Experimenting growing media through local bio-resources valorisation: A design-oriented approach for living walls

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Abstract

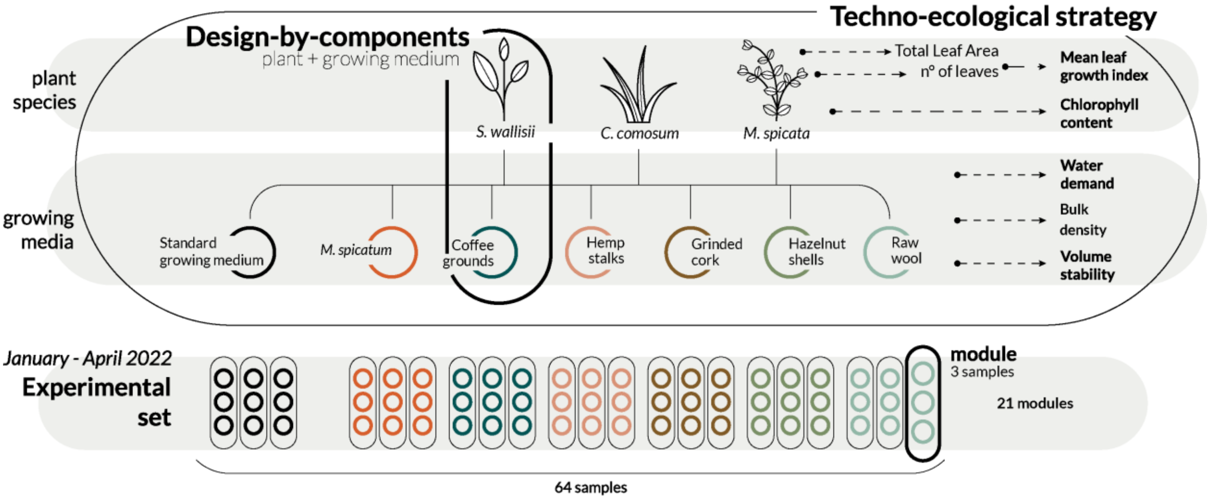
In the context of densely populated urban areas, vertical greenery systems are gaining momentum for their role in reintroducing nature and enhancing buildings sustainability. Despite this trend, the absence of a standardised methodology for designing sustainable vertical greenery systems and guidelines for selecting appropriate growing media for this technology are two crucial gaps in academic research. This study addresses this by testing six alternative growing media derived from local bio-resources (dried *M. spicatum*, hazelnut shells, coffee grounds, hemp stalks, grinded cork, and raw sheep wool) and comparing them with a standard growing medium. The experiment was conducted over 120 days, monitoring the health and growth of three plant species - *C. comosum*, *S. wallisii*, and *M. spicata*. Innovative tools, such as a multi-criteria matrix and the Mean Leaf Growth Index, were introduced to assess sustainability and plant development. The findings highlight promising outcomes for hazelnut shells-based, hemp stalks-based, and grinded cork-based growing media, showcasing their lightweight and stable attributes compared to standard growing medium and assuring good plants health and growth. In contrast, raw sheep wool-based, *M. spicatum*-based, and coffee grounds-based growing media present challenges in plant health and growth, despite interesting attributes concerning lightweight and low water demand. This research contributes to shaping a design-by-components strategy for more sustainable vertical greenery systems, emphasizing the crucial role of circular bio-resources in nature-based technological innovations.

Keywords: organic substrates, laboratory experiment, design-by-components, plant health and growth, techno-ecological evaluation

Highlights

- Experimental activity to test six alternative growing media obtained by local waste and by-products.
- Plant growth and health, and growing media lightweight, low watering demand and volume stability are describing criteria for growing media suitability.
- A baseline to assess and compare sustainability and performance of growing media for vertical greening.

Graphical Abstract



1. Introduction

The increasing urbanisation trend causes critical environmental and social issues that compromise human well-being and challenge the sustainability of cities. Urban greening is a fundamental strategy that can drastically improve the liveability of current congested cities (Musa et al., 2022) and is often adopted to mitigate these critical issues through *nature-inspired* strategies (Dorst et al., 2019). In the framework of urban greening, vertical greenery systems (VGSs), well known as green walls, are useful technology to green densely populated cities and make buildings more sustainable (Douglas et al., 2021). Green walls are space-efficient systems that support the growth of plants on vertical surfaces, and they present a wide range of technical solutions such as green façades and living walls (Manso & Castro-Gomes, 2015). Green façades consist in the use of climbing plants growing directly on a wall or indirectly on a support system (Vox et al., 2018). Instead, living walls are more complex systems that provide a more uniform vegetation coverage, but they usually require frequent maintenance (Gunawardena & Steemers, 2019, 2020). Living walls consist of a supporting structure attached to the wall that contains growing medium and vegetation, usually classified into modular or continuous systems (Perini et al., 2013). VGSs provide multiple environmental and social benefits to human into the built environment (Goel et al., 2022) such as the improvement of air quality (Pettit et al., 2019; Srbinovska et al., 2021), the increase of urban biodiversity (Madre et al., 2015), the reduction of noise pollution, the mitigation of urban heat island effect (Susca et al., 2022), and the improvement of human well-being (Chung et al., 2022). VGSs are multifunctional nature-based solutions that "protect, sustainably manage, and restore natural and man-made ecosystems in order to effectively and adaptively address societal challenges, and to simultaneously benefit people and nature" (IUCN, 2020). However, there are no specific indications to design and produce VGSs in a sustainable way and to reduce their impact on the environment.

