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Investigating the Impact of Various Growing Media on the Expansion of Green Wall Plant Coverage with Image Analysis

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Abstract: Green walls are seen as an important architectural element in the design of sustainable cities, helping to make cities ecologically rich, green, and healthy places to live. The use of green walls, which have seen a wide range of applications worldwide, is supported mainly because of their potential in combating climate change, and international standards are being developed for the design, implementation, and monitoring of green wall projects. In this study, the effects of different growing media used in green wall systems on plant area and the increase in green wall performance were evaluated using an indirect monitoring technique. Peat, hazelnut husks, rice hulls and perlite were mixed in different proportions to produce the growing media, and their physical and chemical properties were determined. Western red cedar (*Thuja plicata*) and boxwood (*Buxus sempervirens* L.) were used for planting the green wall. To measure the growth of the green wall and the planting area, images were taken and examined after planting and at the end of the growing period. According to the findings of this study, we found that growing media with a high water holding capacity and high organic matter content were more successful in terms of increasing plant area and green wall performance. However, factors such as pH and phosphorus were found to have negative effects on plant growth. In addition, it was determined that the physical and chemical properties of the growing media used in green wall systems are important for the plant area in green wall systems and that a balanced optimization of these properties increases the efficiency of green walls. The results obtained in this study show that the use of indirect monitoring techniques is a fast and effective method for monitoring the development of green wall systems. The appropriate use of this technique could be an effective tool for the standardization of installation and could contribute efficiently to the maintenance of green wall systems.

Keywords: green wall systems; growing media; image analysis; plant area

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1. Introduction

Many innovative approaches and technologies are being used in architecture today to increase the environmental sustainability of urban areas and improve residents' quality of life. Among these innovative technologies, green walls stand out, being structural elements covered with vegetation placed vertically on the outside of buildings [1]. Green walls serve as important sources of green space in modern cities, where natural habitats are diminishing, and make an important contribution to city dwellers, buildings, and the natural ecosystem. These structures improve air quality by increasing carbon dioxide absorption and reducing the level of greenhouse gases in the atmosphere [2]. In addition, green walls make important contributions, such as minimizing urban heat islands, trapping airborne particles, increasing biodiversity, balancing indoor temperature fluctuations, providing thermal and acoustic insulation, and reducing energy consumption. Due to these features, green wall systems are mostly used in hot climate conditions [3–8].

Van Renterghem et al. investigated the reduction in the impact of traffic noise in buildings with green wall systems by combining 2D and 3D full-wave numerical methods. As a result of their study, the authors reported that green walls provide the most effective sound insulation when used in narrow urban street canyons with acoustically rigid facade materials, and that green walls with dense plant layers used on the upper floors of buildings and on facades in courtyards achieve the best noise reduction results [9]. Using a simulation model that they developed, Kontoleon and Eumorphopoulou showed that a green wall with a large plant area with dense foliage can effectively reduce the cooling needs of buildings by neutralizing the solar effect [10]. In their earlier studies, Dede et al. also came to the conclusion that, in addition to shading by plants in green walls, the plant growing medium used also plays an important role in thermal insulation [1]. However, many studies in the literature have reported that the critical factor for the performance of green wall systems in providing these benefits is the optimization of the increase in plant area [1,9,10].

The results of the studies in the literature on this topic indicate that the effects of increasing the planting area need to be studied in detail in order to optimize the benefits of green walls and ensure their sustainability. However, it is very difficult to observe plant growth and measure the amount of growth in green wall systems. Since plants in green walls grow to cover the building wall, the leaves or branches of the plants can block access to the entire green wall system. Because green wall systems are often installed at high elevations or in confined areas, it can be difficult to gain access to these areas to measure plant growth. Environmental factors such as light, humidity, temperature and wind can also present additional challenges. There is also a high likelihood of damage to the plants, fittings, and irrigation system in the green wall systems while measurements are being carried out. However, indirect monitoring techniques offer significant potential for determining plant growth on green walls [11]. Studies focusing on estimating the increase in plant area through indirect monitoring techniques have generally been conducted in areas such as forests and orchards [12]. For green walls, these studies are rare and generally aimed at determining the leaf area index [13,14].

This study aims to provide a starting point for understanding the ecological and structural benefits of green walls and to provide a scientific basis for increasing the effectiveness of these structures by investigating the effects of different growing media on the increase in plant area of green walls using an indirect monitoring technique.

2. Materials and Methods

2.1. Components of Growing Media

In this study, growing media consisting of mixtures of peat, hazelnut husks, rice hulls, and perlite in various proportions were prepared for use in green wall applications. Since peat is a commonly used growing medium in green walls, a growing medium consisting of 100% peat was used as a control application. Peat and agricultural expanded perlite are commercially available products. The rice hulls were taken after the rice had been separated from its hulls after harvesting, and no pretreatment such as washing or shredding was performed. The hazelnut husks were collected after the hazelnut harvest and shredded with a shredding machine. The prepared growing media and mixing ratios are given in Table 1. Peat and hazelnut husk growing media were the main materials used in the mixtures. Hazelnut husks were chosen here as an alternative to peat and were used both as a mixture and in pure form. Rice hulls and perlite were also components of the growing media. The mixing ratios most commonly used in the literature were used for the mixtures [1].

