Vertical greening systems – A review on recent technologies and research advancement

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Abstract

Vertical greening systems represent an emerging field in technology and research since they are traded as promising measure to encounter the negative impacts of climate change. Research and development in the field of green infrastructure are steadily progressing, determining aesthetic improvements as well as environmental, social and economic benefits.

The purpose of this paper is to provide a systematic state-of-the-art in the field of vertical greening systems and identify significant gaps in research. Additionally, recent scientific studies are analysed to bundle existing knowledge on research in the specific field of green walls and to derive indications on set up practices to facilities and improvement of their post-comparability. The study is based on literature review using scientific literature such as peer-reviewed journals, conference papers and books as well as master and doctoral theses, research reports, research articles and recommendations.

The study concludes that benefits of vertical greening systems in current literature often refer to general benefits of vegetation. Specific knowledge has been promoted on microclimatic effects, but complementary studies with focus on vertical greening systems are still lacking. Additionally, it was revealed that there is great potential for research on vertical greening systems in rural areas, especially taking into consideration the application of green walls on construction buildings like shotcrete walls, tunnel portals or highway bridges. For better comparability of future studies, single parameter-centered analyses under constant and comparable conditions are recommended.

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1. Introduction

Research on urban green has substantially increased from the beginning of the twentieth century [1], and a great number of studies has proved the importance of green in urban environments [2–6]. In this context, attention on the use of vertical greening systems and green roofs is steadily rising due to the fact, that the environmental impact of buildings on the inner and outer climate becomes more and more apparent [1]. Green buildings nowadays are designed in order to provide sustainable solutions in mitigating significant impacts of the building stock on the environment, society and economy [7]. Recent green building strategies do not only include the use of sustainable materials in their construction, but also consider natural processes like the shading effect of trees, insulation capacities of green roofs and vertical greening systems, or mitigation of urban heat due to evapotranspiration [1]. Recently, research is strongly focusing on the ‘greening process’ [1] by using plants to create green building envelopes. Relating to this, vertical green plays a central role.

Vertical greening systems have ancient history, reaching back to the Babylonians taking the example of the famous Hanging Gardens of Babylon [8]. About 2,000 years ago, vine trees were used in Mediterranean areas as the earliest forms of façade greening providing shading for the façades, transpirative cooling and economic benefits like the production of fruits. In the early twentieth century the use of English and Boston Ivy aiming at a complete green coverage of brick façades was most prominent [9]. In the 1980s Bartfelder & Köhler [10] started initial research activities concerning ecological functions on façade greening thus laying the groundwork for an innovative line of research. More recently, the development of green wall systems represents the latest technology advancement in the field of wall cladding [11]. This type of wall was pioneered by Patrick Blanc, who reported his ‘Mur Vegetal’, using the first hydrosystem for green walls, in 1994 [11–13]. Nowadays green walls are of special interest particularly to engineers, architects, planners and ecologists, since they provide proven services to buildings and cities [14].

Vertical greening systems, including green wall systems as well as green façades, mobilize high research potential, particularly addressing their contribution to thermal regulation of building envelopes. Latest developments in 2017 have been focusing on the possibility of simultaneously using green façades and photovoltaic systems on a building façade. The green buffer layer provides a cooling effect for the photovoltaic module and the building façade, due to the transpiration of plants. Results showed that the green buffer has positive influences on the photovoltaic module performance especially in summer by keeping the module operating temperature lower in comparison to the module without green buffer [15,16].

To provide condensed information on hitherto scientific approaches it appears appropriate to extract the common understanding of vertical greening systems, particularly in the scientific practice. Literature research reveals a variety of definitions referring to all types of vertical greening systems, causing sometimes confusion and misunderstanding in assigning systems and components. Commonly applied terms are ‘green wall system’ [8,11,17–19], ‘vertical greening system’ [20–25], ‘vertical greenery system’ [17,26–30], or ‘green vertical system’ [18]. Green façades are also known as ‘façade greening’ [11,31–33], while ‘vertical garden’ [11,20,34–37] and ‘living walls’ [9,13,21,31,38–40] are common nomenclatures for green walls. For clearer understanding, we will further only use the terms ‘vertical greening system’ in general, when speaking about both green façades as well as green walls, and the terms ‘green façade’ (=direct and double-skin green façade) and ‘green wall’ (=all kind of living wall) in particular, even though other names (but with same definitions) are used in original literature.

Within this paper, we review literature to synthesize the current knowledge on vertical greening systems. The aim of the study is to provide a systematic state-of-the-art in the field of vertical greening systems and their performance. The study gives an overview on current debates and state-of-the-art technologies as a basis for further development of green walls, highlighting main results and thus revealing future research needs. In this course, we evaluate the comparability of current scientific studies and try to identify significant gaps in currently available research.

2. Material and methods

2.1. Study design and methodological issues

This paper comprises two major parts. Part one discusses vertical greening systems in general, including common classifications, system components and benefits. For this purpose, different source types were addressed: peer-reviewed journals, conference papers and books, complemented by master and doctoral theses, research reports, research articles and recommendations. In the first selection stage, only peer-reviewed scientific papers, found by means of keyword search through online databases (ScienceDirect, Google-Scholar, Springer Link) were selected using the keywords ‘vertical greening system’, ‘green wall’, ‘green façade’ and ‘green infrastructure’. Since these papers primarily covered recent scientific issues on vertical greening systems, literature research was extended to university libraries and unpublished work from the scientific community to gain more insight into general knowledge on vertical greening systems, also including sources apart from scientific matters. During the review process, references were categorized according to topic areas (‘general’, ‘classification’, ‘benefits’, ‘study’, ‘review’ and ‘others’) to obtain an initial, rough structure and to allow a better overview.

