

Article

Biochar for Vertical Greenery Systems

Michal Kraus ^{1,*} , Kateřina Žáková ² and Jaroslav Žák ¹

¹ Department of Civil Engineering, Institute of Technology and Business in České Budějovice, Okružní 517/10, 370 01 České Budějovice, Czech Republic; zak@mail.vstecb.cz

² Department of Statistics and Operation Analysis, Faculty of Business and Economics, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic; myskova@mendelu.cz

* Correspondence: info@krausmichal.cz; Tel.: +420-602-357515

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Abstract: Vertical greenery systems (VGS) are effective at solving urban heat. They can absorb noise pollution and dust, and, aesthetically, they are positively perceived. Systems using hydroponic irrigation and nutrition, in combination with mineral wool as a base, are light and effective (they are able to hold water, with a high percentage of air, and a good mechanical structure to hold the plant stable). m of a system can be compromised if the water supply is depleted or the irrigation system fails. This deficiency can be partially remedied if a certain amount of biochar or a suitable organic fertilizer is also a part of the system. The research task consisted of verifying this assumption and determining the effective amount of the biochar. Samples with different amounts of biochar were examined under the same temperature and humidity conditions; extended drying times, additional costs, and safety tank size savings were found. Subsequently, the effective amount of the biochar was determined by the Data Envelopment Analysis (DEA) method. It has been experimentally verified that biochar has a positive effect and prolongs the drying time; the additional costs are almost offset by the benefits. It should be noted that the results are valid for central Europe, and may be modified for different climate and economic zones.

Keywords: vertical greenery systems; biochar; DEA; effective solutions

1. Introduction

Changes in metropolis environments have led to significant vegetation losses, as spaces are often allocated to concrete structures, buildings, large parking lots, and other paved surfaces. It is clear that loss of vegetation is an essential contributor to urban heat. Urbanization (urban sprawl and degradation of the natural area) plays a key role in an ever-deteriorating environment, especially in the context of thermal anomalies [1]. The extent of temperature anomalies is determined by the size of the cities and the level of their urbanization [2]. Vegetation provides shading, especially evapotranspiration services that are crucial for cooling, and decrease of surface and atmospheric temperatures. Evapotranspiration is the combined process of direct evaporation at the ground surface, direct evaporation on plant surface, and transpiration [3]. Transpiration is the action of water relocation away from the vegetation canopy to the leaf stomata [4]. This process significantly contributes to lowering temperatures, especially in the centres of cities, and helps avoid urban heat islands (UHI). According to [5], urban heat islands result in an increase in global warming of 2–4%. UHI can be determined as the air temperature difference or surface temperature difference between a city's urban and un-urbanized rural areas. To illustrate, for the centre of Prague (Czechia), the ambient temperature is 2 °C higher compared to the temperature of the non-urbanized parts of the city (suburbs). It is difficult to retain water on paved surfaces of concrete and asphalt due to the absence of a sufficient proportion of greenery in cities. Natural drainage (runoff) points are missing, which reduces the cooling potential of the surroundings due to the natural evaporation of water.

Urban heat islands cause a number of health risks. Some of them are caused by increased temperatures and others as an indirect result of air pollution. Elevated temperatures can cause heat discomfort [6], overheating, heat stroke, and premature death. The World Health Organization (WHO) states that 7 million premature deaths are associated with polluted air and pollutants [7]. There is a positive correlation between temperature and concentration of air pollutants, such as ozone (O₃), particulate matter PM₁₀, and nitrogen oxide (NO₂) [8]. Study [9] describes the relationship between the elevated ambient temperature and mortality in some cities. People with health problems or weakened immune systems are at an increased risk of death due to increased ambient temperatures.

Human discomfort (because of high heat) can lead to an increased demand for air conditioning. About half of the energy consumed in cities is for heating and cooling. Currently, global energy consumption for cooling exceeds energy consumption for heating. The higher the level of urbanization, the higher the energy consumption will be [10], with 66% of the global population predicted to be living in urban areas by 2050 [11]. A great source of air pollution resulting from increased temperatures in cities is excessive energy demand. High temperatures generate high electric energy demand that lead to high production in coal and gas power plants. The essential pollutants from power plants are sulphur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM_x), carbon monoxide (CO), and mercury (Hg) [12]. Smog (ground-level ozone) is created by the reactions of NO_x and volatile organic compounds (VOCs) in the presence of sunlight and warm weather.

