of global CO_2 emissions.[75] Unfortunately, as the global population continues to grow, these emissions are projected to escalate, exacerbating the environmental impact of the construction industry. Therefore, it is imperative to prioritize the use of construction materials with minimal carbon footprints as viable alternatives.[76] Past literature has showcased the potential of incorporating supplementary materials into cement, including

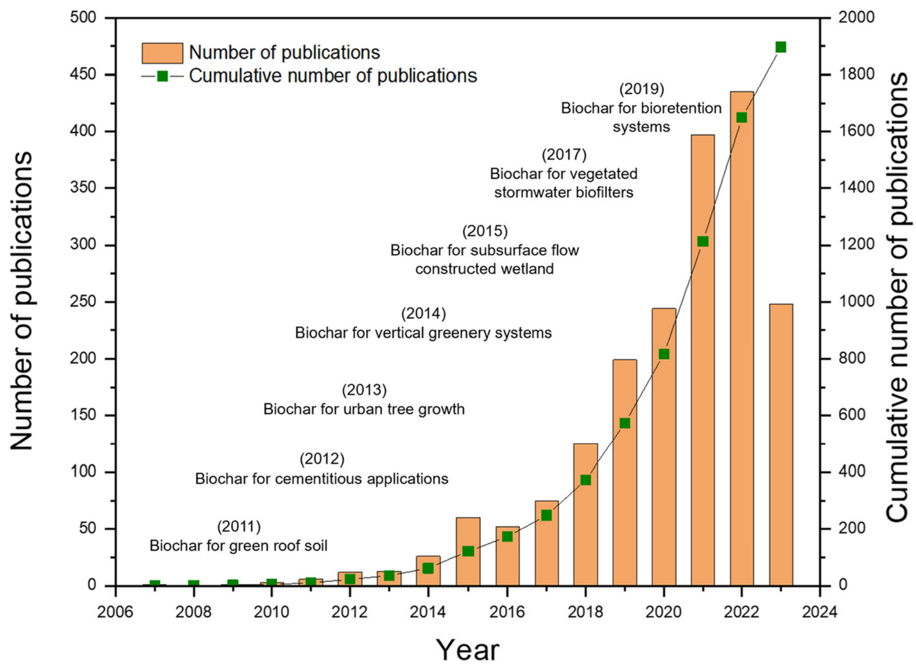

Fig. 1 Analysis of 1897 papers on biochar applications in green infrastructure retrieved from the Web of Science database from 2007 to 2022.[67–73]

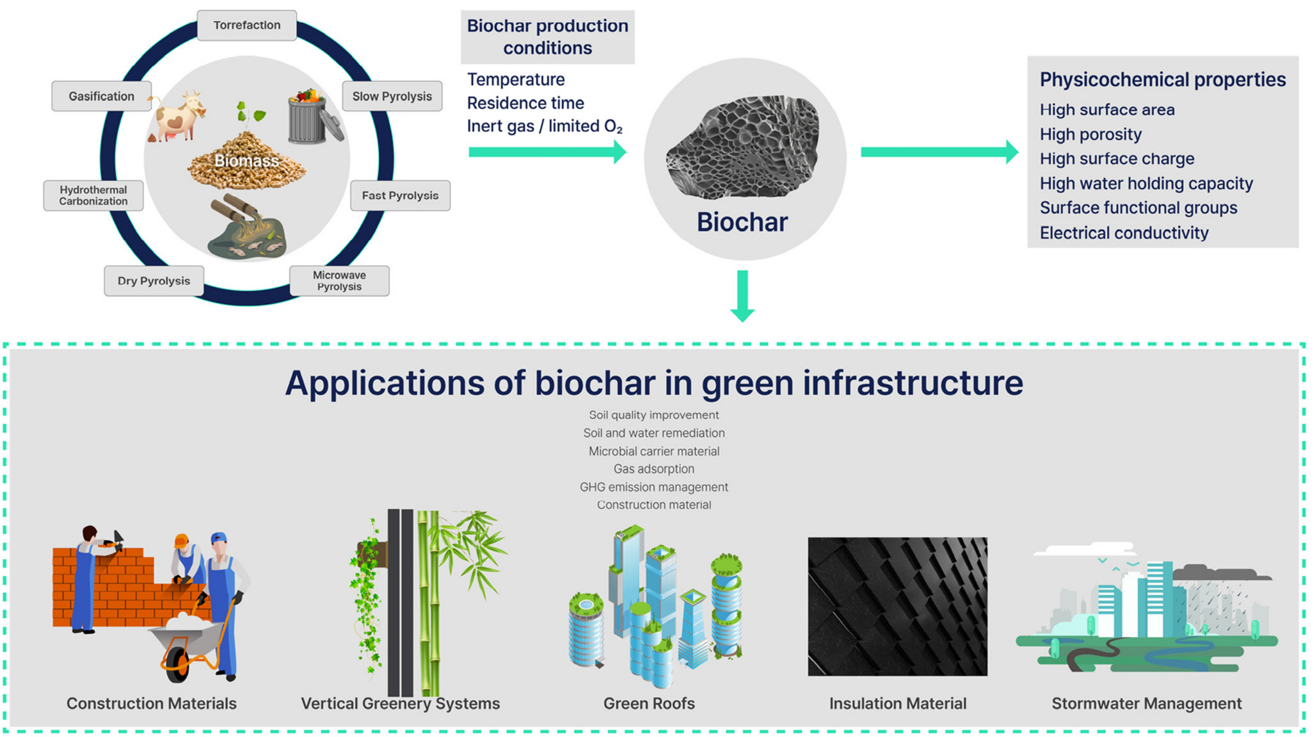

Fig. 2 Application of biochar in green infrastructure.

industrial byproducts and recycled construction wastes.[77–80] Acknowledging the significant role of the cement industry in greenhouse gas (GHG) emissions, there is a growing focus on mitigating its environmental impact through adopting sustainable materials and socially responsible strategies. The incorporation of biochar into the building construction field is a promising strategy for reducing CO_2 emissions, marking significant progress toward carbon neutrality.[76,81]

Biochar has garnered attention as a possible substitute for cement, potentially enhancing structural properties when used in appropriate quantities. Extensive research has demonstrated that biochar can enhance the quality of materials used in construction, including asphalt for road construction. Its positive impact also extends to the concrete sector, where adding biochar in the concrete admixture is gaining momentum as an emerging green solution in the construction sector.[82,83] Previous studies have confirmed that the biochar particles exhibit exceptional structural compatibility and stability with the cement matrix. Microscopic examination provides evidence of a strong and intimate bond between the biochar particles and the surrounding cementitious material, validating their compatibility and effective integration within the composite system.[84] Biochar chemical properties, including surface functional groups, can vary due to oxidation and aging over time. Consideration of these changes is crucial for consistent and predictable outcomes when using biochar in cementitious mixtures.[23,24,85]

According to Gupta, *et al.*,[86] the improved bonding between biochar and cement mixtures can be attributed to biochar's porous and ridge-shaped structures. These characteristics contribute to enhanced interfacial interactions and bonding between biochar and the cementitious matrix. In an experiment conducted by Gupta *et al.*,[87] it was discovered that adding biochar particles, specifically those smaller than 200 μm, prepared from mixed sawdust, can enhance the properties of concrete specimens. This improvement was observed under both normal and elevated temperature conditions. The findings suggest that incorporating biochar as an additive in the concrete mix can positively affect the material's performance. Biochar's suitability as a construction material stems from its high chemical stability and low thermal conductivity. The presence of a porous structure in biochar is attributed to its low thermal conductivity, as highlighted by Gupta and Kua.[83] In addition, Gupta *et al.*, hypothesized that at high temperatures, pores in the concrete matrix containing biochar can potentially serve as pressure release valves.[88] This phenomenon may occur because of the release of water vapor from these pores, which helps to alleviate internal pressure within the concrete structure. Furthermore, experiments conducted by Gupta *et al.*[88] have revealed that incorporating biochar with a range of particle sizes, including coarser and finer particles, can improve the workability and rheological properties of binder pastes. These findings demonstrate that utilizing a combination of biochar particle sizes yields better results in terms of the workability and flow behavior of the binder pastes compared to using only coarser biochar particles.

During the concrete preparation process, when grounded biochar is added to the cement mixture, it tends to adsorb a portion of the mixing water. This reduces the amount of free water available in the pores of the concrete matrix.[87,89] The moisture exchange between porous admixtures and the cement paste plays a significant role in moisture regulation and internal curing action. This exchange allows moisture absorption and release, helping to maintain optimal moisture levels within the concrete matrix. As a result, porous admixtures facilitate internal curing, which promotes hydration, improves strength development, and reduces the potential for cracking in the hardened concrete. However, it is suggested not to replace more than 5% of the concrete mass with biochar as it has been observed to negatively impact strength development. For example, Sirico *et al.*[90] found that the addition of 10% waste wood-based biochar had no notable impact on the densities of concrete specimens; however, it was found that the inclusion of biochar led to a maximum reduction of 5% in strength when compared to concrete without biochar.

