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Review

Maximising CO_2 Sequestration in the City: The Role of Green Walls in Sustainable Urban Development

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Abstract: Environmental issues are a pressing concern for modern societies, and the increasing levels of atmospheric CO_2 have led to global warming. To mitigate climate change, reducing carbon emissions is crucial, and carbon sequestration plays a critical role in this effort. Technologies for utilising CO_2 can be divided into two major categories: direct use and conversion into chemicals and energy, and indirect use as a carbon source for plants. While plants' ability to absorb and store CO_2 makes them the best CO_2 sink, finding suitable urban areas for significant green spaces is a challenge. Green walls are a promising solution, as they require less land, provide more ecosystem services than horizontal systems do, and can contribute to reducing environmental problems. This study evaluates the conceptual potentials and limitations of urban biomass circulation in terms of energy production, food production, and CO_2 consumption, focusing on growth-promoting bacteria, urban agriculture, and vertical systems. The aim of this research is discovering new methods of carbon sequestration using multi-purpose green walls to achieve sustainable urban development and CO_2 reduction strategies to contribute to a more sustainable future.

Keywords: carbon sequestration; CO_2 reduction; growth promoting bacteria; multi-purpose green walls; urban agriculture; vertical systems

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1. Introduction

Carbon dioxide (CO_2) is one of the most significant greenhouse gases, and reducing its emissions has become a pressing concern for environmental scientists, economists, and policymakers [1]. At the same time, CO_2 is a valuable carbon source that can be used to produce fuels and chemicals through various processes such as hydrogenation, cycloaddition, and carbonisation [2,3].

In recent years, innovative technologies have emerged for industrial applications, including selective CO_2 copolymerisation with other organic compounds that generate valuable materials. Photobiological processes that use solar energy, living organisms, and enzymes have also shown promise for hydrogen production from water. Cyanobacteria, green algae, photosynthetic bacteria, and enzymes such as nitrogenase and hydrogenase are examples of organisms that can be used in these processes [4–6].

The growing human population has led to a significant increase in CO_2 and greenhouse gas emissions in the current century. Climate change, global warming, and sea level rise have been attributed to high CO_2 concentrations in the atmosphere [7,8]. During the period between 1950 and 1970, atmospheric CO_2 levels reached levels of 300–320 ppm. In 1970–2010, however, the concentrations reached 400 ppm, and it is estimated that concentrations will rise to 700 ppm by 2100 [9,10].

Meanwhile, energy supplies are diminishing, the population is growing, and intensive construction causes environmental harm [11]. The world's urban population was

4.2 billion (55.3%) in 2018 [12]. There needs to be an increase of 1.5 million square kilometres of urban land [13], considering that the population of 2030 will be twice that in 2000 [14]. Climate change is influenced by urban growth at different scales [15]. Hence, the increase in urban heat islands (UHI) can be attributed to the change in the natural balance of radiant energy caused by urbanisation [16]. According to projections, 153 cities will experience an increase of 1.4–3.1 °C in temperatures by 2050 [17]. Global warming is already a significant problem in cities, where about 75% of CO_2 emissions are generated by energy use [18]. The effects of global climate change on human populations are particularly significant in urban areas [19]. Adapting to climate change and reducing its effects on urban areas requires reducing CO_2 emissions and increasing carbon reservoirs within the city boundaries [20–22].

A significant amount of greenhouse gas emissions are produced by the construction sector. According to predictions, the construction sector has contributed at least 30% to reducing the country's total greenhouse gas emissions since the Paris Agreement was signed [23]. This sector will have to reduce its greenhouse gas emissions by 4%. Taking into account Iran's average per capita CO_2 production of 8.3 tons, this 4% amounts to 27.1 million tonnes of CO_2, of which 8.12 million tonnes come from construction. It has been found that in the absolute best scenario, an assessment of 2.4% of a nation's international building sectors is possible using green buildings and walls nationwide. The production and transportation of raw materials and construction activities contribute significantly to carbon emissions [24]. Also, construction produces approximately 30% of all CO_2 emissions worldwide. Therefore, achieving an acceptable carbon emission level should be prioritised in developing sustainable solutions [25]. UHI and building energy consumption are positively impacted by urban green space, while other adaptation strategies cannot provide these benefits. For instance, the creation of green spaces in urban areas can improve the quality of the air [26] and support biodiversity [27] while contributing to human psychological health [28]. Among the challenges of converting urban spaces is finding enough remaining urban space. A vertical green system is one of the most effective ways to reduce the negative impacts of urbanisation, and it also reduces CO_2 emissions to an essential degree [29]. Global energy shortages present a viable opportunity for vertical green systems in cities [30].

Green systems have been proven to enhance indoor thermal comfort and energy efficiency [31]. In Beijing, environmental pollution has become a major concern, posing a threat to the health of the populace [32]. In response, green walls are being promoted worldwide as a means of reducing this phenomenon through the use of vegetation and other methods. Based on the results of these studies, it has been concluded that green walls offer promising alternatives for improving building carbon emissions and energy efficiency, particularly when combined with urban air quality and vertical green systems. Green walls have been shown to reduce building heating and cooling energy consumption by up to 17% and 51%, respectively [33,34]. In addition, Coma et al. [35] have shown that moving the indoor air temperature set point from 24 to 18 °C can reduce cooling energy consumption by approximately 30%. Therefore, it is critical to provide clear instructions on the indoor air temperature set point when prioritising building energy efficiency through green walls to prevent nullifying their thermal performance.

2. Research Method in Reviewed Studies

A comprehensive review of the literature was conducted to analyse the current evidence on the roles of green walls in urban carbon sequestration and sustainable development. Three major academic databases were utilised: PubMed, Web of Science, and Elsevier's ScienceDirect. Multiple combinations of relevant search terms were used, such as "green walls" OR "green facades" OR "vertical greenery systems" AND "carbon sequestration" OR "CO_2 absorption".

The initial search results were carefully screened for relevance based on the title and abstract analysis of the topics of interest. After removing duplicate records, the remaining articles underwent a full-text review to evaluate their scientific quality, recency, and usage of primary data. Studies containing original empirical findings on quantifiable environmental impacts were prioritised in order to construct an evidence-based synthesis.

In total, 235 articles met the final inclusion criteria and were analysed in depth. The key data, methods, findings, and recommendations from these works were systematically extracted and categorised. Through an integrated analysis, the current state of research could be holistically examined to provide insights into real-world green wall implementations for enhanced urban sustainability.

3. Review of Existing Studies

Research has shown that green buildings can save between 24% and 50% of energy [36], emit 3% to 39% less CO_2 [37], and use 30% less water [38] compared to traditional building methods for sustainable buildings.

Vertical green systems, such as landscapes, can effectively absorb CO_2. However, the building occupants are responsible for maintaining it [39]. Studies have shown that Sedum species are efficient at absorbing carbon, require less irrigation, and have higher cold tolerance than other cover plants [40,41]. In Sacramento, California, Akbari [42] conducted an experiment during the summer of 2003, measuring indoor and outdoor temperatures, humidity, and cooling energy consumption before and after implementing vertical green systems. The findings indicated a 30% reduction in energy consumption and significant CO_2 emission reduction, resulting in the conservation of resources and the protection of the environment.

