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Vertical greenery system: a model for improving energy efficiency of buildings

Authors:

Assoc.Prof. **Tanja Trkulja**, PhD. Arch.
University of Banja Luka, Bosnia and Herzegovina
Faculty of Architecture, Civil Engineering and Geodesy
tanja.trkulja@aggf.unibl.org
Corresponding author

Milana Radujković, MSc. Arch.
University of Banja Luka, Bosnia and Herzegovina
Faculty of Mechanical Engineering
milana.radujkovic@student.mf.unibl.org

Prof. **Marina Nikolić-Topalović**, PhD. Arch.
Academy of Technical and Art Applied Studies Belgrade, Serbia
Department School of Civil Engineering and Geodesy
mntopalovic@vggs.rs

Research Paper

Tanja Trkulja, Milana Radujković, Marina Nikolić-Topalović

Vertical greenery system: a model for improving energy efficiency of buildings

Adaptation to climate change in cities is essential, and vertical greenery systems (VGSs) are used as a means of restoring the urban areas' ecological integrity. This paper presents the classification, typology, and benefits of the VGS for the energy performance of buildings. To analyse its energy and environmental impacts, the use of VGS was simulated on the façades of residential buildings in the urban area of the City of Banja Luka. The results showed that VGS reduced the temperature of the wall and air in and around the buildings, as well as the emission of CO_2 in the air.

Key words:
vertical greenery systems (VGS), urban environmental quality, energy-efficient buildings, sustainable planning

Prethodno priopćenje

Tanja Trkulja, Milana Radujković, Marina Nikolić-Topalović

Sustav vertikalnog ozelenjavanja - model za poboljšanje energetske učinkovitosti zgrada

Prilagodba klimatskim promjenama u gradovima je bitna, a sustavi vertikalnog ozelenjavanja (SVO) primjenjuju se kao sredstvo za obnavljanje ekološkog integriteta urbanih područja. Ovaj rad predstavlja klasifikaciju, tipologiju i prednosti SVO-a za energetske performanse zgrada. Kroz eksperimentalni dio rada simulirana je uporaba SVO-a na fasadama stambenih zgrada, u urbanom području grada Banja Luke, a za analizu utjecaja energije i okoliša. Rezultati istraživanja pokazali su da SVO smanjuje temperaturu zida i zraka u zgradama i oko njih, kao i emisiju CO_2 u zrak.

Ključne riječi:
sustav vertikalnog ozelenjavanja (SVO), kvaliteta urbanog okoliša, energetski učinkovite zgrade, održivo planiranje

1. Introduction

Global surface temperatures over the past decade have been 0.8 °C higher than in the early 20th century according to NASA's Goddard Institute for Space Studies, and two-thirds of this warming has occurred since 1975 [1]. Increases in heat waves and heavy rainfall have intensified during the 21st century as a consequence of the global temperature increase [2]. Thermal stress threatens human health and leads to increased mortality [3], and extreme climate events are expected to be extremely risky for society and ecosystems [4].

The increase in global temperature was also influenced by the uncontrolled growth of cities. For the first time in 2008, more than half of the world's population lived in cities. The United Nations estimates that by 2050, approximately 67 % of the world population will live in urban areas [5]. Rapid urbanisation causes environmental problems (noise, pollution, and urban heat islands) and a serious threat to the quality of urban life [6]. Furthermore, population growth, higher needs for construction services, and increased in time spent inside buildings have all resulted in an increase in energy consumption [6]. Cities have a high level of energy consumption that could be offset by using renewable energy sources and taking advantage of the urban environment's characteristics [7]. Architectural facilities consume 32 % of the total final energy, while the share of primary energy consumption is 40 %, which exceeds energy consumption in the industrial and transport sectors. According to available data, in the territory of Bosnia and Herzegovina, existing buildings of individual and collective housing consume the same amount of energy as the buildings of similar characteristics in Europe in the 1990s [8].

From 1990 to 2010, the primary energy input increased by 49 % and CO_2 emissions by 43 % [9]. The construction sector, including households and the service industry, is one of the largest energy consumers with two-thirds of final energy consumption in 2010. It is estimated that about 56 % of the total energy is consumed in the housing sector [10]. Energy consumption in the construction sector is continuously growing and will continue to do so until the buildings are designed to use energy more efficiently. Otherwise, energy demand is expected to increase by 50 % by 2050, indicating the importance of reducing energy consumption in buildings [11].

Thermal characteristics are affected by building envelope, internal temperature, ventilation system, infiltration, conductivity, glazing type, and insulation level [12]. The building envelope is a key element of a building that affects its energy balance and the quality of the inner climate (thermal, sound, air, and light comfort) [13]. It is affected by the temperature differences between inner and outer spaces. The building loses heat directly through the envelope; thus, its design is very important and the first step towards energy-efficient construction [14]. The thermal characteristics of the building envelope depend on the physical attributes of the envelope and internal temperature [12].

In their recent study, Li et al. [15] recommend the use of green structures in cities. However, it is impossible to plant green material on the ground floor in a densely built city centre. Therefore, green roofs and vertical greenery systems (VGSs) are increasingly being used as a means of restoring the ecological integrity of urban areas and reducing energy consumption in buildings.

Green roofs are a passive cooling technique. They stop incoming solar radiation from reaching the building structure below [16]. VGS encompasses any method of plant placement on a vertical surface, independent of the growth mode of the plant material [17]. The theoretical part of this paper provides an overview of the literature about various VGS types and studies about the impact of a VGS on the energy efficiency of a building envelope. The applied research includes an investigation in a residential block in the urban area of Banja Luka, where high-rise buildings are abundant. In addition to the environmental impact of VGS, the limited space in the area prevents planting trees, making the implementation of VGS effective for creating identity and increasing spatial and visual attractiveness.

