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Impact of vertical greening on urban microclimate and historic building materials: A meta-analysis

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ABSTRACT

An urban environment is subject to elevated temperatures and higher pollution levels compared to less densely populated areas. Implementing green infrastructures, such as vertical greening, is one method to mitigate this effect. Vertical greening is especially suitable for built heritage in city centres due to the limited space required for plant growth, while still providing substantial green surface area. However, built heritage is often excluded from mitigation strategies due to the unknown potential risks of vertical greening on the degradation of historic building materials. This paper provides a meta-analysis of the literature to establish a current understanding of how the introduction of vertical greening affects microclimates near the surfaces of built heritage and associates those changes with common degradation mechanisms of historic building materials including salt crystallization, freeze-thaw weathering, biodeterioration and chemical weathering resulting from pollutant dispersion. Vertical greening can reduce the fluctuations of surface temperature, air temperature, relative humidity and the amount of solar irradiation and particulate matter on a wall, which is likely to reduce the risk of most common degradation mechanisms in historic building materials induced by salts and frost. Even though degradation induced by particulate matter and bio-activity has received less attention in the literature, our analysis suggests that these factors can also be influenced by vertical greening. The risk of chemical degradation appears to decrease with vertical greening while bioactivity may increase.

1. Introduction

Climate change is one of the major global challenges for society in the 21st century [1]. Global temperatures are rising due to greenhouse gas emissions, causing changes in weather patterns, including more frequent and more extreme weather events. This has drastic consequences for the natural and human environment [2,3]. The effects of climate change are not only observable on a global scale but are also apparent when considering individual cities. The urban fabric, with its lack of vegetation, is responsible for the urban heat island (UHI) effect, which is the most pronounced at night [4–9]. Due to higher rates of hard coverage and building materials, cities experience higher temperatures and pollution levels relative to their less dense surroundings. Urban materials absorb heat from solar irradiation and re-emit the absorbed heat to the environment at night. This effect can influence both the health and well-being of city residents and the biodiversity: changes in temperature, relative humidity or precipitation can cause a wider spread of infection and increase the risk of mortality [10] and pollution levels might lead to severe respiratory problems. Moreover, the UHI has intensified over the past few decades, contributing to an increase in the frequency and severity of extreme weather conditions such as heat waves [9–13].

To mitigate the UHI effect in urban environments, cities are implementing nature-based solutions (NbS). They are sustainable methods of implementing blue (water-based) and green (plant-based) infrastructure in the urban environment to address environmental, societal and economic challenges [14–16]. Some well-known types of NbS are green walls, green roofs, parks, street trees, and rain gardens, each having particular requirements for regarding implementation and potential contributions to adaptation and mitigating of the adverse effects of climate change. In cities, nature-based solutions are known for providing multiple benefits including health impacts, UHI mitigation,

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carbon sequestration, biodiversity, urban agriculture, improving air quality, acoustic benefits, opportunities in jobs and investment and social cohesion [16–18].

One of the well-known green initiatives implemented in dense urban environments is vertical greening due to its small footprint and ability to cover a large surface area with vegetation. There are generally two types of vertical greening: green façades and living wall systems. Green façades consist of vegetation growing on wall surfaces, either by attaching themselves to the surface or a supporting trellis. Living wall systems are systems where plants grow in planter boxes attached to the walls and are not connected to the ground surface. Compared to green initiatives such as trees, living wall systems or green roofs, ground-based vertical greening is a poorly researched green initiative. Even though there is a growing interest in exploring ground-based vertical greening and its mitigating impact on the nearby environment, the research often overlooks the potential impact of such vegetation on the surrounding buildings. Consequently, this paper delves into the implication of ground-based vertical greening on the built environment, with a specific focus on its influence on the urban microclimate and building façades.

Historic buildings are often excluded from mitigation strategies despite their prominent presence in the centre of urban areas as an integral part of urban environments. Due to their abundance in historical, archaeological, architectural, aesthetic and cultural values, it is critical to keep historic buildings well preserved and maintained. However, the growing urgency to tackle the climate stressors by improving sustainability puts additional stresses on historic buildings. Due to their prominent presence in city centres, where the urban heat island effect is most pronounced, built heritage has a significant potential to contribute to the current mitigation strategies by providing ample opportunities for the implementation of vertical greening.

The dense urban fabric, conservation principles and restrictions, and the apprehension due to possible biodegradation and perceived material fragility hinder the implementation of urban green in built heritage sites [17,19]. However, recent claims demonstrate positive effects resulting from the interaction of greening with built heritage. The multiple benefits – social, environmental and economic benefits – provided by NbS evolve in mutual benefits for built heritage and the NbS. In contrast to the general perception, greening built heritage can potentially minimize or mitigate deterioration of the historic building materials, encourage investment, and enhance the values of the built heritage [17,20–22]. The preference for ground-based vertical greening can be attributed to its lower installation and maintenances costs, as well as ability to cover a large green surface area while only needing a limited footprint [23–26]. Due to restricted space in city centres, these characteristics make an implementation of vertical greening on built heritage a feasible option for mitigating the urban heat island effect. However, the current state of the evidence base for understanding technical compatibility of built heritage with vertical greening is not well known.

To address this gap, this review provides a comprehensive meta-analysis of experimental results in published academic literature to establish current understanding of the impact of vertical greening on the local microclimate.

2. Methodology

This paper analyses peer-reviewed academic literature that includes experiments performed in the field evaluating microclimatic conditions for bare walls and how these vary with the implementation of vertical greening. Vertical greening is in literature often understood as plants, rooted in the ground, climbing up the façade by either attaching themselves on the exterior surface or by using metal wires to attach them (Fig. 1).

The aim was not a systematic literature review but a meta-analysis (a statistical combination of results from several separate studies), collecting all data dealing with the impact of vertical greening on the local microclimate to have a range of the performance of vertical greening.

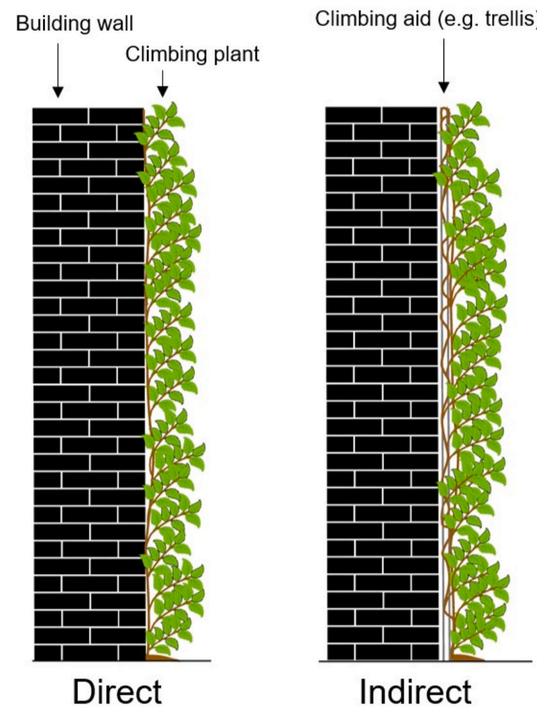

Fig. 1. An example of different ground-based vertical greening: direct and indirect green façade. Figure is based on Bustami et al. [27]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The term microclimate refers to "the whole ambience which is necessary to study in order to know the factors which have a direct influence on the physical state of the monument and the interactions with the air and the surrounding objects." [28]. The local microclimate is herein defined as the microclimatic conditions on or nearby the wall surface. The analysis includes 58 publications discussing the impact of vertical greening on the local microclimate and 47 of which provide detailed data [20,22,25,33–85]. Every publication was manually selected from literature based on availability, including all relevant publications mentioned in the reference list of formally extracted publications. Authors were personally contacted to retrieve additional data for conducting this meta-analysis. All data from the selected literature is collected in Excel and all graphical analyses were performed using the statistical software RStudio. The selection of publications was not exhaustive, but broadly applied the following criteria.