Energy consumption is increasing in microclimate environments (in large agglomerations) due to the increasing use of air conditioning equipment. According to the International Energy Agency (IEA), the demand for electricity for cooling will triple worldwide by 2050. In Europe, climate change mainly affects the south of the continent, but, gradually, it is also affecting central European and Nordic countries. In 2010, the Central Bohemian Region (Czech Republic) recorded 33.6 cooling days (days that give an indication of how much cooling is needed in buildings). In 2018, 61.9 cooling days were already monitored. Data from the European Environment Agency (EEA) show that, in Europe, between 1981 and 2017, there was an average increase of 0.9 cooling days per year. From statistical data, for example, the Czech power plant, Chvaletice (one of the five largest thermal power plants in the Czech Republic, with an installed capacity of 820 MW) produced an average of 54,000 MWh more during the summer of 2018 than during the winter months, when distribution network operators usually record higher loads. The highest consumption is for buildings located in city centres, such as administrative and commercial buildings, shopping centres, and data centres. The expansion of vertical greenery systems (VGS) in city centres is a relatively inexpensive environmental tool used in mitigating a thermal urban island (and saving energy).

The materials used on roofs and facades have a decisive influence on rising temperatures in the centres of large cities because of the way they affect the overall albedo value of an area. Conventional building roofs in dark shades absorb high levels of solar radiation, resulting in significantly increased surface temperatures and higher indoor temperatures.

Greenery systems also show a markedly higher ability to deposit and accumulate atmospheric pollutants than other surfaces [13]. Greenery systems are capable of accumulating contaminants, or their thermal, chemical transformation, or phytodegradation. The ability to decontaminate harmful substances from the air depends on the type of pollutant, the type of plant, the size and type of leaf surface, as well as the chemical and biological composition of the leaves. There exists positive correlation between the rate of transpiration and chlorophyll concentration of the type of vegetation, and efficiency of the plant to remove pollutants (e.g., benzene) from the air [14].

According to the architect Le Corbusier (1923), the time when the roof garden was a curiosity rather than a real need ended. With newly acquired data from the environmental field [15–18], the function of purely representative architecture and aesthetics, or the ingenuity of the architect and urban planners recedes into the background, and the green elements are applied for pragmatic, environmental, and health reasons. The primary purpose of the VGS, also referred to as living walls (LW) [19] or green facades (GF) is to give structures a better image of aesthetic recognition, and to

propose new ways of providing energy optimization of structures. VGS systems of building envelope are effectively able to reduce indoor air temperature by 3 °C and 4 °C [20], which significantly increases thermal comfort and reduces the cost of possible air conditioning.

While roof structures and their greening are, currently, technically, and technologically well managed, vertical systems face a number of problems. Irrigation of a green roof is technologically relatively easy and does not require an additional irrigation system. Rainwater is captured and pooled on the waterproofing, from where it is gradually taken by the plant root system. Knowledge gap is for vegetation vertical structures. In the case of vertical green walls, irrigation water, under the influence of gravitational forces, flows rapidly through the vertical layer of the substrate, with almost no accumulation. The lack of irrigation is a problem for plant growth. Regarding water leaches nutrients, fertilizer, minerals, substances, phosphates, and amino acids from the top layers of VGS, which are essential for a good aesthetic appearance of plants and their longevity, VGS require an additional irrigation system. It is not uncommon for small profiles of irrigation hoses to become clogged and the supply of water and necessary nutrients to fail. In addition, it is not possible to use the additional irrigation system at sub-zero temperatures, as the water in the hoses would freeze. Plants very often do not have to survive the winter [21].