Previous results have highlighted biochar's positive contribution to the mechanical, thermal, and physical properties of cement when appropriate quantities of biochar and cement are combined.[91] Moreover, vegetation concrete, primarily composed of cement, water, and coarse aggregate, serves as a foundational reinforcement layer and is covered with a soil layer to support vegetation growth.[92] This material is effective for enhancing the landscape, reducing pollution, and protecting the environment. To further enhance plant compatibility with vegetation concrete, Zhao *et al.* suggest incorporating biochar particles into the mix.[93] Therefore buildings designed and constructed with incorporated biochar have the potential to serve as long-term carbon sinks and promote sustainable practices.

3.2. Biochar for vertical greenery systems

Vertical Greenery Systems (VGS) are structures that use various types of plants to create green walls, facades, and roofs. They refer to structures that support vegetation growth, whether they are attached to a building's facade or interior wall. These systems are designed to spread greenery in a vertical direction, adding natural elements to urban environments and enhancing the aesthetic appeal and environmental sustainability of the surrounding areas.[73] They have numerous benefits, including improving air quality, increasing biodiversity, and also helping to minimize the urban heat island effect.[94] However, the success of VGS largely depends on the type of growing medium used. Plant growing media usually comprises inorganic materials such as sand, expanded clay, volcanic rocks, perlite, rockwool, and shale and organic components such as peat, compost, or coconut coir. The substrate blend used for growing media should possess a high capacity for water retention and efficient drainage properties. Additionally, fertilizers can be incorporated into the growing media to ensure plants receive adequate nutrients.[95,96] Traditional growing media, such as soil, can be heavy and have limited water retention capabilities, making them unsuitable for use in VGS. Contrarily, biochar, has been found to have numerous properties that make it an ideal growing medium for VGS.[94]

The use of biochar in the VGS substrate has multiple benefits, such as improving filtration, porosity, and mechanical load-bearing capacity. One of the main advantages of biochar in VGS is its water-holding capacity.[1,94,97] Biochar has a high porosity, which allows it to absorb and retain water for long periods. Biochar's water-holding capacity improves plant health and growth during the growing season. Additionally, biochar has been found to increase plant water use efficiency, which is essential in VGS, where water conservation is critical. The high surface area, which allows it to adsorb and retain nutrients such as nitrogen, phosphorus, and potassium, is another advantage of biochar in VGSs. This property is particularly beneficial in VGS, where traditional growing media may not have sufficient nutrients to support plant growth. The high nutrient retention capacity of biochar means that less fertilizer is needed, reducing the environmental impact of VGS. Additionally, the high surface area of biochar creates a conducive environment for beneficial microbes that can aid in nutrient uptake and disease suppression.

3.3. Biochar application in green roofs

Recently, green roofs have gained recognition as an innovative solution for managing urban stormwater due to their efficient utilization of limited space and resources effectively and as a strategy for mitigation and adaptation to climate change. However, the success of green roofs largely depends on growing medium used. The disadvantages of traditional growing media discussed in section 3.2 also make them unsuitable for use in green roofs. However, biochar's unique properties make it an ideal growing medium for green roofs.[98] These roofs are designed to mitigate stormwater by incorporating thin engineered soil profiles (substrates less than 20 cm deep) that support vegetation. According to the research conducted at Portland State University, green roofs incorporating soil with 7% biochar by weight demonstrated notable improvements in water retention capacity. Additionally, these green roofs exhibited reductions in the discharge of nitrogen, phosphorus, and organic carbon.[72] For practical applications of biochar, Rob Lerner introduced a simple method to enhance plant growth on flat rooftop gardens. The process involved first screening the biochar through a 1 cm sieve to ensure uniformity followed by mixing with various ingredients in the specified proportions: 16% biochar, 6% red pumice, 9% mixed compost, 6% white pumice, 16% mushroom compost, 9% leaf mold, 6% earthworm compost, 6% river silt, 9% goat manure, 6% decomposed bark, and 9% black earth.[99] Apart from the stormwater reduction capabilities, green roofs also contribute to delaying peak runoff and improving the quality of stormwater.[100,101] This multi-functional approach enhances the overall performance of green roofs, making them an attractive option for urban water management strategies. Additionally, green roofs are gaining popularity in urban environments because of their advantages in reducing urban heat island effects, enhancing air quality, and fostering increased biodiversity.[98]

One of the main benefits of using biochar in green roofs is its ability to retain water,[97,102,103] and its low bulk density.[104] Biochar has a high porosity, which allows it to absorb and retain water for long periods. A study by Cao *et al.*[105] revealed that at a 40% green waste biochar concentration, an additional 2.3 cm of rainfall could be retained in substrates that were 10 cm deep. This increased water retention also resulted in additional plant-available water, effectively delaying permanent wilting by two days, particularly with a 30–40% biochar concentration. In addition, substrates with a 40% biochar content were lighter, allowing an extra 1.5 cm of substrate to be installed per square meter. As a result, biochar not only reduces the weight of green roof substrates but also improves water supply to plants, making it a beneficial addition to green roof systems. Sludge-derived biochar altered microbial community structure and adjusted temperature, increased substrate moisture content, and promoted the growth of ryegrass (*Sedum lineare*), and cucumber (*Cucumis sativus*). The optimal application rate of 10–15% sludge biochar had the most beneficial effects on microbial biomass and plant growth, forming an ideal soil environment.[103]

Moreover, biochar does not readily ignite when mixed into the soil, and its inclusion could enhance the fire resilience of adequately planted and well-maintained green roofs. To further mitigate the risk, the implementation of fire-activated sprinkler irrigation systems can be beneficial. For those contemplating the installation of green roofs or walls in regions prone to bushfires, it is crucial to verify whether they comply with the bushfire attack level regulations relevant to their property as per the applicable standards.[106] Green roofs possess the potential to enhance urban ecological conditions by reducing the heat island effect and absorbing harmful gases (Fig. 3a). A study investigating the carbon capture and storage (CCS) potential of green roofs, amended with both biochar and sludge, revealed that biochar exhibited a significantly higher carbon storage potential than sludge. Specifically, a biochar green roof demonstrated carbon storage of 9.3 kg C m^{-2}, while a sludge green roof stored 7.9 kg C m^{-2}. Biochar derived from sludge has shown the ability to enhance carbon content, thereby improving soil physical and chemical properties and promoting plant growth. Simultaneously, sludge application has demonstrated effectiveness in improving soil chemical properties. Moreover, biochar presented additional advantages, including reducing roof weight, enhancing soil moisture retention, and utilizing municipal sludge as a resource. Consequently, biochar emerges as an effective material for fostering carbon storage on green roofs.[102] Green roofs are also becoming popular in urban areas worldwide as an ecological alternative. A study was conducted analyzing the effects of biochar substrate on water quality, runoff retention capacity, pollutants releasing characteristics, and pollution load.[97] Gan *et al.*[1] found that a green roof incorporating 10% biochar (w/w) exhibited superior comprehensive rainwater management capabilities, demonstrating the highest peak outflow reduction and the longest delay in rainwater outflow. Conversely, a green roof with 5% biochar showcased the

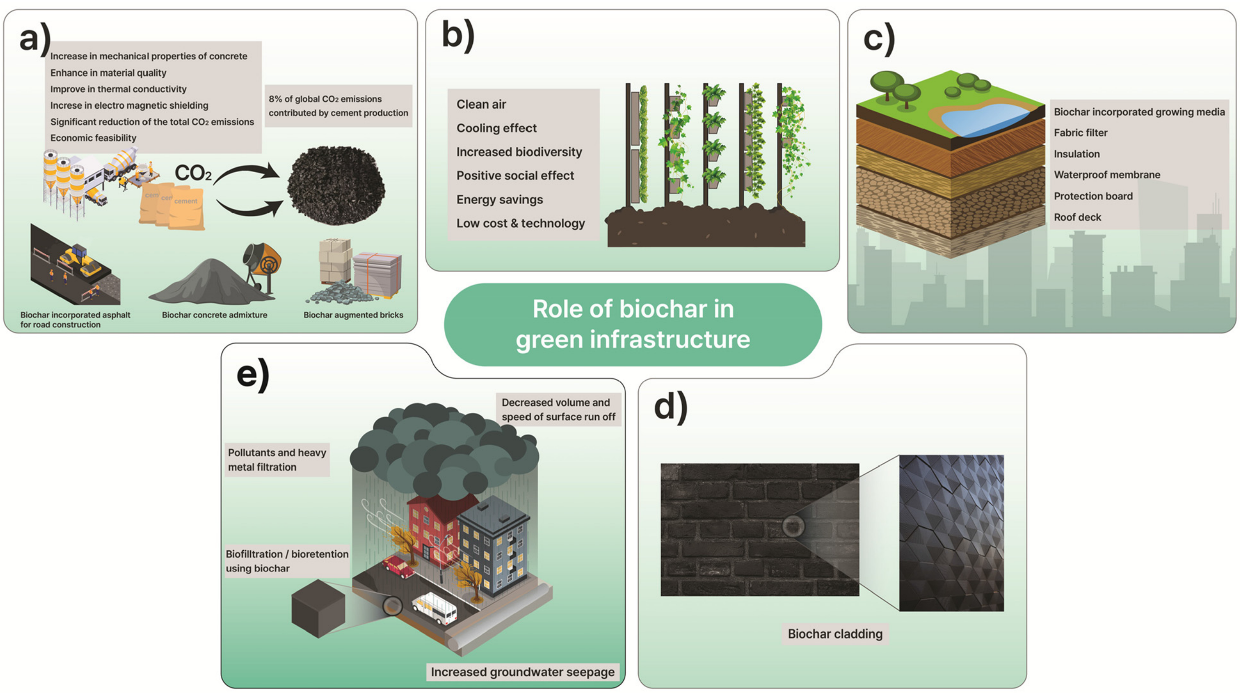

Fig. 3 Role of biochar in green infrastructure. (a) Biochar as an additive in cementitious mixtures. (b) Biochar for vertical greenery systems. (c) Biochar application in green roofs. (d) Biochar as an insulating material for walls. (e) Biochar for stormwater management.