In fact, scientific research mainly focuses on the assessment of the environmental benefits, in particular thermal performance, offered by VGSs in built environment (Chàfer, et al., 2021a). In its review Nugroho (2020) highlights the necessity for VGSs to evolve into more sustainable solutions using materials with less incorporated energy and CO2 emissions, showing the use of natural or recycled materials as possible innovation paths. In recent years some academic studies analysed for the first-time environmental impacts of VGSs in order to assess the sustainability of them. Some studies adopted the Life Cycle Assessment (LCA) to identify impact hotspots related to VGSs typology and their components. The first study using the LCA applied to VGSs was conducted by (Ottelé et al., 2013), who compared the environmental burden of five different VGSs typologies. The study concluded that materials used to build components of any green wall system were significant in terms of environmental burden. The study highlighted the need to use sustainable materials for VGSs toward a sustainable design strategy. In this study and in the subsequent work of Manso et al. (2018) it was assessed that the support system was the component with the highest environmental burden due to the impactful supply chain of stainless steel. All the following works applying LCA on VGSs highlighted the huge influence of their structural components on the life cycle (Cortês et al., 2021; Salah & Romanova, 2021; Serra et al., 2017). In agreement with these results, Pan & Chu (2016) recommended reducing the amount of material of the structural components in order to drastically decrease the environmental impacts of VGSs. Thanks to the emphasis given to the sustainability of materials composing the structure of VGSs, interesting material research and optimisation was developed in the last few years. Manso et al. (2018) propose an innovative modular VGS composed by scraps of the cork and glass production. Similarly, Cortês et al. (2021) developed and tested the mechanical performances of a new modular living wall made with expanded cork agglomerate. However, just recently LCA studies highlighted the pivotal role of growing media in the counting of VGSs environmental impacts. Oquendo-Di Cosola et al. (2020)

and Mannan and Al-Ghamdi (2022) confirmed in their work the importance of considering environmental impacts for the selection of materials and recommended for the first time the use of organic growing media as a fundamental aspect for a sustainable design of VGSs. Particularly, Chàfer et al. (2021a) in their comparative LCA between different typologies of VGSs suggested the application of sustainable strategy for growing media (e.g. recycled growing media) to drastically decrease the total environmental impacts of the whole system. Reyhani et al. (2022) highlighted the high influence of some of the most commonly used artificial and inorganic growing media on the whole environmental assessment of VGSs. In their work LCA was applied for the first time as a guiding tool for the design of sustainable VGSs, suggesting the replacement of impactful artificial growing media with more sustainable organic ones. Nevertheless, as highlighted by Chàfer et al. (2021b), material research and optimisation for VGSs is still a major gap of research in literature. Particularly, studies on sustainable growing media experimentation are very few. Nevertheless, relevant studies conducted by Parada et al. (2021), Manríquez-Altamirano et al. (2020) and Manríquez-Altamirano et al. (2021) sustained that the careful design, scientific evaluation and production of bio-resources-based growing media are pivotal strategies for sustainable urban greening projects. In its review Koviessen et al. (2023) strongly advocates the urgency of finding alternative substrates through the circular use of local by-products and waste to be applied in specific nature-based-solutions and how this strategy can boost the green transition of contemporary cities. As stated by Toboso-Chavero et al. (2021), besides the chemical, physical and biological properties of growing media and general economic aspects, now environmental sustainability is gaining importance in the selection of growing media. Vandecasteele et al. (2023) sustains that developing new blends using renewable resources represents the next frontier in advancing the sustainability of soilless horticulture. Some studies emphasised the use of organic materials as constituents of alternative growing media such as composts, bark, wood residues and coconut coir (Barrett et al., 2016; Gruda, 2019), generally amended to inorganic ones such as perlite, vermiculite, calcined and expanded clay (Sabatino, 2020). In particular, circular economy has been applied for the creation of sustainable growing media derived from industrial by-products or from agricultural, industrial and urban organic waste (Raviv, 2013). Nevertheless, De Lucia et al. (2021) and Rivas-Sánchez et al. (2017) are the only works that tested an agricultural by-product, such as rice husk, as sustainable growing media for VGSs.

Nevertheless, the effectiveness of a growing medium in supporting plant growth is the most important aspect to be considered to assess growing media efficacy. An alternative growing medium is promising if it must ensure plant growth equal to or greater than the regular one (Leiber-Sauheitl et al., 2021). Non-destructive methods adopted to assess plant growth are preferred to destructive ones thanks to the opportunity to preserve plants and repeat measurements during the experiment (Hilty et al., 2021). Leaf length and width, number of leaves, plant or stem height, length, volume and density of roots are parameters usually measured to assess the growth of plant biomass (Furbank & Tester, 2011). Moreover, leaf length and width can be used for the determination of the Total Leaf Area (TLA) (Koyama & Smith, 2022), and these three parameters can be used to define the growth rate (Charles et al., 2011). Other studies measure chlorophyll content through a specific instrument that provides on-site information about plant health in a non-destructive way (Brown et al., 2022; Gottardini et al., 2014). Applying circular economy and sustainable design thinking, the present work develops an experimental campaign on different bio-resource-based growing media to be applied to VGSs, using organic waste and by-products from the Piedmont Region (Italy). The main challenge of this work is that no protocols have been defined to test the sustainability of a growing media. So, evaluation criteria for sustainable VGSs growing media were set as follows. The work of (Alexander & Bragg, 2014) was followed to define a multi-criteria matrix to evaluate and compare the sustainability of the alternative growing media tested. Through a sustainable design perspective, three main functional requirements of VGSs growing media defined by Vinci and Rapa (2019), e.g. lightweight, durability, low water demand, have been used as evaluation criteria for growing media sustainability. Moreover, the Mean Leaf Growth Index (MLGI) was proposed to synthesise information on plant health and growth.