As shown in Fig. 1, a total sum of 99 sources dealing with vertical greening systems (59 sources), green roofs (3 sources) and closely related subjects (e.g. environment, meteorology: 37 sources) were reviewed. This overview revealed that the majority of recent studies deals with achievable benefits of vertical greening systems in city zones, especially their contribution to thermal behaviour of building envelopes (24 sources). From these, we decided to select specific studies with special focus on this certain issue to evaluate their comparability. To limit our selection, we have decided to only chose studies with main emphasis on green walls, not older than 2010. Consequently, 11 recent studies were selected for a more detailed analysis. Hence, part two of the here presented paper
demonstrates a comparison of these 11 studies, aiming to gain an insight on study structures and set ups and investigated system parameters. From this, we target to bundle existing knowledge on research in the specific field of green walls (state of the art in research, performances of green walls in various respects) and derive indications on set up practices to facilitate and improve the post-comparability. In both respects, the considered studies were analysed according to ‘study parameters’, ‘system elements and plants’, ‘considered parameters’ and ‘synopsis of key findings of the compared studies’.

3. Vertical greening systems

Hereafter we discuss the present state-of-the-art of vertical greening systems, focusing on current classifications, commonly used system components and benefits.

3.1. Classifications: green façades vs. green walls

Fig. 2 demonstrates that vertical greening systems are classified according to two main types: green façades and green walls [9,31]. To encourage a clearer understanding, it is useful to apply the German terms ‘bodengebundene Begrünung’ and ‘fassadengebundene Begrünung’ [41], which are well established current German terminology and can be directly translated as ‘ground-based greening method’ and ‘wall-based greening method’. Ground-based greening methods rely on natural ground and refer to green façades, whereas wall-based greening methods include direct planting on the wall, without connection to natural ground, referred to green walls.

Green façades are further classified according to the location of plants, which can either be placed directly into the soil, or in soil-filled planter boxes [42], consequently the third term ‘planter box-based greening method’ is suggested to be appended. Green façades involve climbing plants to cover vertical surfaces and are subdivided into direct and indirect green façades [11,20,28,39,43]. Direct green façades, as referred to in traditional architecture (traditional green façades), do not need structural support since clinging climbing plants adhere to the external walls through adventitious roots or self-adhesive pads [43,44]. Indirect green façades are referred to as double-skin green façades which include supporting systems such as stainless steel cables, modular trellises, or stainless steel mesh to assist the upward growth of climbing plants by creating a second skin layer in distance to the wall [11,18,29,39]. Green walls are designed with pre-vegetated panels, vertical modules, or planted blankets that are fixed vertically to the surface, allowing plant growth without relying on rooting space at ground level [9,13]. According to their application method, green
walls consisting of a double-layered steel grid construction.

New research approaches are also dealing with continuous green fabric layer (permeable, base panel and protects the wall from humidity. The application of a properties but tendrils. Plants to be applied are climbing species without adhesive prop-

- elements like cables, meshes, trellis or nets made of steel (stainless, adhesive root structures that enable attaching themselves directly to the wall in a linear way [41].

3.2. System components

Since direct green façades are characterised by plants with ad-

- root structures that enable attaching themselves directly to the façade additional supportive system components are not needed. Double-skin green façades are equipped with supporting elements like cables, meshes, trellis or nets made of steel (stainless, coated or galvanized), hard wood, aluminium and plastic [23,45]. Plants to be applied are climbing species without adhesive properties but tendrils.

Continuous green walls usually include a frame that holds the base panel and protects the wall from humidity. The application of a fabric layer (permeable, flexible and root proof screens, also serving as drainage) serves as growing media. Continuous green walls therefore often do not have any further requirement for soil sub-

strate. This hydroponic technology provides water and nutrients to the plants. The fabric layer is attached to waterproof membranes that protect the construction material from moisture [11,21,42]. New research approaches are also dealing with continuous green walls consisting of a double-layered steel grid construction filled

with a mixture of rock share and compost serving as plant substrate [46,47].

Modular green walls consist of several modules in form of pocket-typed planters and panels. Each module is designed to hold soil or substrate and is fixed to a structural frame behind [21]. Growing media are either organic (e.g. soil) or inorganic (e.g. granular material like perlite, foam, mineral wool, felt [11,42,48]. Linear green walls are composed by linear planter boxes (e.g. aluminium or plastic (HDPE), that are applied one above the other and filled with substrate (e.g. soil or mineral granules. [11,35].

Table 1 summarizes all basic characteristics of the described vertical greening systems.

4. Benefits of vertical greening systems

In urban regions, where green areas are scarce and open ground space is limited, vertical greening methods represent an innovative and promising opportunity for increasing green infrastructure in cities. Apart from aesthetic, ecological and social values, economic benefits are proved by several studies (e.g. Refs. [8,29,39]). All types of benefits are associated with each other and are discussed in detail in the following chapters.

4.1. Environmental benefits

Due to the continuing increase of artificial and sealed surfaces replacing green spaces in urban areas, shading and evaporative cooling benefits provided by plants have progressively been lost. This, in combination with the reflection from mineral surfaces such as concrete, asphalt, plaster etc. has been resulting in accumulation of raised temperature hot spots, also known as the urban heat island effect (UHI [30,43]), which is primarily influenced by wind speed, temperature difference between the undisturbed air and the building surface temperature and the height of the buildings [49]. The study performed by Mitterboeck & Korjenic [4] in the city of Vienna confirmed that greenery in urban areas has a powerful impact on the role of passive cooling of a building surrounding, and consequently of buildings cooling.

Thus, vertical greening methods represent a promising measure to counterbalance the UHI phenomenon [50,51], while saving valuable space resources as they are applied on perpendicular surfaces [33]. Ottelé et al. [52], Sternberg et al. [53], and Perini et al. [54] proved the commonly known environmental benefit of plants of improving air quality by filtering particles in their leaves as adaptable for vertical greening systems. Further, Köhler [55] highlights the ability of plants to reduce carbon dioxide emissions produced by traffic and heating by transforming them into carbon hydrates and oxygen. However, Charoenkit & Yiemwattana [21] point out within their review that recently only one modeling study of green walls carbon sequestration [56] was carried out. In 2017, they published first results of an experiment focusing on carbon sequestration properties of living walls in tropical climate and concluded, inter alia, that plants with higher woody stem proportion are more preferable for green walls due to higher carbon sequestration [57]. As a further environmental benefit, the retention of rainwater by green infrastructure is highlighted in several papers. However, up to now only experiments on green roofs were conducted (e.g. Refs. [58–60], and confirmatory studies concerning water retention ability of green walls are still lacking.