Table 1. Growing media and mixing ratios (V%).

Growing Media	Mixing Proportions of Materials
P	100% Peat
H	100% Hazelnut Husk
R	100% Rice Hull
PE	100% Perlite
PH1	87.5% Peat + 12.5% Hazelnut Husk
PH2	75% Peat + 25% Hazelnut Husk
PH3	50% Peat + 50% Hazelnut Husk
PR1	87.5% Peat + 12.5% Rice Hull
PR2	75% Peat + 25% Rice Hull
PR3	50% Peat + 50% Rice Hull
PPE1	87.5% Peat + 12.5% Perlite
PPE2	75% Peat + 25% Perlite
PPE3	50% Peat + 50% Perlite
HR1	87.5% Hazelnut Husk + 12.5% Rice Hull
HR2	75% Hazelnut Husk + 25% Rice Hull
HR3	50% Hazelnut Husk + 50% Rice Hull
HPE1	87.5% Hazelnut Husk + 12.5% Perlite
HPE2	75% Hazelnut Husk + 25% Perlite
HPE3	50% Hazelnut Husk + 50% Perlite

2.2. Installation of Green Wall System

As part of this study, model buildings with dimensions of 125 cm × 125 cm × 125 cm and a thickness of 20 mm (wall thickness of model building) were constructed from precast concrete panels and green wall systems were installed on four identical facades of the model buildings (Figure 1). The floors and roofs of the model buildings were clad with 5 cm thick carbon-reinforced polystyrene and thermally insulated. A gap of 3 cm was left between the green wall system and the outside of the model building to ensure air circulation. The green wall system consisted of 40 plastic pots with a capacity of 2 L placed at a certain angle on a 5 mm thick steel cage for each facade of the building and a drip irrigation system reaching each pot. Each green wall unit consisted of an 8 × 5 matrix of pots (5 pots in a column and 8 pots in a row). The pots were filled with the prepared growing media and boxwood (*Buxus sempervirens* L.) and western red cedar (*Thuja plicata*), obtained from a local nursery in the form of rooted seedlings, were planted. The plants were irrigated regularly with tap water via the drip irrigation system. The irrigation dosage was 10 L/m^2 in April and May and 15 L/m^2 in June, July, August and September. Additionally, no fertilization was performed throughout the study.

Figure 1. Construction of model buildings and the green wall system.

2.3. Physical and Chemical Properties of Growing Media

The physical and chemical properties of the growing media were determined using standard methods and methods recognized in the literature. The particle size distribution was determined by sieving the samples dried at 35 °C for 10 min in a vibrating sieve (16, 8, 4, 2, 1, 0.5, 0.25 and 0.125 mm) and then calculating the ratio of particles remaining in each sieve gap to the total sample [15,16]. Particle density was calculated using the organic matter content and the percentage of ash [17]. The bulk density, total porosity, and water holding capacity were determined using the "gravitational drainage technique" [16,18]. pH and EC values were measured using a pH and EC meter taking into account the temperature in a mixture of material and pure water at a ratio of 1:5, as specified in the EU standards [19,20]. The organic matter content was determined by firing the samples at 550 °C for 4 h [15]. The total nitrogen content of the samples was determined using the Kjeldahl method, which is based on the principle of converting the nitrogen in the compounds into ammonia with concentrated sulphuric acid and retaining the ammonia in the medium in the form of ammonium sulphate [21]. The macro- and micronutrients of the plants were measured using ICP-OES after wet digestion with nitric acid peroxide in a microwave [16,20].

2.4. Plant Area of Green Wall

In this study, plant area calculations were performed using the image analysis method to investigate the effects of different growing media on the development of plants in the green wall. For the image analysis, digital photographs were taken when the plants were planted in the green wall system (Figure 2a,b) and at the end of the growing period (150 day) (Figure 2c,d). The images were created with the ImageJ program (NIH, v. 1.51 64-bit, Bethesda, MD, USA). To obtain more accurate results, background artifacts were removed from the images prior to image analysis. The free ImageJ program for scientific studies is the most commonly used software in this field. ImageJ, a Java-based image processing program, uses a threshold-based pixel count measurement to calculate the plant area [22–27].

(**a**) İnitial plant area (**b**) İnitial plant area (converted to 8-bit)

Figure 2. *Cont.*

(**c**) Final plant area (**d**) Final plant area (converted to 8-bit)

Figure 2. Photos used in calculating green wall plant area, western red cedar (*Thuja plicata*).

