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Optimizing Energy Efficiency through Vertical Greenery Systems

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Abstract— As modern buildings become more airtight to improve energy efficiency, indoor air quality can decline due to reduced ventilation and increased energy use. Plants offer a viable solution to this problem by enhancing indoor air quality through CO_2 reduction, humidity control, and pollutant filtration, while also providing cooling and psychological benefits. The primary mechanisms involved are photosynthesis, which absorbs CO_2 and releases oxygen, and transpiration/evapotranspiration, which cools indoor environments and improves air quality. Recent advancements in vertical greenery systems (VGS) have significantly enhanced indoor phytoremediation by optimizing space and plant biomass. VGS can reduce indoor temperatures by up to 6°C, decrease cooling energy consumption by up to 58.9%, and lower CO_2 levels by up to 17%, offering considerable environmental and economic benefits. The effectiveness of VGS depends on factors such as plant species, light conditions, and CO_2 levels, with optimal lighting and substrate moisture improving CO_2 assimilation and cooling effects. However, challenges such as high initial costs, maintenance requirements, and climate-specific performance issues persist. This review examines the mechanisms by which plants regulate temperature, humidity, and CO_2 levels, evaluates the effectiveness of VGS, and discusses factors influencing their performance. It also addresses the current limitations of VGS and provides recommendations for future improvements.

Index Terms—Plants, Vertical Greenery Systems, Energy Efficiency, CO_2 reduction, Cooling effects

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1 INTRODUCTION

AS climate change exacerbates extreme temperatures, urban environments face increasing challenges, including heightened energy use for cooling buildings. In contemporary society, individuals spend approximately 80-90% of their time indoors [1]. This trend, combined with the ongoing energy crisis and the expansion of enclosed spaces, has led to elevated levels of indoor air pollutants, which can be two to five times more concentrated than those found outdoors, and in extreme cases, up to 100 times higher [2], [3]. While ventilation is a common approach to improving indoor air quality, it often results in significant heat loss and may be insufficient, particularly in winter [4].

The energy demands of buildings have surged, increasing by 93% from 1917 to 2014, with buildings now accounting for approximately 40% of global energy consumption [5]. In Europe, buildings contribute 36% of total greenhouse gas emissions, primarily due to energy consumption for heating, cooling, and air purification [6]. Indoor air quality issues also include elevated CO_2 levels; the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends a maximum indoor CO_2 concentration of 1000 ppm, yet actual levels often exceed 2000 ppm and can reach up to 5000 ppm [7], [8]. Relative humidity (RH) further affects indoor air quality: low RH (<30%) can cause eye irritation and dryness, while very low RH (<10%) can lead to discomfort, and high RH (>60%) can promote mold growth and damage building materials. Maintaining RH between 40-60% is generally advised [9].

The increasing severity of urban problems due to climate change underscores the need for effective solutions. Urban green spaces, such as vertical greenery systems (VGS), offer promising strategies for addressing these issues. VGS, which include various plant species, contribute to cooling through shading and evapotranspiration, enhance air quality by absorbing pollutants, and aid in carbon capture and storage [10], [11]. These systems not only improve urban climates and energy efficiency but also reduce greenhouse gas emissions [12], [13]. Additionally, plants in VGS help regulate CO_2 levels, maintain appropriate humidity, and offer psychological and aesthetic benefits by reducing stress and enhancing emotional well-being [14], [15]. This review examines the role of VGS in energy savings, focusing on their mechanisms for cooling, CO_2 removal, and overall improvement of indoor environments. It also addresses the current limitations of VGS and provides recommendations for future improvements.

2 MECHANISMS OF PLANT-BASED CARBON REMOVAL AND ENVIRONMENTAL REGULATION

Plants play a vital role in improving indoor air quality, enhancing human productivity, and reducing stress [4]. The plant's capacity to mitigate CO_2 levels and regulate environmental conditions is mediated through the processes of photosynthesis, transpiration, evapotranspiration, and evaporation.

2.1 Photosynthesis

Photosynthesis is a vital biological process where light energy is converted into chemical energy, enabling plants to absorb CO_2 and release O_2 [13]. Plants act as natural carbon sinks by capturing carbon dioxide through this process and storing it in their tissues for varying periods. This stored carbon can either be transformed into humus or retained within the plant material [16]. Carbon sequestration refers to the long-term

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storage of carbon dioxide in plants, which helps mitigate the effects of climate change and air pollution [17].

Photosynthesis not only produces O_2 but also generates negative air ions (NAIs), which aid in air purification and dust absorption. For instance, Shiue [18] demonstrated that NAIs can effectively control ultrafine aerosol pollutants in controlled environments. However, under indoor conditions, plants produce only a small amount of NAIs. Enhancing the production of fresh air rich in NAIs using plants presents a significant challenge. Among these ions, superoxide ($O_2^{\cdot -}$) is the primary NAI and is more stable than other ions [19].

Factors such as light intensity, CO_2 concentration, and temperature influence the rate of photosynthesis. Effective photosynthesis requires adequate light, which can be limited in indoor settings. Light conditions significantly affect CO_2 absorption and O_2 release. Plants need light levels above the compensation point—where photosynthesis and respiration rates are balanced—to maintain their biological functions and improve air quality [20], [21]. Excessive temperatures above 30°C can reduce photosynthesis rates in species such as *Quercus suber* [10]. While elevated CO_2 levels can enhance photosynthesis and O_2 release, the benefits are dependent on light quality and CO_2 concentration [22]. Optimal photosynthesis conditions—temperatures between 21–25°C, light fluxes of 100–500 lx, and wavelengths between 400–700 nm—support CO_2 sequestration, slow global warming, and maintain ecological balance [19].