Coconut fibre expanded clay or biochar are very often added to the composition of the substrate in order to increase accumulation abilities and eliminate other negative manifestations. Biochar plays an important role in the VGS substrate. The biochar fulfils the function of filtration, increases the overall porosity, and improves the structure and mechanical load-bearing capacity of the substrate. The porous structure (large surface area) is used as a filter material that is able to absorb impurities and pollutants. Water and necessary nutrients are also retained in the biochar itself and ensure healthy growth and vitality of plants throughout the growing season. According to [22], biochar (also called biocarbon) is porous carbonaceous material produced from a variety of plant and wood biomass by different thermal decomposition methods, including carbonization, hydrothermal treatment, and pyrolysis (heating without oxygen). Biochar contains a majority part of trace elements that the original pyrolyzed biomass contained. During pyrolysis, key trace elements become part of the carbon structure, thus preventing their escape and making them available to plants through root exudates and microbial symbiosis. Mainly due to the increase of soil retention capacity, soil aeration, and release of nutrients due to increasing pH value, biochar can be used as an effective substitute for peat, and it can be used in special cultivations. By stimulating microbial symbiosis, the plant takes nutrients from the pores in the biochar structure [23,24]. Among other things, the sorption of the biochar to pollutants and risk elements from the substrate (e.g., organic pollutants, cadmium, copper, lead, nickel) was monitored [25–27]. The sorption of biochar to VOCs (benzene, toluene, methyl chloride, xylene, and others) is in the range of 1.9–65.5 mg/g [28].

Many studies [21,29–31] have shown that VGS protect against direct, diffuse, and reflective solar radiation. The ability of VGS to absorb noise and increase the acoustic insulation of buildings is well- documented [32]. Experiments have shown “high potential for energy savings during the cooling season for green wall and double-skin green facade in comparison to the reference system” in [33]. On the other hand, for heating periods no extra energy consumption was observed.

The relationship between urban heat island and energy consumption in buildings has been widely studied [34]. It was confirmed that UHI has a negative impact on a building’s cooling load. It was also shown that VGS has a negligible benefit in the rural case, but quite significant in the urban case. The maximum wall surface temperature drops by about 10 °C.

The potential of energy saving through vertical greenery systems was studied in [35]. Their results show that the integrated VGS model satisfactorily predicts the effect of VGS on indoor air temperatures, and exterior and interior surface temperatures of facades with VGS.

Vertical greenery systems, as a strategy in urban heat island mitigation, were introduced in [36]. VGS theoretically offers the most practical and abundant space per square foot in an urban environment

for the implementation of vegetation. They also offer a combination of benefits from both vegetation and pavement cooling mitigation techniques.

Other useful studies pointing to the positive effects of VGS can be found in [37–39]. While many papers have focused on its energy benefits and environmental impacts, there have not been many studies on its life cycle cost (LCC), which is a principal factor for building owners to apply VGS, as well as to compare among various types of systems. To fill this gap, the three basic types of VGS located in Singapore are identified and monitored in terms of LCC [40]. The performed life cycle analysis showed that the selection of plants and their eventual maintenance contributes approximately by 85% to the life cycle costs compared to other parts.

According to study [38], four species of plants and shrubs commonly used in vertical green systems were evaluated for heat performance in the humid subtropical Hong Kong over a one-year period. However, the transferability of this experience to the climatic conditions of central Europe remains an issue.

The following works reflect the most relevant research in this area. Study [41] showed that the addition of biochar to green roof soil improved both runoff water quality and retention potential.

Research into the use of one type of green-waste biochar to two scoria-based substrates on water holding capacity (WHC), bulk density, permanent wilting point (PWP), and time taken to reach PWP were studied in [42]. Biochar was highly effective in increasing both WHC and plant available water in green roof substrates, resulting in up to a 2 day delay in the onset of permanent wilting.

It was found in [43] that the effect of biochar seems to depend on prevailing weather conditions, as the water retention capacity was improved by biochar, especially during the summer with infrequent precipitation events, but was less effective during the autumn with frequent precipitation.

Study [44] examined the benefits of using two green roof substrates, namely the commercial substrate and the biochar substrate. These substrates were tested in the examined green roofs to determine the water quality and the amount of simulated runoff using different precipitation intensities. No significant differences in average effluent retention rates were found between the commercial substrate and the biochar substrate.

The effects of biochar dosing on plant growth have been the subject of research in [45]. This article shows that eco-physiological responses to biochar are dose-dependent, and are driven mainly by changes in nutrient availability. The results of this study showed that the eco-physiological responses of plants to biochar are highly dose-dependent and appear species-specific. The research was performed on two plants, *Abutilon theophrasti* and *Trifolium repens*. The results are valuable, but because they are species-specific, one should be careful applying the results to English ivy.