- Focussed on ground-based vertical greening and its influence on local microclimate; vertical greening often also includes living wall systems, which are excluded from this research [23,27];
- Including sufficient data for comparing bare and greened walls in the same scenario, sometimes acquired by contacting authors directly, or through open access and institutional repositories;
- Experimental case studies in ambient outdoor environments (i.e., laboratory investigations and simulations were excluded);
- Data of publications contains information on the impact of vertical greening on the maximum, minimum and average values of the environmental parameters.
- Providing detailed information of the experimental case studies, including boundary conditions such as climate type, orientation, seasonality, foliage thickness
- Published before May 2022, when this meta-analysis started.

Most publications included were published after 2008 and all investigated the impact of vertical greening on the local microclimate in northern hemisphere locations, except for one study. Due to the limited data available from the southern hemisphere, this meta-analysis concentrates solely on studies from the northern hemisphere. It is interesting to note that a high number of publications were found in *Building and Environment*, as well as in energy related journals such as *Energy and Buildings* and *Applied Energy*.

Five environmental parameters – surface temperature, air temperature, solar irradiation, relative humidity, and particulate matter – are chosen to be covered in this analysis due to their availability and importance in the deterioration of building materials. The impact of vertical greening on the maximum, minimum and average values of those parameters was collected in a datasheet and analysed in Rstudio. The analysis discusses the mean value and range of the influence of vertical greening to provide insightful conclusions on the impact of vertical greening on the maximum, minimum and average values of those parameters. Each of the minimum, average and maximum values of the environmental parameters contribute to one of the most common deterioration processes of historic building materials: salt crystallization, freeze-thaw weathering, biodeterioration and chemical deterioration. The maximum and minimum values are most significant in determining the risk on salt crystallization or freeze-thaw weathering, while the average values are most significant in establishing the risk on the chemical deterioration and biodeterioration.

2.1. Preliminary analysis of environmental parameters

An overview of the analysed publications illustrates that some parameters receive much more attention in literature than others (Table 1).

Most studies focus on the effect of vertical greening on surface temperature in order to understand the energy performance of a building. The surface temperature is seen as the energy balance centre of cities and is one of the most important factors affecting urban climate, and regulating and controlling various ecological processes [10].

Further, almost half of the articles examine how vertical greening impacts the air temperature in front of the wall and the amount of solar irradiation received by a wall. The focus on air temperature is particularly related to improving thermal comfort and mitigating climate stressors in an urban environment. The air temperature at 2 m height is widely recognized as a key indicator for the urban heat island effect since it can directly influence human comfort [13]. Meanwhile, solar irradiation is investigated regarding the energy performance of a building to prevent overheating during extreme weather events in an urban environment, such as heat waves, and to regulate the energy efficiency. The importance of incorporating solar irradiation lies in the strong correlation with air temperature, surface temperature and relative humidity.

Next, only one-fourth of the observed literature considers the impact of vertical greening on the relative humidity, even though, relative humidity is inversely correlated to air temperature and is frequently studied simultaneously [29]. The relative humidity is defined as the difference between the actual amount of water vapour in the air and the maximum amount of water vapour that can exist in the air at the current temperature [30]. However, the relative humidity occasionally depends on meteorological factors including rainfall, wind speed, and whether it is a cloudy or sunny day [29].

Lastly, only a few articles scope the impact of vertical greening on air pollution. Human activities reliant on the combustion of fossil fuels, such as industrial processes, construction, electricity production, and transportation, have increased the concentration of particulate matter drastically during the past few decades. Air pollution is included in this meta-analyses due to their abundance in city centres affecting health and well-being of the residents and being part in degradation processes, such as the formation of gypsum and soiling processes [28,31,32]. However, only six articles focus on the impact of vertical greening on air pollution and two of them analysed the quantity of particulate matter captured by vertical greening. In comparison with ground-based vertical greenery systems considered herein, vertical living wall systems and their relation with particulate matter receive a lot more attention in research. The living wall systems, referring to vegetation grown in planter boxes on the façade, can be implemented on new buildings, but such implementation would be too complex and harmful for historic buildings.

2.2. Physical processes characterizing the performance of vertical greening

The presence of vertical greening can alter the local microclimate resulting from the occurrence of three main processes whereas the magnitude of the impact of vertical greening is affected by the characteristics of the wall and the vegetation.

Plants create transpiration when exposed to solar irradiation since vertical greening compromises living plants. During transpiration, plants absorb liquid water from the ground and release it as a gas phase through the stomata of their leaves which makes the environment more humid and cooler. A low amount of moisture in the environment, which is related to a warm environment, generates a gradient for water to move from the leaves to the environment [30,86,87].

Vertical greening is able to delay the heating and cooling process of the bare wall due to the presence of an additional vegetative layer in front of the bare wall. This layer covers the wall from the environmental factors, such as solar irradiation, air pollution and precipitation, resulting in a delay in the heating process of a wall behind the vertical greening compared to a wall without any greening. Additionally, this phenomenon also works in the opposite way. The heat, coming through the layer of vertical greening, is absorbed by the wall behind the vertical greening and cannot easily be exchanged with the environment to cool down the wall. In this case, the layer of vertical greening acts as a blanket by keeping the heat in the layer between the vertical greening and the underlaying wall. This phenomenon is known as the thermal blanketing effect of vertical greening. As a result, vertical greening delays the cooling process of the wall behind the vegetation layer compared with the cooling process of a wall without vertical greening

Table 1
The number of articles investigating the impact of vertical greening on the local microclimate, divided by five environmental parameters. [20,22,25,33–85]. A subdivision is made between publications that provide numerical data and publications with a descriptive analysis only. For some environmental parameters, the publications with numerical data are subdivided into the publications that cover the impact of vertical greening on the maximum, minimum, and mean values of the environmental parameter, represented by 'Max', 'Min', and 'Mean'.

Parameter	Total number of articles	Number of articles with numerical data				Number of articles with a descriptive analysis
		Total	*Max*	*Min*	*Mean*	Total
Surface temperature	46	38	*29*	*20*	*35*	8
Air temperature	27	22	*12*	*8*	*20*	5
Relative humidity	20	11	*6*	*7*	*10*	9
Solar irradiation	20	11			*11*	9
Particulate matter	6	2			*2*	4
Total	*56*	*47*				*9*

[86,88,89].

Solar irradiation, vegetation traits, and wall features influence these processes. Higher amount of solar irradiation increases plant transpiration, heats the bare wall, and is more likely to cast shadow on the wall behind the vegetation. This amplifies the thermal differences between a bare wall and one with vertical greening.

The amount of shading, thermal blanketing and transpiration is depending on the characteristics of vertical greening, such as the dimensions of the vertical greening layer, the leaf area index of the species or the type of plant [84,86,87]. For instance, increasing the density of the vertically greened façade, which is often related with a higher (wall) leaf area index, provides more cooling potential due to a higher shading potential [84]. The plants characteristics are also depending on the amount of solar irradiation receiving as this is a necessary component for plant growth.

Additionally, how much a wall can heat up depends on its heating capacity and the surroundings. In an urban environment, hard coverage and building materials can absorb solar irradiation and reflect solar irradiation to surrounding surfaces resulting in possibly higher amount of solar irradiation reaching the wall [11,90,91]. Each material has its own thermal capacity which relates to the rate and intensity of heating. In situation of a sunny day, solar irradiation will heat up the wall during the day, while at night, the temperature in the environment will lower and the wall will exchange the aborded heat with its colder surroundings. As mentioned before, vertical greening delays this effect and the magnitude will be determined by the materials used in the building envelop.