2. Methodology

This paper presents the literature about classification and application of a VGS on a building envelope, with a focus on topics related to the energy efficiency of buildings. The literature review considers the time frame from 1980 to the end of 2019 and covers two primary VGSs: the green façade and living wall systems. The system analysis includes an overview of definitions, characteristics, and potential benefits of VGS for the energy efficiency of buildings. There is limited research on the topic and its specific application in Bosnia and Herzegovina; thus the study aims to establish the importance of this field and lay the foundations for initial research at institutes and faculties, as well as for the design of architectural projects. The research involves the application of a content analysis method (analysis of available literature within the subject area) to present the relevant data and form a theoretical research base.

The first part of this paper explains the classification and typology of the VGS. Individual descriptions of different types of VGSs are given, realised by mutual comparison of individual types, as well as a detailed analysis of the classification system by several authors in this scientific field. The benefits of the VGS for the energy performance of buildings are then listed: the heat gains of VGS. The analysis was conducted in relation to the shading effect (through the calculation of the leaf area index (LAI)) and evaporative cooling, as well as the orientation of the VGS, reduction of wind speed, analysis of the VGS life cycle, and the effect of UV radiation on the building materials.

The second part of the paper describes experimental research on the sampled area of the Borik residential block in the urban area of the City of Banja Luka. The analysis of spatial planning documentation includes the analysis of different types of maps (orthophotos and geodetic maps) to obtain data on the total area of façades on which the VGS can be applied. The scope of the pilot area and the objects to be treated in the study are shown on an orthophoto map using Autodesk AutoCAD Map 3D software. Then, the photographs showing the buildings in the researched area were taken during fieldwork. A 3D model of the space was then made using SketchUp software. The final phase of the experiment involved the simulation of environmental and energy impacts and was performed using two software programs: EnviMET and EnergyPlus. The following parameters were taken into account: reduction of temperature in buildings and energy savings, reduction of wall and ambient temperature, reduction of carbon dioxide emissions, and the amount of polluting particles in the air that green façades can clean.

The results and contribution of this paper are presented and argued in the conclusion of the paper. VGS has an impact on increasing the green properties of the urban matrix, improving the environmental quality of cities and energy efficiency of buildings.

3. Classification and typology of VGS

The concept of VGSs dates to the Babylonian civilisation and the construction of the Hanging Gardens of Babylon around 600 BC as one of the original Seven Wonders [18]. As a significant element of the built structure, vegetation was introduced in ancient Greece in the form of planting corn and other plant species on roofs in honour of Adonis, the Greek god of beauty and desire. Furthermore, pergolas with climbing roses and vines were an inevitable element of Roman gardens. From an urban planning perspective, a significant contribution was made by Ebenezer Howard, who introduced the idea of a garden city in 1898 and highlighted the importance of green structures for urban design and planning [19]. While the application of climbing plants over a wall is not a new trend, the systems and purpose of using them have changed over the last few decades [20].

VGS consists of the system substructure, growing media, plants, and often, installation systems for irrigation and fertilisation. Plants are an important element in the entire system and their selection should be adapted to the system type, environmental factors, and microclimate conditions, as well as the expected level of maintenance and budget. Growing media are substrates in which the roots of plants find their nutrition, such as regular soil (nutrients are produced by decaying plants and animals), lightweight soil (balance of compost, peat moss, and minerals), felt (soil substrate that provides a platform for plant growth), or foam (a light and stable substrate that transfers nutrients from the water to the plants). The type of growing media determines the type of system [18].

In foreign literature, there are different terms for VGS; terms such as vertical greenery system, green wall, and vertical garden are synonymous and are often used interchangeably in the scientific literature. The VGS classification presented in this paper was created after the comparison of some VGS types and a detailed analysis of the classification system, according to several authors in this scientific field [17, 21–23], depending on the primary aspect of considering the realised benefits. The classification principle is based on the vegetation growth mechanism and the method of application of the appropriate types of substructures, as well as the plant substrate and irrigation system; it is primarily based on the classification made by Perini et al. [23]. In their research paper, the authors divided the VGSs into green façades and living wall systems (Fig. 1).

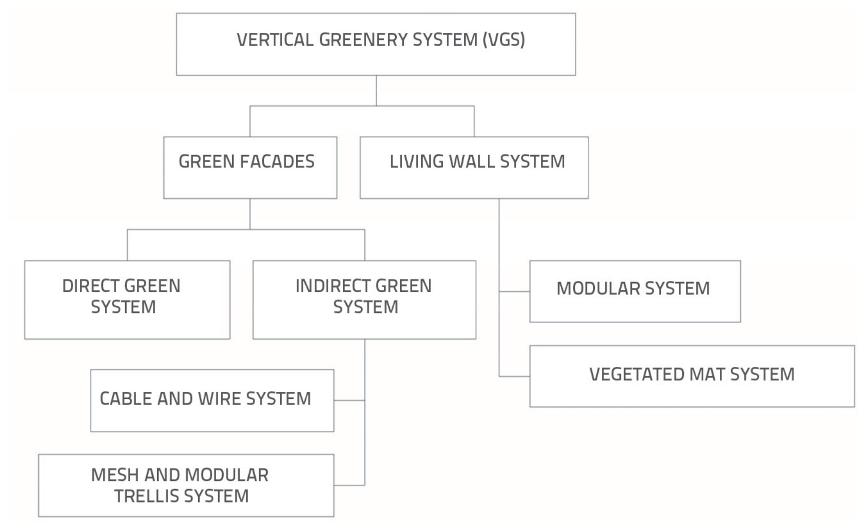

Figure 1. Classification of VGS [24]

