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Developing a Digital Workflow to Estimate Green Walls' Performance for Enhancing Indoor Air Quality

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Abstract

Vertical greening systems, or living walls, are increasingly used indoors due to their potential to improve air quality by mitigating excess Carbon Dioxide (CO_2) levels (Dominici et al., 2021). This study introduces a parametric workflow that utilizes digital light simulations to estimate the performance of green walls in terms of their ability to perform photosynthesis and subsequently reduce indoor CO_2 levels. To accomplish this, the workflow uses the Rhino inside Revit plugin to identify any Revit model and then uses Rhino plugins, Grasshopper and Honeybee to simulate cumulative radiation on a grid of sensors on each leaf, after that the plant leaves' capacity to perform photosynthesis based on the compensation point of light and calculates the amount of CO_2 reduction accordingly was tested. The workflow was applied in the study using a sample plant, Epipremnum aureum.

This research demonstrates that early-stage simulations using the proposed parametric workflow can provide valuable insights for architects and designers to make informed decisions regarding the positioning and orientation of indoor green walls. The study suggests that different performance outcomes can be estimated depending on light levels, highlighting the importance of using sunlight simulation strategies in the early design stages when considering implementing green walls in indoor environments. However, further validation of the proposed workflow against physical lab tests is necessary to enhance its reliability and accuracy.

Highlights

- Avoiding the negative effect of using vegetation-based solutions such as green walls by implementing early stages studies.
- Proposing performance-based simulation to bridge the gap between lab testing and in-situ studies of green walls.
- Enhancing indoor air quality by using early stages simulations for green wall implementations.
- A Parametric workflow to estimate and optimize green walls performance in early design stages.

Introduction

Indoor Air Quality (IAQ) of buildings has been recognized as a key factor affecting the health and well-being of occupants, where CO_2 and ventilation have been shown to significantly impact mental productivity (MacNaughton et al., 2017). Nature-based solutions have been suggested in various studies as a feasible and effective approach for improving indoor air quality (Mohajeri et al., 2015), Where recent research has highlighted the significant potential of phytoremediation in treating indoor air pollution (Liu et al., 2022). In addition, studies have quantified the ability of indoor plants to sequester carbon and reduce CO_2 concentration levels (Pennisi & van Iersel, 2012; Tudiwer & Korjenic, 2017). Meng et al.(2022) reported a reduction of 25.7%–34.3% in indoor CO_2 concentrations due to the presence of indoor plants, compared to no planting. These findings demonstrate the potential of indoor plants as a sustainable and natural solution for improving IAQ in buildings.

The vegetation component is especially important in this context, as such, research has focused on studying the amount of CO_2 sequestered by plants relative to their leave's surface area. Photosynthetically Active Radiation (PAR) that an area receives is crucial for the plant to perform photosynthesis (Wetzel, 2001). Vegetation can be a substantial photosynthetic CO_2 sink in the correct environmental conditions, such as those with enough light, water, and airflow (Soreanu et al., 2013). However, it should be noted that a plant's respiration can also generate CO_2 in a variety of circumstances (Lehmann & Kleber, 2015).