2.3. Environmental and experimental boundary conditions characterizing the performance of vertical greening

Each of the publications included in the analysis contains information about the impact of vertical greening on the aforementioned environmental parameters. This meta-analysis investigates various scenarios affecting the performance of vertical greening on the local microclimate. The scenarios consist of different environmental situations or situations with different plant or experiment characteristics. The impact of vertical greening on the local microclimate is investigated for each scenario independently to understand the impact of a certain environmental or experimental boundary condition on the performance of vertical greening. Four boundary conditions, such as climate type, seasonality, orientation and foliage thickness, are considered in this meta-analysis and are interdependent and closely correlated with the impact of vertical greening. Although there is expected to be variation in the performance of vertical greening on the local microclimate if vertical greening is implemented in different scenarios, trends and commonalities can still be obtained or contradictories can be explained by relevant local factors.

The literature provides sufficient information on the impact of vertical greening on the surface and air temperature, relative humidity and the amount of solar irradiation in all different scenario's, except for the analysis on solar irradiation with different foliage thicknesses. The impact of vertical greening on the deposition of air pollution cannot be investigated in different scenario's due to the lack of data in literature.

2.3.1. Climate type

The literature deals with field experiments performed in different climate types, according to the Köppen classification [92]. The climate types, for which there is adequate data to compare, are: hot-summer Mediterranean climate (Csa), temperate oceanic climate (Cfb), hot-summer humid continental climate (Dfa), humid subtropical climate (Cfa), dry winter and hot-summer humid continental climate (Dwa) and the tropical rainforest climate (Af). While each environmental parameter is not examined equally in all six classifications, there is sufficient coverage to enable a general discussion.

Each climate type has unique characteristics that will influence how vertical greening affects the local microclimate. For example, one climate type, the tropical rainforest climate (Af), is not characterised by warm and cold months and has an average temperature in every month of the year of 18 °C. Other climate types have an average temperature of 22 °C in their warmest months, except a temperate oceanic climate (Cfb) has an average temperature of lower than 22 °C. A hot-summer humid continental climate (Dfa) has a dry winter and a hot-summer Mediterranean climate (Csa) has a dry summer, while the other climate types have no dry season.

There are considerable differences in the quantity of yearly horizontal solar irradiation received by each climatic type: a high amount for the tropical rainforest climate (Af) (±1800 kWh m^{-2}), and a low amount for a temperate oceanic climate (Cfb) and a hot-summer humid continental climate (Dfa) (1000–1200 kWh m^{-2}). Other climate types of this meta-analysis have a quantity of the yearly horizontal solar irradiation between those two values.

2.3.2. Season

In the meta-analysis, the year is simplified into three seasonal categories – winter, summer and 'other' (combining spring and autumn) – based on variation in weather, ecology and the number of daylight hours giving in a region [93]. Spring and autumn are combined in the subcategory 'other' due to their similar environmental conditions and the lack of data to make a large distinction between autumn and spring.

These categories facilitate the data comparison across studies, reflecting the distinct temperature and solar irradiation conditions that can influence plant growth and deciduous leaf presence [94]. For instance, summer is characterised by warm temperatures and a high amount of solar irradiation while winter has the opposite characteristics. Autumn and spring have more moderate characteristics which are represented by moderate temperature and moderate amount of solar irradiation.

2.3.3. Orientation

In order to determine the place of vertical greening on a building envelop, the observed publications use the four cardinal directions (north, east, south, and west). The cardinal directions use the rising (east) and setting (west) of the sun as a reference for determining the directions. Intercardinal directions, such as northeast, northwest, southeast and southwest, are also present in the observed literature but the focus tends to the cardinal directions to investigate the main influences of orientation on the impact of vertical greening on the local microclimate.

Since plants rely on solar irradiation for growth and transpiration, the application of vertical greening might affect the growth and the local microclimate differently in each orientation. This meta-analysis contains studies where the south orientation is known to receive the most solar irradiation throughout the day as the sun is at its highest point, while the north orientation receives the least.

2.3.4. Foliage thickness

As this meta-analysis investigates the impact of vertical greening on the local microclimate, the thickness of the vertical vegetation layer is likely to define the extent of the impact on the local microclimate. The more plants available or the thicker the vegetation layer, the more vertical greening can have its impact on the local microclimate [39,46].

The analysed publications contain experiments of vertical greening with foliage thicknesses varying from 10 mm to 950 mm. In order to investigate the relationship between the thickness of the vegetation layer and the impact of vertical greening on the local microclimate, the results of the publications are divided in subcategories based on their foliage thickness. Each subcategory contains experiments between a range of 50 mm whereas the name of the subcategory is the middle of the interval.

3. Results of meta-analysis

3.1. General impact

The literature agrees that vertical greening can reduce the amplitude of temperature and relative humidity variation in relation to the local conditions, as well as reduce the amount of incoming solar irradiation and particulate matter on a wall. The effect of vertical greening on the surface temperature, air temperature and relative humidity is analysed using their maximum, minimum and average values, whilst the amount of solar irradiation and air pollution is analysed using average values. The maximum values of the surface and air temperature is more affected by an implementation of vertical greening than the minimum values, meaning that a maximum surface or air temperature changes more than the minimum surface and air temperature of a wall by an implementation of vertical greening. As the surface and air temperature are inversely related with the relative humidity, the opposite effect is valid for the maximum and minimum values of the relative humidity due to an implementation of vertical greening. More specifically, vertical greening has a more significant increase on the minimum relative humidity than on the maximum relative humidity due to the evaporation and the inverse relationship with air temperature. Additionally, vertical greening will act as a protection layer on the wall resulting in a lower amount of solar irradiation and air pollution reaching the wall.

3.2. Performance of vertical greening considering environmental or experimental boundary conditions

3.2.1. Climate types

The amount of solar irradiation can be related to a climate type of a certain region and may have the most significant impact on the vertical greening performances due to its relationship with the aforementioned processes, which enables vertical greening to change the local microclimate. The more solar irradiation a climate type receives during the year, the more pronounced the impact of vertical greening is on the surface temperature, air temperature, and relative humidity of the local environment. One of the observed climate types, temperate oceanic climate (Cfb) deviates from this hypothesis due to strong wind effects [95]. However, the hypothesis is not true for the impact of vertical greening on the amount of solar irradiation reaching the wall.

By analysing the maximum and minimum values of the environmental parameters (surface and air temperature and relative humidity), literature concludes that vertical greening has the most significant impact on the maximum surface and air temperature and the minimum relative humidity for an implementation in each climate type (Table 2).

Vertical greening implemented in a tropical rainforest climate (Af) was able to reduce the maximum surface temperature of a wall by an average of 8.0 °C, while respectively, vertical greening implemented in a temperate oceanic climate (Cfb), hot-summer Mediterranean climate (Csa), humid subtropical climate (Cfa) or hot-summer humid continental climate (Dfa) could reduce the maximum surface temperature by an average of 7.7, 6.4, 5.0 and 4.6 °C respectively. However, only one article discusses the impact of vertical greening on the maximum surface implemented in a tropical rainforest climate (Af) [44].

The impact of vertical greening on the maximum air temperature was less pronounced than the impact on the maximum surface temperature but has a higher variability across the different climate types. Surface temperature is more dependent on shadow effect, while air temperature relies on the transpiration of plants which varies more due to the diverse plant characteristics. Vertical greening could reduce the maximum air temperature the most when vertical greening is implemented in hot-summer humid continental climate (Dfa) by an average of 6.3 °C, followed by humid subtropical climate (Cfa), the tropical rainforest climate (Af), and temperate oceanic climate (Cfb). The average reduction of 6.3 °C in hot-summer humid continental climate (Dfa) is derived from two articles, published by the same author who performed several experiments leading to results ranging from −2.7 °C [33] to −10.3 °C [74].

Table 2
The impact of a green façade on a wall's maximum, average and minimum surface temperature, air temperature, relative humidity and a wall's average percentage of shielded solar irradiation relative to a corresponding bare wall, regarding different climate types.