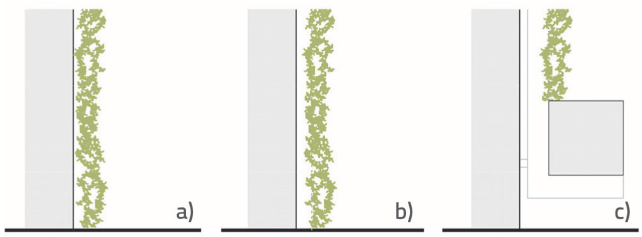

Figure 2. Green façade: a) direct greening system; b) indirect greening system; c) indirect greening system with planter box [25]

Green façades are a type of VGS for greening façades exclusively with evergreen or deciduous plant species of climbers and creepers (e.g. *Hedera Helix* or *Parthenocissus tricuspidata* (Boston Ivy)). Green façades use climbers attached directly to the surface of the building envelope, called direct greening systems (Fig. 2a). Climbers planted in the ground at the bottom of the building are the oldest greening principle. Simple maintenance and low costs of installation ensured the widespread use of this VGS type, although façade damage is occasionally possible due to the aggressive growth of certain plant species. When planning green façades, it is important to consider that some plants can grow about 5–6 m and as high as 25 m. Moreover, green façades use climbers attached indirectly to the surface of the building envelope, called indirect greening systems. These can be supported by cables or wires (Fig. 2b) or with a planter box (Fig. 2c) with plant species of climbers and creepers (e.g. *Wisteria, Clematis, Ipomoea quamoclit, Campsis grandiflora,* and *Akebia quinata*).

Living wall systems, pioneered by botanist Patrick Blanc, are a more complex type of VGSs, consisting of modular panels which contain the substrate or other artificial growing media such as foam, felt, perlite, and mineral wool. Panels require hydroponic cultures using balanced nutrient solutions to provide all or part of the plant's food and water needs. These systems usually use evergreen plants (small herbaceous species, perennial flowers, low shrubs, ferns, and grasses). Different types of systems have developed over the past several years. Each has specific characteristics, starting with the growing media. Living wall system is divided into vegetated mat and modular systems with plants, such as *Sedum, Heuchera, Pilea, Deutzia, Acorus, Enonymus,* and *Asplenium*. Figure 3 shows three types of living wall systems with different cultivation and planning principles: living wall system based on planter boxes (Fig. 3a), foam substrate (Fig. 3b), and felt layer (Fig. 3c) [25, 26].

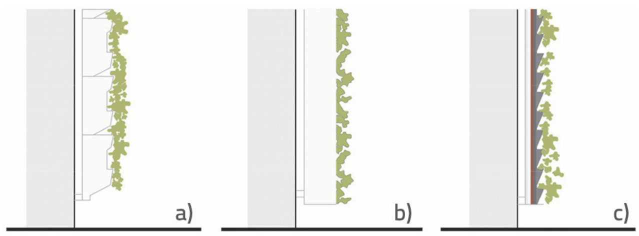

Figure 3. Living wall system: a) based on planter boxes; b) based on foam substrate; c.)based on felt layer [25]

Living wall systems increase the diversity of plant species and offer much more creative design solutions. Growing plants in each module of the living wall system to cover the entire surface requires less time than green façades. If one plant is damaged or wilted, it is possible to change only that module instead of the entire façade [20]. The substrate also contributes to the growth of the plant, where 5–10 cm is suitable for application in living wall systems [25]. Functionally, most of these systems require a more complex design than green façades. They are often very expensive, energy consuming, and difficult to maintain [26]. Perini & Rosasco [27] concluded that VGSs are more expensive than walls without vegetation, but this investment pays off because of their multiple positive effects.

Green façade and living walls have different characteristics, cooling, and insulation effects [28]. Inadequate plant selection and mismatch with location requirements can lead to various problems, such as overgrowth, plant wilting, problems with pests or diseases, demanding maintenance, poor aesthetics, and unattractive wall structures [25]. Therefore, it is necessary to select adequate plants for green façades, to choose a façade in a sunny location, and to water and regularly prune the plants [29].

4. Benefits of the VGS for the energy performance of buildings

Greening the building envelope is a sustainable solution for improving the ecological balance of cities; supporting biodiversity; reducing urban heat islands, storm water, noise, and CO_2 emissions; improving air quality [30]; and saving on energy consumption in buildings by protecting buildings from excessive solar heat and cold air infiltration [23, 31].

Numerous studies have shown that vegetation on the building envelope can be effective at the level of environmental performance of the building. In their research in 1980, DeWalle & Heisler [32] suggested that vegetation can reduce cold air infiltration into the building envelope by up to 40 %.

Vegetation absorbs a large amount of solar radiation for its growth and biological functions [26]. It can significantly reduce the temperature around the building envelope and thereby reduce the amount of energy required to heat and cool buildings [33]. Moreover, it reduces cold air infiltration and convective heat losses in a building [23]. In most regions of the world, heating and cooling loads represent the highest energy consumption in the construction sector [22].

Several experimental studies have investigated heat gains and losses in green façades [21, 34]. The research by Djedjig, Belarbi & Bozonnet [35] was conducted over two winters using small brick physical models covered with *Hedera helix* to investigate the insulating properties of plants during cold weather. The results showed a 21 % reduction in average power consumption compared with bare models during the first winter (4.3 and 5.4 kWh per week, respectively). During the second winter, when the leaves were larger, savings of 37 % were achieved (3.7 compared with 5.9 kWh per week). The presence of the *Hedera helix* significantly improved the temperature of the brick over the stripped wall. The greatest energy savings were associated with more extreme weather conditions (cold temperatures, strong wind, or rain). In such cases, green façades could increase energy efficiency by 40–50 % and increase building envelope temperature by 3 °C.