Research questions can be formulated as follows. Can added biochar prolong the drying time of ivy? Can the additional costs be offset by the benefits? Can VGS systems with added biochar be effective in terms of Data Envelopment Analysis (DEA)? What amount of added biochar is effective in terms of DEA?

The following hypotheses were assumed. The added biochar can prolong the drying time of ivy. The additional costs are offset by the benefits. VGS systems with added biochar are effective in terms of DEA. The effective amount of added biochar will be stated by DEA.

2. Materials and Methods

2.1. VGS and Experiment Set-Up

VGS can help minimize the risk of urban heat islands in large urban agglomerations, at an affordable price. Based on our previous studies [46], we used a system based on the placement of ivy in mineral wool using hydroponic irrigation and nutrition. Hydrophilic mineral wool is especially suitable due to high water retention. The system is fixed in two welded wire meshes according to Figure 1. Figure 2 shows a detail of the composition of the VGS module. The ivy is undemanding to the habitat and care; it adheres to the substrate and then climbs the wall, wood, mesh, or forms a

carpet on the ground. In addition, it has evergreen leaves. Ivy leaves show a high rate of absorption of particles in the air and, thus, function as an effective sink of particles in urban areas [47]. In this case, a one-sided vegetation panel is tested and monitored. However, the system can also be used for a vegetation panel on both sides.

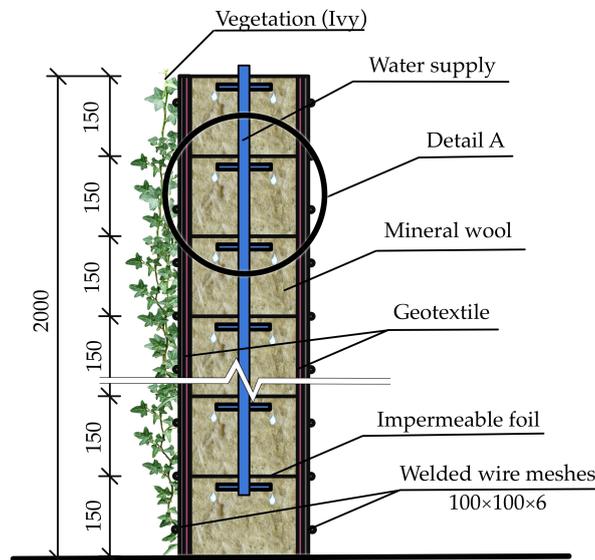


Figure 1. Vertical greenery systems (VGS) panel, all dimensions in mm.

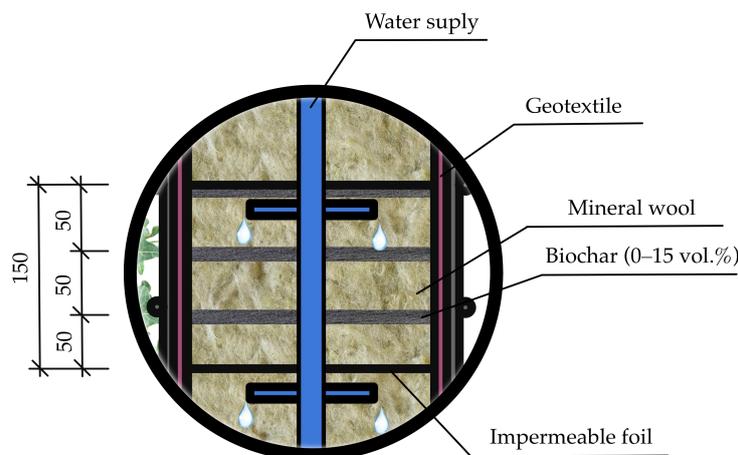


Figure 2. Detail of VGS panel, all dimensions in mm.

In order to eliminate the mentioned risks, i.e., drying of vegetation in case of a system failure or unexpected irrigation failure, the addition of different amounts of fertilizer with a high content of biochar was tested. This material will allow the ivy to extend the time it dries and, thus, degrade the system (overdrying and loss of bearing capacity of plant roots). For our experiment, a biochar produced by pyrolysis from corn stover (*Zea mays*) at 650 °C was selected. The slow pyrolysis was performed in a vertical, tubular, stainless steel reactor, which was heated by an electric furnace. During the process of pyrolysis, the heavier hydrocarbons are fractured to form lighter hydrocarbons, methane and hydrogen at high temperatures in the absence of oxygen. The highest treatment temperature of 650 °C was applied. The basic parameters of the used biochar are presented in Table 1.