Green walls bring plants to the building facade, and the available area for green wall application is almost twice that for green roofs [43]. Patrick Blank [44], credited with inventing the term "mur végétal" (vertical garden), can be considered the father of modern living green walls. His work, spanning several decades since the late 1970s, includes over 40 projects of vegetated wall coverings worldwide [45]. Green walls provide more green space than do green roofs in modern cities [46]. Yeang [47] estimated that the facade area of a skyscraper is approximately three times its area if the plant ratio is one to seven. If the building covers two-thirds of the facade, the vegetation on the site is twice as large. As a result, the organic mass of a site can be substantially increased by a skyscraper [48]. Green walls have several benefits, such as reducing atmospheric CO_2, pollution in urban areas, runoff, building energy consumption, and the effects of global warming and urban heat islands [49]. Although photosynthesis is the primary mechanism for consuming CO_2, relying solely on green walls is not enough to improve environmental quality. Green walls play a significant role in improving urban ecological systems and maintaining the outdoor environment.

A study by Besir and Cuce [50] investigated the impact of green buildings and facades on greenhouse gas emissions in Europe. The study revealed that buildings contribute to 36% of greenhouse gas emissions in the continent. Furthermore, the study established that vertical green systems are an effective way to reduce city emissions and the thermal effect. Infrared gas analysis (IRGA) was used by Li et al. [51] to determine the amount of CO_2 absorbed by green buildings. Cole [52] and Abbasi [53] investigated carbon sequestration in the construction of concrete structures and related transportation activities. The study demonstrated that the amount and quality of reinforcement materials significantly impacted carbon sequestration. Whittinghill et al. [39] measured the amount of CO_2 sequestered by green buildings with sedum plants over periods of 12 and 14 months.

Huang et al. [54] examined the carbon footprint of urban structures and the potential for reducing carbon emissions. Their findings showed that a greenhouse gas reduction program for buildings is necessary in the urban report as they are primary producers of greenhouse gases. Yang et al. [55] conducted an investigation of greenhouse gas emissions in the construction sector using life cycle assessment and building-by-building information modelling to estimate the carbon footprint of each building.

Collazo-Ortega et al. [56] used the conventional IRGA method to measure the CO_2 sequestration of green roof vegetation. Gogoi et al. [57] demonstrated that the construction industry's carbon footprint is one of the primary sources of greenhouse gas emissions. Their findings showed that a building's carbon footprint comprises transportation, energy consumption, and construction. Gamarra et al. [58] investigated water and energy consumption in a school in a hot, dry climate, along with its carbon footprint, and noted that schools have a high potential for reducing energy consumption in urban areas and creating favourable environmental effects.

Although vertical green systems have a positive effect on the carbon sequestration of buildings and the urban climate, their use is mainly to reduce heat island effects and energy losses. Only a few studies have examined the effect of green buildings on their carbon footprint. While studies have measured and reported the amount of CO_2 absorbed by green roofs, they have underestimated the amount emitted [59]. It is essential to note that a building's carbon emission comprises every new component of the building that contains. Adding new materials in construction increases significant carbon footprints, according to the US Environmental Protection Agency (USEPA) [60].

Despite their many advantages, the construction of green systems is believed to have obstacles. The high costs of installing and maintaining primary and secondary resources are of particular concern to decision-makers, leading to the avoidance of constructing green walls [61]. Furthermore, plant stress management is one of the most challenging aspects of keeping walls green [62]. Urban policymakers consider green walls strategically crucial because of their numerous benefits. Some countries have subsidised their installation, and city councils have implemented them in recent years [63]. For instance, the City of Cologne, Düsseldorf, and Sydney have published programs to promote the installation of green walls [64,65]. The City of Cologne offers installation costs of up to EUR 40 per m^{-2} and pays up to EUR 20,000 per year for green wall installation [63].

3.1. Types of Green Walls and Their Comparison in Terms of Energy Saving

There are two main vertical green structures: systems of living walls and green facades (Figure 1). A green wall could also be considered a green facade, depending on the environment where it grows. The vegetation that grows vertically and is rooted on the ground is known as a green facade. An envelope connected vertically to the substrate is called a living wall [66,67]. Climbing plants with roots in the soil comprise a green facade that grows upwards using auxiliary devices such as wires and frames and that gives a green cover to the wall. Living walls require more maintenance than do green facades, which are cheap and sustainable. Several drawbacks to this type of green facade include a limited variety of plant species, the need for time to create the entire facade, and the destruction of the building wall [68]. Various species of plants can be grown in living green walls, an advanced type of vertical green system [68]. A living wall system consists of plants that are independently planted in pots and boxes fixed to a wall and are irrigated regularly [69]. Planting lichens, mosses, shrubs, herbaceous plants, and climbers together in a living wall system and replacing damaged plants can be easily carried out without affecting other plants [70]. Additionally, they reduce the energy used to heat and cool a building. While living walls perform best during the warm season, green facades do better during the cold season. According to the climate zone, green facades reduce heating energy demand in buildings by between 1 and 30% [50].

The accumulation of CO_2 and CO in the indoor environment occurs when incomplete combustion occurs during indoor heating and food preparation [71,72]. It has been demonstrated that liquefied petroleum gas (LPG) increases CO_2 and CO levels in closed or semi-closed environments [73,74]. It is possible to reduce indoor carbon dioxide emissions by saving energy, which then results in a reduction in fuel consumption.

living walls **green facades**

Figure 1. Systems of living walls and green facades.

3.2. The Effect of an Internal Green Wall in Reducing Emissions CO_2

In most cases, people spend the majority of their time indoors. Therefore, maintaining good indoor air quality (IAQ) is vital since harsh surfaces can be unhealthy for people, resulting in sick buildings syndrome [75]. There is a serious concern about deteriorating IAQ, and prolonged exposure to pollution can have adverse health effects. Although the space of apartments is limited, some houseplants can purify a wide range of pollutants. One study used the Areca palm potted plants to treat primary indoor air pollutants. According to the results, Areca palm potted plants can effectively decrease TVOC, CO, and CO_2 levels by 88.16% in site IV and 95.70 and 52.33% in site III, respectively. Findings showed that these trees could enhance the well-being and productivity of humans in enclosed and limited spaces by improving indoor air quality efficiently, cost-effectively, and in a self-regulating manner [76].

Pollutants, such as VOCs, are primarily caused by humans and have known health effects, including irritation of the eyes and respiratory tract, cancer, and liver damage [77]. It has been reported that some of the most common uses of VOCs in construction are as paints, solvents, varnishes, and many everyday products (e.g., detergents, air fresheners, cleaning, personal care products, etc.) [78]. There are nearly 3.8 million deaths caused by indoor air pollution worldwide every year. As a result of the type, duration, and toxicity of exposure to a pollutant, several health problems have been reported to vary from person to person, such as pneumonia, ischemic disease, lung cancer, and chronic obstructive pulmonary disease (COPD) [79]. There are several ways to improve indoor air quality, including ionisation, activating carbon, photocatalysis, ozonation, and air filtration. In the case of pollutants with different physical and chemical properties, such techniques can be complex and potentially hazardous (especially ozonation). The phytoremediation of pollutants can be carried out either actively (such as via bio-covers, buildings, and green walls) or passively (such as via rhizosphere microbes and potted plants). These systems can be an efficient and cost-effective green alternative [80,81]. Nevertheless, these plants' effectiveness depends on the species of plants and the concentration and type of air pollutants [82]. Organic pollutants can be absorbed through some mechanisms, distributed, and/or transported by ornamental plants. They include phytoextraction (extraction from plant liquid), phytodegradation (via enzyme catalysis), rhizosphere biodegradation (by microorganisms), stomatal uptake (plant gas extraction), and plant transpiration (directly through leaf evaporation or indirectly through plant transpiration) [83]. There has been a great deal of research conducted on the bioremediation capability of different pollution-reducing plants by reducing carbon in *Dieffenbachia compacta* [84], *Chlorophytum comosum* [85], *Sansevieria trifasciata* [86], and *Schefflera actinophylla* [87]. The recognition of indoor plants has contributed to their increased sales. Therefore, living walls are a good solution for improving air quality indoors due to their limited space [88]. Moreover, they contribute to improving aesthetics and providing psychological benefits with indoor vegetation [89]. Living walls have been found to remove indoor pollutants more efficiently than potted plants have, according to some studies [90,91]. Green infrastructure derived from sustainable urban development can provide ecosystem services that address many urban challenges [92,93].