VGSs improve thermal insulation through the regulation of outdoor temperature. The extent of saving depends on various factors, such as climate [34], the distance from the façades of the surrounding buildings, the type of building envelope, and the density of leaves. This can affect both the cooling and heating of the building. VGSs limit the movement of heat through dense vegetation mass, create a buffer against wind effects during the winter months, and reduce the energy required for heating and cooling [29]. The positive effect of VGS on the indoor air temperature during the winter months in comparison with the walls without vegetation was emphasised by Ottelé & Perini [33] who stated that this effect was significant for reducing energy used for heating the building. The indoor air temperature was 2.1 °C higher than that of the wall without vegetation. This led to an improvement in the R-value of the green wall compared with that without vegetation.

Also, Lesjak, Pajek and Košir [36] in their experimental research, conducted during the summer of 2018, show a simulation of the influence of an indirect green facade on the thermal behavior

of a building located at the Punat location, on the island of Krk in Croatia. By applying an indirect green facade, the influence of solar radiation was reduced to 505 W/m^2, and the temperature on the outer surface of the facade was reduced to 13.5 K. The experimental results were used to simulate thermal comfort in the interior of the building using a simple model. When an indirect green facade was installed over the entire wall exposed to the sun, the average reduction in operating temperature was up to 6 K for a new building, i.e. up to 5 K for a traditional stone house. The results of the research show that the indirect green facade can be applied as protection against excessive heating of building elements exposed to extreme weather influences, such as those prevalent in the Kvarner Bay area in Croatia.
Perini et al. [23] studied the difference between direct and indirect green façades. When the wall surface behind the direct green façade was compared to the surface of the bare wall, a decrease in temperature of 1.2 °C was noticed. A decrease of 2.7 °C was found for the indirect greening system. Furthermore, Ottelé & Perini [33] presented a comparative thermal analysis of a VGS attached to the building envelope. The results show that the temperature differences between the bare wall and the different VGSs go up to 1.7 °C for the direct greening system and 8.4 °C for the living wall system after 8 hours of heating in the summer, due to different wall layers.
Yin et al. researched the cooling effects of direct green façades [37] through a case study conducted at the Executive Office Building on Nanjing University's Xianlin Campus, China. The results showed that the daily average surface temperature of the direct green façade was significantly lower than that of the bare wall, with a maximum decrease of 4.67 °C. The cooling efficiency of the direct green façade was most evident between 10:30 am and 4.00 p.m., and it significantly decreased at night. This research shows that the use of direct green façades in the design of building envelope contributes to the efficient cooling of the environment and reduces the energy required for cooling in buildings.
Several studies have been conducted regarding the orientation of the VGS. Dependence on the orientation of the façade is confirmed by the contribution to energy savings in the east and west [22]. Lee & Jim [38] conducted an experimental study on wire rope climber green walls, oriented northeast and northwest, with different air-gap depths. The best results in cooling the outer surface of the wall were achieved in the range of 3.49 °C, 0.52 °C, and 0.03 °C in sunny, cloudy, and rainy weathers, respectively; during the night, the values were 0.78 °C, 0.05 °C, and 0.03 °C, respectively. The northeast wall achieved greater external air cooling than the surface of the northwest wall by 0.38 °C and 0.77 °C in sunny weather. The northwest-oriented green wall had a greater cooling of the outer surface by 0.47 °C overnight. A greater distance between the vegetation and the outer surface of the wall provides greater cooling of the outer surface. The authors' observation is that the façades more exposed to the sun should be given priority for greening.
Evapotranspiration leads to a reduction in energy for cooling buildings. The air cavity between the green wall and the building façade acts as a thermal buffer that can reduce the heat flux through the building envelope [20]. Wong et al. [21] studied eight different VGS types on concrete walls and discovered that living wall systems with modular panels showed a better capacity for reducing wall surface temperature and the lowest daily fluctuation range of average wall surface temperature in comparison to green façade. The maximum decrease in temperature of the living wall surface by evapotranspiration was 11.58 °C.
The project of the Institute of Physics of the Humboldt University of Berlin Adlershof combined rainwater management and energy savings with natural conditioning through walls. The shadow created by plants provided cooling effect that influenced the energy consumption of the building, thus becoming a true passive air conditioner. The results of the project in Berlin Adlershof show that the level of evapotranspiration is about 2 litres a year. This is 2 × 2670 kJ, which represents an effect of energy of approximately 1.483 kWh of cooling load per year. Thus, evapotranspiration is the cheapest and most efficient way of cooling the building and the most important environmental benefit of vegetated façades (and roofs) in urban areas. It affects urban hydrology, reduces the temperature of the surfaces, and improves the management of rainwater [29].
The efficiency of VGS depends largely on climatic factors such as temperature, relative humidity, solar radiation, and wind speed. Owing to its leaves, vegetation can reduce the wind speed on the building envelope [28, 29]. In winter, the wind drastically reduces the indoor temperature of buildings that do not have insulation and wind protection. Even in buildings that are hermetically sealed, wind reduces the efficiency of regular insulation. VGS plays a key role in reducing the wind speed and increasing the insulation effect.
Most research studies focus on the shading effect delivered by plants. VGS could provide shade to the building, and more thermal energy enters the walls without shade due to direct sun exposure. The façade, fully covered with greenery, is protected from the intense solar radiation in the summer months and can absorb 40–80 % of the radiation owing to its leaves, depending on the amount and type of greenery. The shading effect can significantly reduce the heat flow through the wall and therefore lower the ambient temperature [31].
The best orientation for VGSs applied in cold climates is in a way that reduces the cold winter wind but provides direct sunlight to the south and east walls. In temperate climates, the vegetation layer should not block summer winds but should reduce the cold winter wind. In addition, direct sunlight to the south wall is necessary for places with a high degree of heating. In tropical climates, both shading effect and wind speed should be increased by using a suitable type of plants, whereas in hot and dry climates the highest amount of shading and evapotranspiration is required. The west and east walls require the most sun protection. Dry environment increases the rate of evapotranspiration, and wind accelerates this trend by removing moisture from nearby vegetation [20]. Perini et al. [23] evaluated the impact of two green walls on wind speed and found that the plants create an outer insulation layer and contribute to energy savings and heat loss in colder weather. The wind speed near the façades of the building decreased from 0.56 m/s to 0.10 m/s starting from 10 cm in front of the façade to the air cavity.
One way to characterise the potential shading effect of vegetation is by calculating the density of the foliage using the LAI. The density of the foliage depends on the VGS type, plant species, development stage, and climatic conditions [34]. LAI is defined as the one-sided