2.2 Transpiration and Evapotranspiration

Transpiration is the process by which plants release water vapor from their leaves into the atmosphere, contributing to the cooling of the surrounding environment [23]. This process also includes guttation, where liquid water is expelled through specialized plant pores. This process, which involves water moving from the roots to the leaves and evaporating into the atmosphere, also aids in regulating indoor relative humidity [24].

Transpiration plays a crucial role in regulating the energy and mass balance within enclosed environments. It influences plant production by affecting the exchange of energy through radioactive and convective transfers. During transpiration, absorbed solar energy is partly converted into latent heat as plants work to maintain a stable, moderate temperature within their canopy. The efficiency of this process is influenced by factors such as radiation, vapor pressure deficit (VPD), temperature, humidity, and plant type [19].

Evapotranspiration combines transpiration and soil evaporation, further enhancing cooling by removing moisture from soil surfaces and plant tissues [25]. Figure 1 illustrates the mechanisms of evapotranspiration in plants. Increased evaporation through evapotranspiration can reduce building energy demands by moderating temperature fluctuations in both summer and winter [26]. Additionally, evapotranspiration contributes to atmospheric convection and cooling, while purifying the air by removing water vapor [27]. Boysen et al. [28] found that moisture fluxes could be enhanced, leading to additional cooling effects. Overall, plant evapotranspiration not only cools the plants but also improves air convection and quality [27].

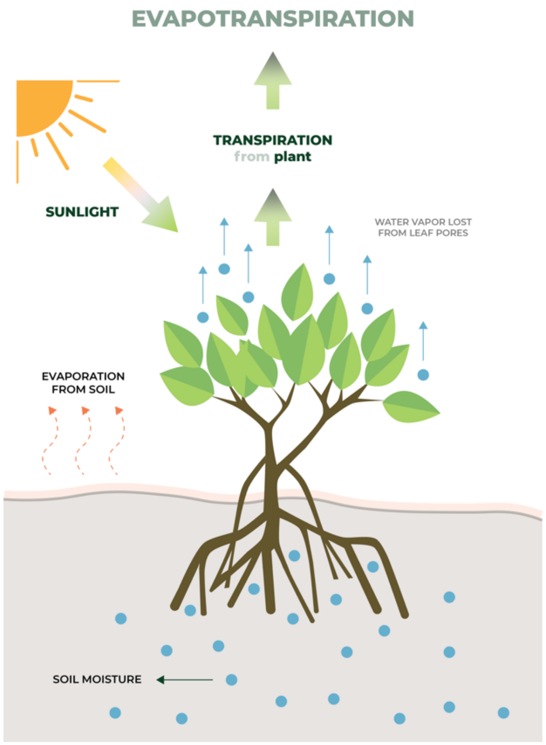

FIGURE. 1. THE PROCESS OF EVAPOTRANSPIRATION IN PLANTS, HIGHLIGHTING THE RELEASE OF WATER VAPOR FROM LEAVES INTO THE ATMOSPHERE AND THE ROLE OF GUTTATION IN EXPELLING LIQUID WATER THROUGH SPECIALIZED PORES.

3 POTTED PLANTS IN CARBON SEQUESTRATION AND ENVIRONMENTAL REGULATION

NASA's 1989 Clean Air Study highlighted the significant air-purifying potential of indoor plants, demonstrating their ability to remove volatile organic compounds (VOCs) and CO_2 while releasing oxygen [29], [30]. Over the past 30 years, numerous studies have confirmed these findings, showing that indoor plants effectively improve air quality, reduce urban air pollution, enhance humidity levels, and lower temperatures [31]. While advanced ventilation systems are one approach to enhancing indoor air quality, simpler solutions like houseplants have also proven beneficial [32], [33], [34], [35].

Research has shown that various indoor plants reduce CO_2 levels. For instance, *Ficus benjamina* reduced CO_2 from 2,000 ppm to about 480.74 ppm in one hour [4]. *Dracaena 'Janet Craig'* has been reported to reduce CO_2 and CO levels by approximately 10% in air-conditioned spaces and 25% in naturally ventilated spaces [36].

Further studies have identified *Epipremnum aureum* as particularly effective in purifying low-concentration CO [37]. Ventilation enhances the pollutant removal efficiency of plants; *Epipremnum aureum* absorbs CO_2 more effectively in ventilated chambers, particularly two hours after exposure to cigarette smoke [38]. The effectiveness of plant-based air purification also varies with the substrate used. Soil has been found most effective at removing formaldehyde (~0.07–0.16 m^3/h), while peace lilies (0.01 m^3/h) and Boston ferns (0.02–0.03 m^3/h) are more efficient at reducing CO_2 concentrations [39].

Additionally, *Areca Palm* can block solar radiation when placed near double windows in winter, reducing heating needs while maintaining indoor humidity by around 50% [40]. Seasonal studies of *Ficus* and *Epipremnum* in naturally ventilated offices revealed that these plants emit between 35 g (winter) and 58 g (summer) of moisture per day. Despite this, air exchange rates often have a more significant impact on humidity than plant transpiration alone [33]. Han et al. [35] also indicated that window ventilation can be more effective than plant transpiration for cooling and humidity control, with the proximity and number of plants influencing their effectiveness.

4 VERTICAL GREENERY SYSTEMS

Advancements in plant technology have led to the development of vertical greenery systems (VGS), which offer significant advantages over traditional potted plants for indoor environmental improvement. Unlike passive potted systems, which require many plants and are limited by air circulation, VGS optimize space and increase plant biomass exposure, thereby enhancing pollutant removal efficiency [13], [41], [42].