CLIMATE TYPE	MAX	AVERAGE	MIN
Surface Temperature difference [°C]			
Temperate Oceanic Climate (Cfb)	−7.7 (*n* = 8)	−1.4 (*n* = 11)	0.7 (*n* = 9)
Hot-Summer Mediterranean Climate (Csa)	−6.4 (*n* = 6)	−4.6 (*n* = 5)	2.0 (*n* = 3)
Hot-Summer Humid Continental Climate (Dfa)	−4.6 (*n* = 2)	−0.7 (*n* = 2)	1.1 (*n* = 2)
Humid Subtropical Climate (Cfa)	−5.0 (*n* = 8)	−1.9 (*n* = 11)	1.1 (*n* = 5)
Tropical Rainforest Climate (Af)	−8.0 (*n* = 1)	−5.5 (*n* = 3)	−0.1 (*n* = 1)
Air temperature difference [°C]			
Temperate Oceanic Climate (Cfb)	−0.7 (*n* = 2)	−0.7 (*n* = 7)	−0.3 (*n* = 2)
Hot-Summer Mediterranean Climate (Csa)		1.2 (*n* = 1)	
Hot-Summer Humid Continental Climate (Dfa)	−6.3 (*n* = 7)	−1.2 (*n* = 7)	0.8 (*n* = 3)
Humid Subtropical Climate (Cfa)	−3.9 (*n* = 2)	−1.2 (*n* = 2)	0.4 (*n* = 1)
Tropical Rainforest Climate (Af)	−1.5 (*n* = 1)	−1.3 (*n* = 3)	−0.2 (*n* = 1)
Relative humidity difference [RH%]			
Temperate Oceanic Climate (Cfb)	−1.5 (*n* = 1)	2.0 (*n* = 3)	14.5 (*n* = 1)
Hot-Summer Mediterranean Climate (Csa)		−0.5 (*n* = 1)	
Hot-Summer Humid Continental Climate (Dfa)	−1.0 (*n* = 3)	3.1 (*n* = 3)	10.3 (*n* = 4)
Humid Subtropical Climate (Cfa)	1.8 (*n* = 1)	1.8 (*n* = 1)	12.7 (*n* = 1)
Tropical Rainforest Climate (Af)		−1.8 (*n* = 1)	
Solar irradiation difference [%]			
Temperate Oceanic Climate (Cfb)		−69% (*n* = 5)	
Hot-Summer Mediterranean Climate (Csa)		−75% (*n* = 1)	
Hot-Summer Humid Continental Climate (Dfa)			
Humid Subtropical Climate (Cfa)		−70% (*n* = 4)	
Hot-Summer Humid Continental Climate (Dwa)		−85% (*n* = 1)	

Vertical greening is able to increase the minimum relative humidity by average values ranging from 10.3% to 14.5% across the different climate types resulting in smaller relative humidity fluctuations on the wall relative to the relative humidity of the bare wall. The minimum relative humidity is inversely correlated with the maximum air temperature and reached when a lot of solar irradiation is available. As a result, plants are able to transpire more, causing a higher RH in the surroundings. The most pronounced effect was observed for vertical greening implemented in a temperate oceanic climate (Cfb), followed by a humid subtropical climate (Cfa) and hot-summer humid continental climate (Dfa). The most significant increase in minimum relative humidity due to vertical greening is represented by a reduction of 38% in a humid subtropical climate (Cfa). In this study, the relative humidity of the bare wall fluctuates between 60% and 95%, while the relative humidity of the vertically greened wall only fluctuates between 92 % and 99%.

Contrarily, the impact of vertical greening on the minimum surface and air temperature and maximum relative humidity is, according to the average results for each parameter, rather small and does not differ much across different climate types. Vertical greening increases the minimum surface and air temperature for implementations in all climate types except for an implementation in a tropical rainforest climate (Af), probably due to the quite constant temperature throughout the year. A tropical rainforest climate is characterised by an average temperature of 18 °C in every month which lowers the effect of thermal blanketing. However, there were some extreme results in literature on the impact of vertical greening on the minimum surface temperature. The most significant increases on the minimum surface temperature are observed in a hot-summer Mediterranean climate (Csa) by 6.0 °C [47] and in a temperate oceanic climate (Cfb) by 3.5 °C [34] and 3.9 °C [46].

Additionally, vertical greening is able to lower the amount of solar irradiation on the wall surface behind the vertical greening with at least 70%. The most significant reduction is seen in a hot-summer humid continental climate (Dwa) by 85% while the smallest reduction is only 70% in a temperate oceanic climate (Cfb). As a wide variety of results on the shielding properties of vertical greening layer is observed in the analysed publications, the impact on the incoming solar irradiation due to vertical greening is less likely to have a strong relationship with the climate.

3.2.2. Seasonality

As vertical greening comprises living plants, seasonality influences their growth and can determine whether the greening has leaves in the winter. Additionally, seasons are closely related to the amount of solar irradiation in the environment.

Vertical greening has the most significant impact on the maximum surface and air temperature and the amount of solar irradiation during summer and the least significant during winter (Fig. 2). Summer provides a high amount of solar irradiation enabling the transpiration of plants and provide shadow on the underlying wall by shielding the wall from solar irradiation. The opposite effect is observed for the minimum surface and air temperature. It is not possible to make a statement on the variation in effect of vertical greening on the relative humidity between summer and winter due to the lack of data.

More specifically, the presence of vertical greening during summer can lower the wall's maximum surface temperature by an average of 8.2 °C. The findings of 23 analysed studies dealing with the maximum surface temperature of a wall behind a green façade relative to the bare wall are very diverse and range between +0.4 °C [60] and −16.4 °C [51]. In contrast, the presence of vertical greening has nearly no impact on the wall's minimum surface temperature during summertime. The impact of vertical greening on the maximum air temperature is also the most significant in summertime, but has a smaller effect than vertical