2.5. Statistical Analyses

Physical and chemical analyses of the growth media were performed in three replicates and the average of the results was presented. All results were analyzed statistically with variance, LSD (least significant difference), PCA (principal component analysis) and correlation tests using computer software (Origin data analysis software, 2024b).

3. Results and Discussions

The physical properties of the growing media used in green wall systems are crucial for plant growth and thus for increasing the plant area. The reason for this is that although the chemical properties of the growing media can be altered by fertilization and chemical additives during the plant growth period, it is not possible to change the physical properties after planting [18].

3.1. Evaluation of Growing Media Properties

The particle size distributions of the growing media are shown in Figure 3a–d. The particle size distribution has a direct effect on many physical properties of the growing media, especially the water retention capacity [28]. To ensure ideal plant growth, it is desirable that the particles that make up the growing media are evenly distributed and that the majority of particles are greater than 1 mm in size [29]. However, small particles (<0.1 mm) that make up the growing media close the pores and reduce the water capacity and air porosity, which can be useful for plants, while particles larger than 2 mm increase porosity and reduce water retention capacity [30,31].

The proportion of particles larger than 1 mm in the growing medium components used in the study varies between 66% and 98%. The particle size of the peat used as the main growing media in the study (89%) is generally larger than 1 mm. The growing medium components with the greatest proportion of particles larger than 1 mm are the rice hull (98%) (Figure 3b,d) and perlite (96%) growing media (Figure 3c,e). Therefore, the applications PR3 (93%) and PPE3 (92%), i.e., the growing media with the highest proportions of rice hulls and perlite, have a high proportion of particles that are larger than 1 mm. In addition, the proportion of particles larger than 2 mm is high in all applications containing rice hulls. It was found that the particle size distribution of the peat and hazelnut husk mixtures is predominantly between 0.5 mm and 2 mm. Increasing the proportion of hazelnut husks used in the mixtures made it possible for the desired particle size distribution to be achieved under ideal growth conditions in these applications (Figure 3a).