As an especially valuable benefit we stress the increase in heterogeneity and urban habitat biodiversity for plants and anthropods, which was confirmed by a study conducted by Madre et al. [14]. Thus, publications often are related to the general enhancement of biodiversity by vegetation in urban areas, while studies dealing with specific relationships between biodiversity and green
walls are rather scarce. Nevertheless, green walls help developing urban ecosystems providing whole ranges of ecosystem services and thus, according to Ottelé et al. [52], fit the principle of ecological engineering [61,62]. In that regard, an innovative study conducted by Medl et al. [47] opened up new approaches concerning the re-establishment and the connection of fragmented habitats by the use of green walls on built infrastructure (e.g. highway bridges, tunnel portals). The study focused on integrating shotcrete walls from road construction into the landscape, suggesting that the application of vertical greening systems in rural areas may act as a countermeasure against habitat fragmentation, since connection to natural soil is not needed.

4.2. Social benefits

Victorero et al. [63] confirmed the high potential of green walls to reduce UHI problems by reducing wall temperatures due to shading and evapotranspiration. This is particularly promising in terms of heat stress, which poses a serious environmental risk to human’s health [64,65]. The most important meteorological variables concerning thermal sensation and heat stress are air temperature, relative humidity, wind velocity and mean radiant temperature (T_{\text{mrt}}). The latter is defined as the uniform temperature of a hypothetical spherical enclosure emitting blackbody radiation that would result in the same net energy exchange with the human body as the actual complex environment [66–69]. These parameters are required to calculate thermal indices such as Predicted Mean Vote (PMV) or Universal Thermal Climate Index (UTCI) [46,64]. PMV describes the human thermal wellbeing as well as UTCI, which provides an assessment of the human reaction to the out-door thermal environment with respect to heat stress [70,71]. Thus, by calculating PMV, Scharf et al. [70] verified that green walls affect their immediate surroundings. Their results showed a significant reduction of PMV particularly on south exposed façades due to a green wall system. Additionally, the calculation of UTCI done by Medl et al. [46] indicated a reduction of heat stress due to a green wall even without vegetation (cooling already achieved by the substrate-filled green wall system). Since a lower UTCI corresponds to a higher thermal comfort of people, the use of green walls might be advantageous, especially in view of UHIs and expected changes in temperature and precipitation due to anthropogenic climate change [72].

A series of previous studies confirm the enhancement of noise attenuation provided by plants by absorbing, diffracting and reflecting sound [73–77]. This indicates that green walls improve people’s subjective well-being by reducing long-term noise annoyances. Regarding the sound insulation effects of vegetation when incorporated in buildings, Azkorra et al. [78] conducted standardized laboratory tests, concluding that green walls have significant potential as sound insulation tool for buildings. This was in line with findings received by Wong et al. [79] and Van Renteghem et al. [80] and corresponds with results obtained by Pérez et al. [81], Lacasta et al. [82] and Ismail [17].

Considering landscape aspects, green walls are an ideal tool to integrate vertical construction buildings into the natural surroundings, thus optimizing landscape aesthetics [46,47]. Scientific studies confirmed that natural scenery helps people to cope with stress-related psychosocial symptoms [83] and supports a faster recovery from stress by providing pleasant visual quality [84]. When linking these aspects together, it might be reasoned, that these benefits can also be achieved by the application of green walls. However, this review process did not bring to light any references dealing with this issue. We have similar indications referring to issues concerning potential safety and health risks posed by high reflective pavement surfaces in urban areas, like concrete or asphalt. It has been proved that increased glare and UV radiation scatter as well as visual pollution harm eyesight after a long period of exposure [85–87], but studies focusing on direct effects of green walls are still lacking. Vegetation helps to control light intensity and blocks sunlight, thus reducing glare and providing safety and visibility [88]. There is potential that green walls have similar effects due to covering and shading of reflecting concrete surfaces. Initial approaches in this direction were done by Medl et al. [46], who compared albedo between green walls and bare walls, confirming

### Table 1

Common types of vertical greening systems. Basic system components and characteristics (GFs: green façades, GWs: green walls; according to [8,11,21,23,35,39,40,42,43,48].

<table>
<thead>
<tr>
<th>Type</th>
<th>Sub-categories</th>
<th>System components</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct GFs</td>
<td>Ground-based planting</td>
<td>No structural system components</td>
<td>Climbing plants with adhesive pads or clinging roots are directly attached to the building surface and planted in the open ground at the building base.</td>
</tr>
<tr>
<td></td>
<td>Planter box-based planting</td>
<td>Irrigation optional</td>
<td>Climbing plants with adhesive pads or clinging roots are directly attached to the building surface and planted in soil-filled planter boxes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Planter boxes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrigation optional</td>
<td></td>
</tr>
<tr>
<td>Double-skin GFs</td>
<td>Ground-based planting</td>
<td>Structural frame of cables, meshes, trellis or nets</td>
<td>Twining plants or plants with tendrils are supported by a structure, creating an air cavity between building surface and vegetation, and are planted on the base of the building in the open ground or planter boxes.</td>
</tr>
<tr>
<td></td>
<td>Planter box-based planting</td>
<td>Irrigation optional</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous GWs</td>
<td>No sub-categories</td>
<td>Structural frame</td>
<td>Most commonly no requirement for substrate, since fabric layers serve as substrate.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base panel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fabric layers</td>
<td>Hydroponic technology provides supply to water and nutrients.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Drainage</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waterproof membrane</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrigation system</td>
<td></td>
</tr>
<tr>
<td>Modular GWs</td>
<td>Pocket-type planter</td>
<td>For all three categories:</td>
<td>Modules are filled with organic or inorganic substrate.</td>
</tr>
<tr>
<td></td>
<td>Vertical panel</td>
<td></td>
<td>Simple replacement of panels in case of damage is given/required.</td>
</tr>
<tr>
<td></td>
<td>Grid panel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear GWs</td>
<td>Planter box-based planting</td>
<td></td>
<td>Linear planter boxes are applied to the wall, and arranged one above the other.</td>
</tr>
</tbody>
</table>

_A. Medl et al. / Building and Environment 125 (2017) 227–239_
that sunlight reflections can be reduced due to existing vegetation.