3.3. Urban Gardening in Green Walls to Reduce CO_2 Emissions

The production of food has the most significant impact on the environment [94]. Globally, there are growing concerns about reducing agriculture's environmental footprint and raising consumer awareness of food's ecological footprint as the population grows [95]. A further trend is the concentration of the population in cities, which is expected to continue in the coming years [12]. If food production is conducted in a sustainable and environmentally friendly manner, and if the resulting food products are utilised in ways that contribute to carbon storage or offset carbon emissions, then these processes can act as substantial carbon dioxide (CO_2) sinks. As a result, urban agriculture (UA) [96] and zero-kilometre agriculture [97,98] are being developed as new models of agriculture to provide fresh food to cities while minimising environmental impacts. Increasingly, it is becoming a popular option. The reduced impact of food transportation makes UA a viable alternative to providing food to cities and reduces the environmental impact [99]. It is more complicated than location to distinguish rural agriculture and urban agriculture [100]. A reduction in transportation will result in a decrease in CO_2 emissions.

Private gardens have developed green infrastructure in many cities for recreational purposes and food and medicine production [101]. Nevertheless, García-Nieto et al. [102] suggested that rapid vertical structures can be turned into food production areas for urban nutrition without using the ground. An innovative concept called "vertical farming" was conceived in 1915 to address food shortages and space constraints [103]. Then, Blanc [104] introduced vertical agriculture in France through modern green wall systems. The concept aims at reducing citizens' need for agricultural products by utilising a regular and architectural method of crop production. The total growth of plants for food production is achieved by artificially planting them vertically at different levels [105] and in structures without soil [106].

However, cities have a rich source of nutrition that can be exploited to develop urban agriculture despite the problem of the reduction in urban farms and food. Growing crops in cities is possible using urban wastewater and solid waste containing recovered phosphate and nitrogen [106]. It is estimated that food waste accounts for approximately 129 tonnes (20%) of the total 638 million tonnes of foodstuffs imported by the EU each year [107]. The environmental effects of utilising these wastes in food production are reduced, and this helps to produce GAP products using fewer inputs. Furthermore, the product will be less expensive to produce and made available to more people. For instance, many environmental issues may arise related to the disposal of mushroom compost, which contains various components such as manure, cottonseed husk, wheat straw, cocoa husk, and poultry manure. Research in this area becomes more necessary as mushroom production and consumption annually increase, making waste more feasible to use as organic fertiliser. According to Jozay et al. [108], mushroom compost can modify soil conditions for growing ground cover plants on green walls. They found that 25% of the total substrate was the best mushroom compost amount.

Urban agriculture has become increasingly important due to the rapid growth of cities and the need for sustainable food production [109]. Local officials and experts have highlighted the importance of reconnecting urban and local agriculture for promoting sustainability [110]. Although urban agriculture is not a new concept and has historical roots in horticulture and landscaping, it has gained renewed attention from experts and officials of green space management in recent decades [111–113].

However, urban agriculture faces challenges that need to be addressed. One of the major challenges is soil contamination with heavy metals and their transfer to agricultural products. Heavy metals are present in fertilisers and non-potable water sources used in urban green spaces, leading to concerns about the safety of urban-grown produce [114].

To ensure food security and sustainable food production, cities must increase their food production in line with their pre-development conditions. The global population is projected to reach 9.8 billion by 2050, and the current agricultural production must be doubled to meet the demand [115]. Therefore, the development of urban environments should be guided by planning from the perspective of flexibility in the urban food supply to ensure global food sustainability [116,117].

Jansma et al. [118] defined urban agriculture as an industry that promotes food and non-food diversity within or near cities and metropolises. Urban agriculture has social benefits, particularly for social empowerment, including women's empowerment [119]. However, several challenges need to be overcome to make urban agricultural development sustainable in urban environments. One of the most significant challenges is the presence of contaminants in urban environments and their transfer to food products, which raises concerns about food safety [120]. Therefore, sustainable urban agriculture must address these challenges while promoting sustainable food production in cities.

3.4. Safe Urban Gardening through the Application of PGPR

Several challenges prevent the sustainability of green infrastructure in urban environments, which requires planning. Important factors, including agricultural and horticultural factors such as plant growth-stimulating bacteria, design factors, and plant factors and the culture medium, play a role in creating their stability [121].

Plant growth-promoting bacteria (PGPB) are bacteria found in and around plant roots, offering growth benefits through various mechanisms. These include the production of plant hormones, protection against both biotic and abiotic stresses, and the enhancement of nutrient and water absorption [122]. The rhizosphere, enriched with root exudates in the form of carbon compounds and organic acids, typically harbours a higher concentration of bacteria compared to the surrounding soil. These root exudates not only serve as a significant carbon source for plants but also act as mediators in facilitating interactions between plants and bacteria [123].

In a recent report by Kazemi and Jozay [124], it was suggested that PGPRs could be used as a bioremediation method for soils contaminated with toxic metals. PGPRs contain bacteria that are rhizospheric and endophytic, and that facilitate bioremediation. Plants accumulate heavy metals in their roots, reducing their transfer to other parts of the plant. These microorganisms provide benefits to plants by offering nutrients and reducing the harmful effects of contaminants [125].

To achieve sustainable urban development, it is essential to promote safe and healthy agricultural practices in urban environments, as noted by the FAO [126]. At the same time, environmental pollutants in cities must be controlled while using the city's resources and inputs. This study aims to investigate the potential of green wall systems for producing gardening, which aligns with sustainable urban development goals.

Geological sequestration is not sufficient to address transportation and residential carbon emissions. On the other hand, biosequestration can directly remove atmospheric CO_2 from any source. As biosequestration and other alternative sequestration technologies develop and advance, atmospheric CO_2 concentrations can be reduced. According to recent research, the biological sequestration of carbon is faster and less costly than is geological sequestration. The biological absorption of CO_2 minimises the atmospheric CO_2 concentration by separating and storing it in biological organic form, making it an effective method for controlling climate change.

In recent years, algae and bacteria have been used as biosequestration agents for atmospheric CO_2. A future strategy to reduce high CO_2 pollution could involve using bacterial species in bio-aerated concrete bricks (B-ACBs) due to their ability to sequester CO_2. Bacteria can accelerate carbonation processes to absorb CO_2 by converting it into calcium carbonate ($CaCO_3$) with the urease and enzyme carbonic anhydrase. This method of biological sedimentation is more affordable and environmentally friendly compared to geological sedimentation [127].