1.1. Research goal

This study broadens the research of growing media in vertical greening design and deepens the knowledge about: (1) environmental aspects as additional drivers for the selection of growing media and (2) the experimentation of alternative substrates specifically for VGSs. Therefore, the present work is a baseline for the definition of a methodology through which alternative growing media, specifically for vertical greening, can be assessed and compared in terms of their sustainability and performance. An experimental activity has been developed to test the efficiency of six alternative growing media, composed of local organic waste and by-products, for three plant species. From the results of the experimental activity, an analysis of the growing media sustainability has been developed taking into account their effectiveness in supporting plant growth and three criteria referred to growing media technical and ecological aspects: lightweight, water demand and volume stability. Moreover, the present work is meant as a first step in the definition of a strategy for the sustainable design of VGSs that follows a *design-by-components* approach, i.e. starting from the growing media and consequently defining the other components of the system.

2. Desk research: waste and by-products selection for alternative growing media

A preliminary desk research on the main organic by-products and waste of the Piedmont Region (North-west of Italy) has been conducted to identify potential materials for alternative growing media. The economic framework of the Piedmont Region is mainly characterised by agriculture, viticulture, rice-growing, animal husbandry, automotive, textile and food industry, besides financial and tourist activities (Regione Piemonte, 2023). Six waste and by-products deriving from local supply chains and urban flows have been identified following the principles of the circular bioeconomy (Brandão et al., 2021). In this framework, the aim is reducing the need of raw materials by using organic by-products and waste as inputs for a possible local production of growing media to be applied in VGSs (Scarpellini, 2022). Moreover, local waste and by-product (1) abundance and (2) historic value in the territory were taken into account as fundamental aspects in the bio-resources selection. In fact, the valorisation of abundant bio-resources bringing local cultural value (Padilla-Rivera et al., 2020) in a new production system within the territory can create environmentally, socially and economically sustainable innovation (Donner et al., 2022) As explained by Hang (2022), relying on context-specific opportunities and economies is generally a successful strategy toward a green economy and its theoretical framework is applicable in different geographical contexts.

In this desk research regional reports and national databases were used to assess the quantities of local organic by-products and waste, while scientific literature was consulted to prove their potentialities as growing media.

Grinded hemp stalks and hazelnut shells were selected as by-products and both derived from local cultivation and manufacturing. Piedmontese hemp has been recognised as high quality cultivation since the Roman Empire age (Regione Piemonte, n.d.). Even if hemp cultivation does not represent one of the most productive agricultural sectors of the Piedmont Region, accounting for the 7,4% of the national production (ISTAT, 2023a), the innovation in its supply chain would support the diversification of the farming system, the creation of new local activities and the revival of this crop in the market (Aluigi &Viganò, 2016). Hemp fibre and hemp stalks are the two main by-products derived from hemp farming. Hemp fibre is mainly used in the textile supply chain and was already largely tested in previous studies as an alternative growing medium but it didn’t reach any significant result (Dannehl et al., 2015). While hemp stalks, the woody part of the plant stalk, is mainly used in the building sector as sound-absorbent material (Cavallaro, 2015). Many studies (Woznicki et al., 2021, Escobar-Avello et al. 2023) have shown good results using growing media based on wood fibres which are characterised by high total porosity and air holding capacity (Maher et al., 2008) For this reason, this study tested hemp stalks as an abundant and promising valuable by-product at local scale. For the present work the hemp stalks were collected from a hemp farm located in Carmagnola, in the centre of the Piedmont Region (30km from Turin).

Likewise, Piedmont is the most important Italian region for hazelnut cultivation and processing, accounting for 28,5% of the total Italian production (ISTAT, 2023b). Hazelnut shells are the most significant by-product obtained from hazelnut processing in terms of weight and volume, and they are usually used for heating (Battistoni et al., 2020). Hazelnut shells present a high percentage of lignin (Gordobil et al., 2020), a feature that contributes to the physical stability of the substrate according to the research conducted by (Dede & Ozdemir, 2018). Puliga et al., 2022 reported the possibility of using hazelnut shells as basal ingredients of substrate for growing edible and medicinal mushrooms, while any study was carried out in floricultural and vertical greening fields. Anyway, (Barrett et al., 2016) reported that the use of nuts shells as growing media is an ever-increasing trend. Thus, in the present work hazelnut shells were considered a promising opportunity. Hazelnut shells were collected from a hazelnut industry located in Alba (Cuneo), south-east of the Piedmont Region (62 km from Turin).

On the other hand, raw sheep wool, cork stoppers, coffee grounds and fronds of *M. spicatum* were selected as waste materials that present potentialities for alternative growing media.