green leaf area per unit ground surface area. The higher the LAI value, the greater effect of shading quality. The magnitude of the transpiration process and the effect of radiation filtration are also higher [25]. Thicker vegetation is a larger thermal insulator.
However, the literature lacks data on this parameter (e.g. climate impact on LAI values and LAI variations by height, etc.) and appropriate common methodology for measuring LAI so that the energy efficiency of buildings with VGS could be tested. The study by Pérez et al. [23] aimed to establish a common and easy way to measure LAI and the energy savings provided by VGS. The results show that the simplest and quickest procedure to measure LAI is the indirect method based on the amount of light transmitted through the green screen. Considerable energy savings were obtained from the experimental tests: up to 34 % for the Boston Ivy plant species with an LAI of 3.5–4.0 during the summer period under the Mediterranean continental climate.
Hoelscher et al. [3] varied the effects such as shading, transpiration, and insulation. Their study showed that vegetation can mitigate the effect of urban heat islands by directly shading the heat-absorbing surfaces and by evapotranspiration. While the temperatures of inner and outer wall surfaces were lowered by greening, there were no clear differences in ambient air temperature. Based on the temperature of the inner walls, it could be shown that VGSs are most effective during the night, which is very important for reducing the night heat stress indoors. Therefore, the design of the façade greenery has a major impact on the cooling effects of the street canyon and the building. The cooling effects provided on hot summer days mainly depended on shading, whereas transpiration had a lower share in it. Façade greenery must be sufficiently irrigated with up to 2.5 $Ld^{-1} m^{-2}$ (WA) to provide its cooling performance. The symbol L refers to a liter, and $d^{-1} m^{-2}$ represents the daily rate transpiration per unit of wall area (WA).
The analysis of the life cycle is performed to efficiently assess the sustainability of a building. The study by Ottelé et al. [39] concerning the life-cycle analysis of four VGS types shows the environmental load profile in relation to energy savings for air-conditioning and heating in the Mediterranean and temperate climates (Tab. 1).

Table 1. Energy savings for heating and cooling and temperature decrease for Mediterranean and temperate climate [26]

Greening system	Benefit	Mediterranean climate	Temperate climate
Direct green	ESH TD ESC	1.2 % 4.5 °C 43 %	1.2 % 2.6 °C ---
Indirect green	ESH TD ESC	1.2 % 4.5 °C 43 %	1.2 % 2.6 °C ---
Living wall system with planter boxes	ESH TD ESC	6.3 % 4.5 °C 43 %	6.3 % 2.6 °C ---
Living wall system based on felt layers	ESH TD ESC	4 % 4.5 °C 43 %	4 % 2.6 °C ---
ESH - energy savings for heating; TD - temperature decrease; ESC - energy savings for cooling			

For all studied systems, temperature differences between bare walls and walls with VGSs were determined. It was found that the temperature gradient through living wall systems showed an inhibitory effect, resulting in significantly lower temperatures (up to 10 °C) of the outer wall structure. Due to these lower temperatures, less heat is accumulated in the building envelope, which primarily contributes to the effect of urban heat islands (outdoor climate). There is a particularly positive effect of living wall systems on the thermal behaviour of buildings. However, for a sustainable approach, the microclimatic and environmental benefits must be linked to the environmental burden generated throughout the VGS life cycle.
It can be concluded that vertical greening is a way to improve the poor energy performance of buildings. Remodelling existing buildings by altering the façades and their surface properties will also increase their energy efficiency [30].
VGS will also reduce the amount of UV radiation on building materials [29] since large amounts of solar radiation will be adsorbed for plant growth and their biological functions. Because UV radiation impairs the mechanical properties of coatings, paints, and plastics, VGS will also affect the durability of structures [21]. Material choice and durability aspects have a significant impact on the environment, especially when the energy demand of a building can be reduced or when the multifunctionality of a structure can be increased due to the integration of vegetation. However, if the green façade is directly attached, the climbers can damage the outer layer of the building envelope, especially in the case of plaster walls.
Additionally, VGSs give an aesthetic quality to the environment in which people perform their daily activities. Numerous studies have shown that the presence of plants improves human health and mental well-being. The improved aesthetics of green buildings can help launch the project and provide valuable space for people to enjoy their stay [29]. Therefore, the strategy for green buildings is very important, because of both its sustainable approach to construction and its positive impact on human health and the quality of city life.