highest runoff reduction and the longest delay in peak outflow. The coconut shell biochar substrate had a stronger neutralizing capacity for pH. It effectively reduced the pollution load of total nitrogen and chemical oxygen demand in the runoff of green roofs.[97] Hence, applying biochar to green roof substrates could be a viable approach to mitigate the impact of non-point pollution from urban areas on receiving water bodies.[97] These findings support a suitable selection of biochar content for urban areas with varying degrees of rainwater management demands. Additionally, biochar has been found to increase plant water use efficiency, which is essential in green roofs where water conservation is critical.

3.4. Biochar as an insulating material for walls

The use of porous carbon-rich biochar as an insulating material for walls in building structures enhances the thermal insulation in building materials.[57,83] This application is mainly associated with biochar's high porosity and low thermal conductivity, making it a promising option for improving energy efficiency in buildings.[107] At temperatures surpassing 500 °C, there is notable variation in porosity among different raw materials. Recent research indicates that biochar generated at 350 °C generally exhibits an average porosity of 10 μm or less.[108] This highlights the application of biochar as an innovative solution for enhancing the thermal performance of walls and creating more energy-efficient and environmentally friendly buildings. Moreover, studies reveal that integrating evenly dispersed porous biochar into construction materials disrupts heat transmission in various directions, hindering the unidirectional flow of heat.[109,110] Incorporating biochar in building materials offers the opportunity to enhance hygrothermal performance. For example, building materials infused with biochar exhibit improved humidity control capabilities, allowing for better regulation of moisture levels within the indoor environment. Furthermore, the use of biochar in building materials contributes to energy savings, as it assists in maintaining optimal moisture conditions and reduces the energy required for cooling and dehumidification processes.[111] Biochar has a low thermal conductivity, which means it is an effective insulator, keeping buildings cool in the summer and warm in the winter. This property can lead to significant energy savings in buildings, reducing heating and cooling costs and improving overall energy efficiency (Fig. 3d). The feasibility of using LHSBC (latent heat storage biochar composite) as a building material was assessed based on its thermal properties. LHSBCs were created by impregnating bio-based PCM (phase change material) into rice husk biochar.[57] Through a combination of experimental and numerical analyses, the following insights were gained: the exudation ratio of LHSBC stands at 4.87%, indicating notable stability in both exudation and thermal aspects at temperatures below 100 °C. Its thermal conductivity aligns closely with that of a gypsum board. Chemical compatibility was confirmed, as no chemical bonding occurred between the rice husk biochar and PCM during impregnation. While the latent heat of LHSBC tends to decrease compared to pure PCM, it still contributes to a substantial reduction in the maximum annual building energy consumption by 531.31 kW h per year. These findings affirm the high thermal performance, robust thermal and exudation stability, and chemical compatibility of LHSBC, positioning it as an excellent environmentally friendly building material.

Researchers have been actively engaged in developing an innovative bio-composite utilizing biochar in conjunction with natural inorganic clay (NIC). This initiative aims to evaluate the suitability of biochar for various applications in the construction industry.[112] Rice husk, coconut shell, and bamboo biochar were prepared and mixed with NIC at various ratios (1, 2, 5, and 10 wt% of the NIC) to form a board. The TCi (C-Therm thermal conductivity analyzer) analysis revealed a maximum reduction of thermal conductivity by 67.2% due to the presence of biochar. Dynamic heat transfer analysis demonstrated that the bio composite exhibited low sensitivity to thermal changes, attributed to the low thermal conductivity of biochar. Further, an increase in water vapor resistance factor of up to 22.3% was observed when biochar was mixed, indicating reduced water vapor permeability. Another study was conducted by Jeon *et al.*[113] to evaluate the properties of LHSBC as a novel material for latent heat storage insulation, using biochar derived from a pinecone, pine sawdust, and paper mill sludge was mixed with a bio-based phase change material (PCM) – coconut oil – to create LHSBCs. The findings revealed that LHSBCs exhibited a maximum latent heat storage capacity of 74.6 J g^{-1} and a low thermal conductivity of 0.030 W m K^{-1} at its peak, indicating excellent latent heat storage and thermal insulation properties. Furthermore, the LHSBCs demonstrated a high specific heat of 1.69 J g^{-1} K^{-1}, indicating efficient sensible heat storage. The LHSBCs were also found to be thermally and chemically stable. Overall, LHSBCs have the potential to be utilized as materials with strong thermal insulation performance and effective heat storage characteristics.

In addition to its insulating properties, biochar can also provide other benefits when used on walls. Biochar has been found to have moisture-regulating properties, which can help prevent mold growth and improve indoor air quality.[114] The high porosity of biochar also makes it an effective sound insulator, reducing noise pollution in buildings. Cuthbertson *et al.* observed that the incorporation of biochar (derived from dried distillers grains (DDG), a co-product of corn bio-ethanol production) into concrete significantly enhanced its sound absorption coefficient within the frequency range of 200–2000 Hz by creating pore networks within the material.[115]

3.5. Biochar for stormwater management

With the increase in population and urban expansion, the increase in impervious surfaces poses a significant risk to water environments, highlighting the need for effective mitigation strategies. Urban growth alters hydrological dynamics, leading to heightened runoff peak, increased runoff volume, and accelerated time-to-peak flow. These alterations in the hydrological cycle have implications for water management and can lead to challenges such as increased flooding, decreased water availability[116] and degradation of water quality.[117,118]

Urban runoff is known to contain varying amounts of organic compounds, inorganic compounds, metals, and suspended solids. Effective stormwater management practices are crucial for mitigating the impacts of urban runoff and reducing the introduction of these pollutants into receiving water bodies (Fig. 3e). Developers frequently utilize low-impact development (LID) systems to handle stormwater effectively. These systems are primarily designed to alleviate flooding by restoring developed areas' natural stormwater infiltration capacity, aiming to match or approximate their pre-development conditions.[119] LID approaches emphasize sustainable stormwater management practices that mimic natural hydrological processes, such as rainwater harvesting, green roofs, permeable pavements, bio-retention basins, and vegetated swales. By integrating these strategies, LID systems help reduce the adverse impacts of urban development on stormwater runoff and promote sustainable water management practices.[120] While LID systems are effective in managing stormwater and reducing flooding, it is important to note that they are not primarily designed to exclude most stormwater contaminants.[121] For effective stormwater treatment, measures should also meet certain criteria to be considered practical and efficient. These measures should be economical,[119] easily accessible, and capable of removing a broad spectrum of stormwater pollutants under the anticipated conditions during the intermittent infiltration of stormwater.[119,122,123] Biochar offers potential benefits for stormwater treatment as it can adsorb pollutants, enhance water retention in soil, slowly release nutrients for plant uptake, improve soil fertility and support plant microbiota. Its ability to adsorb contaminants such as heavy metals,[124] and hydrophobic organic contaminants,[125,126] improve water infiltration, and sustain beneficial microorganisms can contribute to the removal of pollutants,[127] sequester carbon[128] and enhance water quality in stormwater treatment systems.[119,129–132]

Various factors, including the characteristics of the contaminants, properties of the biochar, type of feedstock and the specific treatment conditions, can influence the effectiveness of biochar in removing contaminants. For example, increasing pyrolysis temperature during biochar production leads to the formation of a more extensive pore structure, including increased micropore volume and surface area,[127,133] which enhances the adsorption capacity. The high cation exchange capacity (CEC) of biochar facilitates the adsorption of cations such as metals (Cd, Cu, Pb, and Zn),[28,134,135] while the high anion exchange capacity (AEC) shows an affinity for anions such as carbonate, phosphate, hydroxide and metalloids.[119] Additionally, biochar with high ash content can raise solution pH, reducing metal/metalloid solubility and enhancing their removal.[136] Moreover, the hydrophobicity of biochar,[137] influenced by its organic carbon content and properties, enhances the adsorption of hydrophobic pollutants and biological contaminants such as fecal indicator bacteria, pathogens, and viruses on its surfaces.[138,139] Organic contaminants, including herbicides, insecticides, oils, PAHs, PCBs, and flame retardants, can be removed *via* sorption. Furthermore, biochar can act as a redox control agent in LID systems, facilitating microbial degradation of contaminants sensitive to reducing conditions and enhancing treatment efficiency.[140] Sorption mechanisms involve π–π electron donor acceptor (EDA), hydrophobic attraction, hydrogen bonding, and electrostatic attraction.[119,127]