Raw sheep wool derived from Piedmontese flocks was collected from a local wool consortium of the Piedmontese Textile District, a well-known excellence of the Made in Italy. Nevertheless, sheep wool of the Piedmont Region is considered a low-quality resource if compared to the international textile market requirements. Indeed, Piedmontese flocks do not present appropriate characteristics to be processed in the textile supply chain, and local breeders often send their raw wool to disposal and treat it as waste. To date, in 2019, 106.670 sheeps flocks have been registered in the Piedmont Region, assuming the disposal of almost 160 tons of wool (Quaglia, 2023). Therefore, the valorisation of the local sheep wool represents a promising challenge that encompasses the interrelation of economic and social aspects (Rajabinejad et al., 2019). As reported by Gabryś & Fryczkowska (2022), many studies tested the use of treated purified wool as growing media for plants. By the way, the use of raw sheep wool can drastically decrease the use of energy and resources for the wool cleaning process, consequently lowering the environmental impacts for the preparation of this alternative growing medium. Moreover, sheep wool that does not undergo cleaning treatment retains lanolin, a substance rich in potassium, that can be used as plant fertiliser (Ikoyi et al., 2020; Cavalcante et al., 2020). The raw sheep wool was collected from a sheep wool collector located in Miagliano (Biella), in the north-east of the Piedmont Region (83 km from Turin) and within the geographical area of the historic Textile District of the Region.

Piedmont is the leading Italian region concerning wine production, from cultivation to sales (ISTAT, 2023c). Many wine shops and wine bars are widely diffused in the region, especially in bigger urban centres (Regione Piemonte, 2021). In this framework, cork stoppers are often disposed of as waste instead of treated as a resource for new supply chains. Indeed, cork presents an interesting hygroscopic feature that can be helpful in vertical greening application because it supports the thermos-hygrometric balance (Contreras et al., 2022). Moreover, Martinez et al. (2013) obtained promising results using a cork-rice husk-based thin layer as a growing medium. Used cork stoppers were collected from two winery shops in the city centre of Turin.

Similarly, coffee is an important food commodity linked to the historical development of the coffee-roasting sector in the Piedmont Region. Spent coffee grounds are abundant food waste produced at the consumption stage of the coffee life cycle, and despite many opportunities to use them as a resource (Bomfim et al., 2022), no alternative applications have been structurally planned at the local scale. Promising results have been reached by Tombarkiewicz et al. (2022) in using spent coffee ground as soil improver and these outcomes led to the selection of this waste as a potential resource for plant growing. Spent coffee grounds were collected from the inner coffee shop of the Polytechnique of Turin.

At the end, fronds of *M. spicatum* were selected as a potential resource because they are usually disposed as special waste by the Municipality of Turin (Gruppo di Lavoro Specie Esotiche della Regione Piemonte, 2017). Indeed, *M. spicatum* is an allochthonous aquatic weed that overgrows during summer in the Po River due to the eutrophication of the freshwater ecosystem. It is included in the lists of invasive allochthonous species of relevance in the Regulation (EU) 1143/2014 (European Parliament and Council, 2014) and its rapid eradication and environmental control is strictly regulated through mechanical removal (Arpa Piemonte, 2016). In this study, fronds of *M. spicatum* were collected manually from the Po River banks along its urban stretch in Turin. The fronds of *M. spicatum* were hand-collected from the riverbanks of the Po River near the city centre of Turin, where the presence of this plant is generally abundant in Summer and early Autumn.

As in Koley (2021) the alternative use of local bioresources is a strategy that can bring multiple positive outcomes in a region, optimising the management and accumulation of resources - of more or less environmental and health risk - and at the same time the creation of new short supply chain growing media. As stated by Taupedi and Ultra Jr. (2022) the development of such a strategy involves the running of laboratory tests investigating the nature of the bio-resource in order to create competitive alternative soils to traditional unsustainable ones.

3. The experiment: materials and methods

This study adopts and improves the experimental protocol proposed by De Lucia et al. (2021) for the assessment of an alternative bio-resource-based growing medium for VGSs. The experimental protocol developed in this study tested a broader number of alternative growing media and analysed their performance according to environmental criteria defined from literature analysis. The experimental protocol consists of two main stages: (Section 3.1.) the preparation of the experiment materials and setting and (Section 3.2.) the experiment running.

3.1. Experiment preparation

This stage is composed by (i) the preparation of the six alternative growing media by mixing the selected bio-resources with standard growing medium; the test of their (ii) phytotoxicity, (iii) physical and (iv) chemical characteristics; (v) the selection of the plant species; and (vi) the preparation of the experimental set.

Growing medium was adopted as a common amendment in order to obtain homogeneous and totally organic alternative growing media. This is a largely used growing media suitable for a huge number of plant species, although less flexible inorganic materials, such as perlite and expanded clay, are often used as growing media in VGSs applications. Therefore, the use of growing medium highlights the influence of the bio-resources added in the mixes.

3.1.1 Growing media preparation

The six alternative growing media were prepared by mixing each bio-resource with standard growing medium for floricultural applications (COMPO SANA®) composed by neutral sphagnum peat, green composted soil improver and a small amount of mineral fertiliser. Each bioresource was manually mixed with 50% in volume of growing medium in order to obtain homogeneous mixtures. The obtained alternative growing media contained a small amount of fertilisers. Raw sheep wool, coffee grounds and grinded hemp stalks did not require any pre-treatment, while cork stoppers, hazelnut shells and *M. spicatum* needed to be grinded before mixing.