While the process of biodeposition may be negatively affected by soil properties [128], bio-enhancement can transform it into a separation system. The carbon sequestration microbial mechanism (CCM) is a highly effective method of reducing carbon emissions by converting inorganic carbon into its organic form [129,130]. Many species of bacteria can absorb CO_2 and HCO_3^- from water environments and use carbonic anhydrase and RuBisCO enzymes to convert them into biomass [131]. The accumulated biomass can be used to produce chemicals like bioplastics and biosurfactants, as well as biofuels like biodiesel. Therefore, CO_2 recovery through biological methods can be used to produce environmentally friendly, carbon-neutral biodiesel [130].

Certain bacteria have the ability to produce biopolymers, such as renewable bioplastics, by sequestering atmospheric carbon within their cells [132]. *Ralstonia eutropha* and *Ideonella* sp. are examples of bacteria that absorb carbon from CO_2 and convert it into biomaterials, such as PHA (bioplastics) [133]. The production of bioplastics coupled with CO_2 sequestration is a key component of sustainable development.

Biosequestration involves using stable solid carbonates like $CaCO_3$ to store CO_2 [134]. Algae are also used to separate CO_2 biologically, although using algae for this purpose can be challenging due to the required size of the photobioreactor for algae growth [135]. An alternative method is to use bacteria that produce carbonic anhydrase (CA) enzymes [136]. Both photosynthetic and non-photosynthetic organisms secrete CA as a hydrolytic enzyme [137]. Many bacteria, including Enterobacter sp., *Bacillus subtilis*, Acidophilia, *Proteus vulgaris*, Staphylococcus sp., Stenotrophomonas, and *Citrobacter freundii*, produce this enzyme [138]. Some non-phototrophic bacteria can grow in different cultures, increasing hydration and accelerating the oxidation of CO_2 into carbonate minerals, such as calcite, magnesite, and dolomite [135].

CA can effectively remove CO_2 from the atmosphere through bioseparation [139]. During the biosequestration process, CO_2 moves through the cell membrane into the cytoplasm, where it undergoes a hydration reaction involving CA and precipitates into bicarbonate. CA enzymes can accelerate the precipitation of $CaCO_3$ in aggressive environments (like strongly alkaline, non-photosynthetic, and different environments), making them excellent candidates for use as new biodeposition applications through carbonation in B-ACB. One of the alternatives to CO_2 sequestration in the near future is carbonation [140].

Carbon biodeposition is influenced by toxins such as Hg^{2+} and Pb^{2+}, which inhibit CA activity. Although Mg^{2+} ions have a strong inhibitory effect on CA activity and $CaCO_3$ deposition [141], Cu^{2+} and Fe^{2+} enhance CA activities. The effects of Ca^{2+} and Mn^{2+} on CA activities are not significant. Meanwhile, the activity of CA is almost entirely inhibited by anions such as HCO_3^- and Cl^-. The most effective anion for increasing CA activities is SO_4^-, which has little effect on NO_3^- [142]. Using growth-stimulating bacteria in green walls not only reduces environmental pollution but also sequesters carbon. Without toxic metal ions, carbon will be deposited at a faster rate.

Agriculture can play a significant role in reducing greenhouse gas emissions as agricultural soils can sequester CO_2 more efficiently than other environments can [143]. Soils with a higher organic content have more significant potential for the sequestration of CO_2 [144]. Microbial activities enhance the biological, chemical, and physical properties of the soil, facilitating carbon sequestration [145].

This research aims to explore and develop sustainable agricultural practices that enhance carbon sequestration through biological processes. By increasing the organic content in soil and promoting microbial activities, we can improve the soil's ability to sequester CO_2 and reduce greenhouse gas emissions. Implementing these practices in industrial cities can have a significant impact on mitigating climate change and promoting a healthier environment for both humans and ecosystems. This study serves as a starting point for further research and the implementation of sustainable agricultural practices that contribute to a more sustainable future.

The ecosystem absorbs, releases, and deposits carbon, and maintaining carbon balance is essential. Nevertheless, human activities such as global deforestation, industrialisation, and transportation unbalance this equilibrium due to high emissions of CO_2 in the atmosphere. The global climate range is changing due to increasing atmospheric CO_2 caused by social and economic changes [146]. The world faces a major environmental challenge with global climate change [147]. As a result, atmospheric CO_2 must be reduced using efficient approaches. Global warming caused by excess CO_2 and other greenhouse gases poses one of the greatest challenges for the future. This warming has exacerbated environmental and energy issues in recent years. More than 30 Gt of CO_2 is emitted each year by CO_2, making it the most significant greenhouse gas contributing to global warming [148,149]. There is currently close to 400 ppm of CO_2 in the atmosphere, a significant increase from about 300 ppm pre-industrially [150].

According to the Kyoto Protocol during 2008–2012, the 37 industrialised countries and the European Union must reduce their greenhouse gas emissions by an average of 5.2% below 1990 levels. A constant CO_2 concentration of 450 ppm was proposed as a ±2 °C goal by the International Energy Agency (IEA) in 2012. A reduction of 43 Gt of CO_2 is also needed to reach 14 billion tonnes. Thus, it is necessary to improve energy efficiency (43%), use renewable energy (28%), and implement carbon capture and storage (CCS) technology (22%) [149].

Global warming can be prevented by reducing CO_2 emissions and making our lifestyles carbon-neutral. Urban green space has been emphasised as one method of reducing carbon dioxide (CO_2) emissions and mitigating climate change in cities, apart from other sustainable electrical energy production methods. Nevertheless, designing for carbon sequestration is still challenging, and no CO_2-neutral forms of agriculture or biomass circulation concepts exist.

The concept should also apply to urban areas since half of the world's population lives in cities. Some urban areas (e.g., Jenfelder Au in Hamburg, Germany [151]) can produce food through green buildings, for instance [152]. Closed biomass cycles in urban agriculture have the advantages of maximising resource efficiency and reducing transportation costs [153].

Additionally, residents can consume food while the collected plant residues are returned to ADP for further biomass processing. This process reduces CO_2 emissions. Despite the higher yields achieved with soil-based agriculture, hydroponic systems produce vegetables faster, with higher product quality, and with less space consumed [154]. The conversion of digested biomass into fertiliser is one of the critical challenges to closing the biomass cycle. Ammonium (NH_4) is found in large quantities in the digestive tract.

Nevertheless, plants can utilise NH_4 as a source of nitrogen (N). High NH_4 concentrations can cause increased nitrogen losses and inhibit the growth of plants, particularly in hydroponic systems. Hence, it is necessary to oxidise NH_4 via nitrite (NO_2) into nitrate (NO_3) (for example, via leaching). Manure's buffering capacity is very low compared to that of soil, which makes it particularly important for hydroponically grown crops [155]. Synthetic fertilisers or mineral fertilisers in hydroponics are typically recommended under perfect conditions [156]. Organic fertilisers can achieve similar or even higher performance than commercial nutrient solutions can by adjusting the dilution ratio and nutrient concentration [157,158]. In conclusion, CO_2-eq reductions can be calculated using a life cycle assessment (LCA) [159].