Vertical greenery systems—commonly referred to as green walls, bio-walls, and vertical gardens—have proven to be highly promising in urban environments. They improve water and air quality, manage stormwater effectively, reduce temperatures, and lower carbon emissions. Additionally, these systems help mitigate the urban heat island effect, thus contributing to urban sustainability [14]. Green walls provide benefits such as reduced wall temperatures through shading and wind barriers, decreased solar absorption, and improved thermal insulation from vegetation and growth substrates. They also enhance microclimate regulation and increase biodiversity [43], [44], [45]. Vertical greenery systems are categorized into two types: green façades and living walls [46].

Green façades use climbing plants on walls or supporting structures and cover surfaces more slowly with fewer plant species. In traditional green facades, the plants use the envelope as supporter material and growing media stays on the ground. [47], [48]. Compared to green facades, living walls necessitate additional essential materials, including support structures, growth substrates, and irrigation systems, to sustain a variety of plants. Consequently, the maintenance costs for living wall systems are considerably higher. However, living walls generally offer superior performance relative to green facades due to the use of pre-cultivated plants and their adaptability. Moreover, if issues with the plants arise, pre-cultivated plants can be easily replaced [14], [49]. The primary types of living walls are classified as continuous and modular systems, with the key distinction being the type of growing medium used. Continuous systems do not require traditional growing media, as they utilize a geotextile membrane as an alternative to soil. In these systems, plants are cultivated using hydroponic techniques facilitated by irrigation [23]. Figure 2 illustrates the green wall systems in detail.

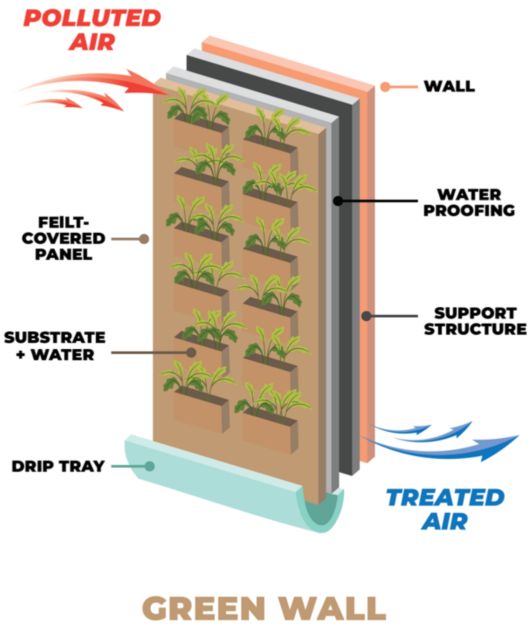

FIG 2. THE COMPONENTS AND STRUCTURE OF A GREEN WALL.

4.1 Effectiveness in Humidity Regulation

Vertical greenery systems positively impact indoor humidity levels, which are optimal between 30% and 70% for spaces like classrooms and hotels. Studies have shown that green walls can increase relative humidity slightly, which often suffices for human comfort. For instance, Poórová et al. [50] reported that a room with a green wall had a relative humidity of 30.1%, compared to 28.7% in a room without. Fernández-Cañero [51] found that green walls reduced room temperatures by 4°C to 6°C while increasing humidity over four months.

4.2 Effectiveness in Temperature Regulation

Vertical greenery systems offer substantial thermal advantages, including reduced energy consumption for cooling. Research consistently demonstrates their effectiveness in lowering indoor temperatures and cooling energy use (Table 1). Cheng et al. [52] found that vertical greening significantly mitigates heat flux and lowers indoor temperatures, leading to reduced air conditioning energy use. Supporting these findings, Coma et al. [44] reported a 58.9% reduction in cooling energy use with green walls, and double-skin green façades achieved a 33.8% decrease. In Genoa, Italy, green façades led to a 26% reduction in summer energy consumption [53]. Dahanayake and Chow [43] reported exterior surface temperature reductions of up to 26°C in hot climates, with a 30% reduction in cooling energy use. Li et al. [54] further observed that partial greening in Ningbo, China, resulted in overall energy savings of about 28%.

Additional studies highlight the cooling benefits of VGS. Jiang and Tang [55] found that extensive green roofs combined with night ventilation significantly reduced indoor temperatures. Yang et al. [56] noted temperature reductions of 0.6–1.1°C in double-skin green façades, and Sudimac et al. [57] observed reductions of 0.56–14.3°C in wall surface temperatures. Afshari [58] estimated cooling load reductions of 5–8% and urban temperature decreases of 0.7–0.9°C.

Indoor temperature management also benefits from VGS as well. Fernández-Cañero et al. [51] found a 4°C average indoor temperature reduction near an 8 m² living wall. Poórová et al. [50] recorded maximum temperatures of 35.5°C in classrooms with green walls, compared to 37.2°C without. Wang and Witte [59] projected up to 25.1% cooling electricity savings in Los Angeles due to vegetation cooling. Abdo and Huynh [60] showed that VGS could reduce ambient temperatures by 0.5°C–3°C, depending on whether active or passive strategies were employed.