4.3. Economic benefits vs. economic sustainability

While so far there are a lot of research approaches proving environmental benefits of green envelopes, information on economic sustainability is still rare. Thus, Perini & Rosasco [20] provided a Cost-Benefit Analysis (CBA) on vertical greening systems to evaluate their economic sustainability. They included initial costs (installation), maintenance costs, disposal costs, economic benefits related to the increase of rent income (due to the increase of property value), building envelope longevity and energy demand reduction for heating and air conditioning. Positive environmental effects (air quality improvement, carbon reduction) were considered in terms of costs savings for the society. Thereby, they cite studies like Peck et al. [37] who assumed that green walls increase the real estate value of a building between 6 and 15%. They further hypothesize that leaves (or other layers) protect building surfaces from climatic stress (freeze-thaw cycle and rapid temperature variations, acid rain, ice accretion, pollution), decreasing damages and reducing maintenance needs. They were confirmed by Wong et al. [26] who mentioned the value of green walls in prolonging the lifespan of building façades and slowing down wear and tear as well as cost savings in maintenance and replacement of façade parts by their capacity of limiting temperature fluctuations of wall surfaces. Concerning energy saving due to green walls Perini & Rosasco [20] assume a reduction of energy costs for air conditioning between 10 and 20%, saving costs of up to 2017 €/year. For evaluation of economic sustainability, they compared a green wall system (based on a mat containing an aggregate mix and composed by two layers of geotextile) with the following other vertical greening systems: a direct green façade, an indirect green façade supported by a plastic mesh (high-density polyethylene HDPE), an indirect green façade supported by a steel mesh, an indirect green façade combined with HDPE planter boxes and an indirect green façade combined with steel planter boxes. For comparison, they assumed three different scenarios (best, middle, worst) using indicators like the Net Present Value (NPV, discounted value of the sum of costs and benefits that occur within the period of life considered) or Pay Back Period (PBP, the number of years from which the total revenue equals (or exceeds) for the first time the total costs). The CBA was developed considering personal as well as social costs and benefits. Table 2 shows a summary of calculated values for the discussed greening systems. According to this approach, a greening system can be considered as sustainable when incomes prevail on costs and consequently NPV is positive and PBP is low. Thus, it appears that the direct green façade is the only vertical greening system, which is economically sustainable for all the scenarios assumed, due to low installation, maintenance and disposal costs. Compared to that, indirect green façades have higher installation and disposal costs due to the supporting system (especially by using steel mesh) and even higher costs in case of planter boxes owing to installation and maintenance of supporting and irrigation system. The green wall system is not qualified as economically sustainable since NPVs are all negative due to high installation and maintenance costs for the whole system (panels to be replaced, plant species, irrigation system). From their CBA Perini & Rosasco [20] finally concluded that it is mandatory to minimize the economic impact of some kind of vertical greening systems, especially green walls, by reducing initial costs for their installation enabling a wider use and thus to improve dense cities’ environmental conditions.

Ottele et al. [23] go conform with these results and conclude from their Life Cycle Analysis (LCA) that none of the vertical greening systems (except for the direct greening system) is sustainable since their environmental burden is higher than benefits gained from energy savings for heating and cooling in temperate climate. The authors showed, that environmental burden can be reduced by a more sustainable material choice and an integrated envelope design.

5. Comparison of selected studies with focus on green walls and their contribution to thermal behaviour of buildings

The preceding literature review revealed that the majority of recent studies deals with achievable benefits of vertical greening systems concerning their contribution to thermal behaviour of building envelopes. Thus, from the total amount of reviewed studies, studies with specific focus on this certain issue were selected for further analysis. Thereby, the emphasis was laid on studies focusing on green walls, conducted after and including 2010. Consequently, 11 recent studies remained for more detailed evaluation. The following paragraph highlights and organizes the selected studies according to four sections (outline of reviewed studies, system elements and plants, parameters investigated, key findings and synopsis of the reviewed studies). We want to point out that some of the studies also investigated other types of vertical greening systems (direct and double-skin green façades, [26,29,32]), which did not receive further consideration. Thus, the following comparison includes 11 studies focusing on the use of innovative green walls, 10 of them dealing with vertical greening systems on building façades and one dealing with the greening of building constructions [46].

5.1. Outline of reviewed studies

A closer analysis of study parameters revealed a majority of experimental studies (9 versus 2 observational studies), presenting samples of green walls installed next to a control wall without greener system. Within the selected studies the term ‘cladding’ is mostly understood as the used vertical greening system. Usually they are installed on a ‘bare wall’, also referred to as ‘wall surface’ or ‘building façade’. Sometimes also materials e.g. concrete are mentioned, but further details are not given. The studies mostly considered type and material of green walls, which is specified in Table 4. Column 2 (Green wall system). Thus, characteristics of wall materials and possible influences could not be considered any further in our review.

Observational studies indicate the on-site use of green walls on buildings or constructions. The main limitation of observational studies is the lowered possibility of replications due to the presence of only one site [35,89], while in experimental studies samples of green walls under similar conditions can theoretically be replicated as often as needed, but are often limited according to project and budget volume.

As Table 3 indicates, practically all studies compared their green wall systems against the performance of bare walls. Only in the case of Perini et al. [32] no data was available for a bare wall situation, thus a hypothetical bare wall was created on basis of the measurements done on other locations. Column 3 of Table 3 shows that all studies lack in replications, having only one single replicate to compare with (green wall vs. bare wall).