Table 1. Basic parameters of the used corn stover biochar.

Corn Stover Biochar	
Biochar yield (%)	28.76
Ash content (%)	27.45
pH	11.54
Electrical conductivity (EC) (ms/cm)	5.07
Surface area (m ² /g)	70.00
Pore volume (mL/g)	0.06
Carbon (C) (%)	63.2
Hydrogen H (%)	1.97
Oxygen (O) (%)	16.09
Nitrogen (N) (%)	1.29

For this experiment, a total of 12 samples were tested, comprising sample without biochar and samples with 5, 10, and 15 volume percent of biochar. For each sample, the time taken for the moisture to drop to 20% was recorded, which is the volumetric water content at which the plant is close to reaching the permanent wilting point and is unable to grow further. It was necessary to determine the conditions for the end of the experiments. In our case, it would not be appropriate to take PWP as a criterion, because plants in such a state are no longer usable for VGS purposes. To ensure VGS functionality, plants may approach PWP, but their leaves must not brown. Based on their previous experience, the authors set the criterion as the volumetric water content of the substrate at 20%. This assumption was confirmed by the continuation of experiments, when the leaves browned, and the plants dried at 16–18% volumetric water content. Importantly, the same criterion was used for all experiments performed –20% volumetric water content. Adding biochar (even a small amount) makes the system more expensive and increases its labour. On the other hand, such a large water safety tank is no longer required because of the prolonged drying period. This makes the system cheaper.

This type of VGS is commonly used in thicknesses of 100, 200, and 300 mm. Therefore, these thicknesses were chosen for the experiments and were treated independently in DEA analysis. Four samples were prepared for each panel thickness, i.e., 100, 200, and 300 mm. Biochar of 5, 10, and 15% by volume percent was added to the sample of each thickness. Larger quantities of biochar than 15% are no longer possible for technological reasons due to high water absorption and the associated increase in volume. One sample from each thickness remained as a reference without added biochar.

For financial reasons, only one sample was performed for each amount of biochar added. It was assumed that when testing multiple samples, the variance of the results would be relatively small, so only one sample could be performed. This hypothesis was verified by testing five identical samples with a thickness of 100 mm and 10% added biochar. The results (prolonged period) are summarized in Table 2. The standard deviation (3.38) is relatively small compared to the average (77.84), only 4.33% as a percentage. In connection with the ratio of the extended time for 10% and 5% of the added biochar (199%), these data indicate that performance of the only one test for a given thickness, and the percentage of added biochar is defensible.

Table 2. Pre-experimental verification of prolonged period (hours) for the reference sample.

Sample No.	Prolonged Period (Hours)
1	73.9
2	79.2
3	82.2
4	78.8
5	75.0

All samples were placed in a single row facing south. The distance between the samples was 2 m to avoid interference. VIRRIB (elongated variant) instruments, including the evaluation units,

were used to measure volumetric water content (%) of the substrate near roots inside the panels. COMET C3121 instruments were used to measure relative humidity (%) and temperature (°C) of the air 2 m above the ground. Concerning the three measuring instruments (VIRRI) used for each sample, the probes were placed in the middle of each layer of the certain thickness, of the sample, and in the middle between the impermeable foils. The resulting temperatures and volumetric water content were determined as the arithmetic mean of three measurements. Individual panels (samples) consisted of two pieces of welded wire meshes 3 × 2 m. The diameter of their wires was 6 mm, and the mesh size was 100 × 100 mm. The welded wire meshes were, alternatively, 100, 200, or 300 mm apart, and were closed with steel clamps. Geotextiles were placed on both internal sides of welded wire meshes. Each panel was filled with 50 mm thick strips of mineral wool (width of 100, 200, and 300 mm, respectively). Every three strips, with a total thickness of 150 mm, were separated by an impermeable foil to prevent water from flowing downwards too quickly.