5. Contextual research of the pilot area

The first condition for selecting the pilot area was that the space must have buildings that have non-transparent façades on which the VGS types can be installed. South-oriented buildings were also preferred as they reduce overheating during the summer period. Another condition for the selection of the pilot area was the reduced spatial capacities for planting trees, which will be partially replaced by the VGS. The residential block Borik in Belgrade Street located in the urban area of the City of Banja Luka was selected as it satisfied all the criteria (Fig. 4).
The residential settlement Borik in Banja Luka got the urban concept in 1964. It was built in the period from 1971 to 1973, after a catastrophic earthquake occurred in 1969 in Banja Luka. The original version of the neighbourhood's urban project was created by Pavle Paštar, an architect of the Urban Institute of Banja Luka. According to the Urban Project of the Neighborhood from the 60s of the last century, Borik was designed on an area of about 40 ha and contained about 3000 apartments; 2700 of them

were planned to be in collective housing buildings with a height of 4 to 16 floors, and the rest in single-family housing. However, in early 1969, the Urban Institute of Banja Luka presented a new version of the neighbourhood's urban project, named "Microdistrict Borik". The invited competition method was used in preparing the technical documents for construction work [40].

Figure 4. Spatial coverage of the pilot area

Borik was the first residential unit in Banja Luka that also contained other functions: a social and shopping centre and a primary school. Spatial boundaries were defined in the form of roads, and between them were three types of residential buildings: towers, blocks of flats, and single-family housing buildings along the perimeter. There are also green areas with children's playgrounds, sports fields, and recreation areas [40].

The block contains two residential lamellas, with a total of 10 buildings of collective housing, from 6 to 18 floors. Residential building blocks have a very discontinuous footprint. The structural system is skeletal and made of prefabricated reinforced concrete (RC) pillars and beams with RC lining. External walls are RC sandwich panels of an overall thickness of 17 cm (RC wall: 9 cm, thermal insulation: 3 cm, and RC wall: 5 cm). Energy renovation of the buildings has not been done, but Arnautović-Aksić et al. [41] conducted research on these building blocks. The thermal imaging of the building blocks indicated that the highest level of heat loss was at the windows, façade walls within the original deep-set balconies, and external wall nosing. Higher levels of heat loss were registered in areas where façade sandwich panels met the load-bearing construction. The U-value for the outer wall was 1.13 W/m^2/K. The authors proposed an improvement by adding 10 cm of thermal insulation and 1 cm of façade plaster to the wall on the outside, resulting in a U-value of 0.30 W/m^2/K for the outer wall. A 20 cm thermal insulation of 20 cm and 1 cm façade plaster resulted in a U-value of 0.17 W/m^2/K. Lower thermal transmittances yielded better thermal protection of the building [41].

When installing the VGS, the wall surfaces must be in a good condition to prevent possible damage to the structure caused by the aggressive growth system. If the wall surface is in poor condition, the plants can trigger the collapse process, so it is necessary to repair the wall surface first. In case of danger of moisture, proper and adequate installation of insulation layers is necessary, as well as waterproof membranes and root protection to ensure the stability of the wall structure [17]. Given the current condition of the building envelopes and the fact that they were built in the 1970s, it was recommended that a test of the load-bearing capacity of the structure be performed prior to the green wall installation and energy renovation, as suggested by Arnautović-Aksić et al. [41]. Furthermore, given the large capital investments, it was proposed that the sources of funding be European funds aimed at increasing the energy efficiency and reducing the negative effects of climate change (this has already been done to the energy efficiency of educational facilities in the City of Banja Luka). Maintenance falls under the jurisdiction of the homeowners' associations (institutions in the housing system of the Republic of Srpska, which is a form of an organisation of homeowners that performs building management activities). Maintenance costs for projects important to the city could be taken over by the City Administration.

The scope included collective housing buildings, single-family housing, a primary school, and business buildings (market and supermarket with a sports hall). The purpose of the areas and objects are shown in Fig. 5. Buildings occupy 25.3 % of the total researched area, greenery about 43.3 %, while paved areas are present on about 31.4 % (parking lots, paths and plateaus, and sports fields in the school yard).

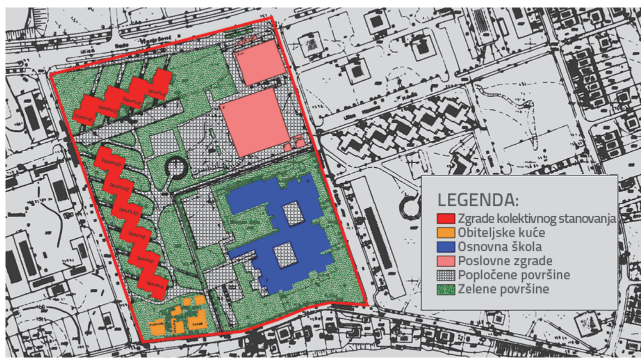

Figure 5. Building typology and spatial purpose of the pilot area

Figures 6a and 6b show residential lamellas and façades on which a VGS can be installed. The total area of non-transparent parts of the façades was obtained by multiplying the length of the wall by