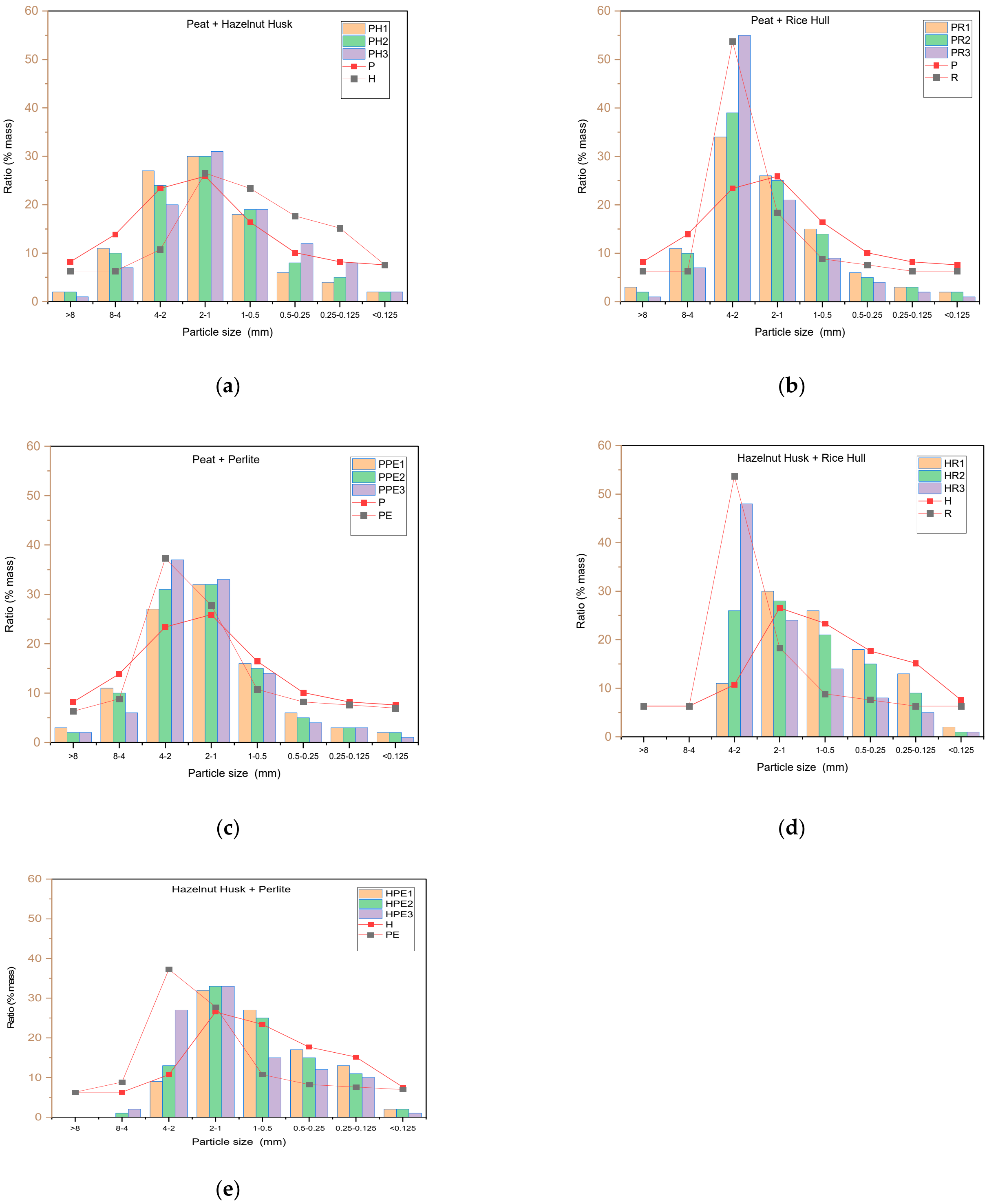

Figure 3. Particle size distributions of growing media (% mass). (**a**): Peat + Hazelnut Husk (**b**): Peat + Rice Hull (**c**): Peat + Perlite (**d**): Hazelnut Husk + Rice Hull (**e**): Hazelnut Husk + Perlite).

The physical properties of the growing media are given in Table 2. Among the growing medium components, hazelnut husks (H) (0.28 g/cm^3) have the highest bulk density (BD) and rice hulls (R) (0.11 g/cm^3) have the lowest bulk density. The bulk density of peat and perlite are 0.21 g/cm^3 and 0.15 g/cm^3, respectively. Increasing the proportion of rice hulls in the mixtures reduces the bulk density considerably. The bulk densities of the applications PR3 and HR3 with the highest proportion (50%) of rice hulls are 0.15 g/cm^3 and 0.18 g/cm^3, respectively. The bulk density of the growing media containing perlite also decreases as the perlite content in the mixture increases. However, the bulk density of growing media for ornamental plants must be <0.40 g/cm^3 [16]. The bulk density of all the growing media investigated is within the desired limit for ideal growing media (Table 2). In general, the porosity of growing media increases with decreasing bulk density. Although the bulk density of perlite is lower than that of rice hull, its porosity (94.39% *v*/*v*) is high. This is due to the microporous structure of perlite [1]. Of the growing medium components used in the study, hazelnut husks (81.43% *v*/*v*) have the lowest porosity (TP) values. Therefore, the porosity of the HR1 (82.41% *v*/*v*) and HPE1 (82.4% *v*/*v*) applications, which contain 87.5% hazelnut husks, is lower than that of the other applications. Increasing the ratio of perlite and rice hulls in the growing media increased porosity. Among the growing media, the highest porosity values (90.24% *v*/*v*) were found for the applications PPE3 (50% peat + 50% perlite) and (90.01% *v*/*v*) and PR3 (50% peat + 50% rice hulls). However, the porosity values of all investigated growing media (Table 2) are at the desired value (>80% *v*/*v*) for the ideal growing media [13,18]. It is important that the growing media to be used in green wall systems are light, reduce the overall weight of the building in which they are used, and are more balanced [32]. The contribution of growing media with a low bulk density and high porosity, made in particular from perlite and rice hulls, to the lightening of the green wall system and to ideal plant growth is therefore remarkable.

Table 2. Physical properties of growing media (* LSD, different letters indicate statistical differences, $p < 0.05$).

Growing Media	Bulk Density (g/cm^3)	Porosity (% *v*/*v*)	Water Holding Capacity (mg/L)
P	0.21 efg *	86.04 fg	770.38 a
H	0.28 a	81.43 k	619.29 ef
R	0.11 k	93.32 b	114.88 j
PE	0.15 j	94.39 a	229.26 i
PH1	0.22 de	85.55 gh	763.50 ab
PH2	0.22 de	85.43 gh	736.37 b
PH3	0.23 d	84.81 hi	651.41 d
PR1	0.2 gh	87.00 e	743.88 ab
PR2	0.18 i	88.27 d	698.91 c
PR3	0.15 j	90.01 c	640.06 de
PPE1	0.2 fgh	86.53 ef	748.45 ab
PPE2	0.19 hi	88.09 d	704.99 c
PPE3	0.18 i	90. 24 c	620.79 ef
HR1	0.26 b	82.41 j	616.33 ef
HR2	0.24 c	82.76 j	602.54 fg
HR3	0.18 i	86.00 fg	566.95 h
HPE1	0.27 b	82.4 j	619.53 ef
HPE2	0.26 bc	84.09 i	601.57 fg
HPE3	0.21 def	88.39 d	580.51 gh