In the production of samples containing biochar, each 50 mm thick strip of mineral wool was sprinkled with an appropriate amount of biochar so that its volume was, alternatively, 5, 10, and 15 percent of the total volume of the panel. In the middle of the panels, a system of tubes providing hydroponic irrigation and nutrition was installed. Plants of English ivy were cultivated for 9 months. The density of planting was 25 plants per square meter (m²), a mesh 200 × 200 mm, 100 mm distance from the edges of the panel.

The samples were tested in the Pilsen Region (Czechia). All experiments started on 1 June 2020, and the last experiment was completed on 15 June 2020. The average air temperatures and relative humidity during the period of the experiments are shown in Table 3. Air temperature and relative humidity have a great influence on the time when the volumetric water content of the substrate around the roots is reduced to 20%.

Table 3. Average air temperatures and relative humidity during the testing period.

Date	Temperature (°C)	Humidity (%)
1 June	18.7	66
2 June	20.8	58
3 June	21.9	52
4 June	21.8	56
5 June	22.0	58
6 June	18.1	81
7 June	18.1	80
8 June	16.3	50
9 June	18.7	60
10 June	22.5	68
11 June	22.3	75
12 June	22.5	56
13 June	20.0	66
14 June	24.1	59
15 June	21.9	68

2.2. Effectiveness Evaluation

Parametric or non-parametric methods can be used to evaluate efficiency. A frequently used parametric method is the stochastic frontier analysis (SFA). This method reflects the fact that there are random influences that are beyond control, but that affect the level of output of individual units. Factors that can affect output typically include various economically unfavourable situations, weather changes, or simple happiness. Each unit is exposed to different influences; however, it can be assumed that these influences act randomly, and can be described by a common probability distribution. The advantage of this method is that if we know the distribution, we can statistically test the estimated parameters. The disadvantage of the method is that it is necessary to specify the boundary function in advance and to assume the distribution of random effects. Since this

is not possible in our case, we opted for a non-parametric method, specifically for DEA analysis. DEA analysis is a special case of linear programming; it allows the inclusion of both financial and non-financial quantities and does not need any additional information.

Data envelopment analysis (DEA) is a method of multi-criteria decision-making. It evaluates the effectiveness of individual variants based on the comparison of inputs and outputs. The variants that reach maximum outputs with minimum inputs is considered effective. Specifically, the input oriented CCR model of Charnes, Cooper, and Rhodes [48] was used. We consider m inputs and r outputs for n decision-making units (DMU). The model for q th DMU can be mathematically formulated as follows:

$$\max z = u' y_q \quad (1)$$

$$\text{s. t. : } v' x_q = 1,$$

$$u' Y - v' X \leq 0,$$

$$u \geq \varepsilon, v \geq \varepsilon. \quad (2)$$

A notation $X = \{x_{ij}, i = 1, \dots, m; j = 1, \dots, n\}$ is used for the matrix of inputs, $Y = \{y_{ij}, i = 1, \dots, r; j = 1, \dots, n\}$ for the matrix of outputs, x_q for the q th column of matrix X and y_q for the q th column of the matrix Y , v for the vector of weights for inputs, u for the vector of scales for outputs, ε for an infinitesimal constant, θ_q for relative efficiency of q th DMU, s^+ and s^- for input and output slacks, respectively, λ for a vector of weights and $1'$ is a row vector with all elements equal to 1 in the previous and next equations. The following dual model is used for calculating:

$$\min z = \theta_q - \varepsilon(1's^+ + 1's^-) \quad (3)$$

$$\text{s. t. : } X\lambda + s^- = \theta_q x_q,$$

$$Y\lambda - s^+ = y_q,$$

$$\lambda \geq 0, s^+ \geq 0, s^- \geq 0. \quad (4)$$

More details can be found in [48]. The effective DMU reaches the value 1, the inefficient DMU takes the value 0 and all the others are between 0 and 1, with the closer to 1 the closer to the effective. The data were processed in the MATLAB program.

2.3. Alternative Evaluation Methods

Thick Frontier Approach (TFA) and Distribution Free Approach (DFA) are parametric variants. Using econometric theory, we can roughly specify functional form. Inefficiency can be then modelled as an additional stochastic term. Again, it is necessary to specify the boundary function in advance and to assume the distribution of random effects. This is not possible for our problem.

