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Thermal Efficacy of Green Walls in Building Structures in the Northeast United States

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Honors Thesis Project

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1 Introduction

1.1 Background and Motivation

Climate change is one of the most threatening issues that humankind faces in the 21st century. There is indisputable evidence that our planet is experiencing global temperature rise, shrinking of ice sheets and sea level rise, warming oceans, extreme weather events, and ocean acidification, all at an unprecedented and alarming rate [1]. Human influence on these changes is an established fact [2]. The rapid growth of urbanization is a driving force behind these changes; as natural vegetated spaces are replaced with buildings, paved roads, and other low albedo surfaces, urban spaces absorb and retain more heat than their rural, vegetated counterparts. This tendency for urban environments to be warmer than their surroundings is known as the Urban Heat Island (UHI) effect. From 1900 to 2000, global urban population increased from 13% to 46%, and by 2050 this number is likely to reach 69% [3].

The UHI effect is a serious issue worldwide. Urban dwellers in particular are directly threatened by heat risk caused by UHI [4]. With average temperature increases of 4–5°C and peak increases over 10°C there are more heat related mortality and morbidity in cities [5]. Air pollution is another hazard associated with urban areas; it was estimated that globally in 2015, 8.9 million deaths were attributed to ambient fine particulate air pollution [6]. Additionally, impervious surfaces in urban areas significantly increase the amount of stormwater runoff, which during large storm events, can easily overwhelm urban stormwater infrastructure systems. Untreated wastewater is directly released to the environment as a result, which is a major environmental concern [7].

While buildings and infrastructure are necessary to human development and modern society, building construction and maintenance are significant sources of global carbon emissions. In fact, 40% of global carbon emissions come from the built environment [8]. With global temperature rises, we can expect higher demands on building heating and cooling systems. Santamouris et al. reveals an increase of 0.5%–8.5% of total building electricity demand for each degree of temperature rise [9]. As nonrenewable energy use creates emissions, it becomes increasingly important to conserve energy. Furthermore, solar radiation induces thermal stress and façade deterioration [10] which a depleting ozone layer will only magnify.

Introducing greenery back into the urban landscape offers many benefits, such as energy savings [11] [12] [10], retention of stormwater [13], carbon sequestration [14] [15], air filtration and improvement [16] [17], local microclimate improvement [18], and increasing biodiversity. Greenery systems also offer the potential for food production, and importantly, have essential psychological benefits for humans.

Urban greening commonly involves the installation of green roofs and green walls, which utilize exterior building surfaces to grow plants. The building envelope is a widely unused space, providing a unique planting opportunity, especially for vertical faces. Vertical greenery systems have a larger surface area than their horizontal, green roof counterparts, and in the case of high-rise buildings, façade area can be up to 20 times the roof area [12]. With more space, green walls may offer more benefits given the successful design, installation, and maintenance of the system. Additionally, horizontal space in urban areas is limited, making vertical space more valuable. In the face of climate-induced hazards and mortalities and the state of our planet, we need to understand green walls, their mechanisms, and their benefits more fully to improve design and maximize their benefits.

1.2 Types of Green Walls

Green walls refer to the vertical growth of plants on man-made structures, either by intention or occurring spontaneously. The Hanging Gardens of Babylon in the sixth century B.C. are one of the earliest examples of incorporating greenery systems in our built environment. However, despite the long history of green walls, only recently have we begun to quantify their benefits and exploit them through intentional design.

Green walls are categorized as green façades and living walls (Figure 1). Green façades are formed by a climbing plant or vine that adheres directly to the façade or indirectly to a continuous guide that covers the area of the façade. Living walls can be either continuous or modular and are created with non-climbing plants. The use of substrate distinguishes these two types of green walls; green façades use the ground as substrate whereas living walls arrange substrate vertically, either by modules, hydroponics, or another vertical growing medium.