A meta-analysis by Omondi *et al.*[141] found that adding biochar to soil reduced bulk density and increased soil porosity, water-holding capacity, aggregate stability, and saturated hydraulic conductivity. In bioretention media with sand, the impact of biochar on hydraulic conductivity and clogging varied based on particle size.[142] Particle size of biochar is a critical design consideration for maintaining high hydraulic conductivity and reducing clogging risks in stormwater treatment units. Nevertheless, the impact of biochar on water retention and hydraulic conductivity in soils exhibits inconsistency across various studies, with some reporting improvements,[143,144] and others observing deteriorations.[145,146] Factors such as particle size, soil properties, and biochar hydrophobicity contribute to these discrepancies. As Mohanty *et al.* highlighted, the selection of geomedia for stormwater treatment systems involves considering two critical properties: high hydraulic conductivity to prevent overland flooding and a substantial storage volume from decreasing peak flow and improving contaminant removal.[119] Traditional choices like sand provide good hydraulic conductivity but lack internal pores for storage.[147] Adding fine media like clay increases storage but decreases conductivity. However, biochar, with its internal pore network, can offer both increased storage and improved conductivity when properly sized.[119]

A comprehensive understanding of the relationships between these factors is crucial for optimizing LID system design using biochar, maximizing contaminant removal and system performance.[119] Further research is needed to assess the technical feasibility and cost-effectiveness of biochar chemical modifications for long-term sustainability in stormwater treatment.

Notably, numerous construction materials, such as sand, gravel, stone, geotextiles/geomembranes, timber, and soil mixtures, have been utilized in developing green infrastructure components. These components include rain gardens, filter strips, swales, green roofs, asphalt paving, landscaping, and infiltration systems.[148] For instance, a study by Fini *et al.*[149] indicated that porous pavements made from gravel and sand allowed greater water infiltration and evaporation. However, further research is necessary to understand the durability, maintenance needs, and long-term impacts of porous pavements on soil and plant characteristics. Rain gardens are specifically engineered with beds made of porous substrates, typically loamy sands, and planted with drought-resistant species that can tolerate flooding.[150] Flynn *et al.* investigated a bio-infiltration rain garden constructed with materials such as silica sand, corrugated HDPE, cement, asphalt, grass seed, stone, and bark mulch. The study identified significant environmental, economic, and social factors related to the construction, operation, and decommissioning phases of the Villanova University bio-infiltration rain garden.[151] Despite these advancements, the incorporation of biochar into green infrastructure elements has been limited (Table 1).

4. Case studies of biochar application in green infrastructure

Many countries and regions have been promoting nature-based solutions and rejuvenating urban areas through the Re-Naturing Cities initiatives.[182,183] For example, the EU has adopted green infrastructure strategies to preserve biodiversity and ecosystem services in both rural and urban settings.[184,185]

In 2014, Stockholm won the European Mayors Challenge with its visionary plan to combat climate change by converting plant waste into biochar, aligning with the city's goal to become fossil fuel-free by 2040 and carbon neutral by 2045.[186] The city has pioneered the use of a biochar–gravel–soil mix to enhance the vitality and resilience of urban trees, making trees grow stronger and faster. This innovative approach is particularly crucial for trees growing near pavement, where limited oxygen and water pose threats to their health. Biochar's unique porous properties resist compaction and compression while retaining essential water and nutrients, ensuring urban trees thrive.[187] Biochar offers a solution to maximize green spaces' environmental benefits in urban environments with space constraints. From pocket parks to expansive green belts, these extended areas support biodiversity and offer residents opportunities to reconnect with nature amidst urban life's hustle.[188] However, it should be noted that replicating the success of a biochar project requires careful consideration and planning. Key factors to be considered include identifying a viable market for biochar, selecting appropriate biomass for biochar production, securing a suitable site for the biochar plant, adapting to new technologies, and anticipating challenges during site preparation and maintenance. Community engagement also plays a vital role in biochar projects' success. The Stockholm project, provided opportunities for citizens to learn about biochar and contribute to its effective implementation through initiatives such as museum exhibitions, public launches, study visits, and open days.[186]

Building upon Stockholm's success, Uppsala, Sweden, is planning a groundbreaking new city district for 57 000 residents, slated for construction between 2025 and 2050. The municipality aims to reduce the district's environmental footprint by experimenting with innovative technologies such as biochar. This project will assess the potential of biochar carbon sequestration in urban settings.[189] In Helsingborg, a city of 100 000 residents in Sweden, biochar innovation has reached new heights beyond Stockholm's pioneering efforts. This expansion is part of a larger initiative led by Bloomberg Philanthropies involving seven cities worldwide, including Helsingborg (Sweden), Darmstadt (Germany), Sandnes (Norway), Helsinki (Finland) and Cincinnati, Lincoln, and Minneapolis (in the U.S.).[190] Moreover, it is advised that the biochar used meets the European Biochar Certificate (EBC) standards or equivalent to guarantee the quality and effectiveness of the biochar, which is essential for achieving desired outcomes.[187]

Helsinki, embarked on a project to enhance carbon sequestration, circular waste systems, and urban greenery by increasing biochar usage across public green spaces. Through extensive testing of organic waste materials as biochar feedstocks, the project aims to raise awareness and provide practical knowledge about biochar production and application to city officials and residents.[191] Furthermore, biochar application extends to various sites in Helsinki, including a football field in Siltamäki, park lawns, turf tram railroads, and street parking spots. One notable case study is Kuninkaantammi, a new residential area typifying high-density development in Finland. Incorporating biochar into planting beds will potentially store 330 000 tons of CO_2 over 50 years, highlighting the significant climate mitigation potential of biochar and green planning initiatives.[191,192]

The NWE CASCADE project in France focuses on enhancing stormwater management in urban settings, particularly in Brittany, by integrating biochar into solutions. These efforts target the improvement of rainwater infiltration, soil permeability, and groundwater recharge, aligning with the vision of creating "sponge cities" while evaluating biochar's potential for carbon storage. The sustainable approaches include, using biochar to enhance urban soil permeability and exploring other innovative methods for optimized stormwater management. The project is to be facilitated by establishing a dynamic stakeholder network. Effective implementation of the plan within the project is facilitated by the collaboration between municipal administrations, scientists, private sector entities, and stormwater management associations.[193]

In the USA, the City of Minneapolis, Minnesota, has concluded a stormwater infrastructure project in collaboration with Hennepin County. This initiative, conducted along State Highway 55 (Hiawatha Avenue) in 2019, aimed to enhance infiltration, reduce maintenance, and encourage vegetative growth. The project team replaced the existing compacted soil with a compost/biochar mix to achieve these goals.[194] Furthermore, Minneapolis is actively incorporating biochar into various urban applications beyond stormwater management processes. It includes its utilization in infrastructure projects and community gardens, reflecting a broader trend in the city's environmental initiatives.[195] Minnesota has even published specifications for biochar use in stormwater management, with Minneapolis spearheading city-wide programs after drawing insights from successful projects in Stockholm, Sweden. This momentum extends beyond Minneapolis, with other municipalities across the USA exploring biochar's potential in urban stormwater management. As a broader trend in the USA, cities like Chicago have made significant investments in stormwater treatment projects with the potential for biochar