Hazelnut shells were shredded using an electric milling machine (YM221230879, AATAY) in order to obtain shell shreds of 0,5 -1 cm of length and avoid the rotting of plant roots caused by possible water retention in the shell cavity after irrigation. Cork stoppers were grinded with a standard blender with inox steel blades (CB-410, Horett) obtaining cork granulate of 0,3 - 1 cm of length. On the other hand, fronds of *M. spicatum* required the longest pre-treatment process. After their collection from Po River, fronds have been dried at room temperature (17±2 °C) for one week and then grinded with the standard blender obtaining a powder-like material composed of particles ranging from 0,01 cm to 0,3 cm.

3.1.2 Phytoxicity of growing media

The alternative growing media were tested for phytotoxicity following Charles et al. (2011) to assess negative effects of contaminants on seed germination (Martignon, 2009). This analysis is economically viable, easy to conduct, and provides highly reliable results (Bragança et al., 2018; Guevara et al., 2019). The test included triplicate samples of *Eruca vesicaria ssp. Sativa*, *Nepeta cataria*, and *Lactuca sativa*. Each alternative growing medium (10 g) was mixed with 100 ml of demineralized water, shaken hourly for 12 hours, and then filtered through a 45 µm filter paper to obtain an eluate. Then, germination tests were conducted in triplicate samples. Each sample consisted of 10 seeds placed on a cotton filter in a Petri dish. 5 ml of eluate were added to the test samples, while the three control samples received 5 ml of demineralized water. Petri dishes were incubated in the dark at 25±1°C for 72 hours. Germinated seeds were identified by shoots with a root length of at least 3 mm (Margenat et al., 2017).
For test acceptability, Seed Germination (SG) must be equal to or greater than 80% according to the following formula (Margenat et al., 2017):

(formula 1)

$$SG\% = (\text{number of seeds germinated}) / (\text{number of total seeds}) \%$$

3.1.3 Physical and chemical characteristics of growing media

Physical characteristics of growing media was assessed by considering Dry Bulk Density (D) (g cm^{-3}), Total Porosity (TP) (%) and Water Holding Capacity (WHC) (%). D was measured for each growing media following the method of Rai et al. (2017). This is a pivotal parameter for VGSs growing media since it can strongly affect the weight of the entire system influencing the design of the anchoring system (Dede et al., 2019). In fact, the use of lighter growing media would allow a lighter structural system. Thus, growing media D is an important information in the design of a VGS in order to decrease weight and need of materials.
TP was assessed for each growing media following the method of Landis (1990), while WHC was determined following the Keen Raczkowski box method by Govindasamy et al. (2022).
The pH and Electrical Conductivity (EC) (µS/cm) were assessed to characterise chemical properties of the alternative growing media (concentration of 1:2,5) following procedures in Castro Garibay et al. (2019).

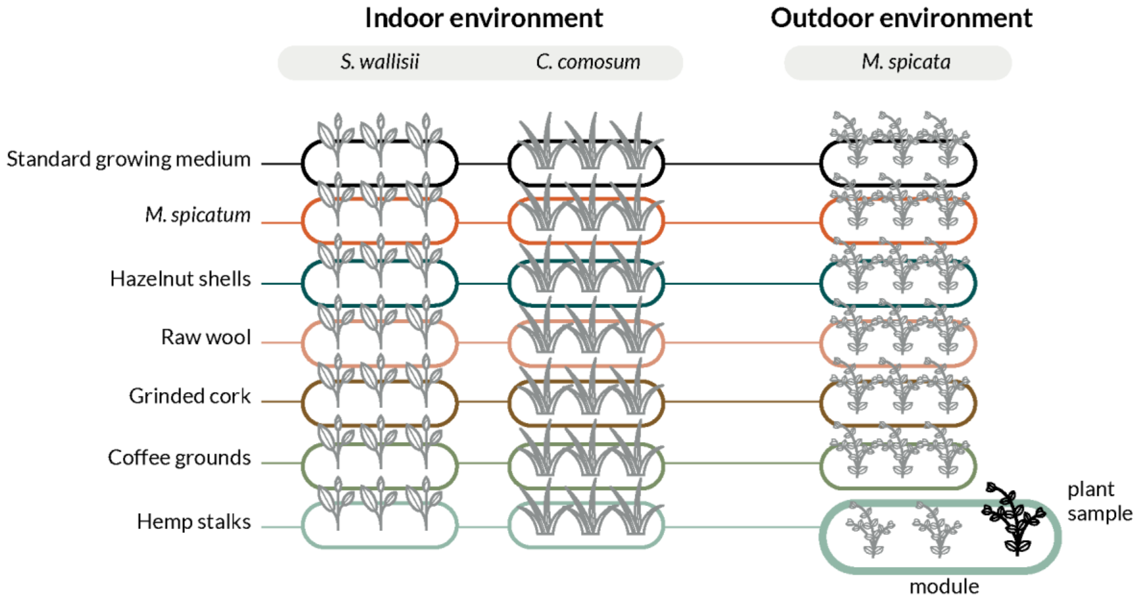
3.1.4 Plant species selection

Plant species for indoor and outdoor environments were used for assessing the efficiency of the alternative growing media. *C. comosum* and *S. wallisii* were selected since they are commonly used in indoor VGSs thanks to their low maintenance demand (Kwon et al., 2021). While *M. spicata* was selected as outdoor plant species for its features, i.e leaves and stalk wax, *trichomes*, leaves morphology and roughness, which are considered promising in air pollutant capture (Vigevani et al., 2022) *M. spicata* as well is successfully used in VGSs (Dorais et al., 2020).