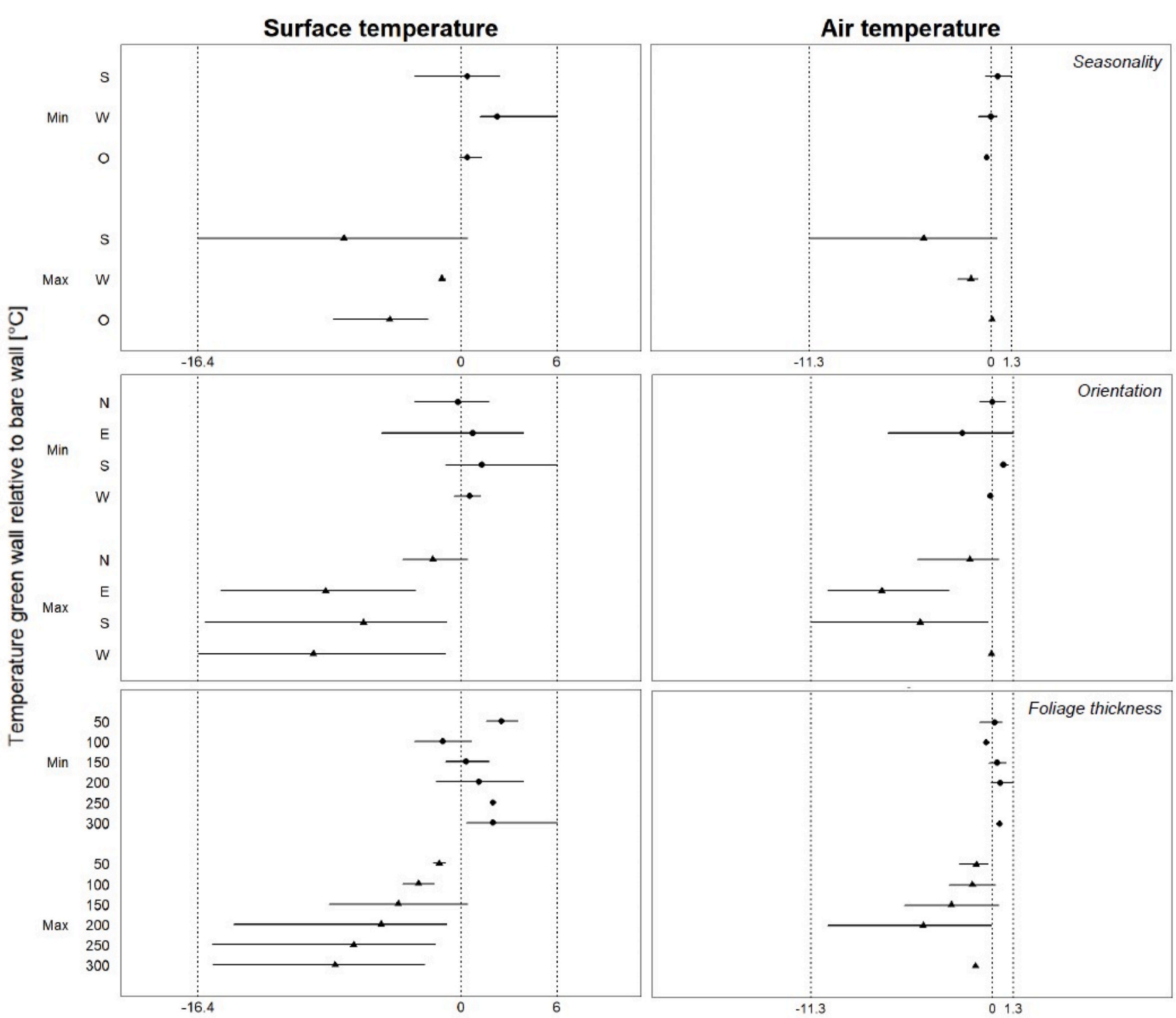

Fig. 2. Temperature differences of the green wall relative to the bare wall for surface and air temperature in different seasons, orientations and for different foliage thicknesses. The dots represent the mean value of the minimum values for a certain scenario while the squares represent the mean value of the maximum values for a certain scenario. The line represents the range in which the values are varying.

greening on the maximum surface temperature. Similar to previous scenario, the available solar irradiation in summer provides the possibility of transpiration of plants, but shielding the wall from solar irradiation by vertical greening looks more effective on the temperature results. The outcomes of nine publications ranged the impact of vertical greening on the maximum air temperature widely from +0.4 °C [60] to −11.3 °C [56]. Meanwhile, the minimum relative humidity can increase by 14.5 RH% in summertime due to the presence of vertical greening (Fig. 3). Since the increase in minimum relative humidity is highly dependent on the amount of solar irradiation available for transpiration of the vegetation layer, the results in the observed publication vary from −4 RH% to +38 RH% [59]. Additionally, during summer season, vertical greening allow the least amount of solar irradiation to pass, whereas winter and "other" seasons allowed twice as much. This phenomena might be related to the higher leaf area index of plants in summer, which means that a higher area of leaves can shield solar irradiation more [94].

It is obvious that vertical greening will have a high impact in summertime on the maximum surface and air temperature and minimum relative humidity but have almost no impact on the minimum surface and air temperature and maximum relative humidity. This phenomenon occurs because the results are highly dependent on the solar irradiation which is not available at night.

Publications investigating the impact of vertical greening on the local microclimate during winter season are scarce (n = 11) and their results are minimal. Due to the thermal blanketing effect and the available solar irradiation in winter, the minimum surface temperature increases and the maximum surface temperature decreases by an implementation of vertical greening. Although, vertical greening can, in comparison to a bare wall, raise the minimum surface temperature of a wall the most in winter: most results are between +1.2 °C [22] and +1.7 °C [42]. Two studies have found more extreme results such as +3.5 °C [34] and +6.0 °C [47]. Further, vertical greening in winter barely affect the maximum and minimum air temperature. In comparison to the air temperature in front of the bare wall, the minimum and maximum air temperatures around the green façade are, respectively, reduced by an average of −0.2 °C and −1.5 °C, due to the lower amount of transpiration. Only one study investigated the effect of vertical greening on the incoming solar irradiation in winter, and has a wide range of results, varying from 19% to 67% [37].

Spring and Autumn are more moderate in the amount of solar irradiation and their temperature which results in more moderate microclimatic changes by vertical greening.

3.2.3. Orientation

Generally, the analysed publications still agree with the general impact of vertical greening on the local microclimate when implemented in any orientation. More specifically, regardless of the orientation in which it is implemented, vertical greening will always have the most significant impact on the maximum surface and air temperature and minimum relative humidity and the least significant impact on the minimum and average temperatures and the maximum and average relative humidity.

However, comparing the magnitudes of the impact of vertical greening on the local microclimate across orientations, delivers noticeable discrepancies (Figs. 2 and 3). The observation related to orientations are only valid for the northern hemisphere, as this meta-analysis is limited to studies in the northern hemisphere.

First of all, literature is in agreement that the north orientation always has the lowest impact on the performances of vertical greening. While vertical greening, implemented in other orientations, can reduce the maximum surface temperature up to 16.4 °C [51] and the maximum air temperature up to 11.3 °C [56], north facing vertical greening is only able to lower the maximum surface temperature up to 3.6 °C [83] and the air temperature up to 4.7 °C [74]. Additionally, the most extreme impact of vertical greening on the minimum relative humidity, observed in literature, is an increase of 9.6 RH%, which is only a small impact compared to the increase in the minimum relative humidity up to 38 RH % if vertical greening is implemented in another orientation. The impact on the solar irradiation is also the least significant for an implementation of vertical greening in the north orientation, probably due to the less likeliness of having a full grown and dense layer of vertical greening and the indirect solar irradiation.

Moreover, observing the most significant orientation for an implementation of vertical greening in order to create the highest impact on the microclimate, is less straightforward. Vertical greening facing an east, south or west orientation receive more solar irradiation, which is favouring the transpiration of plants, than vertical greening in a north orientation. According to the average impact of vertical greening on the local microclimate, calculated for each orientation, the implementation of vertical greening on an east and west façade has the most significant impact in lowering the maximum surface and air temperature. However, some publications show that south facing vertical greening can lower the maximum surface temperature two times more than vertical greening orientated east or west. The results are highly influenced by the solar irradiation, resulting in high transpiration rates and shading purposes during the moments with a lot of solar irradiation, which can explain the high variability across literature.

Nevertheless, two of the observed publications specially examined the impact of vertical greening on the surface temperature of walls located in the four orientations. One study, performed in the UK [22], supported the findings of the observed publications, while the other study, performed in Chicago [74], shows contradictions regarding the maximum surface temperature. In the latter publication, south facing vertical greening had the most potential to reduce the maximum surface temperature of a wall, whereas east-facing vertical greening had the least potential. This difference is potentially related to the shading effects of the surrounding trees.

Further, the most significant impact of vertical greening on the minimum relative humidity and the amount of solar irradiation is reached when vertical greening is facing south. A south facing vertical greening can increase the relative humidity up to 38 RH% due to the

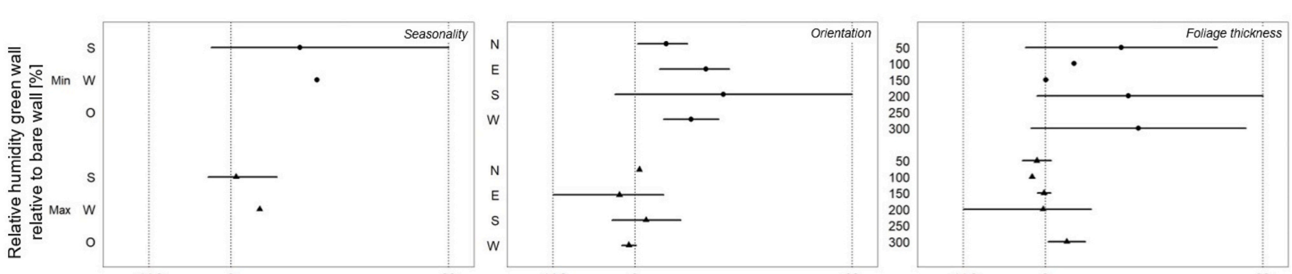

Fig. 3. Relative humidity differences of the green wall relative to the bare wall in different seasons, orientations and for different foliage thicknesses. The dots represent the mean value of the minimum values for a certain scenario while the squares represent the mean value of the maximum values for a certain scenario. The line represents the range in which the values are varying.

high amount of transpiration cooling the surrounding air. This increase in relative humidity due to the implementation of vertical greening result in a smaller range in which the relative humidity on a wall is fluctuating relative to a bare wall.