The water-holding capacities (WHC) of the growing medium components peat (770.38 mg/L) and hazelnut husks (619.29 mg/L) were significantly higher than those of rice hulls (114.88 mg/L) and perlite (229.26 mg/L) (Table 2). The water retention capacity of HP3 (566.95 mg/L) containing 50% hazelnut husks and 50% rice hulls and that of HPE3 (580.51 mg/L) containing 50% hazelnut husks and 50% perlite are within the desired value range for ideal growing media (800–1000 mg/L) [16]. The water retention capacities of other growing media applications are within the limits of the ideal value range. Increasing the proportion of highly porous rice hulls and perlite in the growing media mixtures reduced their water retention capacity. Although water retention is directly related to porosity, differences in surface and internal properties also affect water retention [33]. For this reason, perlite, which contains many micropores, can retain more water, although its porosity is higher than that of rice husks. Irrigation in green wall systems is usually carried out via automatic irrigation systems and drip irrigation.

However, growing media with high water retention capacities, especially for green walls installed in hot climates, reduce operating costs as they prevent the irrigation system from being overloaded [34].

Some chemical properties of the growing media are presented in Table 3. Ideal growing media for ornamental plants should have a pH of 5.2–6.3, an electrical conductivity (EC) of 750–3490 µS/cm, and an organic matter content of >85 [18]. The pH values of peat, hazelnut husks, rice hulls and purified perlite, which were the base materials for the growing media, were found to be 5.63, 7.54, 6.25, and 6.33, respectively (Table 3). The fact that the pH values of the base materials of the growing media are within the desired range for ornamental plants ensures that the pH values of the mixtures are at ideal levels. The EC values measured in all growing media are lower than the desired values for the ideal growing media. The highest EC value measured among the growing media applications was 482.78 µS/cm (HPE3). However, the low EC values measured in the growing media were considered an advantage due to situations that increase EC, such as the long-term irrigation of green walls and the decomposition of dried leaves and twigs in the pot. The organic matter content of peat (92.31%) and hazelnut husks (89.2%) was at the ideal value desired for ornamental plants, while the organic matter content of rice hulls (83.87%) was close to the lower limit of the ideal value range. However, in all growing media applications where perlite, an inorganic growing medium, was used, the amount of organic matter decreased when the amount of perlite in the mixture was increased. The lowest organic matter content among the growing media was found in the application of HPE3 (50.74%).

Table 3. Chemical properties of growing media (* LSD, different letters indicate statistical differences, $p < 0.05$).

Growing Media	pH	EC (µS/cm)	Organic Matter (%)
P	5.63 f *	209.03 l	92.31 a
H	7.54 a	256.09 j	89.2 de
R	6.25 b	496.96 b	83.87 hi
PE	6.33 b	693.24 a	0 n
PH1	5.78 def	223.9 k	91.69 ab
PH2	5.96 cd	226.1 k	90.64 bc
PH3	6.26 b	228.24 k	90.09 cd
PR1	5.71 ef	355.84 h	90.13 cd
PR2	5.93 cde	366.72 h	88.44 ef
PR3	6.12 bc	468.63 d	84.81 gh
PPE1	5.75 def	287.51 i	90.563 bc
PPE2	5.97 cd	354.14 h	79.97 j
PPE3	6.16 bc	447.16 e	56.25 l
HR1	7.52 a	257.48 j	87.56 f
HR2	7.48 a	265.99 j	85.38 g
HR3	7.46 a	416.14 f	83.07 i
HPE1	7.53 a	292.99 i	87.83 f
HPE2	7.51 a	383.37 g	73.1 k
HPE3	7.46 a	482.78 c	50.74 m

In order to investigate the effects of the growing media on plant development in the green wall system in more detail, the macro- and micronutrient contents of different growing media were determined. The results are shown in Table 4. The highest values of nitrogen and potassium, which are the most important nutritional elements for plant development, were found in hazelnut husks (N: 1.48%; K: 2442.67 mg/kg) and for phosphorus in rice hulls (P: 3231.26 mg/kg). In addition, peat had the highest levels of Ca (2587.28 mg/kg) and Fe (192.39 mg/kg), rice hulls had the highest levels of Mg (1183.74 mg/kg), and hazelnut husks had the highest levels of Cu (5.87 mg/kg) and Zn (36.35 mg/kg). The macro- and micronutrient contents of perlite, which is an inorganic growing medium component, was found to be quite low (Table 4). In general, the plant nutrient content of the growing media in the peat–hazelnut husk and peat–rice hull mixtures increased as the proportion of hazelnut husks and rice hulls in the mixture increased. In contrast, the plant nutrient content of the growing media in the peat–perlite and hazelnut husk–perlite mixtures decreased as the proportion of perlite in the mixtures increased. Since rapid plant growth disturbs the appearance of the green wall system and requires additional interventions such as pruning, maximizing plant growth is not an aim in the cultivation of green walls, as in conventional plant cultivation [16,34]. In addition, the required plant nutrients can easily be provided with a fertilization program. Therefore, the main role of the growing media used in green wall systems is not to provide plant nutrients, but to contain the necessary water for the plant and to support the plant by holding the plant roots.