Within the reviewed papers, studies were carried out in seven different climatic regions: Af, tropical rainforest; Cfa, humid-subtropical; Cfb, temperate-oceanic; Csa, hot-summer Mediterranean; Csc, cool-summer Mediterranean; Cwa, Monsoon-influenced humid subtropical; Dfb, warm-humid continental (typing according to Köppen-Geiger, Körte et al., [90]). Mazzali et al. [34] conducted investigations in two climatic regions (Lonigo and Venice (Cfa); Pisa (Csa)). Studies were predominantly performed during summertime, within one study [29] summer as well as winter data.
Table 2
Indicators of economic sustainability of vertical greening systems. Comparison of different scenarios according to Perini & Rosasco [20].

<table>
<thead>
<tr>
<th>Type of greening system</th>
<th>Net Present Value (NPV) (€)</th>
<th>Pay Back Period (PBP) (number of years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Worst</td>
<td>Middle</td>
</tr>
<tr>
<td>direct green façade</td>
<td>9500</td>
<td>21,140</td>
</tr>
<tr>
<td>indirect green façade (plastic mesh)</td>
<td>-12,749</td>
<td>2061</td>
</tr>
<tr>
<td>(steel mesh)</td>
<td>-28,915</td>
<td>-9800</td>
</tr>
<tr>
<td>indirect green façade with planter boxes (plastic mesh)</td>
<td>-36,263</td>
<td>-18,748</td>
</tr>
<tr>
<td>indirect green façade with planter boxes (steel mesh)</td>
<td>-69,311</td>
<td>-49,497</td>
</tr>
<tr>
<td>green wall system</td>
<td>-116,488</td>
<td>-92,846</td>
</tr>
</tbody>
</table>

Table 3
Overview on study parameters of the selected studies.

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Control wall</th>
<th>Location</th>
<th>Climate</th>
<th>Period</th>
<th>Orientation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>exp</td>
<td>BW</td>
<td>China</td>
<td>Cfa</td>
<td>s</td>
<td>W</td>
<td>Chen et al. [91]</td>
</tr>
<tr>
<td>(2)</td>
<td>exp</td>
<td>BW</td>
<td>Hong Kong</td>
<td>Cwa</td>
<td>s</td>
<td>W, W-SW</td>
<td>Cheng et al. [22]</td>
</tr>
<tr>
<td>(3)</td>
<td>exp</td>
<td>BW</td>
<td>Spain</td>
<td>Csa</td>
<td>w, s</td>
<td>E, S, W</td>
<td>Coma et al. [29]</td>
</tr>
<tr>
<td>(4)</td>
<td>exp</td>
<td>BW</td>
<td>Italy</td>
<td>Cfa</td>
<td>s</td>
<td>SW</td>
<td>Mazzali et al. [34]</td>
</tr>
<tr>
<td>(5)</td>
<td>obs</td>
<td>BW</td>
<td>Austria</td>
<td>Dfb</td>
<td>ms</td>
<td>SE</td>
<td>Medl et al. [46]</td>
</tr>
<tr>
<td>(6)</td>
<td>exp</td>
<td>BW</td>
<td>Spain</td>
<td>Csa</td>
<td>a</td>
<td>E</td>
<td>Olivieri et al. [92]</td>
</tr>
<tr>
<td>(7)</td>
<td>exp</td>
<td>HBW</td>
<td>Netherlands</td>
<td>Cfb</td>
<td>a</td>
<td>W</td>
<td>Perini et al. [32]</td>
</tr>
<tr>
<td>(8)</td>
<td>exp</td>
<td>BW</td>
<td>Australia</td>
<td>Csa</td>
<td>ms</td>
<td>W</td>
<td>Razzaghmanesh &amp; Razzaghmanesh [24]</td>
</tr>
<tr>
<td>(9)</td>
<td>obs</td>
<td>BW</td>
<td>Austria</td>
<td>Dfb</td>
<td>ms</td>
<td>S</td>
<td>Scharf et al. [35]</td>
</tr>
<tr>
<td>(10)</td>
<td>exp</td>
<td>BW</td>
<td>Chile</td>
<td>Csc</td>
<td>s</td>
<td>N</td>
<td>Victorero et al. [63]</td>
</tr>
<tr>
<td>(11)</td>
<td>exp</td>
<td>BW</td>
<td>Singapore</td>
<td>Af</td>
<td>ms</td>
<td>nd</td>
<td>Wong et al. [26]</td>
</tr>
</tbody>
</table>

Table 4
Overview on system elements and plants of the selected studies.

<table>
<thead>
<tr>
<th>No.</th>
<th>Green wall system</th>
<th>Plot size (m²)</th>
<th>Cavity (mm)</th>
<th>Substrate</th>
<th>Plant specifications</th>
<th>Foliage thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>mod metal frame</td>
<td>6.25</td>
<td>30–600</td>
<td>light growth media</td>
<td>nd</td>
<td>6; nd</td>
</tr>
<tr>
<td>(2)</td>
<td>(cont) aluminium module</td>
<td>0.5</td>
<td>nd</td>
<td>hydroponic medium</td>
<td>pg</td>
<td>1; defined 2; defined</td>
</tr>
<tr>
<td>(3)</td>
<td>mod polyethyl pot</td>
<td>9</td>
<td>nd</td>
<td>coconut fibre</td>
<td>ep</td>
<td>1; defined 16; defined</td>
</tr>
<tr>
<td>(4)</td>
<td>(cont) aluminium frame</td>
<td>9</td>
<td>50</td>
<td>felt</td>
<td>(e)p</td>
<td>1; defined</td>
</tr>
<tr>
<td>(5)</td>
<td>cont steel grid</td>
<td>144</td>
<td>0</td>
<td>rock material + compost</td>
<td>grasses/herbs/leguminosae</td>
<td>nd</td>
</tr>
<tr>
<td>(6)</td>
<td>mod metal box</td>
<td>3.24</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>ep</td>
</tr>
<tr>
<td>(7)</td>
<td>mod plastic box</td>
<td>nd</td>
<td>40</td>
<td>potting soil</td>
<td>ep</td>
<td>0.100</td>
</tr>
<tr>
<td>(8)</td>
<td>(mod) polyprop. trays</td>
<td>28</td>
<td>nd</td>
<td>scoria, clay</td>
<td>ep</td>
<td>9; defined 7; defined</td>
</tr>
<tr>
<td>(9)</td>
<td>lin plant aluminium container</td>
<td>850</td>
<td>40</td>
<td>plant substrate</td>
<td>ep</td>
<td>nd</td>
</tr>
<tr>
<td>(10)</td>
<td>(cont) sedum panel</td>
<td>4</td>
<td>60</td>
<td>scoria, clay</td>
<td>ep</td>
<td>3; defined 3; defined</td>
</tr>
<tr>
<td>(11)</td>
<td>(mod) plastic pot</td>
<td>4</td>
<td>60</td>
<td>scoria, clay</td>
<td>ep</td>
<td>nd</td>
</tr>
</tbody>
</table>