Food and traditional medicines can be produced in green infrastructure systems in cities at any time, especially during the COVID-19 pandemic. Several things need to be achieved, including increasing independence from traditional food sources, improving household economic well-being (especially for those whose jobs were lost due to quarantine), engaging parents in entertainment for children, and enhancing community psychological health. Another issue in urban environments is food shortages due to reclaiming agricultural land in suburban areas and developing it into a city. Consequently, green spaces in urban areas are expected to function as pollution removal infrastructures. The space is still expected to function as a multifunctional space that can produce food for human consumption. Therefore, they also play a crucial role in urban agriculture [160].

It is possible to remove contaminants by analysing several factors, such as design, plant factors, and agronomic and horticultural management methods (e.g., using PGPR for soil filtration). According to a recent report, soil contamination caused by heavy metals can be reduced with plants grown in substrates containing some PGPR [161]. Additionally, vertical green wall systems have also successfully used alternative soil substrates, such as waste materials [162].

Santoso et al. [163] used a vertical wall of vegetables in their research. The results showed that these walls decreased air temperature by 0.4 °C and CO_2 levels by 0.12 ppm, and raised O_2 release by 0.4%. Also, this vertical wall's neutral temperature and humidity are 26 °C and 40%, respectively. Moreover, the green wall can reduce the temperature in a room by 0.8 degrees by shading the building and vertically arranging plants and gardens on the building's facade or other parts of the building. In addition, it prevents CO_2 emissions by reducing the effects of heat islands. Airspeed, temperature, radiation temperature, and relative humidity are the climatic variables that affect thermal comfort [164]. The presence of green walls in indoor environments can help prevent heat from entering and leaving indoor environments when the outdoor temperature is high in summer and low in winter, respectively, and thus provide heat retention and insulation benefits.

Photosynthesis and respiration co-occur via the consumption and production of O_2 in plants, and they are typically distinguished by dark and light respiration [165]. The rate of plant respiration has been estimated from 50% in various crops to 65–70% in tropical and northern trees, and coastal swamps [166]. It is beyond the scope of this review to discuss whole-plant respiration. Still, approximately an O_2 respiration rate of about 50 nmol O_2 g^{-1} DW s^{-1} [167] for leaf and stem tissues is comparable to an O_2 respiration rate of 10 nmol O_2 g dry weight (DW) s^{-1} (0.03 g O_2 g^{-1} DW d^{-1}) [168] for roots. It is reasonable to expect that the overall respiration rates of the whole shoot (canopy) and root will be similar since leaves are comparable to roots in dry mass. The leaf respiration rate of 3 O_2 m^{-2} d^{-1} (1 mmol m^{-2} s^{-1}) [169] is typical at 25 °C based on the regional respiration rate. An index of 2.5, for example, corresponds to about 7.5 g O_2 m^{-2} d^{-1} of respiration per plant leaf, similarly to the typical RR rate in heavily cultivated soils, which is typically about half the total respiration rate in the soil of 15 g O_2 m^{-2} d^{-1}. Animals and the Earth's microbiome receive about 25% of their oxygen from plants, phytoplankton, algae, and cyanobacteria. Hypoxia and even anoxia can affect their roots due to poor oxygen transport mechanisms.

As a byproduct of the photosynthetic cycle [170], green plants absorb ambient CO_2 and produce molecular O_2. Leaf uptake depends on CO_2 concentration, but plants can absorb enough CO_2 in light or darkness [171]. In a study conducted by Tarran et al. [172], the presence of three potted plants of Dracaena "Janet Craig" was found to reduce CO_2 levels by 10% and CO concentrations by 86–92% and 25% in air-conditioned offices and naturally ventilated buildings, respectively. Additionally, the CO_2 concentrations in small, sealed chambers were reduced by 657 ppm, 252 ppm, and 1252 ppm with the use of potted plants containing Ficus benjamin, Fuchsia magellanica, and Schefflera arboricola [173,174]. These findings suggest that incorporating areca palm potted plants into indoor environments can provide a cost-effective, environmentally friendly, and efficient way to reduce CO_2 emissions and biologically clean indoor air.

It is worth noting that cultivated plants tend to avoid oxygen deficiencies rather than tolerate or reduce them [175]. When exposed to low oxygen levels, plant cells rapidly shift their metabolic processes to increase anaerobic ATP production via cytosolic glycolysis [176]. Some studies [177]. suggest that plants can decrease internal respiration [178,179] due to Michaelis–Menten kinetics, which limit the respiratory response to O_2.

3.5. Indirect Effects of Anoxia on Plants

Plants are not limited to the direct effects of O_2, but they can also be affected indirectly by O_2, especially when the conditions are anaerobic [180]. Plant nutrients and toxic compounds are converted differently due to changes in soil chemistry (redox potential and pH). The reduced growth rate and productivity of crops can be partly explained by the denitrification of $NO_3{}^-$ and $NO_2{}^-$ by heterotrophic and facultative anaerobic bacteria in prolonged anoxia as they generate agricultural N_2O (greenhouse gas) and molecular N_2 [181]. Thus, increasing green substructures as urban lungs is the only and best solution for chemo-oxygen. Increased photosynthesis and carbon dioxide consumption in these urban lungs increases oxygen in the environment. Increased oxygen in the environment reduces CO_2 emissions indirectly by preventing harmful greenhouse gases from being produced.

Sustainable energy and environmental sustainability require CO_2 reduction. The key to reducing CO_2 levels globally is to use CO_2. This may take the form of environmentally safe processes, the production of industrially valuable chemicals from CO_2, or recycling CO_2 along with renewable energies. Plants have been extensively studied for their capacity to fix CO_2 through photosynthesis. These concepts are also effective in urban areas because half of the world's population lives there. Table 1 shows the CO_2 absorption rate of different plant families.

Plant carbon sequestration can be promoted and made sustainable using optimal planting strategies. Carbon sequestration efficiency and its potential changes should be considered before choosing planting designs for urban green spaces [182]. Plant species with high carbon sequestration efficiency and medium-sized evergreens for urban green spaces were selected based on the plant selection method [183]. Evergreen trees provide a wide range of ecosystem services in addition to their role in carbon sequestration. A study by Foster et al. [184] found that evergreen trees in parks provide a favourable nesting and foraging environment for birds and can reduce pollution. Adaptation to urban environments requires graft recovery when transplanting large trees from nurseries to urban green spaces, which delays carbon sequestration and increases planting, maintenance, and procurement costs [185]. Thus, growing urban greenery with sustainable carbon sequestration, low maintenance costs, and selected additional benefits can be achieved using medium-sized evergreen trees and plant species with high carbon sequestration efficiency. Urban green space planting design affects carbon sequestration, perceptions, attitudes, and the use by residents of green spaces [186]. Urban dwellers must understand how ecological processes (e.g., photosynthesis and leaf surface gas exchange) affect human well-being and how they can help sequester carbon [187,188]. The role of plants in improving environmental quality is valued by urban residents concerned about rapid urbanisation [189,190]. Several critical factors affect the efficiency of reducing green emissions, including the type of plant planted in green systems, soil characteristics, moisture level, and leaf area index (LAI). Experimentally, plant carbon sequestration with different vegetation covers is measured each month during the year by measuring their dry weights (indicating net carbon sequestration) [39,191]. Collazo Ortega et al. [56] reported that green building vegetation with Sedum dendroideum could sequester 0.49 kg m^{-2} of CO_2. The results showed that the difference is due to the broader leaves of the Sedum species used in this study compared with those of the Sedum acre species. It found that plants with lower leaf density absorb less carbon than do those with high leaf density, as reported by Charoenkit and Yiemwattana [192] and Eksi et al. [193]. Thus, Sedum dendroideum absorbs less CO_2 than does Sedum acre.