3.1.5 Preparation of the experimental set

In the experiment, 21 pots (40cm x 14cm x 12cm) were used as individual modules to observe how the different growing media affect the growth of *C. comosum*, *S. wallisii*, and *M. spicata*. For each plant species, six pots were arranged, each containing 3 l of a different alternative growing medium. Additionally, one pot for each species was filled with 3 l of the standard growing medium as a control test for comparison. Within each pot, three plants (samples) of the same species were planted (Figure 1). This setup allows for the observation of how different growing media impact the growth of three samples of each plant species. Plant pot trays were placed at the bottom of each pot in order to collect the drained water and assure to each plant the same amount of water despite the different growing media TP and WHC.

Figure1. Experimental set, composed of 21 pots (modules). For each plant species, one module has been prepared for each of the six alternative growing media and for the standard growing medium. Each module contains three plant samples.



Pots containing *C. comosum* (7 pots) and those with *S. wallisii* (7 pots) were placed in a room at 17±2 °C, a good temperature for these two plant species. Pots containing *M. spicata* (7 pots) were placed outdoor. Both indoor and outdoor plants allocation allowed an indirect source of sunlight. Plant acclimation was performed for 14 days in order to match the requirements of the different plant species (Retkute et al., 2015). During this period irrigation was managed according to measured growing media humidity and environmental conditions (in the case of *M. spicata*) in order to fit the water demand of plants of each module.*C. comosum* and *S. wallisii* were watered using 300 ml of water per pot, while

M. spicata with 500 ml. An average amount of water was defined following the works of Gubb et al., (2018), Gabrys and Fryczkowska (2022) and De Lucia et al. (2021). Liquid fertiliser for ornamental plants (NPK 7-5-6 with boron, copper, iron, manganese, molybdenum, zinc, potassium and iron) was provided to all pots during the experiment setup through fertigation (20 g of liquid fertiliser in 2 l of water).

3.2 Experiment running

Specific criteria were measured in order to evaluate the efficiency and sustainability of the six alternative growing media in comparison to the one composed by growing medium (control test) for a period of 120 days. These criteria were taken into account to obtain an overall description about growing media characteristics and plants growth and health. Thus, criteria were divided into two groups: (1) those referring to growing media characteristics such as humidity, water demand and volume stability, and (2) those referring to the plants growth and health such as number of leaves, Total Leaf Area (TLA)and chlorophyll content. Applying a sustainable design perspective, humidity, water demand and volume stability were selected as significant information on growing media environmental sustainability, defining water use and material duration (Vinci and Rapa, 2019). As established from literature, number of leaves and TLA allowed the calculation of plants development, while chlorophyll content is a reliable parameter for plant health (Paturkar et al., 2022; Dominici et al., 2021; Kakouei & Salehi; 2013).

3.2.1. Monitoring the growing media characteristics: water demand, humidity and volume stability

Water demand (ml per each module) was monitored as a crucial parameter to elucidate on the water consumption of each growing media. Watering quantities were added up through the experiment in order to obtain the water consumption for each growing media. Soil humidity was measured to regulate the irrigation frequency. It was monitored for each of the 21 pots with a 10-point scale manual hygrometre (T10 Bodentester, BATOU) every three days. Moreover, volume stability is a fundamental parameter to understand the structural stability of a growing medium. More stable is its volume, less maintenance and replacement will be required for the growing medium, decreasing waste and economic expenses for specialised labour and disposal service. Volume stability (%) was monitored by measuring the D of each pot at the beginning and at the end of the experiment.

3.2.2. Monitoring the plant health: chlorophyll content

Chlorophyll content (in μmol of chlorophyll per m^2 of leaf) was measured using the optical manual metre Apogee Mc-100. Chlorophyll content sampling was performed twice per month since the focus of the experiment was the response of plants in the long period, not at daily base (Padilla-Rivera et al., 2020). According to Pavlovic et al. (2014) and Liang et al. (19967), chlorophyll content is commonly used as an indicator of the plant health since it decreases in plants under stress conditions. The Apogee Mc-100 metre is normally used in agriculture to estimate plant health of crops and provide an evaluation of the stress condition due to the lack of nutrients, insufficient irrigation and adverse climatic conditions (https://www.apogeeinstruments.com). The chlorophyll content was measured by sampling three randomised leaves for each plant and performing five consecutive measurements per leaf.