Table 1 Application of biochar in green infrastructure

Application	Type of biomass	Pyrolysis condition (temperature: °C, residence time: h)	Findings	Ref.
Biochar as an additive in cementitious mixtures	Masson pine wood	Temperature: 500, 700; residence time: 2	• Biochar is employed as a substitute for river sand in concrete mixtures at dosages of 1, 2, and 5 wt% • The high dosage (5 wt%) of biochar negatively impacted the mechanical strength, which is attributed to the porous structure and brittleness inherent in biochar	44
	Mixed wood saw dust	Temperature: 300, 500; residence time: 1	• Addition of biochar at 1, 2, 5 and 8% by weight of cement • The flow rate of the mortar mix experienced a significant decrease when biochar was incorporated beyond 5 wt% to replace cement • An optimal improvement in compressive strength of cement mortar was observed with a biochar addition ranging from 1–2 wt% • The addition of biochar did not affect flexural strength and drying shrinkage in the cement mortar	89
	Food waste (FW), boiled rice (RW), mixed wood waste (MW)	Temperature: 500; residence time: 1	• 1 wt%, 2 wt% and 5 wt% of cement in the mortar • The air content of fresh mortar is found to increase with an increase in biochar dosage, irrespective of the feedstock from where it is derived • At 5% dosage of MWBC, RWBC and FWBC, the air content of the mix is higher by 12, 29 and 21%, respectively, compared to plain mortar	87
	Wood waste from local forests (mainly chestnut, pine and fir)	Not available	• The addition of 10% waste wood-based biochar had no significant effect on the densities of concrete specimens, but caused a maximum of 5% reduction in strength	90
	Poultry litter	Temperature: 450; residence time: 1	• Replacing sand with 20% biochar improved the flexural strength up to 26% • The thermal conductivity of mortars can be reduced by 26% with a 10% biochar addition • The density of the mortars decreased by around 20% with a 40% biochar addition • There was a reduction of 20% in net CO_2 emission with a 40% biochar addition	152
	Rice husk	Temperature: 500; residence time: 2	• The addition of RHB significantly improves strength due to the internal curing effect • The combination of RHA and RHB eliminates autogenous shrinkage for a reasonable period	153
	Rice husk	Temperature: 450–550	• Strength, hydration heat, degree of hydration, and workability decreased with increased biochar content • Conversely, chloride diffusivity, electrical resistivity, and meso air voids exhibited an increase as the biochar content increased	84
	Waste coconut shell, mixed tropical wood	Temperature: 400–450	• Biochar was fixed at 2% by weight of cement • The incorporation of coarser biochar leads to a reduction in strength and rheology • Blending finer and coarser particles enhances the rheological properties of biochar-cement • Blended biochar particles contribute to improved packing density and strength development • The combination of different particle sizes enhances the hydration kinetics and overall hydration of cement	88
	Mixed wood saw dust	Temperature: 300	• The addition of 2% by weight of cement to mortar during mixing reduced the initial setting time and significantly improved the early compressive strength of mortar	154
	Mixed wood saw dust	Temperature: 500; residence time: 1	• The biochar was added to the cement paste in amounts of 2, 5 and 8% of the mass of the cement • The presence of 5% fine biochar in the paste accelerated cement hydration, leading to a higher peak heat evolution, associated explicitly with C_3S hydration at 5 hours	155
	Peanut shell (PS), hazelnut shell (HS)	Temperature: 850; residence time: 1; Ar atmosphere; 0.2 bar pressure	• An increase in electromagnetic radiation shielding effect when adding 0.5 wt% of PS or HS in cement composites	156
	Bamboo	Temperature: 850; residence time: 1	• The incorporation of 0.08 wt% carbonized particles resulted in a 66% improvement in flexural strength • Similarly, the inclusion of 0.08 wt% carbonized particles led to a substantial 103% enhancement in toughness	157
	Tropical mixed wood saw dust	Temperature: 400; residence time: 1	• Hydration and early-age strength are improved due to the addition of 2.5 wt% biochar • The carbon uptake of biochar-paste is enhanced at 28-day age than the control • Internally carbonated biochar-cement shows 25–30% higher strength than control	158
	Mixed wood waste	Temperature: 450	• Enhanced hydration in biochar-foamed mixtures improves strength and sorptivity • The addition of biochar reduces yield stress and plastic viscosity of foamed paste mixtures • Biochar-foamed mortar retains higher strength after prolonged carbonation	159
Biochar for vertical greenery systems	Corn stover (Zea mays)	Temperature: 650	• Biochar of 5, 10, and 15% by volume percent was added to the sample of each thickness (100 mm, 200 mm, 300 mm) • Technological constraints prevent the use of biochar in quantities exceeding 15%, primarily due to its high water absorption and the resultant increase in volume	94
	Carbofex Oy	Not available	• Biochar was added at a ratio of 7 : 3 (substrate : biochar) by volume • The largest reductions in concentration and total load (>90%) were found in P, Pb, Mn, and Fe • The smallest reductions in concentration and total load (<50%) were found in Se, Al, and As	160
	Rice husk	Temperature: 400	• 2.5% wt biochar was mixed with surface soil (<10 cm depth) • Promotion of macro-aggregation, potentially leading to the formation of mesopores that play a crucial role in retaining a greater amount of soil water, thereby facilitating improved water availability for plant uptake	161

Table 1 *(Contd.)*

Application	Type of biomass	Pyrolysis condition (temperature: °C, residence time: h)	Findings	Ref.
Biochar application in green roofs	Coconut shell biochar	Temperature: 600	• Biochar substrate green roofs mainly include peat, vermiculite, perlite, biochar, and sawdust, with an allocation ratio of 2 : 3 : 3 : 1 : 0.5, respectively • Effectively reduce the pollution load of Total Nitrogen (TN) and Chemical Oxygen Demand (COD) in the runoff of green roofs	97
	Hardwood mixture	Temperature: 450; slow pyrolysis	• Crushed concrete with 20% volume of biochar • Amending concrete substrate with 20% (v/v) biochar improved retention of nitrogen in <20 mm events • Biochar amendment reduced NH_4^-N availability by half (p = 0.035) but did not affect NO_3^-	162
	Maize straw, rice husk	Temperature: ~650; residence time: 2	• Treatments of local soil, perlite, and vermiculite (CK) were mixed with 10, 15, and 20% rice husk biochar (RHB) or maize straw biochar (MSB) • Addition of biochar significantly affected the runoff quality • With an increasing biochar addition rate (10–20%), the mean total nitrogen (TN) concentration in the runoff decreased from 103.68 mg L^{-1} (CK) to 26.21–52.77 mg L^{-1} (RHB) and 10.12–3.97 mg L^{-1} (MSB), the mean dissolved organic carbon (DOC) concentration decreased from 94.47 mg L^{-1} (CK) to 101.76–59.41 mg L^{-1} (RHB) and 52.45–26.73 mg L^{-1} (MSB), and the mean pH increased from 7.15 (CK) to 7.42–7.50 (RHB) and 7.49–7.71 (MSB)	163
	Sugar-maple sawdust	Not available	• Amended with 5.4% (v/v) biochar • Biochar had positive effects on water retention and peak discharge for testbeds with native plants (forbs and grasses) and small events and the vegetation growth of these plant species	164
	Conifer sawmill waste	Temperature: 600–650; residence time: 0.3	• The dosage for biochar application was 25 t ha^{-1} (~18 g per pot), which is equivalent to 4.5% w/w • Biochar amendment resulted in a 74% reduction in biochar erosion and a 39% reduction in total substrate erosion. This outcome is likely attributed to the increased bulk density and particle size of biochar and the improved moisture retention in biochar-amended substrates	165
Biochar as an insulating material for walls	Rice husk	Temperature: 450; residence time: 2; heating rate: 7 °C min^{-1}; limited oxygen conditions	• Biochar was mixed at 1, 2, 5, and 10 wt% of the natural inorganic clay (NIC)	112
	Coconut shell	Temperature: 800; residence time: 2; heating rate: 7 °C min^{-1}; limited oxygen conditions	• A higher mixing ratio of biochar reduces the thermal conductivity	
	Bamboo	Temperature: 1000; residence time: 2; heating rate: 7 °C min^{-1}; limited oxygen conditions	• The thermal conductivities of the NR10 (NIC + rice husk biochar 10 wt%) NC10 (NIC + coconut shell biochar 10 wt%) and NB10 (NIC + bamboo biochar 10 wt%) were 0.138, 0.101, and 0.155 W m^{-1} K^{-1}, respectively	
	Pinus elliottii cellulose fibers	Temperature: 800; residence time: 2; heating rate: 5 °C min^{-1}; N_2 flow of 150 ml min^{-1}	• Incorporating 40 wt% biochar resulted in a 60% boost in the compressive strength of the aerogel compared to the cellulose aerogel • The addition of this carbonaceous structure did not significantly influence the thermal conductivity of the aerogels, maintaining a thermal conductivity range of 0.021–0.026 W m^{-1} K^{-1}	107
	Waste pine wood (Pinus radiata)	Temperature: 400, 450	• Biochar was mixed with wood polypropylene composite in ratios of 12, 18, 24 and 30% • The incorporation of 24 wt% biochar yielded a composite with comparable tensile strength but higher flexural strength than conventional wood/polymer composites • An addition of 6 wt% biochar to the composite showed no discernible difference in its mechanical, chemical, or thermal properties • The highest thermal stability was achieved when the biochar content reached 18 wt% in the wood and polymer composite	166
	Spruce	Temperature: 600; fast pyrolysis (<10 min)	• A wood-derived biocomposite (WB) was created by incrementally increasing the biochar ratio to the total weight by 2%, ranging from 0 to 10 wt% • The thermal conductivity of the WB10, with a biochar content of 10 wt%, was measured at 7.98%, showcasing a reduction attributed to the high porosity of biochar and its microstructure • With an increase in biochar content in the WB, there was a tendency for the bending strength to decrease, attributed to the pore structure of biochar and lower compatibility of the biochar surface with chemical functional groups and adhesives	167
	Rice husk	Temperature: 450; residence time: 2; heating rate: 7 °C min^{-1}; N_2 flow	• Biochar (100 g) and Phase Change Material (PCM) (200 g) were mixed for 5 min, vacuum dried at 80 °C for 2 h, and filtered • The resulting bio composite exhibits impressive exudation and thermal stability, evidenced by a thermal conductivity of 0.1727 W m^{-1} K^{-1}	57
	Water hyacinth (WH) Yellow oleander (YO)	Temperature: 550; residence time: 1; heating rate: 10 °C min^{-1}	• The PCM-biochar composite material is prepared *via* the direct impregnation method • Thermal conductivity enhancement up to 23% can be observed with composite phase change material (added with biochar)	168
	Sugarcane bagasse (SCB)		• The thermal conductivity is significantly influenced by the properties of the biochar matrix	