Table 1. The CO_2 absorption rate of different plant families.

	Names of Plants	CO_2 Absorption Amount	Description	Source
Plants green structures	*Sedum acre* L.	0.143 μmol CO_2 m^{-2} s^{-1}	Plants exposed to high levels of sunlight (around noon) and during hotter seasons (summer) are more efficient at absorption.	[194]
	Sedum pectabile Boreau	-	Less light intensity (1000–1500 μmol/m^2/s) = CO_2 absorption with increasing light intensity	
	Frankenia laevis	2.070 μmol CO_2 m^{-2} s^{-1}	Higher light intensity (1500–2000 μmol/m^2 s^{-1}) = 5-foldincrease	
	Vinca major	0.607 μmol CO_2 m^{-2} s^{-1}	The plants exposed to high levels of sunlight (around noon) and during hotter seasons (summer) are more efficient at absorption.	
	Carpobrotus edulis	Almost proportional increase in CO_2 absorption with increasing light intensity	-	
	Aptenia cordifolia		-	
	Alysicrpus vaginalis	High carbon absorption capacity	They are not suitable for planting on green roofs since they do not tolerate direct sunlight.	[195]
	Baccharis bilularis			
	Dichondra repens			
	Gallium odoratum			
	Sarcococca hookeriana var. humilis			
	Sedum dendroideum		Compared to Sedum dendroideum, Sedum acre has wider leaves, which absorb less CO_2.	[56]
	Portulaca grandiflora	20.22 μmol CO_2 m^{-2} s^{-1}	As a result, heat-resistant plants can absorb more CO_2 during photosynthesis.	[195]
	Alternanthera paronychioides	23.59 μmol CO_2 m^{-2} s^{-1}		
	Sansevieria trifasciata	8.77 μmol CO_2 m^{-2} s^{-1}		
	Tradescantia spathacea	7.65 μmol CO_2 m^{-2} s^{-1}		
	Chrysothemis pulchella	10.72 μmol CO_2 m^{-2} s^{-1}		
	Sansevieria trifasciata var. laurentii	12.43 μmol CO_2 m^{-2} s^{-1}		
	Plectranthus barbatus	8.21 μmol CO_2 m^{-2} s^{-1}		
	Episcia cupreata	14.32 μmol CO_2 m^{-2} s^{-1}		
	Sphagneticola trilobata	6.58 μmol CO_2 m^{-2} s^{-1}		
	Mentha spicata	19.58 μmol CO_2 m^{-2} s^{-1}		
Potted plants	*Areca palm*	According to site changes	Related to the article titled "reduction of indoor air pollutants using potted plants of areca palm in real environments".	[196]
	Dracaena "*Janet Craig*"	Reduction of up to 10% in CO_2 levels	The CO_2 level is reduced by 10%, and the level of CO_2 in the air-conditioned and naturally ventilated buildings is decreased by up to 86–92% and 25%, respectively.	[172]
	Epipremnum aureum	0.31 ppm cm^{-2}	About 1328 cm^2 of leaf area is present in an *Epipremnum aureum* pot. This indicates that the plant can absorb 412 ppm of CO_2 from 7 mornings to noon.	[197]
	spathiphyllum wallisei	0.1 ppm cm^{-2}	About 2438 cm^2 of leaf area is present in a *spathiphyllum wallisei* pot. Accordingly, the plant is capable of absorbing 244 ppm in the morning.	
	Dieffenbachia sp.	0.19 ppm cm^{-2}	About 535 cm^2 of leaf area is present in a dieffenbachia sp. pot. Therefore, the plant is capable of absorbing 102 ppm in the morning.	

Table 1. *Cont.*

	Names of Plants	CO$_2$ Absorption Amount			Description	Source
Potted plants	*Aloe vera*	487 ppm cm^{-2}			In addition to reducing CO$_2$ concentration and humidity, aloe vera also released less CO$_2$ after absorbing CO$_2$ for eight hours than SMTA and TNF.	[173]
	Spanish moss Tillandsia Aerobic (SMTA)	276 ppm m^{-2}			The efficiency of TNF is higher according to volume and weight than that of SMTA, even though SMTA can reduce CO$_2$ concentration more than TNF can (the initial CO$_2$ concentration is between 4750 and 4990 ppm).	
	Thailandia Native Fulia (TNF)	185 ppm m^{-2}			(Concentration of density CO$_2$ between 4750 and 4990 ppm)	
	Ficus benjamina	657 ppm m^{-2}			Multi-fold decrease in CO$_2$ concentration in small chambers.	[173,174]
	Fuchsia magellanica	252 ppm m^{-2}				
	Schefflera arboricola	1252 ppm m^{-2}				
	Epipremnum aureum	natural light ppm	Artificial light 1000 lux	Artificial light 2000 lux	Total leaf area 1814 cm^2	[198]
		1058	407	467		
	Spathiphyllum spp.	1036	390	450	Total leaf area 1796 cm^2	
	Ficus lyrata	947	376	429	Total leaf area 1840 cm^2	
	Syngonium podophyllum	827	350	401	Total leaf area 1791 cm^2	
	Sansevieria trifasciata prain	718	329	392	Total leaf area 1771 cm^2	
	Calathea makoyana (E.Morr.)	426	114	215	Total leaf area 1665 cm^2	
	Bromus tomentellus	Root organs (g/m^2)	Aerial organs (g/m^2)		Storage capacity of carbon (carbon stored) in the organs of some important pasture plants in grams per square metre	[199]
		12.68	1.96			
	Agropyron trichophorum	1.74	4.63			
	Astragalus verus	1.48	15.90			
	Astragalus cephalantus	0.69	5.80			
	Prangos ferulacea	0.56	2.99			
	Scariola orientalis	0.39	2.41			
	Cousinia cylindracea	0.29	1.44			
	Echinops leiopolycerus	0.26	1.79			
Plant shrubs	*Magnolia denudate*	0.92 (gC m^{-2} d^{-1})			Poor carbon sequestration efficiency (various deciduous tree species)	[182]
	Acer truncatum	0.94 (gC m^{-2} d^{-1})				
	Berberis thunbergii	0.47 (gC m^{-2} d^{-1})				
	Weigela florida	0.89 (gC m^{-2} d^{-1})				
	Clerodendrum trichotomum	0.93 (gC m^{-2} d^{-1})				
	Viburnum opulus	0.98 (gC m^{-2} d^{-1})				
	Platycladus orientalis	2.92 (gC m^{-2} d^{-1})			Semi-open grey spaces need to be planted with large plants with a long lifespan and high carbon sequestration efficiency.	
	Ginkgo biloba	1.51 (gC m^{-2} d^{-1})				