TABLE 1

A COMPREHENSIVE OVERVIEW OF THE AIMS, KEY FINDINGS, AND COOLING EFFECTS OBSERVED IN VARIOUS STUDIES ON VERTICAL GREENERY SYSTEMS

Reference	Aims of Research	Key Findings
Cheng et al. (2010)	Compare vertical greening with traditional concrete walls.	Vertical greening more effective at reducing heat flux and indoor temperatures. Demonstrated effectiveness in reducing heat flux of vertical greening.
Coma et al. (2017)	Assess cooling energy savings of green walls and DSGF.	Green walls reduced cooling energy use by 58.9%; DSGF by 33.8%. No additional heating energy required.
Katia Perini et al. (2017)	Evaluate summer energy consumption with green facades.	Buildings with green facades experienced a 26% reduction in summer energy consumption. Focused on seasonal energy savings.
Li et al. (2019)	Analyze effects of partial horizontal and vertical greening.	Reduced cooling and heating loads by 8.8% and 1.85%, respectively, with potential overall savings of 28%.
Jiang and Tang (2017)	Study effects of green roofs combined with night ventilation.	Significant reduction in indoor temperatures and heat gains on sunny days. Benefits of combining green roofs with night ventilation.
Dahanayake and Chow (2017)	Assess VGS impact on exterior temperatures and cooling energy.	Reduced exterior surface temperatures by up to 26°C; 30% reduction in cooling energy consumption. Noted potential winter drawbacks.
Yang et al. (2018)	Evaluate cooling performance of DSGF on a university campus.	Observed temperature reductions of 0.6–1.1°C, and up to 2.7°C in operative temperature. Focused on cooling performance in a campus setting.
Sudimac et al. (2019)	Measure temperature reduction of vegetation walls.	Reduced external wall surface temperatures by 0.56–14.3°C. Significant range of temperature reduction.
Afshari (2017)	Use a model to estimate cooling load reductions.	Estimated cooling load reductions of 5–8% and urban air temperature drops of 0.7–0.9°C.
Poórová et al. (2020)	Compare indoor temperatures with and without green walls.	Maximum air temperature with green wall was 35.5°C, compared to 37.2°C without. Observed temperature difference in a classroom setting.
Fernández-Cañero et al. (2012)	Measure temperature reduction near an indoor living wall	Average temperature reduction of 4°C near an indoor living wall of 8 m². No air circulation in the test area.
Wang and Witte (2022)	Model cooling electricity savings in Los Angeles.	Maximum cooling electricity savings of 25.1% due to vegetation cooling. Focused on modeled savings in a specific location.
Abdo and Huynh (2021)	Evaluate temperature reduction with active vs. passive VGWs.	VGWs reduced ambient temperatures by 0.5°C–3°C, depending on active or passive systems. Differentiated between active and passive systems.

4.3 Effectiveness in CO_2 Reduction

Vertical greenery systems also impact indoor CO_2 levels and associated energy consumption. Tudiwer and Korjenic [11] found VGS could reduce CO_2 levels by about 3.7%, though this reduction was accompanied by increased relative humidity. Meng et al. [61] demonstrated that integrating VGS with air conditioning systems led to a 10% reduction in CO_2 levels. Recent studies show that VGS can lower the need for fresh air and reduce ventilation energy consumption by 12.7% to 58.4%, with CO_2 reductions of 12% to 17% [62], [63]. Poórová et al. [50] found a 14% lower increase in CO_2 concentration with green walls compared to classrooms without. Yungstein and Helman [15] reported a 5% reduction in CO_2 and a 20% energy saving in Heating, Ventilation, and Air Conditioning (HVAC) systems due to VGS, with reduced air circulation requirements.

Overall, these studies illustrate that VGS can play a crucial role in reducing indoor CO_2 concentrations and lowering energy consumption associated with ventilation. While VGS effectively contribute to CO_2 sequestration and energy savings, their impact on relative humidity must be considered to ensure balanced indoor environmental conditions.

5 PARAMETERS INFLUENCING VERTICAL GREENERY SYSTEM EFFICIENCYEQUATIONS

The efficiency of vertical greenery systems in indoor environments is influenced by various parameters, including plant species, light conditions, and CO_2 levels. Different plant species have varying capacities for CO_2 assimilation and cooling effects through photosynthesis and transpiration, which are also dependent on indoor light and CO_2 conditions [21].

5.1 Lighting and Substrate Conditions

Optimal lighting and substrate moisture are crucial for maximizing the effectiveness of VGS in reducing indoor CO_2 levels and moderating temperature. Low light and dry substrates can limit plants' ability to sequester CO_2 and affect indoor relative humidity through reduced transpiration [10]. Indoor light levels are typically 100 times lower than outdoor levels, ranging from about 1–50 $\mu mol\ m^{-2}\ s^{-1}$ [64], [65]. Higher indoor light levels, around 30–50 $\mu mol\ m^{-2}\ s^{-1}$, are suggested to improve occupant comfort [66].

Dominici et al. [21] observed that many plant species used in VGS experienced suboptimal lighting, resulting in negligible CO_2 removal in typical workplace settings. Torpy et al. [67] evaluated CO_2 assimilation for eight common indoor plant species by analyzing light response curves and light compensation points (LCPs). Their findings suggest that while some CO_2 sequestration is feasible under current indoor lighting, enhanced lighting levels could improve the efficacy of these plants in carbon capture. In a follow-up study, Torpy et al. [7] identified that the LCPs for these species ranged from 10 to 15 $\mu mol\ m^{-2}s^{-1}$ photosynthetic photon flux density. Given that these levels are typical of natural light conditions in many offices, CO_2 absorption may be limited, with plants often releasing more CO_2 than they capture.

5.2 Plant Species and Environment

Pennisi and Iersel [68] studied CO_2 assimilation in 17 houseplant species under different light levels and found that larger woody plants, such as *Ficus benjamina*, performed better in CO_2 absorption compared to smaller herbaceous species. Yungstein and Helman [15] assessed the carbon assimilation rates of six indoor plants—*Peperomia obtusifolia, Tradescantia spathacea, Chlorophytum comosum, Spathiphyllum wallisii, Aeschynanthus radicans,* and *Philodendron hederaceum*—under varying light conditions and CO_2 levels. They found that *Spathiphyllum wallisii* and *Chlorophytum comosum* had high assimilation rates under low light, and all species, except *Philodendron hederaceum*, were effective at high CO_2 levels when light was adequate. *Tradescantia* demonstrated the highest cooling effect through transpiration.