As vertical greening absorbs solar irradiation for transpiration and has a certain presence in front of the wall, the underlayer wall is covered from the solar irradiation and receives up to 96% less solar irradiation compared to a bare wall. Data of the observed literature illustrates the most significant impact of vertical greening on the amount of solar irradiation is an implementation of vertical greening in the south orientation.

3.2.4. Foliage thickness

Similar to other scenarios, even by dividing the observed publications into different subcategories based on the foliage thickness of the vertical greening of their experiments, the conclusions are mainly the same. The impact of vertical greening on the maximum surface and air temperature and minimum relative humidity is more significant than the impact on the minimum and average temperatures and the maximum and average relative humidity.

The subdivision of the observed literature illustrates that the impact on the maximum and minimum surface and air temperature and relative humidity is more significant as the foliage thickness increases (Figs. 2 and 3). Since more leaves are available in a denser layer of vertical greening, the process of transpiration and shading is more likely to occur. The impact of this relationship is more significant for the maximum values of the surface and air temperature relative to the minimum values and for the minimum values of the relative humidity compared to their maximum values.

However, the relationship between the thickness of vertical greening and their impact on the local microclimate is not always straightforward. One of the observed publications examined three thicknesses of vertical greening and their impact on the wall's surface temperature [59]. The thicknesses used during the experiment were 72 mm, 198 mm and 305 mm. Vertical greening with the moderate thickness of this experiment reduces the wall's maximum surface temperature twice as much as the most dense vertical greening. More specifically, vertical greening with a thickness of 198 mm showed to reduce the maximum surface temperature of a wall by 4.3 °C while vertical greening of 305 mm only reduces the maximum surface temperature by 2.3 °C.

4. Impact of vertical greening on the microclimate-induced deterioration

Building materials are subjected to deterioration caused by their interaction with environmental conditions. The magnitude and type of deterioration, typical for built heritage, depends on intrinsic (material properties) and extrinsic factors (the local environment). The environmental parameters affecting the deterioration process significantly are including air temperature, solar irradiation, air humidity, various types of precipitation (rain, snow etc.) and wind velocity and direction [31, 96]. However the impact of ground-based vertical greening on various types of precipitation, wind velocity and direction could not be considered in this paper as it is currently poorly researched. Each environmental parameter is affected by seasonality, orientation, and urban or rural environment, which will impact the deterioration process differently [31,96].

Examples of the important material properties for degradation are porosity, size and structure of pores, the composition of minerals, permeability, physic features, the nature and degree of cementation etc. Each material had unique properties leading to unique deterioration.

This section discusses four degradation types that mainly occur in stone-built heritage: salt crystallization, freeze-thaw weathering, biodeterioration, and chemical deterioration. Each subsection describes how the degradation occurs, which environmental parameters driving this process, and how changing environmental parameters, due to an implementation of vertical greening, are likely to affect the degradation processes (Table 3).

4.1. Salt crystallization

Stone decay is often related to salt crystallization [97]. The physical weathering of materials occurs by repeated crystallization-dissolution cycles, especially by salts with substantial volume expansion. The volume expansion causes an increase in stress on the pore walls, which can lead to cracks if the macroscopic stress is higher than the tensile strength of the materials [98,99].

The likelihood of salt crystallization to occur strongly depends on the critical crystallization relative humidity of the salt (mixture) [31,100]. The relative humidity (RH) is, for example, influenced by orientation, water load (rain, rising damp, etc.), wind and sun exposure [101]. In order to reduce the moisture content of building materials, moisture needs to evaporate. The evaporation rate is determined by the difference between the ambient relative humidity and the water activity, which controls where to water in a building material moves, from high to low water activity zones. Repeated fluctuations around the crystallization and dissolution RH are considered as high risk for decay. Thus, it is preferable to maintain the RH below the critical transition value to avoid cycles [31,100]. Not only extrinsic, but also intrinsic factors such as pore size, pore structure, pore filling, depth and location determine the crystallization potential [101].

However, in the built environment, single salts are rare. As in most natural environments, salts in building façades occur in a mixture of ions. Godts et al. (2023) describes the analysis of 11412 samples and classified them in two categories: calcium rich mixtures and sulphate rich mixture [102]. Both mixtures are equally important when looking at the first centimetres of the surface with sulphate rich mixture defined as less hygroscopic and calcium rich mixture is more hygroscopic, supported by the median of the mutual crystallization RH of 72% for sulphate rich mixtures and 46% for calcium rich mixtures.

Since phase changes of salts are mainly dependent on temperature and relative humidity, the frequency of environmental changes will have significant impact on salt decay processes [31,100,101]. Hereby, vertical greening will most likely have an influence on salt crystallization.

Following the analysis presented in this paper, the relative humidity of a vertically greened wall mainly remains above the critical RH of both salt mixture types, while the relative humidity of a bare wall fluctuates within a wider range of RH causing more risk events when salts are available. For instance, Sternberg et al. (2011) illustrate relative humidity fluctuation on a vertically greened wall between 91.75% and 99.00% while the relative humidity of the bare wall is fluctuating between 60.25% and 94.50%, both results are calculated by the average daily maximum and minimum relative humidity [46]. Another study from China outlines that during summertime when the risk on salt crystallization is higher due to elevated temperatures, the RH of the vertically greened façades stays above the critical RH of calcium rich mixtures [59]. The minimum RH of a bare wall goes below 46% for nine of the 12 testing days during a mid-summer period while the minimum RH of a medium thick vertically greened façade (19.8 cm) is between 55% and 68% during all testing days. Even the smallest green façade of this study improves the risk on crystallization of calcium rich mixtures significantly by increasing the minimum relative humidity.

However, it remains important to note that almost all building materials contain a certain amount of gypsum, thus the higher RH range on a vertically greened wall could potentially provoke more dissolution and recrystallization of highly destructive (less soluble) sulphate salts. Additionally, less soluble carbonates can potentially dissolve in higher contents.

Table 3
The relationship between the impact of vertical greening on the environmental parameters and the impact of vertical greening on the degradation of building materials.

Environmental parameter	Boundary condition	Impact of greening on parameter*	Impact on risk of degradation			
			Salt crystallization	Freeze-thaw weathering	Bio-deterioration	Chemical weathering
Maximum surface temperature	*Climate* *Season* *Orientation* *Thickness*	Sunshine ↗ = ↘↘ ↘ (summer ↘↘) ↘↘ (north ↘) Thickness ↗ = ↘↘	↘↘	—	↗↗	—
Minimum surface temperature	*Climate* *Season* *Orientation* *Thickness*	↗↗ ↗ (winter ↗↗) ↗ ↗↗	—	↘↘	↗↗	—
Maximum air temperature	*Climate* *Season* *Orientation* *Thickness*	↘ (summer ↘↘) ↘↘ ↘	↘	—	↘	—
Minimum air temperature	*Climate* *Season* *Orientation* *Thickness*	↘ ↘ ↗ (East ↘) ↗	—	↗ - ↘	↗ - ↘	—
Maximum relative humidity	*Climate* *Season* *Orientation* *Thickness*	↘ ↗ (only summer) ↗ ↘↘	—	↗ - ↘	↗ - ↘	↗ - ↘
Minimum relative humidity	*Climate* *Season* *Orientation* *Thickness*	↗↗	↘↘	—	↗↗	↗
Solar irradiation	*Climate* *Season* *Orientation* *Thickness*	↘ —	↘ —	↗ —	↘ —	—
Air pollution		↘	—	—	↘	↘

* ↗↗ = significant increase of risk on degradation or the values of environmental parameters due to an implementation of vertical greening, ↗ = modest increase, — = no impact, ↘ = modest reduction, ↘ ↘ = significant reduction.