Key: cont., continuous; mod., modular; lin., linear; nd, no details; pg, perennial grass; ep, evergreen perennial.
were compared. Two studies were carried out in autumn [32,34], four study papers revealed investigations over an extended period of at least two seasons [24,26,35,46]. Coma et al. [29] stress the exposition of walls as most influential parameter relating to temperature reductions on the building wall, especially on south and west oriented surfaces. Accordingly, experimental fields in the reviewed studies mostly were oriented towards West, South or South-West. Two times east-facing walls were used, one experiment, respectively, oriented the green walls towards South-East and North. One study [26] did not give any indication on the façade orientation.

Key: BW, bare wall; HBW, hypothetical bare wall; exp., experimental; obs., observational; s, summer; w, winter; a, autumn; ms, multi-seasonal; W, West; E, East; S, South; N, North.

5.2. System elements and plants

Some authors did not clearly describe the system type of green walls used in their studies, thus several times it was just possible to derive it from the context (Table 4, Column 2 shown in brackets). Within two study papers [26,34] more than one green wall system was investigated.

The most common type of green wall used among the compared studies was the modular one, only four papers described continuous systems, once a linear green wall system was used. The most common construction materials used were metal (aluminium, steel) and plastic (polyethylene, polypropylene). The size of the test fields varied strongly. The observational studies both used the largest areas ([46]: 144 m² [35]: 850 m²), the other experimental plots ranged between 0.5 and 30.2 m². Façade greening systems often had an insulating layer of air between the construction system and the building wall. Within the compared studies cavity depths varied from 30 to 50 mm, with only four studies providing any information, while Wong et al. [26], only mentioned the cavity width of one investigated green wall out of seven. Chen et al. [91] compared different distances of air cavities reaching from 30 to 600 mm. The smallest air cavity of 30 mm indicated best performance according to the lowest temperature of the exterior building wall surface, and suggesting a stronger cooling effect of the greenery system.

Referring to the substrate, the here presented green walls can be categorised in two main types: green walls with continuous geotextile felts supporting the plants, and green walls filled with substrate. Most of the reviewed studies focused on greeneries systems using the latter, only Mazzali et al. [34] related to felt layers serving as growing medium for plants in examining of two systems. They mentioned the use of ‘soil’ for the third system under investigation, without indicating clearer descriptions. Wong et al. [26] used several kinds of substrates for the different investigated systems, whereby a potential distinction between ‘soil planting media’ and ‘soil substrate’ did not come out clearly. None of the conducted studies provided information on chemical substrate properties (e.g. pH, electrical conductivity, plant nutrients availability). As pointed out in Hunter et al. [43], they are quite crucial for growth rate, growth habit, total leaf area and plant health. None of the reviewed studies delivered details about physical substrate properties like soil structure and texture, air-filled-porosity or water holding capacity, which affect plant growth by influencing root distribution and the ability to take up water and nutrients [93,94].

Due to the great importance in façade’s thermal behaviour, plants used in green walls usually are evergreen to benefit in both cooling and heating periods [27]. Plants used among the reviewed studies were mainly evergreen perennials or/and grasses. Wong et al. [26] mentioned some species within the discussion section of the study paper, but it was not clearly described how many different species were actually planted on each green wall and where the mentioned species were located. Thus, plant specifications at this point are defined as ‘no details’ in Table 4. Table 4 indicates species specifications as ‘defined’ in case that plant names were described in the papers under comparison. Lastly, only two studies [26,32] made specifications about foliage thickness of the vegetation.

5.3. Parameters investigated

Among the reviewed studies, a large number of microclimatic parameters was measured, as shown in Table 5. In most cases, microclimatic data were collected by a climate station nearby the test site and microclimatic sensors installed in front of, within or behind the plant canopy established on the green wall. Parameters most commonly recorded by the climate station are air temperature and air humidity, solar radiation, precipitation, wind speed and wind direction, only once the photosynthetically active radiation was additionally measured. Among eight studies, data about air temperature and air humidity also were collected in front of the green walls, two times solar radiation was measured and once wind speed. The most frequent parameter measured behind the plant canopy is the surface temperature of exterior walls (in each study), followed by heat flux (in four studies), air temperature and air humidity (in four studies) and soil temperature (in three studies). Indoor thermal behaviour parameters were collected among seven studies reviewed. In only one case vegetation cover was analysed [22].

5.4. Key findings and synopsis of the compared studies

The comparison of the selected studies revealed a large number of results concerning the benefits of green walls, especially regarding thermal behaviour. Since surface and indoor cooling potential as well as energy saving potential are closely linked to environmental (e.g. counterbalance UHI), social (e.g. reducing heat stress indoor and outdoor) and indirect energy savings (e.g. reduction of energy costs), we follow the logical classification of three main areas: surface cooling potential, energy saving potential and indoor cooling potential (Fig. 3).