Charoenkit et al. [12] investigated the relationship between plant coverage, Leaf Area Index (LAI), and the cooling effect of green walls. They found a moderate positive correlation between plant coverage and LAI with cooling performance. Plants with coverage above 100% and LAI above 3 showed effective thermal performance, while those with coverage above 95% excelled in carbon sequestration. Dense foliage and medium-sized leaves were associated with better temperature reduction, whereas woody plants, with higher carbon content, were most effective for carbon sequestration.

6 CURRENT LIMITATIONS AND FUTURE OUTLOOKS

Vertical Greenery Systems (VGS) encounter several key limitations affecting their effectiveness and implementation. A primary challenge is maintenance; VGS require regular care, including plant health management, irrigation, and pest control, which can raise operational costs and complicate their upkeep [69]. Additionally, the high initial costs of VGS, due to specialized infrastructure and installation requirements, can be prohibitive, especially for smaller projects or in financially constrained regions [70]. Climate and environmental conditions significantly impact VGS performance. Extreme temperatures or low sunlight can hinder their effectiveness, necessitating careful selection of plant species and system design to match local climates for optimal performance and durability [71]. Performance variability is also a concern; the benefits of VGS, such as energy savings and CO_2 reduction, can differ widely depending on design and location, highlighting the need for customized solutions and further research [72]. The additional load and moisture from VGS can affect building structures, potentially requiring modifications. This structural impact must be considered during design and planning to prevent unforeseen issues [73].

Looking forward, technological advancements could address these limitations. Innovations in materials and construction methods may reduce initial costs and maintenance needs, while improvements in plant selection and irrigation could enhance system resilience. Cost-reduction strategies, such as economies of scale and more affordable materials, along with financial incentives, could make VGS more accessible. Future research should focus on developing VGS adaptable to various climates and optimizing performance through standardized guidelines and long-term studies. Additionally, integrating VGS with minimal impact on building structures through lightweight materials and innovative mounting techniques will be crucial. In summary, while VGS offers significant environmental and energy benefits, overcoming current limitations through technological improvements, cost reduction, climate adaptability, performance optimization, and structural integration will be essential for their broader adoption and effectiveness in future urban and architectural applications.

7 CONCLUSIONS

In modern society, efforts to make buildings more airtight to save on energy costs can worsen indoor air quality, as ventilation systems often result in heat loss and high energy consumption. Plants can help improve indoor air quality by reducing CO_2 levels, controlling humidity, and filtering pollutants. They also offer cooling benefits and psychological advantages. Key mechanisms include photosynthesis, which absorbs CO_2 and releases oxygen, and transpiration/evapotranspiration, which cools the environment and improves air quality. Technological advancements in vertical greenery systems (VGS), such as green walls, have addressed several limitations of traditional potted plants by enhancing indoor phytoremediation and optimizing space. VGS offer notable benefits including improved indoor air quality, effective pollutant removal, and significant energy savings through cooling and humidity regulation. Studies show that VGS can reduce indoor temperatures by up to 6°C, cut cooling energy use by up to 58.9%, and lower CO_2 levels by up to 17%, contributing to both environmental and economic benefits. These effects are primarily influenced by factors such as plant species, light conditions, and CO_2 levels, with optimal lighting and substrate moisture enhancing CO_2 assimilation and cooling effects, while larger woody plants and dense foliage are found to be most effective for carbon sequestration and temperature reduction. However, challenges such as high initial costs, maintenance requirements, and climate-specific performance issues persist. Future developments should focus on reducing costs, improving maintenance strategies, and optimizing system performance across diverse climates to fully realize the potential of VGS in sustainable architecture and urban planning.

REFERENCES

[1] J. Saini, M. Dutta, and G. Marques, "A comprehensive review on indoor air quality monitoring systems for enhanced public health," 2020, BioMed Central Ltd. doi: 10.1186/s42834-020-0047-y.

[2] Environment Australia, BTEX personal exposure monitoring in four Australian cities, vol. 6. Canberra, 2003.

[3] H. Teiri, H. Pourzamani, and Y. Hajizadeh, "Phytoremediation of VOCs from indoor air by ornamental potted plants: A pilot study using a palm species under the controlled environment," Chemosphere, vol. 197, pp. 375–381, Apr. 2018, doi: 10.1016/j.chemosphere.2018.01.078.

[4] H. Sevik, M. Cetin, K. Guney, and N. Belkayali, "The influence of house plants on indoor CO2," Pol J Environ Stud, vol. 26, no. 4, pp. 1643–1651, 2017, doi: 10.15244/pjoes/68875.

[5] A. Martínez-Molina, I. Tort-Ausina, S. Cho, and J. L. Vivancos, "Energy efficiency and thermal comfort in historic buildings: A review," Renewable and Sustainable Energy Reviews, vol. 61, pp. 70–85, Aug. 2016, doi: 10.1016/j.rser.2016.03.018.

[6] B. Raji, M. J. Tenpierik, and A. Van Den Dobbelsteen, "An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: A case study in the Netherlands," Energy Build, vol. 124, pp. 210–221, Jul. 2016, doi: 10.1016/j.enbuild.2015.10.049.

[7] F. Torpy, M. Zavattaro, and P. Irga, "Green wall technology for the phytoremediation of indoor air: a system for the reduction of high CO2 concentrations," Air Qual Atmos Health, vol. 10, no. 5, pp. 575–585, Jun. 2017, doi: 10.1007/s11869-016-0452-x.

[8] X. Zhang, P. Wargocki, and Z. Lian, "Physiological responses during exposure to carbon dioxide and bio effluents at levels typically occurring indoors," Indoor Air, vol. 27, no. 1, pp. 65–77, Jan. 2017, doi: 10.1111/ina.12286.