Table 4. Plant nutrient content of the growing media (* LSD, different letters indicate statistical differences, $p < 0.05$).

Growing Media	N (%)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
P	1.34 cd *	1284.83 m	1039.32 m	2587.28 a	1183.74 j	192.39 a	5.34 e	28.38 de
H	1.48 a	2156.82 g	2442.67 a	1432 n	1262.22 e	134.25 i	5.87 a	36.35 a
R	0.42 k	3231.26 a	1186.15 i	1674 j	1346.06 a	168.2 e	1.80 m	8.44 j
PE	0 l	0.73 s	36.43 r	108.3 s	42.53 p	1.62 m	0.11 n	0.19 k
PH1	1.38 bc	1316.01 l	1464.75 h	2183.94 f	1206.36 hi	190.48 ab	5.73 c	32.02 c
PH2	1.41 b	1381.9 k	1634.10 g	1992.23 h	1212.07 gh	185.91 bc	5.75 c	33.55 bc
PH3	1.43 ab	1489.26 j	2193.96 d	1787.7 i	1220.92 g	152.93 g	5.81 abc	37.06 a
PR1	1.15 e	1380.06 k	1052 l	2491.89 b	1197.87 i	161.73 f	5.16 f	24.09 g
PR2	0.97 f	2461.93 e	1087.37 k	2245.72 d	1246.16 f	164.04 ef	2.91 k	15.21 i
PR3	0.52 j	2518.58 c	1119.84 j	2037.95 g	1289.39 c	176.61 d	2.76 l	13.33 i
PPE1	0.96 f	1175.67 n	992 n	2425.5 c	1150.38 k	191.01 ab	5.35 e	27.43 ef
PPE2	0.68 h	986.12 p	953.87 o	2218.84 e	983.78 m	182.48 cd	5.28 e	26.12 f
PPE3	0.44 k	725.51 r	745.44 p	1482.24 m	821.93 o	113.12 k	4.05 i	19.07 h
HR1	1.32 d	2284.46 f	2426.26 b	1484.67 m	1278.43 d	142.16 h	5.83 ab	35.13 ab
HR2	1.14 e	2486.62 d	2163 e	1504.65 l	1296.18 c	148.64 g	4.95 g	28.53 de
HR3	0.82 g	2921.58 b	1948.95 f	1544.77 k	1318.47 b	159.42 f	3.64 j	20.25 h
HPE1	1.39 bc	1986.22 h	2382.56 c	1356.15 o	1203.31 hi	128.58 ij	5.78 bc	32.63 c
HPE2	1.17 e	1823.92 i	2163.19 e	1173.82 p	1092.05 l	122.72 j	5.53 d	29.69 d
HPE3	0.62 i	1147.56 o	1942.08 f	895.36 r	872.18 n	96.55 l	4.24 h	23.61 g

3.2. Evaluation of Plant Area of Green Wall Increase with Indirect Monitoring Technique

The results of the increase in plant area in the green wall obtained by using western red cedar (*Thuja plicata*) and boxwood (*Buxus sempervirens* L.) are shown in Figure 4, and the correlation of these results with the physical and chemical properties of the growing media can be seen in Figure 5. The highest plant area for western red cedar (*Thuja plicata*) was achieved using the PH1 growing medium. In applications with the PH1 growing medium, the initial plant area (PA1-initial) was calculated as 0.327 m^2 and the final plant area (PA1-final) was 0.962 m^2 (Figure 4). The smallest increase in plant area in the green wall was recorded for the HR3 application, with an initial plant area of 0.343 m^2 and a final plant area of 0.612 m^2. The water holding capacity (R^2: 0.89) and organic matter content (R^2: 0.63) are the growing media characteristics with the strongest positive correlation with PA1 ($p < 0.001$) (Figure 5). The PH1 growing medium is the application with the highest water retention capacity (763.50 mg/L) (Table 2) and organic matter content (91.69%) (Table 3) among the applications. HR3 has the lowest water retention capacity (566.95 mg/L) among the applications (Table 2). As a general result, as the water holding capacity and organic matter content of the applications decrease, the plant area also decreases. As explained in the previous section, the low organic matter content in applications with perlite had no negative effects, as the water holding capacity increased while the organic matter content decreased. Therefore, the PA results obtained in the growing media PPE1, PPE2, and PPE3 consisting of peat and perlite mixtures are similar to the results obtained with peat and hazelnut husk mixtures (Figure 4). Bulk density and total porosity, along with other physical properties of the growing media, had no specific influence ($p > 0.05$) on PA in either plant species (Figure 5). Many studies in the literature report a significant correlation between the water holding capacity and the organic matter content of growing media and plant growth [18]. This is particularly evident for plants with high water requirements. Farrell at al. [35] emphasized that a high water-holding capacity and a high organic matter content in the growing medium used increase plant growth [35]. In studies based on similar experiments, Paradelo et al. [36] and Young et al. [37] reported that the positive effects of cheap and readily available growing medium components on the water-holding capacity increased plant growth [36,37].