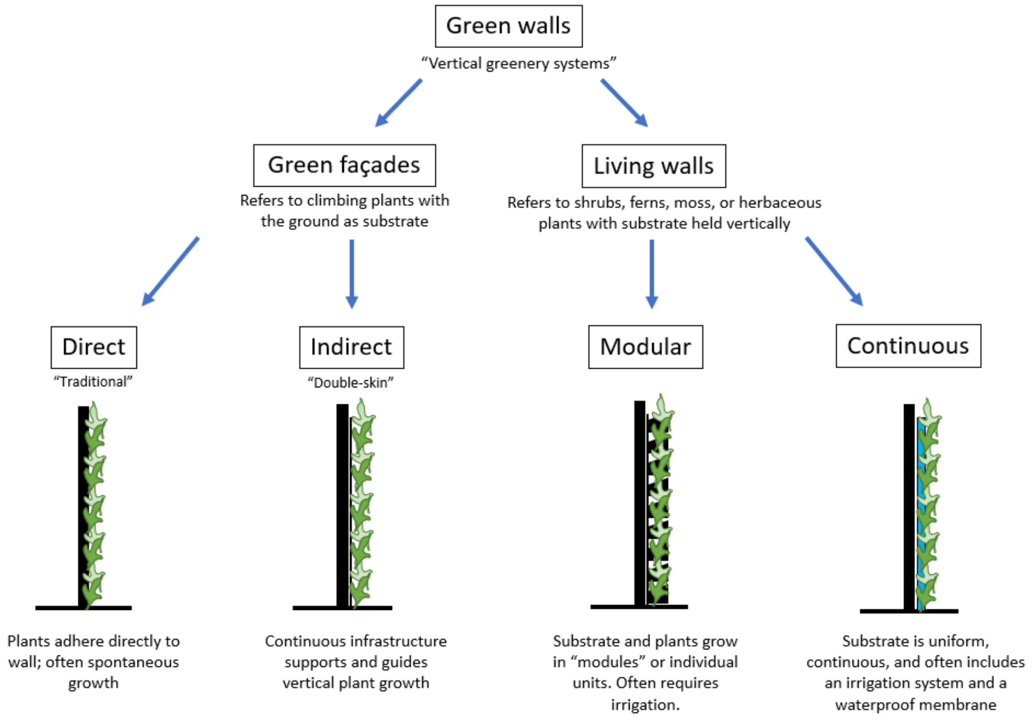

Figure 1. Green wall system classification.

2 Crucial Factors Impacting the Thermal Behavior of Green Walls

Among a vast number of variables that impact the thermal performance of green walls (Table 1), there are five crucial factors: plant and substrate characteristics, the type of system, active thermal mechanisms and their effects, façade orientation, and the surrounding environment, especially climate and weather. These factors are described in detail in the sub-sections that follow.

Table 1. Main variables influencing green wall thermal performance

Plants and Substrate	**Structural Support System**	**Building**	**Environmental Conditions**	**Other**
Plant characteristics*	Type (green façade, living wall)	Existing thermal envelope	Climate	Proximity of surrounding structures or trees
Substrate characteristics**	Design and configuration	Façade orientation	Weather	Substrate properties
Percent coverage	Material properties	Geometry	Season	Other surroundings
Foliage density	Material thickness	Use/energy use patterns	Time of day	
Substrate thickness	Irrigation			
Behavior (evergreen vs deciduous)	Age			
Perennial vs annual				

*such as leaf area index, transpiration, albedo, solar transmittance ration, nutrient requirements and intake, age and development and hardiness

**such as pH, moisture content, conductivity, type, composition, density

2.1 Plant and Soil Characteristics

Plant characteristics play a large role in the thermal behavior of green walls. The type of plant selected first depends on the system structure; climbing plants are used in green façades, while herbaceous plants, shrubs, ferns, and other plants with shallow, strong root systems are used in living walls. There are upwards of 450,000 plant species on Earth [19] with different traits and growing patterns. Among the extensive number of plant characteristics (Table 1), the characteristics that contribute the most to thermal performance of green walls are leaf area index (LAI), percent coverage, and overall plant density.