A very simple option is to use the classical "point system". Each variable is assigned a point value, typically from 1 to 10. Variants with a maximum number of points are effective. We get a slight improvement if we add weight to each variable to emphasize its importance. Both methods are burdened by subjective decision-making when assigning points and weights.

3. Input Data

The input data for the DEA analysis are summarized in Tables 4–6. The hour columns show the times by which the root moisture drop is extended to 20%, i.e., the state when the ivy dries and is unable to grow further. The extra expenses columns summarize all costs caused by adding a biochar to the panel. It is the price of the biochar, its transport, and the increased laboriousness of panel production. Extra expenses also include savings that arise from reducing the volume of the safety tank. All prices were initially assessed in Czech crowns (CZK) and corresponded to current prices in the Pilsen region in June 2020. Prices in CZK were converted to Euros (EUR) at the rate 26.26 CZK/EUR.

The tank columns show litres by which the safety tank can be reduced due to the longer life of the ivy. Safety tank reduction is an independent parameter for DEA analysis. In general, a longer drying time requires a smaller volume of safety tank, hence a larger reduction of safety tank. Tested samples can typically be used for retaining walls, noise walls, or walls in parks and playgrounds. The estimated quantity has a great influence on the final price, as well as the distance to which the material had to be transported. An average distance of 25 km was assumed in this study. The prices of materials were set for 250 m² of VGS area. Effective reduction of the UHI temperature can be achieved by installing a significantly larger area of VGS. In this case, of course, the price would drop significantly. The risks associated with a significant increase or decrease in prices were not taken into account in this study. Interest rates and the method of financing were also not included in the analysis. These aspects need to be taken into account when preparing a real project.

Table 4. Results for the sample thickness of 100 mm.

No.	Added Biochar (% Volume)	Prolonged Period (Hours)	Extra Expenses (EUR)	Tank Reduction (Litres)	Effectiveness
1	0	0.0	0	0	0.51
2	5	40.0	7.62	400	0.10
3	10	79.5	6.85	800	0.22
4	15	118.0	2.28	1200	1.00

Table 5. Results for the sample thickness of 200 mm.

No.	Added Biochar (% Volume)	Prolonged Period (Hours)	Extra Expenses (EUR)	Tank Reduction (Litres)	Effectiveness
1	0	0.0	0	0	1.00
2	5	49.5	5.71	260	0.42
3	10	100.0	7.62	520	0.64
4	15	148.0	7.24	780	1.00

Table 6. Results for the sample thickness of 300 mm.

No.	Added Biochar (% Volume)	Prolonged Period (Hours)	Extra Expenses (EUR)	Tank Reduction (Litres)	Effectiveness
1	0	0.0	0	0	0.96
2	5	58.5	4.95	120	0.44
3	10	117.0	5.33	240	0.81
4	15	178.0	6.47	360	1.00

4. Results

For reference samples without biochar, the volumetric water content of the substrate drops to 20% occurred at 66 and 115, respectively, 155 h for panels with a thickness of 100, 200, and 300 mm, respectively. Furthermore, the time in hours by which the drying (volumetric water content of the substrate drops to 20%) of the ivy was prolonged, for different amounts of added biochar for three different panel thicknesses, was measured.

We should note that all results (columns effectiveness) shown in Tables 4–6 are related to a cubic meter (m³), which correspond to 10 m² for 100 m thick panel, 5 m² for 200 mm thick panel, and 3.33 m² for 300 mm thick panel. The effectiveness (the last column in the Tables 4–6) equalling to one means the most effective sample, while the effectiveness indicating zero represents the least effective sample.

Panels of different thickness (100–300 mm) are used for different purposes and conditions. The thinner panel is of course cheaper (1 m²), lighter, and more compact for transport, and takes up less volume when placed in the final position. On the other hand, it dries faster, and requires a larger safety tank with the same degree of security than wider panels. Wider panels are more expensive

(1 m²), however cheaper in volume (1 m³), they are more expensive to transport. They dry more slowly and do not require a large safety tank.

Reference samples with a thickness of 100 mm are the most prone to drying out. By adding a biochar, the drying time will be extended and, at the same time, the capacity of the safety tank will be significantly reduced. This financial saving almost eliminates the increased costs of purchasing and transporting the biochar and the increased labour in the production of panels. These are the main reasons why the sample with 15% added biochar is clearly the most effective.