4.2. Freeze-thaw weathering

Frost damage, caused by repeating freeze-thaw cycles, is a common phenomenon in building materials, and is one of the major causes in stone and brick deterioration, especially for porous materials [103–105]. In general, the likelihood of frost damage to occurs depends on the amount of available moisture, the (surface) temperature of a material, the material properties, the time of exposure to freezing temperatures and the amount of freeze-thaw cycles [28,31,96,106–109]. However, temperature and moisture are equally important in generating freeze-thaw cycles and thus, in contributing to frost damage. For instance, an equal moisture content can lead to more frost damage with lower temperatures and an equal low temperature can lead to more frost damage with a higher moisture content [110].

The moisture present in building materials is confined in pores and will therefore freeze at low temperatures (<0 °C), potentially creating crystallization stresses on the pore walls. Whether those crystallization pressures have an impact on the state of the material, depends on the critical saturation level of a material which is determined by its pore properties and the amount of moisture available [110]. A critical saturation level is a saturation level above which the material will be affected by the crystallization pressures in the pores [31,96,106–108]. When crystallization induced macroscopic stresses exceed a certain proportion of the materials' tensile strength, frost damage starts to occurs [98,100,106,111].

The low temperatures, at which pure water freezes, depends on the size of the pores. Pure water begins to freeze in large pores of porous material at temperatures slightly below 0 °C due to the more favourable chemical potential for larger ice crystals [112]. The smaller the radius of the pores, the higher the freezing point depression [113]. Additionally, the concentration of dissolved salts in the pores can dramatically lower the freezing temperature of pore water [31].

Therefore, the impact of vertical greening on the minimum surface temperature and maximum relative humidity is important for freeze-thaw weathering. The minimum surface temperature of a wall is likely to increase by an implementation of vertical greening due to the thermal blanketing effect, which is the most significant when a thick green façade is installed on a wall located in climate with a high quantity of solar irradiation during winter season. The risk of freeze-thaw weathering will decrease as the minimum surface temperature rises, unless the minimum surface temperature will fluctuate around the freezing point, which can increase the number of freeze-thaw cycles and thus increase the risk of freeze-thaw weathering. The maximum relative humidity slightly increases with vertical greening in front of the wall resulting in a higher availability of water in the wall for creating freeze-thaw cycles.

However, the occurrence of frost damage depends on reaching the critical saturation level at a certain temperature which is more likely to be reached during or shortly after periods of rainfall. Vertical greening could shield the underlying wall from environmental factors, such as precipitation, resulting in a beneficial impact on the risk of freeze-thaw cycles which is more prominent than the slight increase in the maximum relative humidity. Unfortunately, no study was found to state the amount of reduction in precipitation reaching the wall.

4.3. Biodeterioration

Biodeterioration is caused by diverse populations of microorganisms living in a biofilm and is frequently observed on built heritage made of brick or stone materials [114]. A material's bioreceptivity is influenced by several factors including the amount of moisture available, surface temperature, the roughness and structure of materials, the availability of solar irradiation and the chemical composition of the outer surface of materials (including nutrient such as carbon, nitrogen, sulphur) to sustain their development and growth [31,96,100,115,116]. Both bricks with grouting mortar and stone materials have sufficient nutrients available to influence biological colonization [100]. Air pollutants in the urban environment can provide additional nutrients resulting in an accelerating of biodeterioration [114].

In general, biodeterioration is caused by three main groups – bacteria, fungi and lichen – each of which require unique conditions to occur. Every microorganism has a threshold of water activity below which there are unable to grow [117]. Bacteria, such as algae and cyanobacteria, need a much higher relative humidity than fungi, whereas fungi need higher surface temperatures than bacteria. While fungi and lichen can develop with water activity as low as 0.65 and can withstand periods of complete dryness, bacteria needs a water activity of 0.98. Bacteria prefer surface temperatures between 0 °C and 20 °C to flourish while fungi prefer surface temperatures between 20 °C and 35 °C [28,31,96,117]. Temperature and relative humidity are key factors in the biodeterioration process and will determine whether organisms will flourish or even exist at all [96].

In built heritage, porous stones are more likely to absorb water, which require a longer drying process. Since moisture is such an determining factor for biodeterioration, porous stones susceptible to biodeterioration. In combination with lower temperatures the wetness can extend even further [116]. Additional, algal colonization is an example which tends to form in a film on a surface, particular on sand and limestones of historical buildings. These films can obstruct the material's pores and cause slower drying rates [96].

For this type of degradation, vertical greening is able to change the local environmental parameters resulting in increasing risk of biodeterioration. Since microorganisms are more likely to occur in a humid environment in combinations with favourable temperatures between 0 °C and 35 °C, both maximum and minimum surface temperature and relative humidity are important to determine the risk on biodeterioration. Vertical greening is lowering the amplitude of the temperature and relative humidity fluctuations, resulting in a more stable environment, which is more favourable for microorganisms to grow.

Nevertheless, the risk on biodeterioration by phototropic microorganisms is likely to reduce by an implementation of vertical greening since those microorganisms need solar irradiation to occur and vertical greening responsible is for a lower amount for solar irradiation on the underlying wall.

4.4. Chemical deterioration

Chemical weathering occurs at the surface of the built environment as a consequence of chemical dissolution or alteration between mineral constituents of building materials and air pollutants in the air. This degradation type is particularly seen in cities due to the higher amount air pollutants [31].

One of the most well-known examples of chemical weathering is the formation of gypsum crusts on calcium carbonate rich stone materials, which are formed by reaction of calcium carbonate minerals in the stone and the atmospheric sulphur dioxide. The latter can be deposited on a wet or dry stone's surface but it has a higher deposition rate on a wet stone [28,31,32,100].

Another well-known example of chemical weathering is surface soiling. Surface or black soiling of building materials and monumental stones is seen as a visual nuisance resulting from the accumulation of particulate matter on exposed surfaces [118]. The main component of black soling is particulate elemental carbon or PEC, known as black carbon or graphitic carbon and the rate of soiling depends on the environmental and material characteristics such as atmospheric particle concentration and size, roughness of the deposition surface and positioning of the surface, etc. This is a common degradation phenomena in urban environments due to the accumulation of carbonaceous fine particles produced by the incomplete combustion of fossil fuels. Moreover, the oxidation rate of SO_2, deposited on the stone surface, can accelerate with the presence of deposited particles rich in some elements (e.g. Fe, Ni, Cr). This can contribute to and intensity the stone decay by generating gypsum and other soluble salts [118,119].

Both chemical degradation processes are related with particulate matter and the formation of gypsum is also dependent on the relative humidity. Since vertical greening is able to lower the any dry deposition of particulate matter on the underlying wall, the risk on both degradation processes is likely to be lower. Even though, vertical greening is able to increase the relative humidity on a wall which is increasing the risk on gypsum formation and any dry deposition of particulate matter, the lower amount of air pollution on the wall will still be dominant in lowering the risk on chemical degradation. Additionally, previous research acknowledge leaf wettability as an significant characteristic for PM capture: the amount of PM captured on the leaves increases when the leaf surface is more hydrophilic, resulting in less deposition of air pollution on wall surfaces due to a vertically greened façade [120–122].

5. Discussion

This meta-analysis of the current literature illustrates that ground-based vertical greening can alter the local microclimate which will most likely have an impact on the degradation of historic building materials. In order to estimate the type and extent of the degradation, it is important to consider other effects that influence the microclimate such as the impact of the urban heat island (UHI) effect. The UHI effect is responsible for having a higher air and surface temperature, a changing relative humidity and higher the air pollution levels in city centres relative to the less dense surroundings.

The temperature increase due to the urban heat island effect is beneficial for freeze-thaw weathering, biodeterioration and chemical weathering but not for salt crystallization. The implementation of ground-based vertical greening contribute to reducing the risk on freeze-thaw weathering, increasing the risk on biodeterioration and countering the adverse impact of UHI effect on the risk of salt crystallization. The increase in air pollution reaching the wall surface is reduced by vertical greening shielding the wall surface resulting in a lower risk of chemical weathering.