[9] P. Wolkoff, "Indoor air humidity, air quality, and health – An overview," Int J Hyg Environ Health, vol. 221, no. 3, pp. 376–390, Apr. 2018, doi: 10.1016/j.ijheh.2018.01.015.

[10] C. Gubb, T. Blanusa, A. Griffiths, and C. Pfrang, "Can houseplants improve indoor air quality by removing CO2 and increasing relative humidity?", Air

Qual Atmos Health, vol. 11, no. 10, pp. 1191–1201, Dec. 2018, doi: 10.1007/s11869-018-0618-9.

[11] D. Tudiwer and A. Korjenic, "The effect of an indoor living wall system on humidity, mould spores and CO2-concentration," Energy Build, vol. 146, pp. 73–86, Jul. 2017, doi: 10.1016/j.enbuild.2017.04.048.

[12] S. Charoenkit, S. Yiemwattana, and N. Rachapradit, "Plant characteristics and the potential for living walls to reduce temperatures and sequester carbon," Energy Build, vol. 225, Oct. 2020, doi: 10.1016/j.enbuild.2020.110286.

[13] H. Lee, Z. Jun, and Z. Zahra, "Phytoremediation: The sustainable strategy for improving indoor and outdoor air quality," Nov. 01, 2021, MDPI. doi: 10.3390/environments8110118.

[14] A. B. Besir and E. Cuce, "Green roofs and facades: A comprehensive review," Renewable and Sustainable Energy Reviews, vol. 82, pp. 915–939, 2018, doi: 10.1016/j.rser.2017.09.106.

[15] Y. Yungstein and D. Helman, "Cooling, CO2 reduction, and energy-saving benefits of a green-living wall in an actual workplace," Build Environ, vol. 236, May 2023, doi: 10.1016/j.buildenv.2023.110220.

[16] K. Perini and M. Ottelé, "Vertical greening systems: Contribution to thermal behaviour on the building envelope and environmental sustainability," WIT Transactions on Ecology and the Environment, vol. 165, pp. 239–250, 2012, doi: 10.2495/ARC120221.

[17] M. P. Johnson, "Photosynthesis," Essays Biochem, vol. 60, no. 3, pp. 255–273, Oct. 2016, doi: 10.1042/EBC20160016.

[18] A. Shiue, S.-C. Hu, and M.-L. Tu, "Particles Removal by Negative ionic Air Purifier in Cleanroom," Aerosol Air Qual Res, vol. 11, no. 2, pp. 179–186, 2011, doi: 10.4209/aaqr.2010.06.0048.

[19] L. Deng and Q. Deng, "The basic roles of indoor plants in human health and comfort," Environmental Science and Pollution Research, vol. 25, no. 36, pp. 36087–36101, Dec. 2018, doi: 10.1007/s11356-018-3554-1.

[20] C. L. Tan, N. H. Wong, P. Y. Tan, M. Ismail, and L. Y. Wee, "Growth light provision for indoor greenery: A case study," Energy Build, vol. 144, pp. 207–217, Jun. 2017, doi: 10.1016/j.enbuild.2017.03.044.

[21] L. Dominici et al., "Analysis of lighting conditions of indoor living walls: Effects on CO2 removal," Journal of Building Engineering, vol. 44, p. 102961, Dec. 2021, doi: 10.1016/j.jobe.2021.102961.

[22] E. Zeiger and C. Field, "Photocontrol of the Functional Coupling between Photosynthesis and Stomatal Conductance in the Intact Leaf," Plant Physiol, vol. 70, pp. 370–375, 1982.

[23] F. Ascione, R. F. De Masi, M. Mastellone, S. Ruggiero, and G. P. Vanoli, "Green walls, a critical review: Knowledge gaps, design parameters, thermal performances and multi-criteria design approaches," Energies (Basel), vol. 13, no. 9, May 2020, doi: 10.3390/en13092296.

[24] S. Cascone, J. Coma, A. Gagliano, and G. Pérez, "The evapotranspiration process in green roofs: A review," Build Environ, vol. 147, pp. 337–355, Jan. 2019, doi: 10.1016/j.buildenv.2018.10.024.

[25] Megh R Goyal and Eric W. Harmsen, Evapotranspiration: Principles and Applications for Water Management. CRC Press, 2013.

[26] G. Pérez, L. Rincón, A. Vila, J. M. González, and L. F. Cabeza, "Behaviour of green facades in Mediterranean Continental climate," Energy Convers Manag, vol. 52, no. 4, pp. 1861–1867, Apr. 2011, doi: 10.1016/j.enconman.2010.11.008.

[27] C. H. Lin, "Indoor Air Purification by Plants Experiment and Its Arithmetic Mean and Regression Analysis," in IOP Conference Series: Earth and Environmental Science, IOP Publishing Ltd, Apr. 2022. doi: 10.1088/1755-1315/1008/1/012022.

[28] L R Boysen, W Lucht, D Gerten, and V Heck, "Impacts devalue the potential of large-scale terrestrial CO2 removal through biomass plantations," Environmental Research Letters, vol. 11, no. 12, Dec. 2016, doi: 10.1088/1748-9326/11/12/129502.

[29] B.C. Wolverton, Anne Johnson, and Keith Bounds, "INTERIOR LANDSCAPE PLANTS FOR INDOOR AIR POLLUTION ABATEMENT," Sep. 1989.

[30] F. B. Salisbury, J. I. Gitelson, and G. M. Lisovsky, "Bios-3: Siberian experiments in bioregenerative life support.," Bioscience, vol. 47, no. 9, pp. 575–85, Oct. 1997.