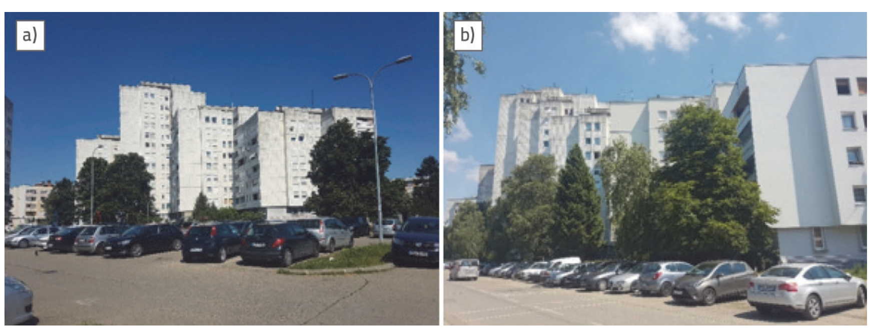

Figure 6. Researched residential buildings

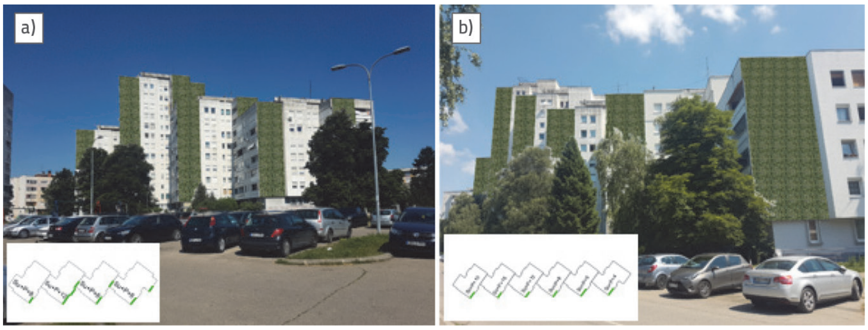

Figure 7. Façades intended for the application of VGS

the height, considering the number of floors multiplied by 3 m and adding the height (1.5 m) of the parapet. According to calculations using AutoCAD Map 3D software, based on orthophoto maps and given floors, the approximate area of non-transparent façades of southern orientation was 1.955,25 m^2. Figures 7a and 7b show the green parts of the façades.

The process of simulating energy consumption was done for a one year period. According to the data from the book Typology of residential buildings in Bosnia and Herzegovina [41], it is assumed that the specific annual energy required for heating in the researched collective housing buildings are 129.85 and 161.55 kWh/m^2/year with and without a heating break, respectively. The average daily maximum air temperature in the warmest months (June and July) for the City of Banja Luka is 28 °C.

During the simulation process, the following energy and environmental impacts of the construction of VGS on residential buildings were observed: air temperature inside buildings, ambient air temperature, wall temperature of buildings, carbon dioxide emissions, and the amount of pollutants in the air. The financial aspect of constructing green walls on façades is shown as a comparison of current energy use in money in buildings, the application of thermal improvement measures, and finally the construction of VGS. The annual energy savings and the investment's payback period are displayed.

6. Results and discussion

The obtained results (Table 2) show that the VGS can reduce the building, ambient, and wall temperatures by up to 2 °C, 3.7 °C, and 8 °C, respectively. In addition, there is a significant environmental impact in terms of reducing carbon dioxide emissions due to the reduced need for heating and cooling of buildings by approximately 5.28 t/year. One square metre of green areas on the façades can clean approximately 0.1 kg of polluting particles annually, all depending on the plant species used for this purpose, that is, the total leaf area. For this research, sedums and mosses were used in the VGS as they require the least care and can be maintained on their own. A modular living wall system with plants planted in boxes was selected, which was attached directly to the façade.

According to the data from the book Typology of residential buildings in Bosnia and Herzegovina [41], the annual required thermal energy for heating is 287.32 MWh/year. By installing green façades, consumption can be reduced by up to 264.52 MWh/year, which yields approximately 8 % savings annually. It is estimated that the consumption of fossil fuels in these types of residential buildings totals approximately 76.08 t/year CO_2eq,for two lamellae in the pilot area. Installing the green façades resulted in a reduction of approximately 5.28 t CO_2eq (6.9 % reduction). A comparative analysis of energy consumption and reduction of carbon dioxide emissions, the two most relevant indicators of the benefits of using a VGS, is presented in Figure 8.

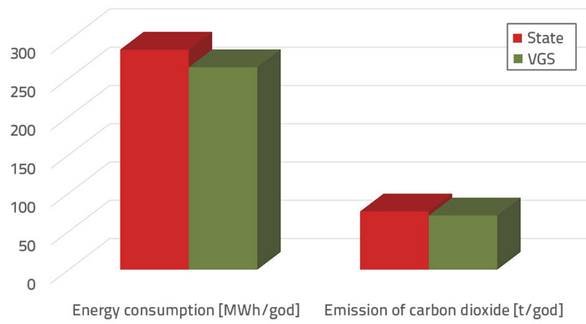

Figure 8. Comparative analysis of energy and environmental impacts before and after the installation of VGS in the pilot area

Vegetation directly reduces CO_2 in the air by photosynthesis, storing carbon in the aboveground parts of plants and roots. In this example, an indirect impact is shown, which implies a long-term effect of green façades, that is, a reduction in energy consumption in buildings, which leads to a reduction in the consumption of fossil fuels for heating. A 3D model of the area in which the simulation of the reduction of the wall temperature of the buildings was performed and the surrounding space is shown in Figure 9.

To justify the capital investment for the proposed measures to optimise the building envelope, it is necessary to calculate the

Table 2. Energy and environmental impact of VGS in the pilot area

	Reduction of the temperature in the building	Reduction of the ambient air temperature	Reduction of the wall temperature	Reduction of the CO_{2eq} emissions [kg/year]	Purification of polluting particles in the air [kg/year]
1 m^2	2 °C	3.7 °C	8 °C	2.7	0.1
1.955.25 m^2				5.279.175	195.525

Table 3. Economic aspects of building envelope optimisation

	Energy consumption [kWh/m²/year]	**Energy savings** [kWh/m²/year]	**Energy savings** [€/m²]	**Total annual savings** [€] **for 1.106.35 m²**	**Capital investment** [€]
State	161.55	-	-	-	-
Thermal optimisation	64.62	96.93	15.50	17.148.42	113.046.65
VGS	148.62	12.92	2.07	2.290.14	43.560.00
Thermal optimisation + VGS	51.70	109.85	17.57	19.438.57	156.606.65

payback period, with a period of up to 8 years being considered optimal. In this analysis, only immediate benefits were observed – specifically the monetary energy savings for building heating. The estimate was obtained by dividing the total investment by the total monetary energy savings on an annual basis for a 5-floor building (1,106.35 m^2). If cooling energy that would be saved annually by thermal optimisation and VGS installation was also considered, the investment would return in a shorter period than calculated.