The investigation of CO_2 levels under a variety of lighting conditions by Torpy et al.(2014) revealed that there were fluctuations in CO_2 leaf uptake regarding the use of different plant species under different environmental factors. Overall, the tested species attained 50-65% of their maximum CO_2 removal rates at an intensity equivalent to or below 350 μmol PARm^{-2} s^{-1}(Torpy et al., 2014). The process of photosynthesis is dependent on the availability of sufficient light and higher light intensities were found to have a significant positive effect on net CO_2 (Dominici et al., 2021). However, CO_2 production resulting from plant respiration and rhizosphere, the narrow region of soil or substrate that is directly influenced by root, could have counterproductive effects in indoor environments under certain environmental factors such as low levels of irradiance (less than 1,000 lux) or during prolonged diurnal dark phases (Daugaard et al., 2019). Torpy et.al (2017) findings indicated that 250 μmol m^{-2} s^{-1} is a suitable light level for a highly efficient green wall, whilst some CO_2 will still be removed at 50 μmol m^{-2} s^{-1}. However, below 10–15 μmol m^{-2} s^{-1} green walls may increase indoor CO_2 levels. (Torpy et al., 2017). Interestingly, when the two best-performing plant species in Torpy et at. (2017) were subsequently tested for quantitative CO_2 removal, both were found capable of removing substantial quantities of CO_2 from chamber environments when the light level was greater than 50 μmol m^{-2} s^{-1}. Thus, when tested in a more realistic room-sized chamber, CO_2 removal was modest at a 50 μmol m^{-2} s^{-1} light level but, was highly effective when supplementary lighting to 250 μmol m^{-2} s^{-1} was applied (Torpy et al., 2017). In a study conducted by Guo et al. (2014), the authors aimed to investigate the capacity of indoor salad gardens to balance the respiratory emissions of humans. The study involved testing CO_2 removal rates in a sealed facility using red and blue LED lighting with a 24-hour photoperiod, at a supplied light level of 450-550 μmol m^{-2} s^{-1}. Results indicated that increasing the light level from 450 to 550 μmol m^{-2} s^{-1} had a significant effect on CO_2 removal rates (Guo et al., 2014). However, The majority of studies examining this component are conducted within a controlled laboratory environment. The current study proposes a methodology that utilises computer simulations to analyse the environmental factors and estimate green wall performance based on the results of laboratory experiments in the same environmental factors.

The early inclusion of vegetation in the design process is often driven by aesthetic considerations. However, to fully leverage the potential of plants as natural-based solutions for improving air quality and reducing CO_2 levels in buildings, designers require sufficient tools that draw on scientific evidence and allow for real-time performance simulation. Although modelling approaches have been proposed to study the phytoremediation potential of plants in improving air quality, they have not always been parameterized by experimental data obtained through targeted and precise laboratories (Prigioniero et al., 2021). The emerging concept of parametric performative design can address this issue by integrating advanced Building Performance Simulation tools that can provide insights into various aspects of building performance, such as, thermal, lighting, acoustic, and ventilation performance. By using computer simulations to bridge the gap between laboratory results and real-world scenarios, this research aims to provide designers and architects with a design aid tool that can assist them in making informed decisions regarding the use of green walls.

The current study introduces a parametric simulation-based workflow that models the biological needs of plants and their ability to perform photosynthesis in response to their surrounding environment. The proposed workflow can be utilized by designers and architects to estimate the performance of green walls before their implementation in a design. Such an approach allows for effective estimation of green wall performance during the early stages of design, thereby reducing the negative impact on IAQ. Moreover, the use of this workflow can result in lowered CO_2 levels, thus enhancing IAQ.

Methods

The current study proposes a methodology that utilizes computer environmental simulation to establish a link between laboratory testing results and in-situ investigations. As shown in Figure (1), this research involves two stages: the first stage focuses on the proposal of the methodology, while the second stage employs the proposed methodology as a test example to demonstrate its efficacy. Specifically, the proposed methodology offers a systematic and practical approach to extrapolate laboratory data to real-world scenarios, thus enabling the estimation of performance and behaviour under different environmental conditions, particularly, lighting levels.

The plant species chosen for this research to test the workflow was Epipremnum aureum (commonly known as Golden Pothos). It is a hardy plant which requires little maintenance or care. No direct sunlight is required. It can tolerate bright light but achieves the best results under medium indirect light. Minimal temperature required is: 14-16 °C optimal temperature is: 22-26 °C (Meshram & Srivastava, 2015). In order to develop this workflow, the study draws upon Pass and Hartley's (1978) investigation of the net CO_2 exchange, dark respiration, light compensation points, and light acclimatization rates for Epipremnum aureum under four irradiation levels. Their experiment was conducted in a closed testing chamber, which modelled the environmental conditions of 25°C temperature and four different irradiation levels (14, 29, 38, and 70 PAR). This was the basis for choosing the four light levels in this study.