In this context, a comparison is made between the impact of vertical greening on the average air temperature in cities and the expected air temperature changes in different climate types, based on future Representative Concentration Pathways (RCP) scenario's (Table 4). The range in which the air temperature is expected to change in different climates

Table 4
Comparison between the average air temperature induced by vertical greening and the expected air temperature increase of the climatic model simulation for each specific climate zone [128].

Climate	Impact on average air temperature induced by vertical greening	Expected air temperature increase of the climatic model simulation	
		Min	Max
Temperature Oceanic Climate (Cfb)	−0,7	1,38	1,82
Hot-Summer Mediterranean Climate (Csa)	1,2	1,46	2,02
Hot-Summer Humid Continental Climate (Dfa)	−1,2	1,6	2,25
Humid Subtropical Climate (Cfa)	−1,2	2,09	3,13
The Tropical Rainforest Climate (Af)	−1,3	1	1,5

is determined by the RCP2.6 and RCP8.5, referred to as the minimum and maximum changes in the expected air temperature. Ground-based vertical greening may have an impact on the local microclimate but the effect is less important than assumed temperature rise due to climate change. However, it still has a serious impact on the maximum air temperature which will determine the comfort of the residents in the city.

To foster a complete understanding of the real impact of vertical greening on the local microclimate and the degradation processes, further research is required. Literature focuses on the comfort and health of the residents of the cities or the energy efficiency of buildings, resulting in poorly researched environmental parameters contributing to the materials degradation, such as wind velocity and direction, or types of precipitation [31,96]. Studies published after May 2022 (the cut-off of our meta-analysis) demonstrate that the direction of the field remains the impact of vertical greening on the energy performances of buildings resulting in studies analysing the impact of vertical greening on the thermal parameters and the remaining need for research on the vertical greening performances on additional environmental parameters. Additionally, research on the performance of ground-based vertical greening is expanding in the southern hemisphere. Even though the main focus in the south hemisphere is also energy-based, they analyse multiple parameters together including air velocity measurements [123–127].

As vertical greening exists of living plants, characterised by different behaviour and characteristics, such as the difference between evergreen or deciduous plants or between their adhesion mechanisms, more research needs to be done to fully understand any difference that can occur in the impact on built heritage and its microclimate due to different plant properties. Future studies should consider that vegetation can alter the local microclimate through a variety of mechanisms, including transpiration, shading, and thermal insulation, all of which are subject to change as plant characteristics do.

Since this paper focuses on climate-driven degradation processes of stone-built heritage, further research is necessary to consider the impact of vertical greening on different building materials. The overview in the paper on the impact of vertical greening on the local microclimate can be a useful analysis to start developing the impact of vertical greening on different building materials. Additionally, current literature is often ambiguous about the positioning of the measurement devices. They often do not describe carefully at which distance the monitoring devices are installed and if this distance is defined from the vegetation layer or from the wall surface. The positioning of the measurement devices will clearly affect the impact of vertical greening on the local microclimate and degradation processes and the incomplete description can lead to miscommunication or misinterpretation of the results.

Furthermore, when considering vertical greening on built heritage, it is worth noting that this meta-analysis is a theoretical approach of the impact of a changing microclimate on the degradation of historic building materials. It is recommended to examine the condition of a wall before any implementation of vegetation. Literature is currently limited on the successes and challenges of vertical greening on heritage. The paper of Coombes and Viles (2021) notes the importance of the good condition of a wall before growing vertical green due to the possibility that greening can enlarge existing cracks or defects resulting in serious structural damage. As vertical greening often grows unintentionally on built heritage and is left unmaintained, damage is often related to the growth of vegetation onto walls. However, Coombes and Viles (2021) confirm the potential of greening to reduce deterioration of heritage materials, supplemented with the potential to improve the conditions for those living and working in built heritage and enhance the values of built heritage [17].

The application of ground-based vertical greening can be considered to mitigate specific effects of wall deterioration. The choice of plants and their impact on the local microclimate and corresponding degradation processes should be evaluated per case. If frost damage is a concern, the implementation of vertical greening with evergreen plants could be beneficial by providing a thermal insulation layer on the wall surface. The most significant thermal insulation effect is reached during winter time, which is the season when frost damage is most common. Salt weathering could be mitigated by both evergreen and deciduous plants if the risks are highest in summertime. Vertical greening implemented on shaded façades or north-facing walls has less potential to reduce the risk of salt weathering but can have significant benefits for reducing frost damage. Warmer climates tend to be more suitable with an implementation of deciduous greening, while colder climates could profit more from evergreen vegetation. When implementing vertical greening to reduce air pollution levels on the wall surfaces to reduce biodeterioration and chemical deterioration, it is advised to implement vertical greening with evergreen vegetation. Overall, if the aim of implementing vertical greening is reducing the risk of certain degradation processes, the performance of vertical greening will enhance its impact as the thickness of the foliage increases.

This application of ground-based vertical greening is also limited to low-rise buildings. Some types of climbing plants, such as Hedera Helix or Parthenocissus, have significant climbing heights but are limited to, respectively, 25 m and 30 m. In high-rise urban environments, it is worth considering living wall systems (where building façades allow it), since this type of vertical greening is less limited by height due to its construction of plants in planter boxes attached to the wall.

6. Conclusion

The meta-analysis of the current literature shows a critical role of vertical greening in mitigating the local microclimate, resulting in a positive reduction of risk for the degradation in historic building materials. Generally, vertical greening is able to reduce the fluctuations in surface temperature, air temperature, an relative humidity and the amount of solar irradiation and particulate matter. The changing microclimate due to an implementation of vertical greening enables the mitigating of current climate stressors such as the UHI, contributing to create a healthier urban environment and has the ability to preserve our urban landscape by mitigating potential degradation processes. How significant the effect of vertical greening on the microclimate is, depends on the environmental and experimental boundary conditions including climate type, season, orientations, thickness of the green façade and positioning of the measuring devices. Vertical greening has the most significant impact on the maximum surface and air temperature and the amount of solar irradiation during summer due to the transpiration and shadowing of the vegetation. Maximum surface and air temperatures could be decreased by 16.4 °C and 11.3 °C respectively. It is observed that vertical greening in the north orientation has the least significant impact on the mitigation of the environmental parameters, while other orientations have quite similar behaviour. The most significant impact of vertical greening on the relative humidity is reached on a south-facing wall by a decrease of 38 RH%. The thicker the vertical greening the more significant the impact on the local microclimate will be.

The benefits of vertical greening on the urban microclimate can have a potential to mitigate the degradation processes of the urban landscape. The risk of salt crystallization and freeze-thaw weathering is reduced by smaller fluctuations in surface temperature, while the risk of biodeterioration is increased. Due to vertical greening, there is also less fluctuation in the air temperature and relative humidity, which reduces the risk of salt crystallization, freeze-thaw weathering, and biodeterioration. However, changing relative humidity is more likely to attract air particles contributing to formation of gypsum while the decrease in air pollution on the wall can lower the gypsum formation and soiling on historic building materials. Vertical greening reduces the solar irradiation that reaches the wall behind the green façade which is beneficial for reducing the risk of salt crystallization and biodeterioration but not for reducing the freeze-thaw weathering.

In order make more defined hypothesises on how vertical greening can affect the deterioration of historic building materials, future approaches should consider taking moisture and wind measurements as well. Further research may show potential in using vertical greening as a preventive conservation system for building facades and a widely use of vertical greening could enhance the overall sustainability of urban environments. Nevertheless, an implementation of vertical greening on built heritage remains challenging, as the key results of this paper are at odds with common perceptions held by heritage managers in the field [19].

CRediT authorship contribution statement

M. De Groeve: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **E. Kale:** Writing – review & editing, Methodology, Conceptualization. **S. Godts:** Writing – review & editing, Conceptualization. **S.A. Orr:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **T. De Kock:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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