Pérez et al. 2017 investigated the impact of LAI and façade orientation on cooling. They found LAI to be a key parameter in their literature review and verified this in an experimental study; the Boston ivy investigated had a LAI of 3.5 and produced energy savings up to 34% in a Mediterranean continental summer climate [20]. A model by Susorova et al. 2013 also concluded that leaf area index reduced heat flux and surface temperatures the most, along with the densest plant layers and those with leaves parallel to the wall [21]. In fact, the model showed an exponential decrease in transmissivity as LAI increases, with transmissivity approaching zero for LAI values 4.0 and higher [21].

Koyoma et al. set out to determine the key traits in plants that contribute to the most cooling effects by comparing five different vine species and measuring ambient temperature, relative humidity, wall surface temperature, and plant traits of each vine such as vine length, total number of leaves, leaf surface temperature, percent coverage, leaf solar transmittance, and leaf transpiration rate. The results show that percent coverage of the vines had a direct impact on surface temperature reduction up to 11.3°C [22]. The study also finds leaf solar transmittance to have a noticeable impact on cooling effects.

Kontoleon and Eumorfopoulou investigated the impacts of orientation and percent coverage of plant-covered walls on summer thermal performance of typical buildings in the Greek region. Using a thermal network model, they found a linear relationship between percent coverage and surface temperature reductions; a higher percent coverage yields higher temperature reductions [23]. With a fully covered wall, exterior wall surface temperatures were reduced by 1.62°C to 19.01°C [23]. These findings are reinforced by Nan et al., 2020 [24].

Susorova et al. 2014 comments that air velocities also vary with percent coverage [25]. After observing multiple different species of climbing plants and shrubs, Cameron et al. 2014 found that different plants rely on different mechanisms to provide cooling benefits. They also found that plant characteristics strongly impact cooling potential, especially the number of leaves and the plant's ability to form a dense canopy [26]. Other studies also find the potential of success depends on the mass or thickness of the greenery [27] [20]. Despite the existing literature on plant traits and their impacts on façade performance, many studies highlight a lack of data, especially for establishing LAI for a wider variety of species and understanding its contribution better.

Studies suggest that in living walls, substrate properties are likely to have a greater impact than the plants themselves and that more research is required to determine which properties are optimal for green walls [28] [12]. In fact, there are no studies that specifically investigate the contribution of substrate to green wall heating or cooling benefits [12]. Overall, there is a lack of data on the contribution of plant characteristics and soil properties on green wall performance, and more research is recommended to better understand this relationship. Nan et al. asserts that substrate and vegetation in a living wall system need to be measured separately to identify their thermal contributions [24]. Except for a few studies, authors do not provide reasoning for plant selection; it is assumed that plant species are selected arbitrarily with consideration for the type of system, tolerance to climate conditions, and availability.

2.2 System Type

The system type selected is found to have a great impact on the function of green walls. Besir et al. 2018 summarized literature relating to green walls [10]. There were differences in what each paper measured, but it appears that living façades have the potential to offer more energy savings in both heating and cooling periods. Subsequent studies have also found living walls to provide significant benefits, such as a 31.4% reduction of façade U-value [28], a maximum surface temperature reduction of 6.4°C [29], and a 0.4°C to 1.7°C mean indoor temperature improvement [24]. Shuhaimi et al. found an average OTTV reduction of 6.87%, 6.82%, 2.97%, and 1.32% for a continuous living wall, a modular living wall, an indirect green façade, and direct façade respectively [30].

It is not clear which system is the most effective, especially since other variables such as orientation, solar radiation exposure, weather, and climate impact thermal performance. Susca et al. was one of the only studies to compare the performance of different system types and found living walls to be superior to green façades in terms of decreasing surface temperature and improving thermal performance [11]. Coma et al. directly compared the performance of a living wall and an indirect green façade; during the cooling period, the living wall provided energy savings up to 58.9% and the green façade up to 33.8% [31]. During cooling, the living wall showed 4.2% energy savings and the green façade showed little change compared to a bare wall [31]. From the existing literature, living walls provide have a higher thermal impact on buildings than green façades. Many other case studies and experiments fail to explain system type choices, and within these systems there is little explanation for design choices such materials, air cavity size, and configuration.