Stage one: Methodological flow work proposal

The proposed workflow, as illustrated in Figure 1, starts with the identification of any Revit model using Rhino inside Revit. This initial step aims to enhance the user-friendliness of the methodology, making it widely accessible to architects and designers, given that Revit is currently the most popular Building Information Modelling (BIM) software globally. The second step requires the user to use the newly generated Rhino model to identify the green wall in the design. The third stage entails the utilization of Grasshopper, which is a visual coding plugin for Rhino, to simulate the growth of plant leaves on the designated surfaces within the module based on the plant species. Subsequently, the amount of sunlight received by the plant leaves is simulated, using Honeybee 1.3.0, a Ladybug plug-in, cumulative radiation component in Grasshopper. It is worth noting that sunlight simulation can be conducted using several plugins, one of the most popular is the Honeybee plugin, which was used in this study.

The leaves within the wall system were identified as shaders, this step aims to allow the leaves to cast shadows on each other which will affect the amount of sunlight each leaf will receive. A grid of sunlight sensors was added to the leaves individually. The simulation results, expressed in kWh/m^2, in a data tree representing values of sunlight received by grids of sensors on leaves.

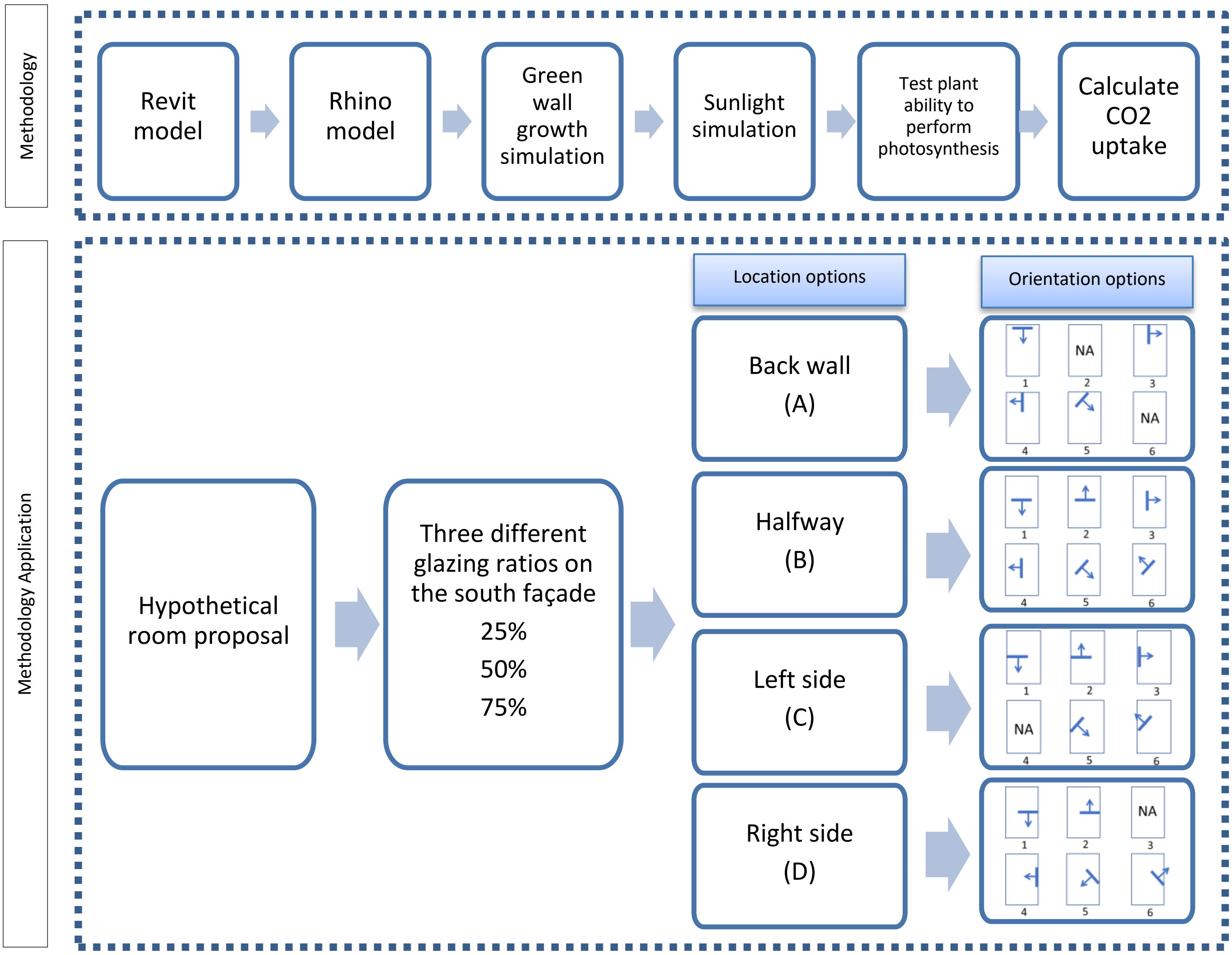

Figure (1) : Methodological Approach
(Source: Authors)

For the purpose of testing the leaves' ability to perform photosynthesis, light levels were converted into photosynthetically active radiation (PAR) (μmole.m^{-2}s^{-1}). Using an approximate conversion value of 4.57 which was proposed by Thimijan and Heins (1983). Lastly, python programming was implemented, to calculate the average PAR received by each leaf, followed by a test of their ability to perform photosynthesis to calculate CO_2 uptake per dm2 for each leaf separately.