Table 1. *Cont.*

	Names of Plants	CO_2 Absorption Amount			Description	Source
		Initial (*v*/*v*) CO_2 (%)	CO_2 biofixation rate (g/L/d)	Biomass yield (g/L)	Plant cultivation system	
Microalgae strains	*Botryococcus braunii* *Chlorella vulgaris*	5	0.5	3.11	Fermenter	[200–204]
		0.03	-	~0.32	Sequential bioreactor and spiral tubular	
		0.09	3.45	0.9	bioreactor with membrane and membrane processes	
	Chlorella sp.	2	0.43	2.03	Vertical tubular bioreactor	[205–207]
		5	0.25	1.94	Fermenter	
		6	2.22	10.02	Glass bubble column	
		2	0.86	-	bubble column	
		5	0.7	-	Vertical tubular bioreactor	
		10	-	2.25	Laboratory scale flask method	
		10	-	5.15	Aerial lift photobioreactor	
	Nannochloropsis oculata *Scenedesmus dimorphus*	2.0–15.0	-	0.25–1.32	Cylindrical glass photobioreactor	[207,208]
		2	-	5.17	-	
		10	-	4.51	-	
		20	-	3.82	-	
	Scenedesmus obliquus *Spirulina* sp.	10	0.55	3.51	Glass jar	[209,210]
		6	-	3.4	Serial tubular photobioreactor	
		12	-	3.5	Serial tubular photobioreactor	
Bacterial strains	*Bacillus subtilis*				The use of bacteria that secrete the [1] CA enzyme is an alternative method [211]. CA * has been extracted from these bacteria in different species.	[139,206]
	Enterobacter sp.					
	Citrobacter freundii					
	Stenotrophomonas					
	Acidophilia					
	Staphylococcus spp.					
	Proteus vulgaris					
	Bacillus pasteurii				CO_2 can be absorbed through pores of aerated concrete as $CaCO_3$. Therefore, [2] B-ACB may be able to be used as a biodegradation technology. Pre-precipitation properties of $CaCO_3$ have been enhanced by named bacterial species and ureolytic bacteria.	[212–216]
	Pseudomonas aeruginosa					
	Bacillus alkalinitrilicus					
	Bacillus sphaericus					
	Bacillus subtilis					
	Enterococcus faecalis					
	Shewanella sp.					
	Sporosarcina pasteurii					
	Arthronema sp.	52.64 (mg L^{-1} d^{-1})			Product formation [3]	[217]
					Biodiesel	
	Chlorella sp.	31.02 (mg L^{-1} d^{-1})			Biodiesel	
	Bacillus cereus SS105	287.21 (mg L^{-1} d^{-1})			Calcite, biofuels, biopolymers	
	Bacillus sp.	not reported			Polyhydroxyalkanoates	[218]
	Nannochloropsis gaditana	1700 (mg L^{-1} d^{-1})			Biodiesel	[219]
	Serratia sp.	not reported			Biodiesel	[220,221]
	Scenedesmus sp. IMMTCC-6	85.7 (mg L^{-1} d^{-1})			Biodiesel	[211]

Table 1. *Cont.*

	Names of Plants	CO_2 Absorption Amount	Description	Source
Bacterial strains	*Scenedesmus obliquus* CNW-N	549.90 (mg L^{-1} d^{-1})	Biodiesel	[222]
	Thiomicrospira crunogena	41.28 (mg L^{-1} d^{-1})	Biodiesel	[223]
Food products and vegetables	Spinach	15.57 t/ha	Land type: agricultural land	[224]
	Chili	27.60 t/ha		
	Eggplant	23.13 t/ha		
	Chinese cabbage	24.75 t/ha		
	Tomato	19.68 t/ha	Land type: non-agricultural land	
	Okra	24.38 t/ha		
	Chili	16.41 t/ha		
	Eggplant	15.46 t/ha		

[1] Photosynthetic and non-photosynthetic organisms secrete CA as a hydrolytic enzyme [225,226]. It is possible to remove CO_2 from the atmosphere using CA for bioseparation effectively [138]. [2] CO_2 biosequestration is a potential future strategy for mitigating high levels of CO_2 pollution with bioaerated concrete bricks (B-ACB). The most appropriate method for biological sedimentation is the use of aerated concrete bricks (unreinforced concrete). [3] CO_2 and HCO_3^- (dissolved carbon) can easily be absorbed by many strains of bacteria, and these enzymes enable bacteria to use the dissolved carbon in water more efficiently. CO_2 is converted into biomass by these enzymes during carbon fixation [227]. The accumulating biomass can be used to produce biofuel (biodiesel) and chemicals (bioplastics and biosurfactants).

Vertical green systems reduce CO_2 emissions in two ways, first by absorbing CO_2 through photosynthesis, and second by reducing the energy demand of buildings, resulting in a reduction in fossil fuel consumption [228]. This study examined CO_2 emissions from vertical systems from both perspectives and how they affect the plant's carbon footprint and CO_2 absorption.

Plants growing on walls improve air quality both inside and outside buildings. They can also make buildings cooler in summer and warmer in winter by blocking direct sunlight, increasing their thermal capacity and heat resistance, thus reducing CO_2 emissions and saving energy [229].

3.6. CO_2 Absorption by Plants in Green Wall Systems

During the day, plants growing on green walls absorb CO_2 for photosynthesis. In photosynthesis, one molecule of glucose is produced by consuming six molecules of CO_2 [170]. The unique process of photosynthesis, in which carbon dioxide and water are broken down into sugar and oxygen, is another way plants release oxygen into the atmosphere. In addition to producing oxygen, this process also reduces carbon dioxide emissions [230].

The basic building blocks of plant bodies are derived from glucose, which is essential for storing and delivering energy. Although all plants undergo the same biochemical reaction, faster-growing plants consume more CO_2 [230]. In addition, plants release about half of the CO_2 absorbed during the day at night. Microbial degradation returns about 90% of the remaining CO_2 to the atmosphere (45% of all absorbed CO_2). Therefore, vegetation will only consume 5% of the total CO_2 absorbed by it [231].

Reducing CO_2 Emissions in Vertical Green Systems by Decreasing Energy Demand.

Previous studies have shown that green systems utilising Vinca major, Sedum acre, and *Frankenia thymifolia* reduced the energy consumption of buildings by 8.5, 9.6, and 10.2 kilowatt hours per square meter, respectively. The United States Environmental Protection Agency (EPA) has reported that every kilowatt hour of electricity produced emits 0.6896 kg of carbon dioxide [232].

This study calculated the reduction in CO_2 emissions per square meter in green buildings based on the proposed ratio and the obtained results. According to the findings, Sedum acre offers the lowest CO_2 emissions for maximum energy efficiency among the three plants considered, which is 28.16 kg CO_2 m^{-2} per year. *Frankenia thymifolia* and *Vinca major* follow in second and third place, with 26.48 and 23.44 kg CO_2 m^{-2} per year, respectively. The best plants for green systems can vary based on the building's purpose. If the goal is to conserve and save energy, Sedum acre is the best option. However, the overall aim should be to reduce the Earth's carbon footprint. *Frankenia thymifolia* is the best option here due to its ability to absorb CO_2 from the atmosphere and reduce energy loss through its roof. It has a significant environmental impact and reduces the building's carbon footprint. Whittinghill et al. [39] found that various Sedum species can sequester 3.9 kg CO_2 m^{-2} per year by using it as green roof vegetation. Collazo-Ortega et al. [56] discovered that *Sedum dendroideum* and *Sedum rubrotinctum* reached 1.8 kg CO_2 m^{-2} of carbon sequestration in green buildings. The differences in reported CO_2 absorption values between studies may be due to light intensity, plant species, and climate. Several studies have explored the relationship between urban plants and air pollution reduction (Figure 2). Cilliers et al. [233] measured the amount of air pollutants absorbed by green buildings in Chicago and discovered that approximately 1675 kg of pollution was removed from the atmosphere each year by 19.8 hectares of green buildings.