According to Wong et al. [26], there is a strong interconnection between surface cooling potential and energy saving potential of green walls since reduced heat flow into the building caused by vegetation subsequently leads to a reduction in energy cooling load and indoor temperatures. All compared studies obtained and presented results relating to surface cooling potential of green walls, only two of them also took energy saving [22,29] and indoor cooling potential [91,92] of green walls into account. Table 6 shows a detailed summary of values concerning thermal effects of green walls derived from the studies, also demonstrating the majority of published temperature data. Temperature values concerning surface cooling potential explain the temperature difference between the wall surface under the green wall system and surface of the comparative bare wall.

Chen et al. [91] conducted an experiment to validate the microclimate of a green wall in a hot and humid climate and to examine how ventilation and wall-vegetation distance affect the thermal performance of the greenery system. Therefore, two identical outdoor labs were constructed with a vertical greening system attached on the west walls. Major findings include a notable cooling effect on exterior wall surfaces (reduction of 20.8 °C), but only small effects on the indoor environment (11 °C) compared to the bare wall situation. Additionally, cooling effects were better with a smaller air gap distance between vegetation and wall.

Cheng et al. [22] carried out an experimental investigation to
assess the effect of vegetation on the thermal performance on an on-site façade wall installation at a public housing apartment. Results showed a reduction of surface temperatures (up to 16.0°C) and a delayed transfer of solar heat, which consequently reduced power-consumption (1.45 ± 1.85 kWh) in air conditioning compared with a bare façade wall. Cooling effects were closely related to moisture in growth media and vegetation coverage, demonstrating the importance of a healthy plant cover and a hospitable substrate.

The main objective of the study conducted by Coma et al. [29] was to compare the thermal performance of a double-skin green façade and a green wall. Three experimental house-like cubicles were implemented, two equipped with vertical greening systems, and one without any green coverage used as reference. Results confirm a high potential for energy savings during cooling season achieving savings of 58.9% attributed to the green compared to the reference cubicle. Green wall related energy savings also were detected during heating period (4.2%) due to the thermal stability.
supplied by the polyethylene modules. The reductions of wall surface temperatures on south exposed walls under the green wall system in comparison to the bare control wall were about 21.5 °C during summertime and 16.5 °C during wintertime. The latter highlights the important solar gains through the southern orientation in comparison to eastern (reductions about 4.5 °C) and western exposure (reductions about 6.5 °C).

Mazzali et al. [34] studied potential effects of the energy behaviour of three green walls on building envelopes in a Mediterranean temperate climate. Three case studies were implemented in Lonigo, Venice and Pisa, performed by means of a microclimatic field measurement. Differences in surface temperatures between a covered and bare wall were revealed up to 20 °C, clearly showing a dependence on the solar radiation. Additionally, monitoring of heat fluxes indicated that green walls significantly contribute to cooling and energy reduction.

Medl et al. [46] carried out a measurement campaign to assess the performance of a green wall system with respect to its microclimatic characteristics. A test field was installed on a shotcrete wall along a highway exit in Tyrol, right next to an uncovered wall segment used as control field. Results indicated a pronounced insulation effect and a significant reduction of temperature fluctuations (temperature difference of 18.9 °C between bare and greened wall during summertime) during summer and winter.

Within the experimental campaign described in Olivieri et al. [92] the effects of a vertical plant layer and substrate on the thermal-energy performance of an insulated façade in a continental Mediterranean climate in summer conditions were scrutinised. Thermal data were obtained from two experimental mock-ups of identical dimensions, one incorporating a vegetation layer. Their findings show that exterior surface temperature reductions reach values up to 31.9 °C at a maximum, thus confirming the cooling potential of green walls during summertime. The study additionally shows that the installation of green walls in buildings lowers interior surface temperatures, resulting in about 4 °C lower inside air temperatures in the module with vegetation compared to the module without vegetation.

In Perini et al. [32] an analysis of the reduction of wind velocity and temperature on the building envelope achieved by different vertical greening systems (direct green façade, double-skin green façade, green wall) was presented. Experimental locations were situated in Delft (direct green façade), Rotterdam (double-skin green façade) and Benthuizen (green wall), whereby a test field was implemented only for the green wall (experimental study). Both the direct and double-skin green façade were installed earlier and independently from the study (observational study). Results indicate a reduction of surface temperatures behind the green layer compared to the bare façades (5 °C) as well as a reduction of wind velocity (0.2 m/s), which has a positive influence on the thermal properties of the building envelope and suggests supporting energy savings for cooling and heating.

Razzaghmanesh & Razzaghmanesh [24] conducted an experiment aiming to collect data regarding the contribution of green walls in building environments and energy performance in dry climates. Thus, an experimental green wall was set up on a west facing building wall and was compared to a bare wall. During the study, warm day's and cold day's scenarios were considered. The results confirmed the potential of the green wall in creating an insulation layer for the building wall, since temperature reductions of up to 25 °C were observed on wall surfaces under the green wall, additions (teasingly decreasing heat transfer through the green wall. Scharf et al. [35] investigated microclimatic effects of a green wall implemented on an office building façade, aiming to ascertain the microclimatic and energetic effects of the green wall in comparison to the bare plaster façade of the building. Cooling (minus 5 °C) and buffering (plus 7 °C) effects were detected in the building during summer and winter, as well were surface temperature reductions of 10–15 °C due to the green wall.

In Victorero et al. [63] an experimental study was conducted to measure surface temperatures and to generate a solar reflectance index of two green wall systems compared with two traditional walls in an urban context under semiarid climatic conditions. With wall surface temperature reductions of up to 30 °C it was concluded that the green wall technology presents a high potential to contribute mitigating urban heat island effects.