Furthermore, aiming to find the overall performance of the system, the CO_2 uptake of the total leaf area was calculated according to equation (1). Where n is the number of leaves which is connected computationally, to the list length in Grasshopper. This allows the methodology to be adapted easily when applied in early design stages, hence the number of leaves will be according to the shape and size of the proposed green wall.

$$Total\ CO2 = \sum_{l=1}^{l=n}(area_l * CO2\ uptake_l * 1000) \quad (1)$$

Where: n is number of leaves, $area_l$, *is the single leaf area,* $CO2\ uptake_l$ *is the uptake of individual leaf according to the PAR level.*

By following these steps, the proposed methodology can effectively simulate the green wall's performance and provide valuable insights into its impact on reducing CO_2 levels.

Stage two: Methodology application

Aiming to test the workflow, an Epipremnum Aureum plant was used as a sample plant on a simple solid wall geometry with dimensions 1m x 3m. The green wall was proposed in a small hypothetical room with dimensions 6m x 8m x 4m with a glazed south façade in Cardiff, Wales, the United Kingdom; therefore, Cardiff weather file was used in this simulation. The proposed room is unoccupied, no HVAC system and no surroundings were proposed. The room was assumed to be naturally ventilated at a rate of 420ml/min. This rate is equal to the experiment conducted by Pass and Hartley's (1978) hence the performance of the leaves was calculated according to this experiment. Initial CO_2 levels were assumed at 400ppmv (775mg/m3) as this is at the lower end of average ambient indoor CO_2 concentrations (Hess-Kosa, 2002) and the same initial CO_2 levels were assumed at the experiment on the same plant conducted by (Torpy et al., 2014). The room has a generic construction set that is not sensitive to the room's climate or building energy code.