2.3 Thermal mechanisms and their effects

There are four mechanisms that significantly impact the thermal behavior of green walls. These are shading, reduction of wind speed, evaporative cooling through evapotranspiration, and thermal insulation through materials and air layers (Figure 2). These mechanisms have effects, which may include the reduction of average and extreme exterior wall surface temperatures, reduction of the exterior-interior surface temperature gradient, limiting air infiltration, increasing relative humidity, creating a local microclimate, and impacting the ambient air temperature. These effects can be quantified by comparing measurements taken on vegetated walls to a bare, control wall with no vegetation.

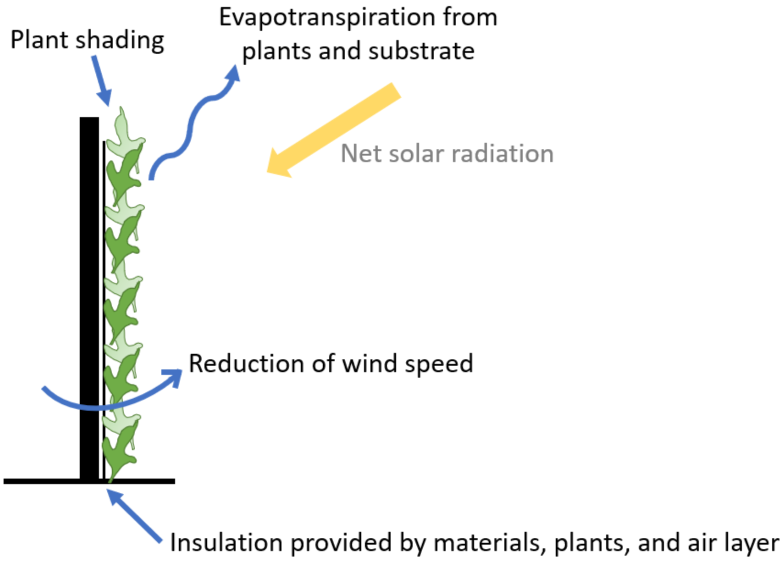

Figure 2. Diagram of green wall mechanisms.

There is very minimal discussion of the relationship between green wall mechanisms and their effects, especially as it relates to the heating and cooling functions of the system. Through shading and evapotranspiration, green walls contribute to cooling by intercepting solar radiation and redirecting it for photosynthesis, transforming it to latent heat, or reflecting it. Only 5–30% of sunlight energy passes through plants in a vertical greenery system [32]. Other studies estimate up to 60% of absorbed solar radiation is converted to latent heat by plants [33]. The effects measured by these mechanisms are not often hypothesis-driven, but the benefits are substantial and significant.

The shading function of plants is assumed to play a large role in reducing exterior wall surface and air gap temperatures especially during cooling periods and in warm climates. In fact, multiple papers claim the shadow effect to be one of the most significant in building energy savings [10] [12] [34] [35], and it is assumed that this refers to cooling energy in warm climates or the summer season. In Hoelscher et al. 2016, three vertical greenery systems experienced mean surface temperature reductions of 0.1°C–11.3°C (average 4.4°C), 0.0°C–12.3°C (average 2.2°C), and -0.8°C–6.6°C (average 2.2°C) on a hot summer day. Stec et al. found plants to be an effective shading system, even more so than blinds; in a simulation, plant temperatures never exceeded 35°C whereas blinds could exceed 55°C [33]. Wong et al. investigated seven living walls and one green façade, finding the green façade reduced the average surface temperature of the wall by 4.36°C which was the most effective of the systems [36]. For the living walls, average surface temperatures were reduced up to a maximum of 11.5°C for one system with peak reductions ranging from 6 to 10°C [36]. Ambient air temperature lowered up to 3.33°C for these systems [36]. Another study found building surface temperature reductions up to 16.4°C, 15°C, and 16°C for west, east, and south facing walls respectively [20]. Hoelscher et al. found that for three climbing plant systems, shading contributed the most to cooling effects on hot summer days up to 87% [37]. On cloudy days, 73% of cooling was due to transpiration, but overall cooling was low [37].