Wong et al. [26] collected data on the thermal impacts of eight vertical greening systems (seven different green walls, one double-skin green façade) of buildings and their ambient conditions. They conclude, that regarding reductions in ambient temperature of up to 3.3 °C and in consideration of the preponderance of concrete and glass façades in the built environment, the use of vertical greening systems to cool the temperature in building canyons is a promising approach. Temperature reductions of up to 11.58 °C on wall surfaces support reduction in energy cooling load and consequent saving in energy costs.

6. Discussion

This study has reviewed 59 sources discussing the emerging field of vertical greening systems, 3 sources focusing on green roofs and 37 sources giving information about surrounding areas (e.g. vegetation in general, ecology, soil, climate, etc.). The review found that general performance of plants on urban city zones have been receiving comprehensive attention, while studies on benefits of vertical greening systems are still fragmented and incomplete. Thus, it was striking that many authors still refer to commonly known benefits of vegetation (e.g. urban habitat biodiversity, faster stress recovery, glare reduction) or green roofs (e.g. retention of rain water) without having any proof if this can also be applied to vertical greening systems. Consequently, complementary scientific studies on benefits of vertical greening systems are needed.

Most of the peer-reviewed literature on the subject of vertical greening systems deals with achievable benefits in city zones, especially the contribution of vertical greening systems to thermal behaviour of building envelopes. Accordingly, almost all of the reviewed studies are focusing on the use of vertical greening systems on residential buildings (or similar) in urban areas. However, the study conducted by Medl et al. [46,47] demonstrates that there is promising potential for the use of vertical greening systems in rural areas, such as the greening of vertical surfaces and highly steep slopes resulting from the continuing expansion of traffic and transport systems. The important factor of thermal behaviour thereby rather drops to the background, while landscape aesthetics come more into focus. Fig. 4 clearly shows the positive effects on landscape scenery achievable due to the application of the chosen vertical greenery system.

Thus, Medl et al. [46,47] discussed that benefits outside urban areas are achieved especially regarding landscape integration as well as biodiversity support. From an ecological point of view, they pose the potential of counteracting ‘habitat fragmentation’ to be another crucial aspect for favouring the use of green walls in rural areas. Davies & Pullin [93] argue, that anthropogenic modification often causes reductions in landscape connectivity which represents one of the major reasons for local species extinction [96], threatening biodiversity and decreasing genetic variability of populations [97]. Relating to this, green walls, characterized by not needing any connection to natural soil, have potential to re-establish a connection between fragmented habitats by being attached on construction buildings like shotcrete walls, highway bridges or tunnel portals in rural areas. Future studies are required to provide
more information on this subject. In addition to the reconnection of habitats by the use of vertical greening systems, Peña-García et al. [98] point out the important benefit of plants based on the use of climbing plants for the greening of tunnel portals. They argue that lighting installations demand the biggest part of the energy consumed in road tunnels, since visual adaptation of the drivers coming from bright environments requests very intense illumination levels, especially in the first part of the tunnel, the so-called threshold zone. Within their study, the lighting demands in this zone arising from the forestation of the surroundings of portal gates with climbing species have been quantified by luminance measurement. Peña-García et al. [98] finally conclude that the use of climbing plants is equivalent to fully forest the surroundings of portal gates, optimizing the binomial energy consumption-landscape integration in a Mediterranean climate. It might be assumed that similar studies using green walls instead of climbing plants would achieve similar results, since Medl et al. [46] proved, that reflected solar radiation of green walls is much lower compared to a bare concrete wall. Thus, the use of green walls on tunnel portals contains high potential for further research.

Hitherto, built constructions in urban areas (as e.g. supporting structures along highways and railway lines) remained widely unobserved in the context of vertical greening. Medl et al. [46] argued that thermal comfort of people can be improved by vertical greening systems on built constructions related to a reduction of heat stress due to the green wall. Thus, positive effects due to application of vertical greening systems on built constructions in urban areas are expected, and intensified further research on vertical greening measures in this context is required.

The review also revealed that recent studies are usually very detailed and well developed, but sound scientific comparisons currently are rather difficult to realize due to wide disparities in study parameters like used greening systems and system elements, climate zones or collected data. This was confirmed in part two of the paper. The here presented comparison of reviewed studies showed a large variety concerning study design and elaborated parameters on green walls. Experiments were conducted in several climatic regions, predominantly in summer over a period of a few days or weeks. Within vertical greening systems, green walls are rather innovative. Hitherto, study emphasis has therefore rather been laid on general system functionalities, and data or setting comparability had only minor or subordinate significance as scientific target. As already mentioned by Wong et al. [26], numerous factors, such as the physical structure, materials, plants species, substrate type, composition, depth or moisture content have an impact on the performance of green walls. Wide disparities among system elements like system type and material, size of test field, cavity width between green wall and building surface or even used plants species make it difficult to compare evaluation results. For future research, this implies single parameter-centered analyses under constant and comparable conditions.

It is rather remarkable that most of the reviewed experimental studies only compare green wall vs. bare wall without having any replications, limiting results both in terms of significance and of interpretation. To improve the significance of experimental results, replication is strongly recommended to reduce variability by increasing statistical significance and confidence level [99].

Plant characteristics and soil property information are not provided in the compared studies. Nevertheless, as previously pointed out by Hunter et al. [43], experimental studies cannot be replicated and investigated by other researchers, for example in contrasting climatic regions, when detailed information is not available. Thus, giving detailed information on study and material characteristics is quite important in case of facilitating further research activities.

7. Conclusion

From this review, we conclude that research in the field of vertical greening is already fairly well advanced, providing central information on system functionality and achievable benefits but still offering huge potential for development. This review illustrates examples for research gaps such as complementary studies on the improvement of urban biodiversity, stress recovery, glare reduction or rain water retention ability of vertical greening systems, the implementation of green walls in rural areas, or the application of green walls on construction buildings. It further offers some ideas on future approaches and complementary studies on e.g. rainwater retention, biodiversity, habitat de-fragmentation in rural areas, the application of green walls on shotcrete walls, on highway bridges or tunnel portals. Research and quality would benefit from more standardized measurement approaches and more detailed information, to guarantee a better comparability of scientific studies.
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