Aiming to examine the performance of the wall in different light levels. Three different glazing ratios were used on the southern façade, and 20 different green wall locations and orientations were studied in each ratio, as shown in Figure (2). Four different locations were proposed for the green wall. The back location, four orientations, Figure (2-a). The middle, six orientations, Figure (2-b). For the side walls, five orientations for each side, Figures (2-c,2-d). A simulation was run to measure sunlight levels received by an empty wall (without leaves) in these locations and orientations in the room as a reference case. Where a grid of sensors was proposed on each wall location and a sunlight simulation was conducted to measure the PAR levels and then an average for the whole wall was calculated.

The proposed green wall dimensions and the number of leaves, which was 500, were kept constant in all iterations. To mimic the growth of the plant on the wall, Figure (3A), the leaves were generated randomly on the wall on multiple surfaces in order for leaves to overlap each other figure (3B) and then a visual comparison was conducted between a real picture of the modelled green wall.

The performance of each wall iteration was calculated following the methodology that was explained earlier. And an alignment between wall performance and the amount of received sunlight was conducted. The final stage of the study was to calculate the best performance for the green wall based on the available data, where all the leaves receive more than 70 PAR, which was considered to be the highest point of light with enough data on the performance of this particular plant. Furthermore, the best and least-performing design options for each glazing ratio were studied according to the PAR levels recommended for this plant species in previous studies.

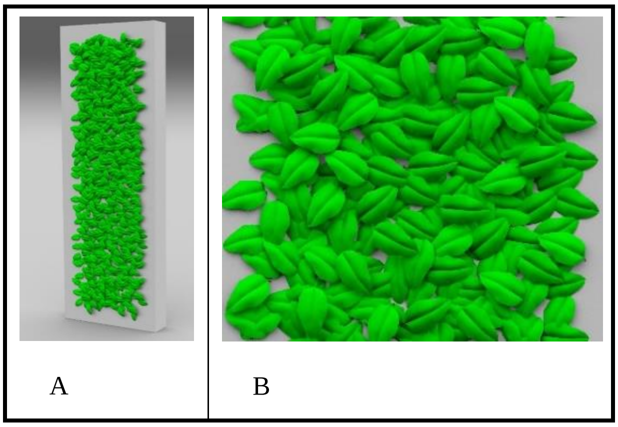

Figure (3) : The proposed green wall. A and B are the modelled Green wall (Source: Authors)

Results

The proposed workflow for estimating the performance of a green wall in a hypothetical room produced results that showed significant fluctuations in estimated CO_2 reduction levels, despite using the same dimensions and leaf count. Tables (1a) and (1b) present average sunlight levels in PAR for the reference case with no leaves on the wall for all the design options presented in the current study in reference to the glazing ratio.

Table 1 a: Average PAR levels received by walls without leaves for each design option in the study according to the glazing ratios (back wall and halfway)

	Back wall (A)			**Halfway (B)**		
Glazing Ratio	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Horizontal (1)	90	177	258	341	636	867
Horizontal (2)				18	36	50
Vertical (3)	18	40	64	29	81	149
Vertical (4)	22	46	71	49	112	180
Oriented45 (5)	74	145	212	279	526	727
Oriented45 (6)				18	34	49