[31] K. T. Han and L. W. Ruan, "Effects of indoor plants on air quality: a systematic review," Environmental Science and Pollution Research, vol. 27, no. 14, pp. 16019–16051, May 2020, doi: 10.1007/s11356-020-08174-9.

[32] C. K. H. Yu, M. Li, V. Chan, and A. C. K. Lai, "Influence of mechanical ventilation system on indoor carbon dioxide and particulate matter concentration," Build Environ, vol. 76, pp. 73–80, 2014, doi: 10.1016/j.buildenv.2014.03.004.

[33] J. Berger, E. Essah, and T. Blanusa, "The impact of plants on the humidity of naturally ventilated office indoor environments," Journal of Building Engineering, p. 108814, Jun. 2024, doi: 10.1016/j.jobe.2024.108814.

[34] X. Tian, S. Wei, A. Mavrogianni, W. Yu, and L. Pan, "The effectiveness of potted plants in improving indoor air quality: A comparison between chamber and field studies," in E3S Web of Conferences, EDP Sciences, Jun. 2023. doi: 10.1051/e3sconf/202339601023.

[35] K. T. Han, "Effects of window status and indoor plants on air quality, air temperature, and relative humidity: a pilot study," Journal of Asian Architecture and Building Engineering, vol. 23, no. 1, pp. 313–324, 2024, doi: 10.1080/13467581.2023.2238027.

[36] F. R. Torpy, M. D. Burchett, J. Tarran, F. Torpy, and M. Burchett, "USE OF LIVING POT-PLANTS TO CLEANSE INDOOR AIR-RESEARCH REVIEW," vol. III, pp. 249–256, Oct. 2007, [Online]. Available: https://www.researchgate.net/publication/228639007

[37] J. Zhu et al., "Experimental study on the purification capacity of potted plants on low-concentration carbon monoxide in indoor environment," Environ Sci Pollut Res Int, vol. 31, no. 4, pp. 6316–6331, Jan. 2024, doi: 10.1007/s11356-023-31497-2.

[38] C. Liu, N. Zhang, L. Sun, W. Gao, Q. Zang, and X. Wang, "Potted plants and ventilation effectively remove pollutants from tobacco smoke," International Journal of Low-Carbon Technologies, vol. 17, pp. 1052–1060, 2022, doi: 10.1093/ijlct/ctac081.

[39] T. Armijos-Moya, P. de Visser, M. Ottelé, A. van den Dobbelsteen, and P. M. Bluyssen, "Air cleaning performance of two species of potted plants and different substrates," Applied Sciences (Switzerland), vol. 12, no. 1, Jan. 2022, doi: 10.3390/app12010284.

[40] Y.-I. Yun and J.-Y. Cho, "The Characteristics of the winter season window and indoor temperature due to the indoor plant," KIEAE Journal, vol. 15, no. 5, pp. 107–112, Oct. 2015, doi: 10.12813/kieae.2015.15.5.107.

[41] P. J. Irga, T. J. Pettit, and F. R. Torpy, "The phytoremediation of indoor air pollution: a review on the technology development from the potted plant through to functional green wall biofilters," Rev Environ Sci Biotechnol, vol. 17, no. 2, pp. 395–415, Jun. 2018, doi: 10.1007/s11157-018-9465-2.

[42] S. Matheson, R. Fleck, P. J. Irga, and F. R. Torpy, "Phytoremediation for the indoor environment: a state-of-the-art review," Rev Environ Sci Biotechnol, vol. 22, no. 1, pp. 249–280, Mar. 2023, doi: 10.1007/s11157-023-09644-5.

[43] K. W. D. K. C. Dahanayake and C. L. Chow, "Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program," Energy Build, vol. 138, pp. 47–59, Mar. 2017, doi: 10.1016/j.enbuild.2016.12.002.

[44] J. Coma, G. Pérez, A. de Gracia, S. Burés, M. Urrestarazu, and L. F. Cabeza, "Vertical greenery systems for energy savings in buildings: A comparative study between green walls and green facades," Build Environ, vol. 111, pp. 228–237, Jan. 2017, doi: 10.1016/j.buildenv.2016.11.014.

[45] H. Feng and K. Hewage, "Lifecycle assessment of living walls: Air purification and energy performance," J Clean Prod, vol. 69, pp. 91–99, Apr. 2014, doi: 10.1016/j.jclepro.2014.01.041.

[46] R. Fernández-Cañero, L. Pérez Urrestarazu, and K. Perini, "Vertical Greening Systems," in Nature Based Strategies for Urban and Building Sustainability, Elsevier, 2018, pp. 45–54. doi: 10.1016/B978-0-12-812150-4.00004-5.

[47] G. Vox, I. Blanco, and E. Schettini, "Green façades to control wall surface temperature in buildings," Build Environ, vol. 129, pp. 154–166, Feb. 2018, doi: 10.1016/j.buildenv.2017.12.002.

[48] M. Radić, M. B. Dodig, and T. Auer, "Green facades and living walls-A review establishing the classification of construction types and mapping the benefits," Sustainability (Switzerland), vol. 11, no. 17, Sep. 2019, doi: 10.3390/su11174579.

[49] M. Manso and J. Castro-Gomes, "Green wall systems: A review of their characteristics," Renewable and Sustainable Energy Reviews, vol. 41, pp. 863–871, 2015, doi: 10.1016/j.rser.2014.07.203.

[50] Z. Poórová, A. Turcovská, P. Kapalo, and Z. Vranayová, "The Effect of Green Walls on Humidity, Air Temperature, Co2 and Well-Being of People," MDPI AG, Sep. 2020, p. 56. doi: 10.3390/environsciproc2020002056.