Table 1 *(Contd.)*

Application	Type of biomass	Pyrolysis condition (temperature: °C, residence time: h)	Findings	Ref.
Biochar for stormwater management	Apple wood saw dust	Temperature: 525; residence time: 4.16	• Wood-based biochar showed null to positive impacts on the earthworm population • Wet biochar application to soil could help mitigate the avoidance of earthworms by preventing desiccation	169
	Biochar composed of 250 kg of charcoal, which was mixed into 1 ton of compost material (50% sewage sludge + 25% freshly chopped lop, grass and leaves + 25% soil, and coarse wood branches (1 : 1))	Not available	• Biochar application induced higher enzyme activities due to improved soil chemical properties, resulting in faster decomposition of plant residue	170
	Fallen leaf	Temperature: 450; residence time: 1	• Biochar loaded with nano-particles significantly improves sorption capacity of Pb(II)	171
	Broiler litter	Temperature: 700; residence time: 1; N_2 flow of 1600 mL min^{-1}	• Enhanced copper retention by biochar amendment due to surface functional groups and delocalized π electrons of carbonaceous materials, and precipitation	172
	Dairy manure	Temperature: 200, 350; residence time: 4; limited O_2	• The biochar was 6 times more effective in Pb sorption than activated carbon • The biochar effectively sorbed atrazine	173
	Pecan shells	Temperature: 450; residence time: 4	• Biochar contains phenolic, carboxylic, and carbonyl surface functional groups that can coordinate copper	174
	Bamboo	Not available	• Removal of extractable Cd by 79.6% within 12 days	175
	Hardwood	Temperature: 450	• Reduction in Cd in soil pore water by 10 folds and Zn concentrations reduced by 45 folds	176
	Wood	Temperature: 200, 400	• Reduction in Zn and Cd leaching loss by >90%	177
	Bamboo	Temperature: 600	• Addition of 5% Bamboo biochar decreased the cumulative leach-loss content of pentachlorophenol by 42%	178
	Greenwaste (mixture of maple, elm, and oak woodchips and barks)	Temperature: 450; residence time: 1; limited O_2	• The sorption of atrazine and simazine increased with decreasing solid (biochar)/waste water solution ratio	179
	Rice husk	Temperature: 450–500; fast pyrolysis	• The surface area showed significant effects on Tetracycline adsorption as well as O-containing functional groups	180
	Orange peel	Temperature: 250, 400, 700; residence time: 6; heating rate: 5 °C min^{-1}	• Effectively remove organic pollutants and phosphate simultaneously *via* sorption	181

usage and demand for large quantities of biochar.[196] As cities continue to prioritize sustainability and resilience, biochar emerges as a promising solution to address diverse urban challenges where biochar's versatility extends to various urban applications, including tree planting, turf/parks management, compost enhancement, bioremediation, construction materials, and water treatment and filtration (Table 2).[197]

5. Role of biochar as an environmental defendant

Including modified biochar in the green infrastructure sphere marks an emerging, transformative solution to counter the escalating environmental challenges within urban systems. Sequestering atmospheric carbon dioxide, a prominent GHG, offers a way to mitigate the impacts of anthropogenic climate change.[202] Such innovative strategies can transition our built environment from a major carbon emitter into a significant carbon sink (stable carbon stored in biochar), thus signposting the route towards more sustainable, resilient, and carbon-neutral urban environments. From a broader perspective, biochar impacts carbon footprint mitigation, both directly and indirectly, as discussed by Legan *et al.*[31] Directly, biochar retains carbon meant to be released into the atmosphere through decay or combustion. Indirectly, biochar's application in energy-intensive building materials reduces associated carbon emissions. The exploration of innovative feedstocks for biochar production, such as a mixture of waste biomass[203] or invasive plant species,[204] improves waste management and reduces the ecological impacts of invasive species.

The employment of biochar in green infrastructure has numerous environmental benefits, from boosting carbon sequestration to enhancing soil fertility and augmenting ecosystem services.[205] The versatile nature of biochar permits its integration into many scenarios, such as urban parks,[206] agricultural landscapes,[207] and ecological restoration projects.[208] Beyond enhancing carbon sequestration, biochar also contributes to soil health,[209] such as improving nutrient availability and overall soil structure. The subsequent impact is an increase in plant productivity and, subsequently, an expansion of the biomass carbon pool, which drives further carbon sequestration. Moreover, the capacity to modify biochar to carry seeds or beneficial microorganisms could significantly enhance ecosystem restoration efforts.[210] By promoting the growth of native plant species and rehabilitating degraded habitats, biochar-assisted habitat restoration can create self-sustaining ecosystems, as discussed by Ghosh *et al.*[211] To realize the potential of biochar in green infrastructure, there is a need for commitment to continuous innovation, rigorous research, and interdisciplinary collaboration.

In urban environments, the application of biochar can play a pivotal role in mitigating the pervasive issue of urban heat islands. These areas, characterized by higher temperatures compared to surrounding rural areas, are primarily the result of heat-absorbing built surfaces and a scarcity of vegetative

Table 2 Biochar-based green infrastructure projects

Country	City	Biochar usage	Ref.
Sweden	Stockholm	One of the five winners of the 2014 European Mayors Challenge. The project utilizes a biochar–gravel–soil mix to improve the health and resilience of urban trees, serving as a soil fertilizer to foster plant growth	186
Sweden	Uppsala	Inspired from the Stockholm biochar project. The project uses the potential for biochar carbon sequestration in urban settings and will explore the viability of district heating *via* biomass pyrolysis	189
Sweden	Helsingborg	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. Intends to expand its current biochar production and inaugurate a central hub for biochar knowledge, fostering communication, research, and global engagement with local communities and researchers	198
Finland	Helsinki	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. The project aims to enhance carbon sequestration, circular waste systems, and urban greenery by increasing biochar utilization in public green areas, intending to repurpose an existing biochar facility to process green biomass sourced from city parks and residents' gardens	198
Norway	Sandnes	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. The project aims to increase biochar production fivefold, concurrently embarking on the creation of educational resources regarding biochar and actively involving school children in the process	198
France	NWE CASCADE project	The project aims to convert biomass into biochar to reduce fossil fuel usage, and biochar will be integrated into stormwater management in urban settings by promoting rainwater infiltration, soil permeability, and groundwater recharge	193
United States	Minneapolis	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. Minneapolis is starting on a stormwater infrastructure project to improve infiltration, minimize maintenance, and promote vegetative growth, with plans to construct a biochar production facility utilizing regional green waste and utilizing the generated heat in a low carbon district energy system	198
United States	Chicago	Inspired by the Stockholm biochar project. For stormwater treatment projects with the potential for biochar usage for cost effective pollutant control	196
United States	Lincoln	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. Lincoln plans to utilize biochar beyond agronomic enhancement, incorporating it into landscaping, stormwater mitigation, and compost enrichment. Collaborating with the Nebraska Forest Service, the University of Nebraska, and stakeholders, Lincoln will establish its inaugural biochar production facility as part of the Lincoln Biochar Initiative, aiming to address climate-related environmental challenges and promote soil health and water quality through community wood waste utilization for various projects including tree plantings, urban agriculture, public gardens, composting, and stormwater treatment	199
United States	Cincinnati	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. Cincinnati aims to produce sufficient biochar for the annual planting of over 3000 trees, utilizing it as a soil amendment to nurture new tree growth while sequestering carbon to bolster climate resilience. The city plans to repurpose green waste from parks, enhance urban planting initiatives, support tree canopy expansion in underserved areas, and integrate biochar into stormwater management operations	200 and 201
Germany	Darmstadt	One of the seven cities selected by Bloomberg Philanthropies after the Stockholm biochar project. Darmstadt aims to manufacture biochar for use in city parks, gardens, private residences, and sports facilities, intending to showcase its potential to other cities across Germany	198

cover. These elevated temperatures can have serious repercussions, from adverse health effects to increased energy consumption and escalated levels of air pollutants and greenhouse gas emissions. By improving soil quality in urban landscapes, biochar fosters plant growth, thereby facilitating the creation of green spaces that provide shade and offer evaporative cooling.[212] This, in turn, leads to a reduction in ambient temperatures. Biochar also contributes to air quality improvement[213] through multiple avenues, especially in urban areas that often grapple with high levels of air pollutants, including volatile organic compounds, particulate matter, and nitrogen oxides. Biochar's porous structure and expansive surface area is beneficial as an effective biofilter, adsorbing and retaining a wide range of airborne pollutants.[214] Its sequestration of carbon and other greenhouse gases reduces atmospheric pollutant concentration while promoting plant growth and enhancing the natural filtration of particulate matter and other air pollutants.[103] Recent research has explored the potential for modified biochar in green infrastructure to enhance pollutant removal. For instance, biochar can be modified to incorporate certain metals (or metal oxides)[215] and nanohybrid materials[216] that can catalyze the breakdown of organic pollutants in media, such as air and water pollutants. Additionally, biochar's ability to augment the soil's water-holding capacity supports the growth of certain plants known for their air-purifying abilities, further contributing to an integrated, efficient system for air quality improvement in urban locales.