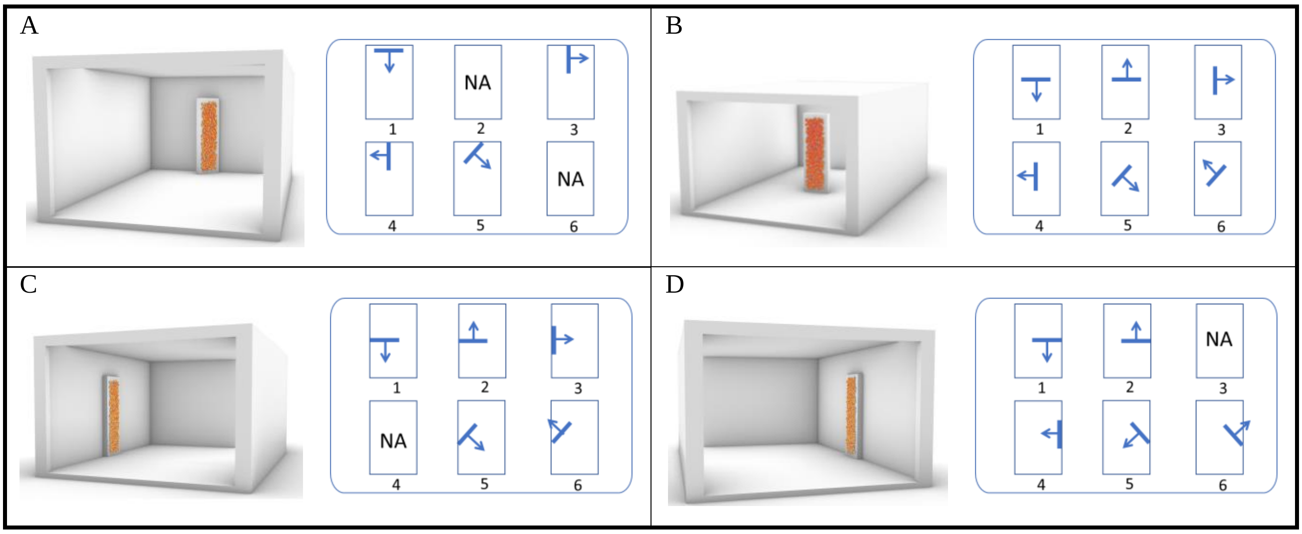

Figure (2) : Green wall Location and Orientation options in the study. (Source: Authors)

Table 1 b: Average PAR levels received by walls without leaves for each design option in the study according to the glazing ratios (side walls)

	Left side (C)			Right side (D)		
Glazing Ratio	25%	50%	75%	25%	50%	75%
Horizontal (1)	200	402	601	164	338	520
Horizontal (2)	21	41	58	18	35	50
Vertical (3)	119	224	302			
Vertical (4)				101	192	262
Oriented45 (5)	215	424	616	166	329	484
Oriented45 (6)	19	38	54	21	41	62

Tables 2a and 2b present calculated performance results for the design iterations in this study, which indicate that the best design option is the one with the minimum distance and facing the glazed façade, regardless of the glazing ratio. Additionally, for lower glazing ratios, the location and/or orientation of the green wall had a major impact on its calculated performance. These findings highlight the importance of carefully considering the placement and orientation of green walls in order to optimize their benefits.

Table 2 a: estimated performance in $mgCO_2/h$ for each design option in the study according to the glazing ratios (back wall and halfway)

	Back wall (A)			Halfway (B)		
Glazing Ratio	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Horizontal (1)	-36.6	601.8	1012.3	1255.2	1549.8	1588.7
Horizontal (2)				354.0	1270.9	1586.6
Vertical (3)	-193.5	-86.5	374.5	263.30	1036.5	1443.9
Vertical (4)	-184.9	-50.3	339.4	93.0	877.3	1348.8
Oriented 45 (5)	-102.9	413.2	839.5	1063.4	1479.7	1569.3
Oriented 45 (6)				134.6	942.7	1439.6

Table 2 b: estimated performance in $mgCO_2/h$ for each design option in the study according to the glazing ratios (side walls)

	Left side (c)			Right side (d)		
Glazing Ratio	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Horizontal (1)	578.8	1351.5	1536.2	674.9	1342.4	1541.2
Horizontal (2)	-242.6	510.6	1229.9	-163.8	517.8	1251.5
Vertical (3)	109.2	981.7	1141.9			
Vertical (4)				96.54	768.9	1146.5
Oriented45 (5)	633.3	1349.7	1516.8	546.3	1245.6	1486.8
Oriented45 (6)	-23.5	781.4	1400.7	-55.3	685.7	1327.2

In order to compare the effectiveness of green walls in enhancing indoor air quality, Table 3a and 3b present the reduction in CO_2 concentration measured in parts per million per hour (ppm/h) for each design option in this study, according to the volume of the hypothetical room.