Green walls are effective at reducing extreme surface temperatures of buildings, especially in warm climates. Hoelscher et al. found extreme surface temperature reductions of 15.5°C, 13.9°C, and 10.5°C at three different sites [37]. Sternberg et al. also found ivy to limit temperature fluctuation and reduce average daily maximum temperatures by 36% and minimum temperatures 15% [18]. Additional studies find that the largest temperature reductions occur during peak exposure to solar radiation [25] [21] [37] [29].

Green walls also provide thermal insulation to buildings through their materials, plants, substrate, and air layers. Of these contributors, plants are expected to provide the least insulation whereas materials and air gap provide the most. There is currently no data on the influence of substrate alone on thermal performance of buildings [12]. Bakhshoodeh et al. measured 6.8°C and 11°C maximum temperature reductions of the air gap for ten pilot scale indirect green façades [38]. Perini et al. 2011 finds that a 40–60mm air cavity can create a stagnant air layer that provides insulation [39]. There are no studies on the impact of materials alone to the author’s knowledge.

Evapotranspiration refers to the evaporation of water from substrate and plant stoma because of solar radiation. Water has the highest latent heat of transformation of any known substance on Earth, making it an effective tool in absorbing solar energy and transforming it into latent heat. In green walls, evapotranspiration intercepts solar radiation and contributes to cooling performance. A recent study in western Australia used shade sails to measure the contribution of evapotranspiration on cooling benefits of ten pilot scale green façades. The authors found a 35% contribution for a deciduous plant and 25% for a non-deciduous plant [38]. Cuce et al. comments that greatest temperature reductions of their green façade system occurred near the ground where evapotranspiration was dominant [40]. Other studies assume evapotranspiration to be a main component of cooling [22], have a high potential to reduce urban temperatures [3], and be most effective in a well-irrigated system [26]. In regards to heating in cold climate situations, evapotranspiration is expected to reduce thermal benefits, but not significantly enough to thwart the overall benefits [24]. Overall, the evapotranspiration mechanism in green walls is widely unexplored and remains mostly theoretical.

The reduction of wind speed is one of the least researched mechanisms of green walls. Perini et al. 2013 investigated the impact of green walls on air flow around buildings most directly. The study finds that green walls do reduce wind velocities; for direct, indirect, and living wall systems, wind velocity was reduced by 0.43m/s, 0.55m/s, and 0.46m/s respectively [39]. Additionally, wind speed was found to be nearly zero in the three types of systems investigated. This is assumed to benefit the thermal performance of the building and lead to energy savings for both heating and cooling [39]. Pérez et al. 2011 also verifies the wind barrier function through measuring relative humidity and finding a 7% higher value in the summer and an 8% lower value in the winter [41]. While there is less quantification of wind velocity and air infiltration in the literature, some studies provide commentary. A sensitivity test run by Susorova et al., 2013 showed wind speed as one of the most impactful weather paraments and Susorova et al., 2014 comments that air infiltration is driven by a difference in indoor and outdoor wind pressures [21] [25]. Additionally, wind is one factor that drives diffusion of water through plant stoma and could enhance evapotranspiration. More research is needed on the wind speed reduction effect [21] [12].

It is widely agreed that these four mechanisms are the main factors that impact green wall thermal behavior. While the contribution of these mechanisms to building heating cooling is widely unknown and there is little discussion of it, the literature widely agrees that these mechanisms are influential on conditions such as ambient air temperature, exterior and interior wall surface temperature, relative humidity, and wind speed, which can improve the thermal performance of buildings.