3.2.3. Monitoring the plants growth: Total Leaf Area, number of leaves and Mean Leaf Growth Index

The assessment of plant growth was performed twice per month by measuring the TLA following the non-destructive method proposed by Dominici et al. (2021). The method consists of measuring manually the length and width of leaves (for each plant species) (Zhang et al., 2018) and categorising them in four *topos* (or leaves models) based on their average leaf surface. Leaf surface was obtained by using an AutoCAD drawing sheet where lengths and widths of each *topoi* were reproduced through [Polylines tool] in order to obtain enclosed polyline geometries needed to define the surface through [AREA Command]. The TLA is obtain summing the surface of the leaves that composed a plant and is expressed by the following formula:

(Formula 1)

$$TLA = (L_1 \times W_1) + (L_2 \times W_2) + (L_3 \times W_3) \ldots + (L_n \times W_n)\ (cm^2)$$

L: leaf length
W: leaf width

Monitoring the number of leaves informs about the modification of the foliage density over time and it gives additional knowledge about the quality of plant growth (Dobrescu et al., 2017).
The TLA and number of leaves of the three plants contained in a pot (module) were used to define the novel Mean Leaf Growth Index (MLGI):

(Formula 2)

$$MLGI = (TLA_f / nl_f) - (TLA_i / nl_i)\ (cm^2)$$

TLA_i : initial total leaf area
TLA_f : final total leaf area
nl_i : initial number of leaves
nl_f : final number of leaves

Accordingly, MLGI informed about the development of plants that composed a module of VGS.
If the MLGI is higher than 0, it means that the growth of plants followed a positive trend (increasing both TLA and number of leaves). If the MLGI is equal to 0, it means that plants didn't grow. While if the MLGI is lower than 0, it means that plant growth showed a decreasing trend. If the three plants contained in a module died during the monitoring period, the MLGI has been considered null.

3.3 Data analysis

A two-way ANOVA was applied to assess the effects of the seven different growing media on chlorophyll content and TLA along the monitoring period. Therefore, two different analyses have been carried out for the TLA (dependent variable 1) the and the chlorophyll content (dependent variable 2). For both analysis plant species and growing media were set as independent variables, respectively with three and seven levels. Two hypotheses were defined for each analysis:

> Null Hypothesis ($H0_1$): There are no significant differences in TLA among growing media and plant species.
> Alternative Hypothesis (Ha_1): There are significant differences in TLA among growing media and plant species.
>
> Null Hypothesis ($H0_2$): There are no significant differences in chlorophyll content among growing media and plant species.

Alternative Hypothesis (Ha_2): There are significant differences in chlorophyll content among growing media and plant species.

Two-way ANOVA was conducted using Excel "data analysis" tool (data > data analysis > two-way ANOVA with replications). The analysis generated p-values for each factor and their interaction, indicating significant differences in TLA and chlorophyll content based on growing media, plant species, and their interaction. Significance was determined at a p-value < 0.05.

4. Results

Results on growing media characteristics and plant development are described below. In order to maintain clarity in the results presentation, this section discussed separately (1) the phytotoxicity, physical and chemical characteristics of growing media (2) the sustainability of growing media, (3) the plants growth and (4) the plants health obtained along the experiment.

4.1 Phytotoxicity, physical and chemical characteristics of growing media

The following tables (Table 1, Table 2, Table 3) report the results for growing media phytotoxicity, chemical characteristics and physical characteristics. All the alternative growing media presented good results for phytotoxicity, allowing the germination of almost 80% of the seeds (Table 1).

Table 1. Results of the phytotoxicity test for each alternative growing media and seed species.

Growing media	***Eruca vesicaria ssp. Sativa***	***Nepeta cataria***	***Lactuca sativa***
Hazelnut shells	90%	90%	100%
Grinded cork	100%	100%	90%
Hemp stalks	100%	90%	100%
M. spicatum	90%	90%	90%
Raw wool	90%	90%	90%
Coffee grounds	90%	90%	90%

TP (Table 2) of all the alternative growing media arelower than the value of growing medium, except for raw wool-based growing media that is equal to standard growing medium. However, according to Havis and Hamilton (1976), TP presents good values - exceeding 50% - for hazelnut shells-based, grinded cork-based, hemp stalks-based and sheep wool-based growing media. For WHC (Table 3), all the alternative growing media showed lower values than standard growing medium. However, all the growing media reach the threshold of 40% (Tjosvold, 2019), thus presenting a valuable WHC. Moreover, hemp stalks-based, raw wool-based and *M. spicatum*-based had the higher WHC within the alternative growing media, showing similar values. It is interesting to note three main range of similar results for the alternative growing media: hazelnut shells-based, with the lowest WHC, grinded cork-based and coffee grounds-based, with the slightly higher WHC, and hemp stalks-based, raw wool-based and *M. spicatum*-based with higher WHC.

Table 2. Results of the Total Porosity and Water Holding Capacity for each growing media.

Growing media	**TP (%)**	**WHC (%)**
Hazelnut shells	60	45

Grinded cork	80	52
Hemp stalks	70	70
M. spicatum	50	67
Raw wool	90	70
Coffee grounds	50	54
Standard growing medium	90	85

The pH values (Table 3) of all the alternative growing media are very close to the pH value of the standard growing medium. Particularly, hazelnut shells-based, grinded cork-based and sheep wool-based growing media have the same pH of the standard growing medium, showing a neutral value of 7. Hemp stalks-based, *M. spicatum*-based and coffee grounds-based growing media have pH 6, thus they are slightly acidic. In general, all the alternative growing media showed acceptable pH values for floricultural applications. Concerning EC, grinded cork-based growing medium (401 µS/cm) present a similar value to standard growing medium (400 µS/cm), followed by hazelnut shells-based growing media (743 µS/cm. However, hemp stalks-based (1116 µS/cm), *M. spicatum*-based (4080 µS/cm), raw wool-based (1540 µS/cm) and coffee grounds-based (2340 µS/cm) present very high values of EC. Particularly, coffee grounds-based and *M. spicatum*-based overcome standard growing medium almost five times.