The advent of biochar modifications through physical and chemical treatments has broadened its functionality, opening new avenues for advanced applications in green infrastructure. These modifications encompass processes such as biochar activation to increase surface area, thus providing more room for interactions with soil components and pollutants, and the incorporation of metal nanoparticles to augment reactivity. Lee & Shin[217] compared the heavy metal adsorption capability of a vast range of biochar feedstock and different modification approaches. These modifications significantly improve nutrient retention and pollutant removal capabilities, thus broadening the environmental applications of biochar. Meanwhile, the exploration of innovative feedstocks for biochar production, such as waste biomass or invasive plant species, delivers dual benefits. This not only provides an effective waste management solution by diverting biomass from landfills but also helps mitigate the ecological impacts of invasive species by utilizing them as a resource rather than viewing them as a nuisance.[218] This approach exemplifies circular economy principles central to sustainable development in the future.[219]

While the potential of biochar in carbon sequestration and ecosystem service provision is undoubtedly substantial, the challenge lies in optimizing these modifications and feedstock choices to maximize the benefits of biochar while mitigating any potential negative impacts. This involves understanding how different modifications and feedstocks influence the properties and performance of biochar in various environmental contexts and how these can be optimized to meet specific environmental objectives. This will require rigorous experimental design, meticulous analysis, and increasingly applying computational methods and machine learning to make sense of complex, multi-factorial systems. The combination of big data analytics, artificial intelligence (AI), and computational modeling with traditional experimental studies promises to accelerate our understanding of biochar and its potential applications. For instance, AI-powered predictive models could be utilized to simulate the behavior of biochar within different environmental contexts,[220] thereby facilitating the design of bespoke biochar solutions tailored to specific settings and objectives. An array of factors, including biochar properties,[62,221,222] feedstocks,[62,223] and soil heavy metal[224] generating predictions about biochar performance and impacts, can be easily performed with an AI-embedded algorithm. Such models could thereby guide the selection and modification of biochar to maximize its environmental benefits. Meanwhile, computational modeling can aid in understanding and predicting the behavior of biochar in different environmental systems, including its interactions with soil, water, and pollutants. Extensive incorporation with an optimization approach can balance a range of factors and constraints. Such factors include carbon sequestration potential,[225] biochar allocation in carbon management network,[226] economic costs, and environmental impacts,[227,228] used to determine the best strategies for biochar use, the effect of biochar on climate mitigation,[229–231] which has been evaluated in a vast collection of related research. Life cycle assessment (LCA) is another useful approach to quantifying and optimizing the carbon-saving potential of biochar applications.[189,232–235] It allows for the systematic evaluation of the environmental impacts associated with all stages of biochar's life cycle, from feedstock acquisition through production and use, to disposal or recycling. This kind of holistic analysis can provide critical insights into the environmental trade-offs associated with different biochar applications, feedstocks, and modifications, helping to guide decision-making towards the most sustainable options while ensuring the application of biochar in the use of green infrastructure (Fig. 4).

6. Concerns over biochar production and usage

6.1. Technical challenges and economic feasibility

According to the 2023 Global Biochar Market Report, one of the main challenges hindering the expansion of the biochar market is limited awareness, estimated at approximately 50%.[236] Furthermore, there is a significant lack of consumer knowledge regarding biochar and its blended products compared to traditional fertilizers or composts. Despite growing research on biochar's effectiveness in agriculture and its economic aspects, public familiarity remains relatively low.[237,238] To tackle this challenge, it is crucial to launch extensive marketing campaigns to educate consumers, policymakers, and industries about biochar's benefits and diverse applications.

Moreover, more than half of biochar producers do not comply with any certification or standard for their production practices.[236,239] The European Biochar Certificate (EBC) represents a significant advancement in establishing quality and sustainability benchmarks for biochar manufacturing. It provides a recognized framework for evaluating and certifying biochar products, promoting trade and market expansion within Europe and globally. This certification enhances transparency in the market, empowering consumers to make well-informed choices and driving the demand for biochar products.[240] For example, At the end of 2023, product certification had been achieved by nearly 70% of Europe's total production capacity, representing a significant increase from below 50% in 2018.[241]

The availability and affordability of biochar production equipment might present challenges, especially for smaller-scale producers. Additionally, unclear or restrictive regulations and policies can hinder biochar production and impede market growth. A well-designed policy incentive tailored specifically for biochar could catalyze the advancement of reliable production technology, economic feasibility, and market expansion. Although research on how urban planning policies respond to climate change has been limited, it is on the rise. Studies have also been conducted in fields related to urban planning, such as water supply and coastal management.[242,243] Although there has been analysis of climate change policies, there is limited published research on the extent to which climate change actions are covered in urban planning policy, particularly across different levels of government and policy disciplines.[243,244] For example, Hurlimann *et al.* conducted a study providing significant insights into how climate change is addressed in Victoria, Australia's planning policies. They examined the extent to

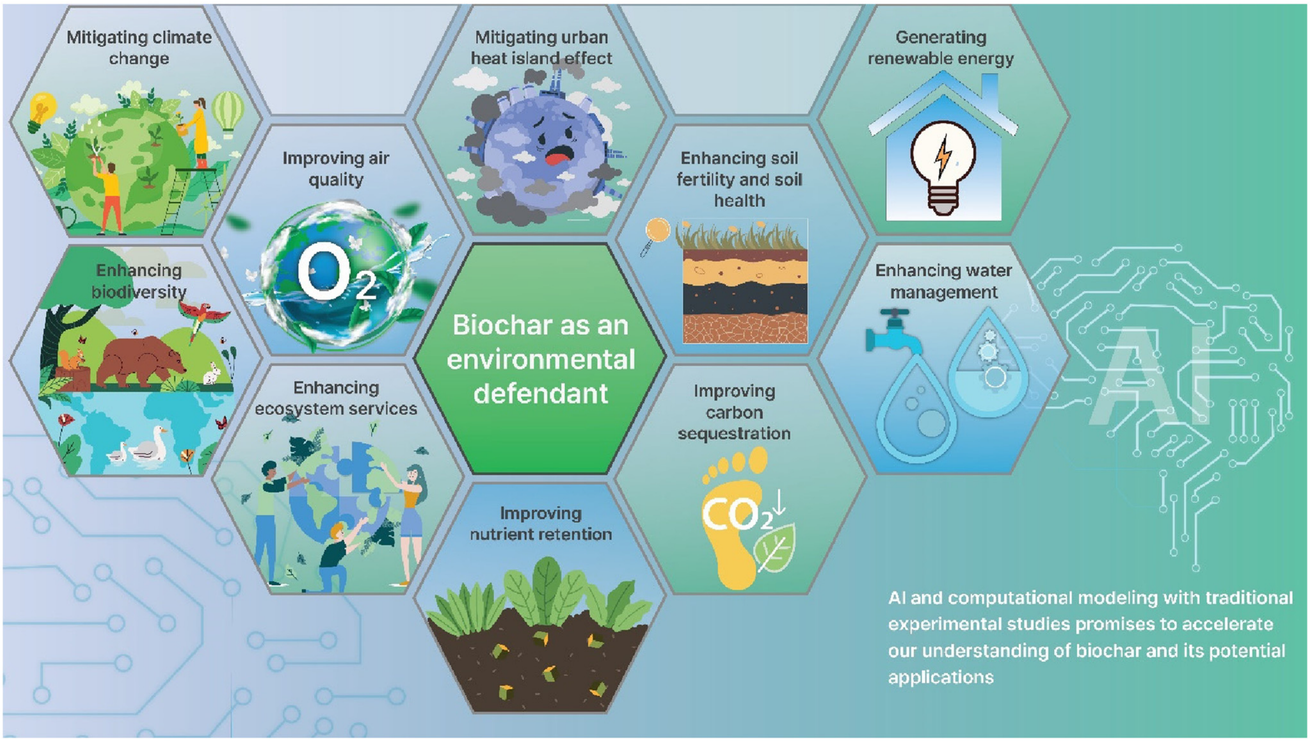

Fig. 4 Role of biochar as an environmental defendant.

which these policies consider greenhouse gas emission mitigation and climate change adaptation, contributing to the limited body of research on this topic. Their analysis spans multiple levels of government (local and state) and various policy disciplines. Key findings reveal that climate change is only minimally included in urban policy documents and that there is insufficient integration of mitigation and adaptation strategies.[245] Government support in the form of financial incentives like tax credits, subsidies, or loan guarantees could significantly foster industry growth. This growth could, in turn, facilitate standardization and learning-by-doing in both production and application methods, resulting in economies of scale and subsequent cost reductions.[246–248]

Additional challenges include insufficient demand for physical biochar, limited access to capital, equipment availability and capacity, technological readiness and scaling, competition and access to feedstock, transportation expenses, environmental considerations, and a shortage of skilled labor.[236] Nematian *et al.*[249] suggest that the local production of biochar in rural areas using portable pyrolysis units is more suitable than the use of centralized facilities. This approach aims to improve production efficiency by reducing feedstock transportation costs in agricultural regions. Moreover another study suggested that, mobile or distributed biochar production systems offer a promising solution by reducing biomass costs through the use of locally generated waste biomass and addressing local bioenergy and biochar needs.[250] Although slow pyrolysis is a common method for biochar preparation, it has significant limitations. The process is energy-intensive and time-consuming, which reduces its viability on a large scale.[251] A study by Vochozka *et al.*[252] highlighted that biochar production costs are approximately 30 times higher than other methods, with a payback period extending over several decades. They suggest that revising the production process is necessary to lower these costs. In China, small and medium-scale gasification systems have energy efficiencies between 15–20%, while large-scale systems achieve efficiencies of 26–30%. However, low system efficiencies and high costs for biomass collection, transport, and pretreatment present significant economic challenges.[250] However, emerging markets for biochar and the scaling up of production are expected to lower the costs of new units and products.