Reference samples with a thickness of 200 mm are less sensitive to drying out. By adding a biochar, the drying time will be extended and at the same time, the capacity of the safety tank will be reduced, but not as much as in the previous sample. This financial saving still partially eliminates the increased costs of purchasing and transporting the biochar and the increased labour in the production of panels. The sample with 15% added biochar is effective, but the reference sample is effective as well.

Reference samples with a thickness of 300 mm are less sensitive to drying out. By adding a biochar, the drying time will be more significantly extended and at the same time, the capacity of the safety tank will be reduced, but not as much as in the previous sample. This financial saving still partially eliminates the increased costs of purchasing and transporting the biochar and the increased labour in the production of panels. The sample with 15% added biochar is effective and the reference sample is almost effective (effectiveness 0.96).

5. Discussion

In general, adding biochar in our case, in an optimal amount to the substrate of vegetation elements represents a high potential for eliminating the risks associated with watering and possibly reducing the suitable moisture of the substrate for plant growth. Thanks to the additives, the demands on possible watering from the water supply system in the time without rainfall are reduced. It brings a positive social externality for the whole society in the context of sustainability. Rainwater is also more suitable for watering plants in terms of its composition compared to chemically treated drinking water. As mentioned above, the proposed VGS system with added biochar also reduces the space requirements for a possible rainwater tank. Ensuring optimal substrate moisture is a prerequisite for proper plant growth, i.e., proper VGS function. The use of biochar as a substrate additive and moisture optimizer is not only necessary for vertical green structures, but also has its potential in the case of green roofs.

The paper takes into account economic, environmental, technological, and construction aspects. The authors are not aware of any similar paper with which to compare the results. There are a number of papers that deal with the influence of biochar and/or moisture of substrates on the growth of various plants. However, they never include all of the above-mentioned aspects. Therefore, only partial results can be compared, e.g., the proven fact that the addition of biochar increases the water retention capacity in [49,50].

6. Conclusions

At the beginning of the contributions from the literature reviews, the escalating need to extensively research this topic, in the context of sustainability and urban development, and the increase in the comfort and health of the population, was explained and documented. Green architecture and the design of vegetation elements are a current trend in urban development and urbanization. Large urban agglomerations have significantly higher temperatures than the surrounding undeveloped environment. Outdoor climatic conditions are the essential key to the proper development of dense urban areas and the comfort of their inhabitants. Vertical greenery systems represent an important element in improving air quality and potential energy savings of UHI mitigation. VGS also represent a relatively cheap (but effective) tool of phytoremediation, i.e., the use of greenery to move, accumulate, and eliminate pollutants from the environment. VGS offer effective opportunities to provide a cleaner and safer environment for the inhabitants of urbanized areas. The leaves of plants effectively absorb and filter harmful substances, such as nitrogen oxides (NO_x), sulphur dioxide (SO₂), or ammonia from polluted

air. The problem of the general use of VGS lies in the need for regular irrigation and maintenance of optimal substrate volumetric water content where heavy rainfalls may satisfy this demand to the maximum ecological effect. Regarding changing rain conditions (lower frequencies of greater intensity), it is necessary to find such options that eliminate the risk of the substrate drying out below the tolerable limit. Ensuring the extension of the optimal volumetric water content of the substrate, in this experimental study of VGS mineral wool, can be achieved with the help of additives. It was experimentally shown that the addition of biochar to VGS prolongs its life. Increased costs and labour are compensated by reducing the volume of the safety tank and extending the time within which the ivy dries. Using Data Envelopment Analysis, it was found that the effective amount of added biochar equals to 15% of the total volume for all examined panel thicknesses. The ineffectiveness of a small amount of added biochar (up to 10%), must give way to leaving the panel without added biochar. A higher amount than 15% is not possible due to technological problems caused by the high expansion of wet biochar.

The authors assume that the addition of biochar to VGS has a good potential for early industrial application. The industrial application of the VGS itself, though, remains the limiting factor. If we take into account only the price or aesthetic benefit, VGS may not be competitive. However, considering the environmental benefits (especially energy savings, reduction of temperature, dust and noise), these systems can be widely applicable. It is clear that more tests, especially for different climate conditions, should be done, to verify the above-mentioned results. Unfortunately, this would exceed the financial possibilities of this project.

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