Table 3a: calculated reduction in CO_2 concentration for each design option in ppm/h (back wall and halfway)

	Back wall (A)			Halfway (B)		
Glazing Ratio	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Horizontal (1)	-0.8	1.4	2.3	2.8	3.5	3.6
Horizontal (2)				0.8	2.9	3.6
Vertical (3)	-0.4	-0.2	0.9	0.6	2.4	3.0
Vertical (4)	-0.4	-0.1	0.8	0.2	2.0	3.1
Oriented45 (5)	-0.2	0.9	1.9	2.4	3.4	3.6
Oriented45 (6)				0.3	2.2	3.3

Table 3b: estimated reduction in CO_2 concentration for each design option in ppm/h (side walls)

	Left side (c)			Right side (d)		
Glazing Ratio	**25%**	**50%**	**75%**	**25%**	**50%**	**75%**
Horizontal (1)	1.3	3.1	3.5	1.5	3.1	3.5
Horizontal (2)	-0.6	1.2	2.8	-0.4	1.8	2.8
Vertical (3)	0.3	2.2	2.6			
Vertical (4)				0.2	1.7	2.6
Oriented45 (5)	.15	3.1	3.4	1.3	2.8	3.4
Oriented45 (6)	-0.1	1.8	3.2	-0.1	1.6	3.0

Aiming to better understand the relationship between light levels and the calculated performance of green walls, Table (4) presents the percentages of leaves receiving different levels of PAR according to simulations for the best and least-performing design options in this study. These results demonstrate that in the best-performing options, leaves were receiving higher PAR levels than in the least-performing options. This suggests that light levels may play a significant role in the effectiveness of green walls. These findings may have important implications for the design and implementation of green walls in indoor environments, particularly in terms of maximizing their potential benefits for indoor air quality.

Table 4: light levels in PAR received by each leaf in the best and least performing options for each glazing ratio.

	25% glazing ratio		50% glazing ratio		75% glazing ratio	
PAR Level	Best	least	Best	least	Best	least
0-14	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%
14-29	8.2%	71.4%	0.0%	54.8%	0.0%	18.4%
29-38	28.0%	28.6%	0.0%	28.4%	0.0%	24.8%
38-70	63.8%	0.0%	4.6%	14.8%	1.0%	50.2%
70-250	0.0%	0.0%	70.6%	0.6%	54.2%	6.6%
250-350	0.0%	0.0%	18.8%	0.0%	25.6%	0.0%
Above 350	0.0%	0.0%	6.0%	0.0%	19.2%	0.0%

Discussion

By bridging the gap between lab testing and in-situ studies, this methodology offers accurate and reliable means of evaluating the potential performance of green walls in real-world settings. Additionally, the methodology incorporates past studies of plant behaviour in different environments, particularly regarding light levels, to estimate the behaviour of the plant and calculate the green wall's performance accordingly. Overall, this study highlights the potential of simulation-based approaches to support the design and implementation of green walls in indoor environments.

The second step of this study involved implementing the proposed methodology to evaluate the performance of a green wall in a hypothetical indoor environment. As expected, the green wall performed better when receiving higher light levels. This was clear when the average sunlight received by the wall was above PAR m^{-2} s^{-1}, which agrees with Guo et al., (2014) and Torpy et al., (2014). On the other hand, in cases where the wall received average sunlight under 25 PAR m^{-2} s^{-1} had a negative impact on the IAQ by producing CO_2, which is in agreement with the conclusions drawn by Torpy et al. (2017) and Lehmann & Kleber, (2015), that lower light levels can increase indoor CO_2 levels. Nevertheless, in some cases such as back wall horizontal (A-1) and back wall oriented 45 (A-5), the average sunlight received by the plain wall was above 70 which in theory will have a positive effect on IAQ. However, the calculated performance results demonstrated a negative impact, which highlights the importance of testing each leaf individually.