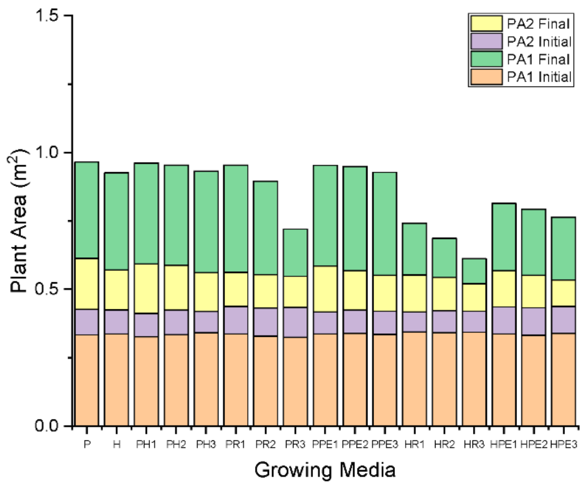

Figure 4. Initial and final plant area of western red cedar (*Thuja plicata*) (PA1) and boxwood (*Buxus sempervirens* L.) (PA2) in different growing media.

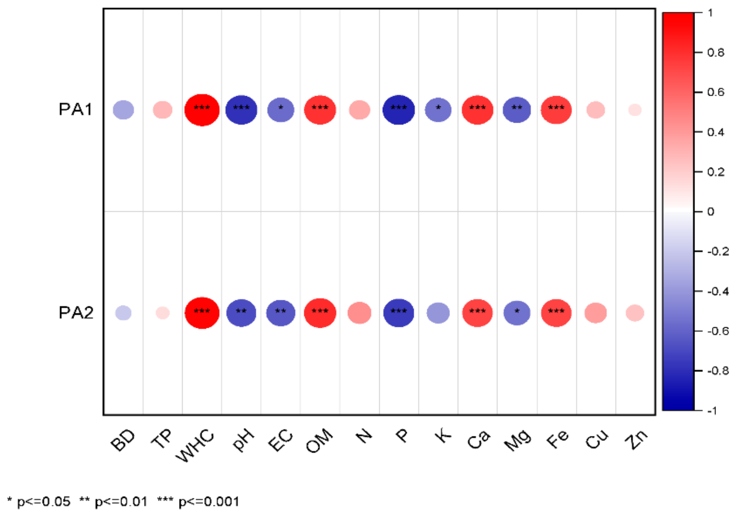

Figure 5. Spearman Correlations between plant area and growing media characteristics (PA1: western red cedar (*Thuja plicata*) plant area; PA2: boxwood (*Buxus sempervirens* L.) plant area). (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$).

When the PA results for the western red cedar (*Thuja plicata*) plant are analyzed according to the content of plant nutrients, the most significant ($p < 0.001$) positive effects are found for Ca (R^2: 0.55) and Fe (R^2: 0.53). Positive effects for Mg (R^2: 0.48) were also observed. No significant correlation was observed between PA1 and the other macro- and micronutrient contents, namely N, K, Cu and Zn. pH (R^2: −0.72) and P (R^2: −0.67) have a significant negative correlation ($p < 0.001$) on PA1 (Figure 5). The negative effect of pH and P values on PA1 was observed in the growing medium consisting of a mixture of hazelnut husks and rice hulls. The PA result of the HR1 application, which has the highest pH (7.52) and P (2284.46 mg/kg) values, was 0.742 m^2, respectively, and these values for PH1 (0.962 m^2), PPE1 (0.953 m^2), and HPE1 (0.814 m^2) were also lower than the PA values found Figure 4. The ideal growing media for Western Cedar (*Thuja plicata*) plant should have a pH between 5 and 6.5. Due to the high pH in the growing media obtained from the hazelnut husk + rice hull and hazelnut husk + perlite mixtures, the disruption of the plant nutrient balance and changes in biological activity and physiological reactions may occur in plants. In addition, a high pH disturbs the balance of nutrients by causing an excess of elements such as P, Mn, B, Zn, and Cu [15,38]. It is assumed that the reason for the negative correlation of a high P content with PA in the western red cedar (*Thuja plicata*) is the high pH value.