2.4 Façade Orientation

Energy savings of façades are influenced by orientation, mainly because façade orientation determines the intensity of solar radiation incidence which determines thermal reduction effect of the building shell [23]. Susca et al.'s systematic literature review in 2022 performed a comparative analysis on façade orientation influences on building energy needs. In a Cwa climate zone (warm temperate, winter dry, hot summer), they found the north orientation to reduce heating energy the most, approximately 10%, as it is the coldest side of the building [11]. The authors find that in most climate zones investigated, application of single façades should be on south facing walls to maximize energy savings [11], but the study is limited by the lack of data from many climate regions, especially Dfa (Snow, fully humid, hot summer) and Cwb (temperate ocean climate).

In Susorova et al., 2014, direct green façades were measured for each orientation (north, south, east and west) for buildings in Chicago, IL, United States. The east and west walls experienced the most benefits on the exterior-interior gradient and hourly maximum temperatures [25]. Heat flux was reduced on average by 16% for the east facing wall, 11% for the west wall, 14% for the north wall, -1% for the south wall, and 10% overall [25]. Despite a 14% reduction of heat flux on the north wall, the authors suggest that the green façade measured is better suited for east and west walls as north and south walls had lower peak and average temperature reductions. This differs from Susca et al. perhaps because south, east, and west walls were on the inside of a semi-enclosed courtyard and all 10 to 20 meter away from nearby trees, and the north wall was shielded by trees 2 to 3 meters away [25]. Surrounding buildings and wind patterns may have influenced Susorova et al. 2014's results; these variables are important to account in design of green walls to maximize benefits. Additionally, this study states that orientation impacts air velocities; reductions of 42% to 43% on the east and west walls, respectively, to 18% on the south wall and 0% on the north wall were measured [25].

Nan et al. asserts that orientation is crucial. In a winter climate, modular systems installed on the North wall alone saw a better regulated thermal environment and more heat preserved. The north wall was effective against wind, weak in heat gain, and weak in plant activity due to a lack of solar radiation [24]. Pérez et al. 2017 researched an indirect green façade on east, south, and west orientations. There is no explanation why the north orientation was not investigated. Peak building surface temperatures decreased up to 16.4°C (west), 15°C (east), and 16°C (south) [20]. Shuhaimi et al.'s model for a building in Malaysia found the south orientation to have the highest overall thermal transfer value (OTTV) for green façades and the east wall to have the highest OTTV for living walls [30]. Pan and Chu investigated the impact of orientation on green wall thermal performance specifically, finding a west wall in Hong Kong, China to reduce daily maximum temperature the most from 0.9°C to 6.1°C [42]. Lastly, Coma et al. found a green wall in northeast Spain to reduce external wall temperatures by 16.5°C, 6.5°C, and 4.5°C for South, West, and East respectively [31].

Evidently, there is some disagreement of orientation on the thermal behavior of façades, and more research is required to fully understand this relationship. Existing literature suggests that in most climates in the northern hemisphere, green walls have the highest impact on heating demand on north walls (up to 10% energy reduction), followed by west (8%), east (6%), and lastly south (3%). In temperate climates with warm and cold seasons, deciduous plants can be used as a dynamic system to maximize solar radiation blockage in the summer and solar gain in the winter.

2.5 Climate and weather conditions

Perhaps the most impactful variable on the thermal performance of green walls is climate and weather conditions [12] [11]. Many individual studies exist and are concentrated in Europe and Asia [11] but few studies take a holistic approach to the influence of climate on green wall thermal and energy performance.