The study also demonstrated the ability of the proposed methodology to differentiate between different glazing ratios. The results showed that in the case of a glazing ratio of 75%, all design options were functional and the difference in performance between them was minimal. This indicates that there is sufficient sunlight levels in the room, allowing for the green wall to perform well regardless of its location or orientation. However, in the case of a glazing ratio of 25%, the study highlighted the importance of carefully considering the location and orientation of a green wall in order to optimize its performance. The results showed that the best-performing design options were those located closer to the glazed facade and facing it. This indicates that in spaces with lower glazing ratios, the availability of light becomes a crucial factor in the performance of green walls.

PAR levels obtained from the simulations of the best and least-performing options for each glazing ratio showed that the least-performing option in the 25% glazing ratio had most of the leaves receiving light levels below the recommended levels for photosynthesis. The results from the best performing option in the 25% glazing ratio, with all leaves receiving light levels below the recommended range of 350 μmol PARm^{-2} s^{-1}(Guo et al., 2014; Torpy et al., 2014), further emphasize the need for careful consideration of light levels in the design of indoor green walls to optimize their performance. Designers who incorporate green walls into their building designs with the assumption that they will enhance air quality, but without considering the light levels received by the plants, may inadvertently undermine indoor air quality. These findings suggest that early design decisions regarding the location and orientation of green walls are essential to ensuring positive impact in enhancing indoor air quality. Designers should also consider the impact of other design elements such as furniture or shading devices that may affect the distribution of light within a space and the performance of green walls.

Conclusions and Recommendations

One of the main challenges in studying vegetation is the variability in plant behaviour across different environments. To address this issue, the proposed methodology leverages the power of simulation to evaluate the environment in which the plant will be grown on-site. This study proposed a method that can estimate the performance of a green wall according to the light levels received by the plant in the environment. This was verified by applying the model to the plant Epipremnum Aureum in various locations and orientations for the green wall. To the best of our knowledge, this is the first tool to be developed with the specific purpose of aiding architects to make informed design decisions regarding the use of green walls in early design stages using computer simulation.

The proposed methodology in this study demonstrated a large range of light levels received by plants' leaves, which means that the leaves' ability to perform photosynthesis varies according to the location and orientation of the green wall or even between different leaves in the same wall. This indicates that each leaf should be studied individually to be able to accurately calculate the overall performance of the green wall.

This study revealed the importance of performing early design simulations when implementing green walls in the design. It defined major performance differences between various options for green walls' location and/or orientation based on the amount of light received by the plants' leaves. The results showed that in some cases using green walls will have a negative effect on IAQ. As expected, the best-performing option was when the wall was exposed to the maximum light level. Additionally, the best performing walls according to this study were in the middle of the room, which in theory will affect light provision within the room. This emphasizes the importance of using this methodology in early design stages. To ensure that the proposed green walls are functional in enhancing indoor air quality without affecting the overall light requirement in the room. Unfortunately, there is a shortage of data regarding plant performance, which the research team believe would be a good area of collaboration between biologists/botanists to generate the data, and architects to use that data in design applications. While the results of this study are promising, further validation through physical testing is needed to ensure the accuracy and reliability of the methodology.

Epipremnum Aureum was used in this study, any plant species with sufficient data on its CO_2 sequestering performance can be employed by designers, through feeding the software the relative information captured from previous studies. More importantly, collaborative efforts could make this data easily accessible through creating libraries that can be adapted directly into design software. Similarly, the research here was based on Cardiff's sunlight and environmental conditions, but other geographical locations and lighting conditions can be utilized.

Limitations and Future Work

This study has limitations that will be addressed in future research. It solely examined the methodological approach of simulating green wall performance through sunlight simulations, and only considered performance differences with changes in location and/or orientation within the same room. Future work will include environmental and contextual factors such as material, building type, occupant number, and window geometry.

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