[51] R. Fernández-Cañero, L. P. Urrestarazu, and A. Franco Salas, "Assessment of the Cooling Potential of an Indoor Living Wall using Different Substrates in a Warm Climate," Indoor and Built Environment, vol. 21, no. 5, pp. 642–650, Oct. 2012, doi: 10.1177/1420326X11420457.

[52] C. Y. Cheng, K. K. S. Cheung, and L. M. Chu, "Thermal performance of a vegetated cladding system on facade walls," Build Environ, vol. 45, no. 8, pp. 1779–1787, Aug. 2010, doi: 10.1016/j.buildenv.2010.02.005.

[53] K. Perini, F. Bazzocchi, L. Croci, A. Magliocco, and E. Cattaneo, "The use of vertical greening systems to reduce the energy demand for air conditioning. Field monitoring in Mediterranean climate," Energy Build, vol. 143, pp. 35–42, May 2017, doi: 10.1016/j.enbuild.2017.03.036.

[54] Z. Li, D. H. C. Chow, J. Yao, X. Zheng, and W. Zhao, "The effectiveness of adding horizontal greening and vertical greening to courtyard areas of existing buildings in the hot summer cold winter region of China: A case study for Ningbo," Energy Build, vol. 196, pp. 227–239, Aug. 2019, doi: 10.1016/j.enbuild.2019.05.025.

[55] L. Jiang and M. Tang, "Thermal analysis of extensive green roofs combined with night ventilation for space cooling," Energy Build, vol. 156, pp. 238–249, Dec. 2017, doi: 10.1016/j.enbuild.2017.09.080.

[56] F. Yang, F. Yuan, F. Qian, Z. Zhuang, and J. Yao, "Summertime thermal and energy performance of a double-skin green facade: A case study in Shanghai," Sustain Cities Soc, vol. 39, pp. 43–51, May 2018, doi: 10.1016/j.scs.2018.01.049.

[57] B. Sudimac, B. Ilić, V. Munćan, and A. S. Anđelković, "Heat flux transmission assessment of a vegetation wall influence on the building envelope thermal conductivity in Belgrade climate," J Clean Prod, vol. 223, pp. 907–916, Jun. 2019, doi: 10.1016/j.jclepro.2019.02.087.

[58] A. Afshari, "A new model of urban cooling demand and heat island—application to vertical greenery systems (VGS)," Energy Build, vol. 157, pp. 204–217, Dec. 2017, doi: 10.1016/j.enbuild.2017.01.008.

[59] L. Wang and M. J. Witte, "Integrating building energy simulation with a machine learning algorithm for evaluating indoor living walls' impacts on cooling energy use in commercial buildings," Energy Build, vol. 272, p. 112322, Oct. 2022, doi: 10.1016/j.enbuild.2022.112322.

[60] P. Abdo and B. P. Huynh, "An experimental investigation of green wall bio-filter towards air temperature and humidity variation," Journal of Building Engineering, vol. 39, p. 102244, Jul. 2021, doi: 10.1016/j.jobe.2021.102244.

[61] X. Meng, L. Yan, and F. Liu, "A new method to improve indoor environment: Combining the living wall with air-conditioning," Build Environ, vol. 216, May 2022, doi: 10.1016/j.buildenv.2022.108981.

[62] Y. Shao, J. Li, Z. Zhou, F. Zhang, and Y. Cui, "The Impact of Indoor Living Wall System on Air Quality: A Comparative Monitoring Test in Building Corridors," Sustainability, vol. 13, no. 14, p. 7884, Jul. 2021, doi: 10.3390/su13147884.

[63] Y. Shao et al., "The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings," Build Environ, vol. 195, p. 107766, May 2021, doi: 10.1016/j.buildenv.2021.107766.

[64] Boyce P and Raynham P, The Sll lighting handbook. The Society of Light and Lighting. London: CIBSE, 2018.

[65] Glenn Hawkins, Rules of Thumb: Guidelines for building services, 5th ed. Bracknell: BSRIA, 2011.

[66] L. Huang, Y. Zhu, Q. Ouyang, and B. Cao, "A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices," Build Environ, vol. 49, pp. 304–309, Mar. 2012, doi: 10.1016/j.buildenv.2011.07.022.

[67] F. R. Torpy, P. J. Irga, and M. D. Burchett, "Profiling indoor plants for the amelioration of high CO2 concentrations," Urban For Urban Green, vol. 13, no. 2, pp. 227–233, 2014, doi: 10.1016/j.ufug.2013.12.004.

[68] S. V Pennisi and M. W. Van Iersel, "Quantification of Carbon Assimilation of Plants in Simulated and In Situ Interiorscapes," 2012.

[69] O. B. Adegun, O. O. Olusoga, and E. C. Mbuya, "Prospects and problems of vertical greening within low-income urban settings in sub-Sahara Africa," Journal of Urban Ecology, vol. 8, no. 1, 2022, doi: 10.1093/jue/juac016.

[70] L. Dominici, E. Comino, F. Torpy, and P. Irga, "Vertical Greening Systems: A Critical Comparison of Do-It-Yourself Designs," Plants, vol. 11, no. 23, Dec. 2022, doi: 10.3390/plants11233230.

[71] H. Yan, S. Fan, C. Guo, F. Wu, N. Zhang, and L. Dong, "Assessing the effects of landscape design parameters on intra-urban air temperature variability: The case of Beijing, China," Build Environ, vol. 76, pp. 44–53, Jun. 2014, doi: 10.1016/j.buildenv.2014.03.007.

[72] N. Dunnett and N. Kingsbury, Planting green roofs and living walls. Portland, 2008.

[73] M. Köhler, "Green facades—a view back and some visions," Urban Ecosyst, vol. 11, no. 4, pp. 423–436, Dec. 2008, doi: 10.1007/s11252-008-0063-x.