Similarly to western red cedar (*Thuja plicata*), boxwood (*Buxus sempervirens* L.) showed the highest plant area (PA2) in the PH1 growing medium (Figure 4). In the PH1 application, where the highest values were obtained, the initial plant area (PA2-initial) was 0.412 m^2 and the final plant area (PA2-final) was 0.594 m^2 (Figure 4). The lowest value for PA2 (0.521 m^2) was achieved with the application HR3. The strongest positive correlations between the physical and chemical properties of the growing media and the plant area (PA2) were observed for WHC (R^2: 0.86; $p < 0.001$), OM (R^2: 0.76; $p < 0.001$), Ca (R^2: 0.52; $p < 0.001$), Fe (R^2: 0.63; $p < 0.001$), and Mg (R^2: 0.57; $p < 0.05$) (Figure 5). These results show that in addition to physical properties that have a major influence on plant growth, such as the water-holding capacity, the plant nutrient content of the growing medium also influences PA. The properties of the growing media that correlated negatively with PA2 were EC (R^2: 0.70; $p < 0.001$), pH (R^2: 0.52; $p < 0.05$), and P (R^2: 0.43; $p < 0.001$) (Figure 5).

The positive and negative effects of the physical and chemical properties of the growing media used in this study on the PA of the two plants are largely similar (Figure 5). As expected, by the end of the study period, the plant area of boxwood (*Buxus sempervirens* L.) was lower than that of western red cedar (*Thuja plicata*). Indeed, it is well known that the species *Buxus sempervirens* L. is characterized by particularly slow growth. Boxwood (*Buxus sempervirens* L.) does not grow flexibly and undulatingly like western red cedar (*Thuja plicata*). It grows slowly, hard and with compacted fibers. Although the slow growth of boxwood (*Buxus sempervirens* L.) increases the time it takes for the green wall to reach its final shape, the fact that the plant is cold-resistant and does not require additional care, such as pruning, is positive for its use in green wall systems.

The results of the principal component analysis (PCA) performed to determine the relationships between the 14 growing media characteristics whose effects on the leaf area of the green wall system were investigated are shown in Table 5. According to PCA, coefficients greater than or equal to 0.3 have a sufficiently large effect to be considered significant, while parameters with coefficients less than 0.2 are considered to have no effect on the overall variation [39]. In PCA, the parameters were grouped into orthogonal components, with the first three groups having eigenvalues greater than unity and together accounting for 94.17% of the total variability (PC1: 39.29%; PC2: 38.10%; and PC3: 16.78%). This means that the characteristics of the growing media have an influence on the plant area of the green wall. The parameters that contributed most to plant area in PC1 were WHC (0.38), Ca (0.34), Fe (0.32), and pH (−0.32).

In PC2, the contribution was manifested by TP (0.39), BD (0.37), K (0.34), Zn (0.34), and N (0.32). In PC3, the most important parameters were P (0.50), Mg (0.50), and OM (0.34) (Table 5).

Table 5. Principal component analysis of growing media properties and plant area (* parameters used for PCA interpretation).

Parameters	PC1	PC2	PC2
BD	−0.09443	0.37949 *	−0.10411
TP	0.00595	−0.39858 *	−0.00744
WHC	0.38277 *	−0.07975	−0.01044
pH	−0.32026 *	0.23017	−0.00949
EC	−0.26822	−0.28162	0.00564
OM	0.26756	0.17847	0.34917 *
N	0.19003	0.32829 *	0.01918
P	−0.16911	0.13091	0.50752 *
K	−0.18691	0.34799 *	0.00519
Ca	0.34645 *	−0.13559	0.1897
Mg	0.08005	0.20685	0.50307 *
Fe	0.32535 *	−0.0518	0.27748
Cu	0.16026	0.29751	−0.29747
Zn	0.1098	0.34872*	−0.22818
Percentage Variation %	39.29	38.10	16.78
Cumulative %	39.29	77.39	94.17

4. Conclusions and Recommendations

There are various input and output relationships in the selection of revegetation systems, whereby both economic and ecological aspects are taken into account. The inputs of green wall systems are the installation costs (materials and labor used) and the operating costs (plant care, irrigation and electricity). The outputs are energy savings, the environmental impact, the increase in property value, and health benefits. However, the choice of growing media used for green walls has a significant impact on these inputs and outputs.

Peat and perlite are generally used as growing media in green wall systems such as potted ornamental plant production. Although the PA results obtained in growing media using hazelnut husks and rice hulls were slightly inferior compared to those of peat and perlite, they revealed the potential of these materials as alternative growing medium components for green wall systems. In particular, the use of hazelnut husks, an organic waste of agricultural origin for which there is currently no practical use, as a growing medium component is important in terms of a sustainable disposal method for this waste. In addition, heat- and sound-insulating materials can be made from agricultural organic wastes and perlite. Therefore, the use of alternative growing medium components in green wall systems can enhance the benefits of green walls, such as thermal insulation, sound insulation, and grey water treatment. New studies demonstrating these benefits will also contribute to the spread of green walls.

In addition, the indirect monitoring technique used in this study to determine plant area allows this work to be carried out safely and cost-effectively without damaging the green wall plants and systems. The simple and quick insights gained using this method will help us to better understand the effects of different growing media on the expansion of the green wall plant area. The practical results can be used to optimize green wall design to improve plant growth and overall system performance in urban areas.

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