Susorova et al., 2013 ran a sensitivity analysis showing that green walls are most effective at cooling in climates with high solar radiation and low wind speeds [21]. According to Pan et al., thermal performance is critically impacted by solar radiation, total bright sunshine, and relative humidity [29], which depends on climate and geographic location. The study authored by Susca et al. most thoroughly investigated the impact of climate on green wall performance by performing a systematic literature review. The study finds a limited number of case studies for certain climate zones, some climate zones with no research, and a dominating number of case studies on cooling energy demand compared to on heating energy demand [11]. The data that does exist shows a reduction in both heating and cooling energy demand for all climate zones, but this amount varies. The highest reductions were found in Cfb (warm temperate, fully humid, warm summer) with a surface temperature reduction of building exterior up to 34°C in the cooling season [11]. In the heating season, green walls improved building energy in all climate zones investigated with the highest being a 8°C improvement Cfa (warm temperate, fully humid, hot summer) [11]. The study concludes that green walls are versatile solutions for all the investigated climate zones, but a proportionate number of studies in across different zones would give more insight. Ultimately, geographical location, climate, and weather influence determine if buildings are heating or cooling-dominant and highly impact the efficiency of green walls. Other environmental surroundings can also influence green wall performance, such as wind patterns or shade created by structures and trees nearby.

3 Heating and Cooling Performance of Green Walls

Many studies do not measure energy savings directly; often, easily measured variables are investigated and the authors hypothesize that building energy loads are impacted positively as a result of the findings. For example, Wong et al. measured ambient air temperature reductions up to 3.33°C and presume that cooler ambient air reduces energy cooling loads by creating less work for air conditioning systems [36]. Few studies use in-situ heat flux to determine the thermal conductivity of green walls. Fox et al. was one study that did; the authors studied a living wall in England for five weeks in November and December, and using heat flux sensors and a thermal camera, they found a 31.4% U-value improvement [28].

A few studies find green walls to be good energy saving tools in winter climates. According to Nan et al., living wall systems can indeed be passive energy saving tools, especially in winter climates; mean indoor temperatures rose 0.4C–1.7°C as a result of the living wall [24]. Sternberg et al. measured spontaneous ivy growth on buildings in England for a year, finding average daily maximum temperatures to be 36% higher [18]. Susca et al.'s systematic literature review finds that green walls can lower heating energy demand up to 16.5% and cooling energy demand up to 51% for buildings [11]. In addition, UHI can be mitigated up to 5% in many climate zones [11]. Depending on orientation, one study found green walls to reduce cooling loads by 12–42% [29].

Green walls can produce energy savings for heating and cooling demand up to 16.5% and 51% respectively [11], but climate, system type, and other variables will ultimately determine where a specific green wall will fall in this range. As mentioned previously, there are drastically more studies on the cooling behavior of green walls as compared to heating. Especially for winter climates and cold regions, more research is needed to better understand the thermal performance of green walls.

4 Cost-Benefit Analysis for Green Walls

The benefits of green walls are well-documented in literature. However, the cost of these systems and their environmental burdens must be considered when determining the overall system sustainability and cost-effectiveness. There is some disagreement as to whether green walls are sustainable and the costs of their design, maintenance, and installation are justifiable.

Feng and Hewage modeled a LEED Gold building in British Columbia, Canada and performed a financial assessment, finding that green walls are not cost-effective, especially in winter months and cold climatic regions. In July, the modeled building saw an 7.3% reduction in cooling energy savings, but in the winter time energy saving are negligible [43]. Considering the performance of the green wall year round, the authors conclude that total energy savings were insignificant compared to the initial capital costs of the system [43]. However, this study fails to consider the impact of the existing thermal performance of the building envelope on energy savings for standard buildings. Instead, comparisons are made to a LEED Gold building, which already meets certain building sustainability criteria, and is newer than the majority of existing building stock. For older buildings or non-LEED certified buildings, green walls may still be cost-effective. Similar to Feng and Hewage, Pan and Chu's case study in Hong Kong, China determined that it was not cost-effective in winter months, but speculate that positive environmental effects can be achieved given a long enough service life, and initial costs could be paid back in roughly 40 years [42]. Feng and Hewage also mentions that the benefits of green walls could offset capital costs [43].