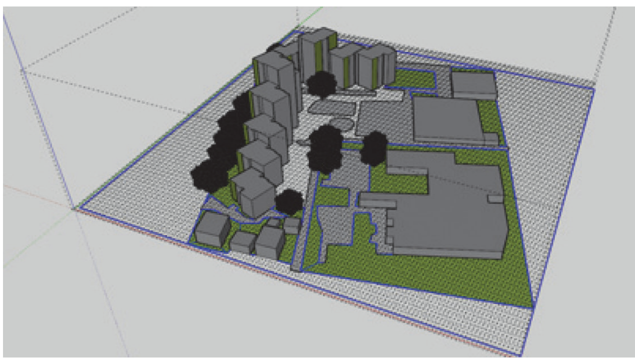

Figure 9. 3D model of the pilot area

Table 3 shows the financial aspect of the proposed measures to improve the envelope, and it is calculated for one building in the study area because the building blocks are typical, built in the same period, and have the same characteristics. The specific annual energy required for uninterrupted heating for one residential building block is 161.55 kWh/m^2/year. If the envelope was renewed according to the proposed thermal optimisation (thermal insulation: 10 cm and façade plaster: 1 cm), this consumption would be reduced to 64.62 kWh/m^2/year (approximately 60 % savings) [41]. With the construction of the VGS, energy consumption would amount to 148.62 kWh/m^2/year (8 % annual savings). The net area of heated space is 221.27 m^2 per floor, which is a total of 1,106.35 m^2 for this building [41].

Banja Luka Heating Plant, which provides the heating service, typically charges according to the size of the heated area with payment throughout the year (12 months), during the heating season (6 months), or according to the consumption read on the calorimeter [42]. When calculating the energy consumption in money for this research, the stated price per kWh/m^2 without value-added tax of 0.16 € was considered.

To estimate the total capital investment for energy renovation of the façade according to the measures proposed in the Typology [41], a residential building block with similar characteristics and the same construction period on which the same thermal measures were proposed was considered. The price of the investment per square metre is approximately 68.50 € [43]. The basis of the building is 336.98 m^2 and has a total of 5 floors. The approximate area of the mantle for renovation is 1,650.00 m^2. Thus, the total price of 113,046.65 € for the energy renovation of the mantle was calculated. The average cost of building modular green walls is 400.00 €/m^2. The object has a total of 108.9 m^2 of the non-transparent façade, which is intended for installing VGS, and the total initial investment was calculated as 43,560.00 €. According to the data on total savings on an annual basis (Table 3), if the implementation of the proposed thermal measures and modular green wall were realised, the initial investment would pay off in 8 years.

7. Conclusions

Introducing the basic features of the vertical greenery system is the basis for defining VGS as a contemporary urban design model whose implementation achieves environmental, economic, social, spatial, and energy benefits for the city and buildings. The principle of the VGS classification covered in this paper were the main criteria on which the VGS types were based. Applying the VGSs and achieving the environmental benefits, which affect climate and many other environmental problems that daily impair the quality of life, lead to the realisation of some social benefits, which makes this urban design model an acceptable way of urban renewal.

Research has shown that VGS limits the movement of heat through dense vegetation mass, creates a buffer against the effects of wind during the winter months, reduces the energy required for heating and cooling, and affects the durability of structures and materials of buildings. The use of VGSs increases the energy efficiency of buildings. However, it can be concluded that, despite the considerable amount of research, this topic is still 'new', under-researched, and requires further study related to:

- finding the optimal configuration of the VGS location, plant shape (LAI and plant height), leaf shading (evergreen and deciduous), and substrate properties (thickness, moisture content, and density) for different types of climates;

- development of steady-state analysis in controlled conditions (building use, morphology, and level of insulation), except for climatic factors on the seasonal energy performance of the VGS;
- studying the impact of VGS on energy savings for buildings;
- discussion of the cost-effectiveness of different VGS types;
- conducting more research studies on the climate conditions of Bosnia and Herzegovina and the region, indigenous plant species and different substrates, and different VGS types;
- regulations based on clear classification and local research that must be adopted at the national level to formulate a strategy for VGS construction more easily;
- creating and initiating a system of incentives for investors, who apply this type of façade in the construction of new or reconstruction or energy rehabilitation of existing buildings, given the multiple positive effects these systems have on the energy needs of buildings (possibly from the energy, ecology, and health fund).

The experimental part of the work showed that the use of VGS on collective housing buildings can save up to 8 % of energy annually. In addition, there was a significant reduction in CO_2 emissions of approximately 2.7 kg/m^2/year. Green façades also have a favourable effect on air purification, reducing the temperature of the wall and the surrounding space, which contributes to reducing the possibility of creating an urban heat island. The capital investment for the implementation of the proposed thermal measures and the construction of a modular green wall would pay off in 8 years. Therefore, the use of VGS should be one of the priority measures in adapting to climate change in urban areas and improving the microclimatic characteristics.

The above list indicates that VGS research is still necessary, especially in Bosnia and Herzegovina and the region, where this field is only in its beginnings and very little scientific research and few practical applications of the VGS exist.

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