This study reviewed green walls to demonstrate their ability to decrease carbon dioxide emissions. Furthermore, their heat retention and insulation effects have also been studied in most dry climate regions due to their climate characteristics, such as hot summers and cold winters. Based on the study's results, green walls are prevalent and applied in hot summer and cold winter regions.

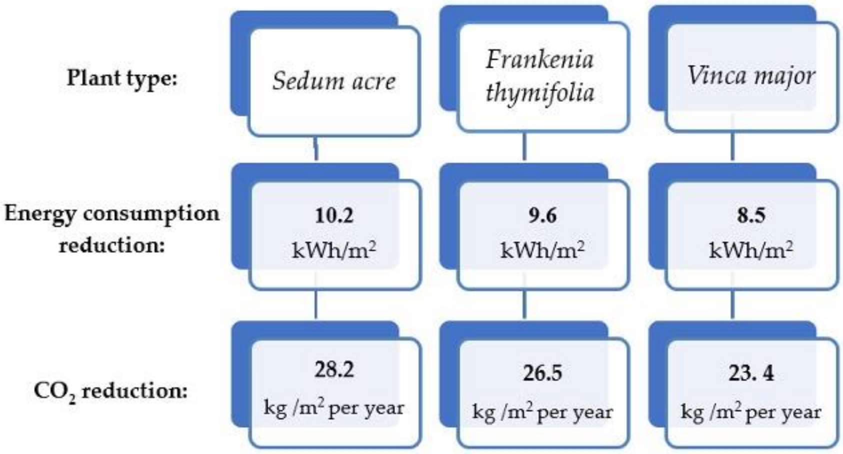

Figure 2. Urban plants and their effectiveness in CO_2 and building energy consumption reduction [39,56].

4. Key Takeaways

The significant increase in industrial activity and human activities has resulted in an imbalance between emissions and carbon storage, causing a dramatic rise in CO_2 levels and environmental disasters in recent decades. The key to reducing CO_2 levels globally is to use CO_2 through environmentally safe processes, the production of industrially valuable chemicals from CO_2, or recycling CO_2 along with renewable energies. Carbon dioxide can be used in green walls as one of these strategies to improve energy efficiency, air quality, and the urban environment. Green systems are crucial to ensuring sustainability in areas of intense urbanisation and reduced green space, providing benefits such as heat retention and insulation, and reduced air pollution. The aim of this study was to use the potential of green walls as a dual-purpose solution in urban environments. Green walls serve as a platform for sustainable food production. They have potential effectiveness in reducing CO_2 along with crop production in urban agriculture. The authors of this article propose the use of growth-promoting bacteria in urban gardening to establish an optimal balance in communications between plants and growth-promoting bacteria in vertical green systems. This is because growth-promoting bacteria on green walls can facilitate nutrient absorption, increase hormones that stimulate plant growth, and enhance plant biomass. Additionally, these bacteria can protect plants against various stresses, leading to increased productivity and higher crop yields. Moreover, by decomposing organic matter, these bacteria provide the necessary nutrients for plants, facilitating increased plant biomass and higher crop production. Together, these factors can contribute significantly to improved crop production and reduced carbon dioxide levels.

5. Research Recommendations

To ensure the more effective implementation and application of green walls, many aspects of the green wall need to be studied further, such as the methods of building a green wall, morphological, anatomical, and physiological characteristics of plant species, and factors that influence urban green space carbon sequestration. Bylaws and regulations should be designed using science-based solutions to maximise their impact on mitigating climate change while enabling adaptation. It is also important to investigate the effects of urban green space on human health.

Based on the discussion in this article, there are several recommendations for future research on green walls and their potential for reducing carbon dioxide emissions:

1. Further studies should be conducted to investigate the most effective methods for building and implementing green walls in different climates and regions;
2. More research is needed to understand the morphological, anatomical, and physiological characteristics of different plant species to ensure optimal selection for green walls;
3. The potential health benefits of green walls, including the impact of bacterial strains, should be studied further;
4. The impact of various factors on carbon sequestration in urban green spaces, such as plant species, size, canopy cover, and dominant categories, should be investigated in more detail;
5. Bylaws and regulations for green walls should be designed using science-based solutions to maximise their impact on mitigating climate change while enabling adaptation.

Overall, there is a need for more research on green walls and their potential as a sustainable solution for reducing carbon dioxide emissions and improving environmental sustainability. By continuing to investigate and develop green wall technology, we can work towards a more sustainable future and protect the natural balance of our planet.

6. Conclusions

In this study, we explored the potential of green walls, augmented with growth-promoting bacteria, as a strategy for CO_2 sequestration in urban environments. Our review underscores the significant role these living systems can play in sustainable urban development, contributing to reducing carbon emissions in densely populated areas. The integration of growth-promoting bacteria not only enhances the CO_2 absorption capabilities of green walls but also presents a novel approach to urban environmental management.

The present research opens several avenues for future investigation, particularly in the diversity and long-term effects of growth-promoting bacteria in different species of plants used in green walls. This study's implications extend beyond environmental benefits, suggesting practical applications in urban planning and policy-making. Implementing green wall systems can be a proactive step towards creating more sustainable and liveable urban spaces.

Moreover, the scalability and replicability of our findings offer exciting possibilities for adaptation in diverse urban settings. Despite varying climatic and socio-economic conditions, the fundamental principles demonstrated in our study can guide the implementation of green walls in a wide range of urban landscapes. Practical guidelines derived from our research can aid urban planners in effectively integrating these systems into existing and new infrastructures.

Limitations

While our study provides valuable insights into the role of green walls in urban CO_2 sequestration, several limitations must be acknowledged:

Generalizability: Our findings, although promising, may not be universally applicable to all urban environments. Variations in climate, urban infrastructure, and social dynamics could influence the effectiveness of green wall systems.

Long-Term Sustainability: The long-term maintenance and sustainability of green walls, particularly in different environmental and urban settings, remain a concern. Future research should focus on the longevity and ecological impact of these systems over extended periods.

Cost Factors: The financial aspects, including the initial investment, maintenance costs, and potential economic impacts of green wall implementation, were not fully explored in this study. These factors are crucial for the practical application and widespread adoption of green walls.

Broader Environmental Impact: While focusing on CO_2 sequestration, our study did not extensively address the overall environmental impact of green walls, such as their effect on local biodiversity, water usage, and potential ecological imbalances.

Data Limitations: The scope of our data and research methods, although comprehensive, may have certain constraints that could affect the broader applicability and interpretation of our results.

Scale of Impact: Finally, it is important to contextualise the role of green walls within the larger framework of urban CO_2 emissions and climate change mitigation strategies. The impact of green walls, while significant, is one of many solutions needed to address these global challenges.

In conclusion, our study highlights the promising potential of green walls in urban CO_2 sequestration and provides a foundation for further research and application in sustainable urban development.

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