Other studies state that greenery systems are one of the most cost-effective and eco-friendly retrofits for building envelopes [10], especially over building lifespan [42] [44]. Pan and Chu's life cycle analysis found that environmental burdens can be paid back in 20 years and that green wall systems are environmentally sustainable regarding energy savings [42]. Köhler et al. finds creating green walls very easy, as little ground space is needed, costs of installation can be low, and ecological benefits are prominent over a 10-year period [27].

Green walls are sometimes criticized for having detrimental effects on building façades. Direct greening systems may be invasive and interfere with the building structure, additionally limiting access for original façade repair. However, ivy is assumed to play a bioprotective role, protecting walls from direct solar radiation, mitigating rainfall intensity, reducing freeze-thaw cycles, restricting light for microorganism growth, and minimizing salt crystallization [18]. This can also be avoided by choosing to install an indirect green façade or living façade.

In a 2017 paper, Riley documents their findings after two years of observing, discussing, and examining green walls with green wall owners, designers, and installers across the world. The paper provides commentary on the construction of successful green wall systems and addresses common criticisms related to cost, sustainability, complexity, and susceptibility to failure. Riley states that cost is the biggest hinderance to the expansion of green walls. After responding to green wall cost criticisms, Riley concludes that green wall costs can be reduced if short-term investment and long-term maintenance are optimized [45]. Additionally, Riley maintains that green walls will become sustainable once they are viewed as entire systems that are integral to building function and little or no potable water is used for irrigation. Susca et al. verifies this, finding 7°C and 60°C reductions in heating energy demand for a single façade compared to an entire building façade respectively [11]. In the literature reviewed, there is no mention of using secondhand materials for green wall construction. Using recycled, upcycled, and reused materials can drastically lower the cost and environmental burden of green walls, and in some cases, eliminate it entirely. Rainwater catchment or water recycling systems can be used as irrigation in green walls to avoid using potable water. Likewise, soil excavated during construction can be recycled into substrate. Lastly, most of the literature fails to consider a social approach to green walls; building occupants and community members can be engaged to maintain green walls, decreasing maintenance costs, and fostering a stronger relationship between humans, their occupied spaces, and nature.

Of the literature that discusses the sustainability of green walls, there are no studies to the author's knowledge that consider the totality of green wall benefits which include stormwater retention, air quality improvement, biodiversity enhancement, habitat creation, food production, and mental health benefits. Energy savings are only one benefit of green walls and to accurately determine their sustainability, one must consider all the services green walls provide. The true extent of the benefits remains difficult to quantify, but it is still necessary to incorporate in the complete picture.

Cost-effectiveness of green walls depends on many variables and circumstances that are specified in Table 1. Literature suggests many benefits of green walls, but there is less reliable information to guide designers and maximize these benefits [28]. There is no universal design due to the vast number of variables involved. The lack of sufficient research on these variables makes optimal design challenging for different geographic areas, building geometry, and environmental conditions. However, it is important to note that green walls may become more cost-effective in the future as our climate continues to warm, pollution concentrations increase, and other harmful conditions need mitigation.

5 Conclusion

Existing literature widely agrees that green walls are passive energy saving tools, and in some cases they can be extremely effective at regulating heat flow in building envelopes. However, given the complexity of these systems, there is a lack of data on the many variables involved and their interactions. Green walls offer a unique opportunity for planting and greening our built environment with many benefits. However, when building height exceeds one story, green walls become an engineering design puzzle that requires intention, intensive design, and more materials to provide adequate structural support and maximize benefits. Planning is also essential in maintaining plant health, proper irrigation, and the success of the system overall. Despite being more complex than green roofs, green walls offer more potential in the available surface area offered and have stronger social impacts as they are more visible.

Green wall energy savings can be maximized through intentional design. Further research is required for many variables involved, especially plant characteristics, substrate, orientation, system type, and climate. More data will inform design and make these system more cost-effective. The benefits of urban greening extend far beyond energy savings, and as we beautify our inhabited spaces with nature and vegetation, we cultivate a higher value of our spaces and a desire to preserve them, which rests at the core of sustainability.

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