Therefore, in summary, the successful commercialization of biochar markets necessitates several key elements: pyrolysis feedstock, quality control and standardization,[253] secondary uses for pyrolysis products, market diversification,[254–257] lifecycle assessment and certification, policy support and incentives.[258]

6.2. Potential negative impacts of biochar usage

While biochar offers numerous benefits, it is important to acknowledge the potential hazards associated with its use. Various studies have identified environmentally harmful substances in biochar, including heavy metals (such as Zn, Mn, Cu, Pb, Ni, and Cr), polycyclic aromatic hydrocarbons (PAHs), dioxins, environmentally persistent free radicals (EPFRs), perfluorinated compounds (PFCs), and volatile organic compounds (VOCs). These substances can pose risks to ecosystems and human health.[259–261] For instance, research has shown that heavy metals like Zn and Cu, prevalent in wood-derived biochar, may exist primarily as monovalent and divalent cations, leading to weak adsorption onto the biochar matrix and potential release, especially under mild conditions such as irrigation.[262] Similar concerns arise with biochar derived from various feedstocks, such as pig manure (Zn and Cu),[263] municipal sewage sludge (Zn, Cu, Pb, and Fe),[264] paper mill sludge (Zn, Cu, Pb, Ni, and Cr),[265] miscanthus (Zn, Cu, Pb, Ni, and Cr),[266] wicker (Zn and Pb),[266] coconut shell (Zn, Cu, and Mn),[267] restaurant food waste (Zn, Pb, Fe, and Mn),[266] and agricultural biomass (As, Cd, Cr, Cu, Ni, and Zn).[268,269] Furthermore, the application of biochar to soil introduces complexities about its actual impacts due to the presence of various influential factors such as soil type, pH, biochar application rate and depth, and the type of crop or plant grown. These factors interact to influence the plant–biochar–soil relationship and its overall impact on GHG emissions and soil health.[270]

As revealed by Llorach-Massana *et al.*,[271] the distribution of the average carbon footprint across different stages of the biomass-to-biochar conversion process reveals that dry feedstock transportation accounts for 18%, grinding for 23%, pyrolysis for 56%, and biochar transportation for 3%. While the short distances traveled by both the feedstock and biochar significantly minimize emissions during these transportation stages, the production phase substantially impacts the overall emissions balance. The concept of closing the loop in the biochar circular economy, achieved through efficient manufacturing practices, is proving beneficial in various case studies worldwide. For instance, employing complementary technologies like anaerobic digestion and composting alongside pyrolysis transforms previously disregarded materials into valuable products. This approach conserves nutrients and allows for the reuse of waste and heat energy, creating more cost-effective and efficient systems and products.[272]

Optimizing heat losses in the pyrolysis plant, even in a small-scale pilot setting, holds promise for significantly reducing emissions during this critical stage. This approach aims to mitigate the carbon footprint associated with biochar production. Additionally, there are concerns about the environmental impacts associated with biochar dust emissions during application, including increased dust emissions, eutrophication, leaching of endogenous pollution, facilitation of pollutant migration, and ecotoxicity to animals, plants, and microorganisms. Moreover, knowledge gaps exist regarding the desorption of attached pollutants, inhalation risks to humans, and the bioavailability of contaminants after entering the human body.[273]

7. Summary and outlook

The properties of biochar can vary depending on the feedstock used and the production process, which can lead to inconsistencies in the applications such as a constituent in cement mixtures, vertical greenery systems, green roofs, insulation material in walls, and stormwater management. Moreover, conditions and parameters such as pyrolysis temperature, pyrolysis rate, and pressure can affect the structure of the biochar produced *via* different methods. In addition, biochar production can be expensive, and may not be feasible for some building projects.

Apart from conventional methods such as slow pyrolysis and fast pyrolysis, biochar can also be generated through flash carbonization (produced biochar is ideal for water filtration and adsorption of contaminants), hydrothermal carbonization (where aquatic biomass and animal wastes can be processed with 60–80% yields), and microwave-assisted pyrolysis (with lower energy consumption, and shorter processing time), each offering unique benefits and potential for cutting-edge research. Additionally, traditional methods of biochar production can be refined and scaled up for widespread use. For example, traditional Korean biochar is made from sections of Korean oak, wherein all moisture and vaporous elements are removed through heat, resulting in a clean-burning product *via* kiln burning. The slow-burning process, regulated by airflow, persists for several days until the wood is fully carbonized. The resultant biochar is renowned for its extended burning time and low smoke emission.

Incorporating biochar into cement mixtures presents compatibility, strength, durability, standardization, and cost challenges. Achieving a compatible blend and homogeneous distribution of biochar in cement is crucial. The presence of biochar can impact hydration, affecting setting time, compressive strength, and resistance to degradation. Standardized guidelines for dosage, particle size, and quality control are lacking. Addressing these challenges requires further research, guideline development, and optimization of biochar properties to ensure its effective and economically viable utilization in cementitious materials.

One of the challenges of using biochar is the potential for moisture accumulation in walls. The high porosity of biochar can lead to moisture accumulation if not properly installed or if the wall system does not have proper moisture management strategies. This can lead to mold growth and other moisture-related issues. Despite these challenges, the use of biochar as insulation in walls has shown great potential in improving energy efficiency and reducing environmental impacts in buildings.

Future research can help address some of the challenges associated with using biochar as insulation materials and improving its performance in wall systems. However, it has shown great potential as an insulating material for building walls. Its high thermal resistance, fire-resistant properties, and potential to reduce environmental impacts make it an attractive alternative to traditional insulation materials. Utilizing biochar in stormwater management also comes with challenges. Proper biochar selection, considering factors such as feedstock and properties, is crucial. In addition, determining suitable application methods for optimal water filtration and retention is important. Furthermore, maintenance is essential for addressing potential degradation or clogging over time. In general, the effectiveness of biochar in various applications depends on physicochemical properties and characteristics. For example, when biochar is used as a soil amendment, it improves the soil fertility, structure, and water retention capacity. High-quality biochar with a well-developed pore structure and a balanced nutrient profile tends to exhibit better performance in improving soil health and plant growth. Similarly, the performance of biochar in water treatment applications is influenced by factors such as pore size distribution, surface chemistry, specific surface area, and functional groups present on its surface. These properties determine biochar's capacity to remove pollutants from water, such as heavy metals, organic compounds, and nutrients. Therefore, a comprehensive understanding of these properties and their impact on biochar's performance is imperative for optimizing its utilization across diverse sustainable green infrastructure applications.

In conclusion, the potential of biochar for advancing green infrastructure is vast and holds great promise for a more sustainable and resilient future. However, it is essential to consider factors such as feedstock selection, production methods, and application techniques to maximize the effectiveness and sustainability of biochar-based solutions. By leveraging advanced technologies and computational tools, we can enhance our understanding, optimize its applications, and ultimately harness the full power of biochar to meet our sustainability goals. The continued exploration, experimentation, and innovation in this field will undoubtedly open up exciting new avenues for research and application, driving us closer to our vision of sustainable, resilient, and carbon-neutral urban environments. By incentivizing the production and utilization of biochar in green infrastructure, governments and organizations can drive the transition towards a low-carbon economy and mitigate the impacts of climate change. Additionally, creating robust markets for high-quality biochar products is important for expanding the industry. Increasing awareness of biochar's versatility in various applications and establishing clear quality standards and certifications such as the EBC Certificate are essential. The cost, availability and scalability of biochar-based systems may hinder their widespread use. Therefore, consistent policies, regulatory frameworks and standardization need to be considered while observing sustainability and ESG principles and working within particular policy and social frameworks to fully harness biochar's potential in green infrastructure and develop resilient, resource-efficient systems for the future.

Author contributions

Sachini Supunsala Senadheera: conceptualization, methodology, writing – original draft, writing – review & editing. Piumi Amasha Withana: conceptualization, methodology, writing – original draft, writing – review & editing. Juin Yau Lim: conceptualization, methodology, writing – original draft, writing – review & editing. Siming You: writing – review & editing. Scott X. Chang: writing – review & editing. Fang Wang: writing – review & editing. Jay Hyuk Rhee: writing – review & editing. Yong Sik Ok: writing – review & editing, investigation, supervision, project administration, funding acquisition.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

The authors declare no competing interest.

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