Table 3. pH and Electrical Conductivity for each growing media.

Growing media	pH	EC (µS/cm)
Hazelnut shells	7	743
Grinded cork	7	401
Hemp stalks	6	1116
M. spicatum	6	4080
Raw wool	7	1540
Coffee grounds	6	2340
Standard growing medium	7	400

4.2 Sustainability of growing media

Table 4. summarises the main characteristics of growing media monitored during the experiment. The D measured during the preliminary stage of the experiment shows that all six alternative growing media weigh less than the standard growing medium (0,52 g cm^{-3}), showing values between 0,04 gcm^{-3} and 0,48 g cm^{-3}. Raw sheep wool-based growing medium presents the lowest D (0,04 g cm^{-3}) of all growing media. *M. spicatum*-based (0,25 g cm^{-3}), grinded cork-based (0,30 g cm^{-3}) and hemp stalks-based (0,29 g cm^{-3}) weigh almost half than standard growing medium. However, hazelnut shells-based (0,48 g cm^{-3}) and coffee ground-based growing media (0,42 g cm^{-3}) show similar D to standard growing medium, being the heavier within alternative growing media.

As a general trend, raw sheep wool-based and *M. spicatum*-based growing media show lower volume stability (between 30% and 50%) than the other growing media (65% - 70%). Coffee ground-based growing media showed the same volume stability of standard growing medium (between 65% and

70%), while hemp stalks-based, grinded cork-based and hazelnut shell-based presented the highest volume stability (75% - 90%). It can be asserted that all the alternative growing media assure a valuable volume stability. Moreover, results suggest that the volume stability of growing media depends on the position of modules, whether inside or outside.

Raw sheep wool-based and *M. spicatum*-based growing media required lower water supply (1500 – 2000 mL per each module) than the other alternative growing media. They showed half the water demand of standard growing medium. Anyway, it can be observed that almost all the alternative growing media (hemp stalks-based = 3000 – 3500; grinded cork-based = 2400 – 200; coffee grounds-based = 1800 – 2000) presented lower water demand than standard growing medium (3300 – 4000 mL per each module). The only exception is hazelnut-shells based growing medium with *C. comosum* and *S. wallisii* (3600 mL), that however presented a very close value to standard growing medium. However, hazelnut shells-based growing medium with *M. spicata* (3500 mL) showed lower water demand than standard growing medium. Also for water demand results suggest that values depend on the position of modules, whether inside or outside.

Table 4. Dry bulk density (g cm^{-3}), volume stability (%) and water demand (ml) of alternative growing media and standard growing medium.

	Dry bulk density (g cm^{-3})	**Volume stability (%)**			**Water demand (ml)**		
		C. comosum	*S. wallisii*	*M. spicata*	*C. comosum*	*S. wallisii*	*M. spicata*
Raw wool	0,04	40	40	30	1500	1500	2000
M. spicatum	0,25	50	50	45	1800	1800	1500
Hemp canapule	0,29	85	85	75	3000	3000	3500
Grinded cork	0,3	90	90	85	2400	2400	2000
Coffee grounds	0,42	70	70	65	1800	1800	2000
Hazelnut shells	0,48	85	85	80	3600	3600	3500
Standard growing medium	0,52	70	70	65	3300	3300	4000

4.3 Plants health in response to different growing media

The seven alternative growing media produced different chlorophyll content in *C. comosum*, *S. wallisii* and *M. spicata*, as shown in figures 2, 3 and 4. The two-way ANOVA analysis shows the consistency of the effect of the seven growing media on the chlorophyll content for all the three plant species. Variance between the seven treatments is significant within plant species, growing media and between the two of them ($\alpha < 0,5$).

Starting with *C. comosum*, it presented a stable trend of chlorophyll content with hazelnut shells-based, hemp stalks-based, grinded cork-based growing media. Moreover, hazelnut shells-based showed a higher chlorophyll content than standard growing medium for all the experiment period, while hemp stalks-based showed lower but close chlorophyll content than standard growing medium for almost all the experiment period. On the other hand, *C. comosum* with raw sheep wool-based growing media drastically reduced the chlorophyll content from the day 30 of experiment. Coffee grounds-based and *M. spicatum*-based growing media showed a reduction of chlorophyll content from the day 45.

S. wallisii presented a decreasing trend of chlorophyll content for almost all growing media, including standard growing medium and this effect is already visible from the day 15 of the experiment period. Only hemp stalks-based and grinded cork-based growing media produced stable trends of chlorophyll content with *S. wallisii*, showing particularly higher values than standard growing medium.

Hazelnut shells-based, grinded cork-based and hemp stalks-based growing media produced stable chlorophyll content trends with *M. spicata* throughout the entire experiment period and present very similar values to standard growing medium. While *M. spicatum*-based, raw sheep wool-based and coffee ground-based growing media produced a drastic reduction of chlorophyll content from the day 30 of the experiment. Despite this, it is interesting to note that after the day 45 raw sheep wool-based growing medium showed a slightly but continuous increase of chlorophyll content.

Figure 2. Chlorophyll content trends in *C. comosum* with the seven growing media. The x axis represents the days and the eight measurement days are reported. The y axis reports the chlorophyll content registered ranging from 0 to 600 µmol m^{-2}.

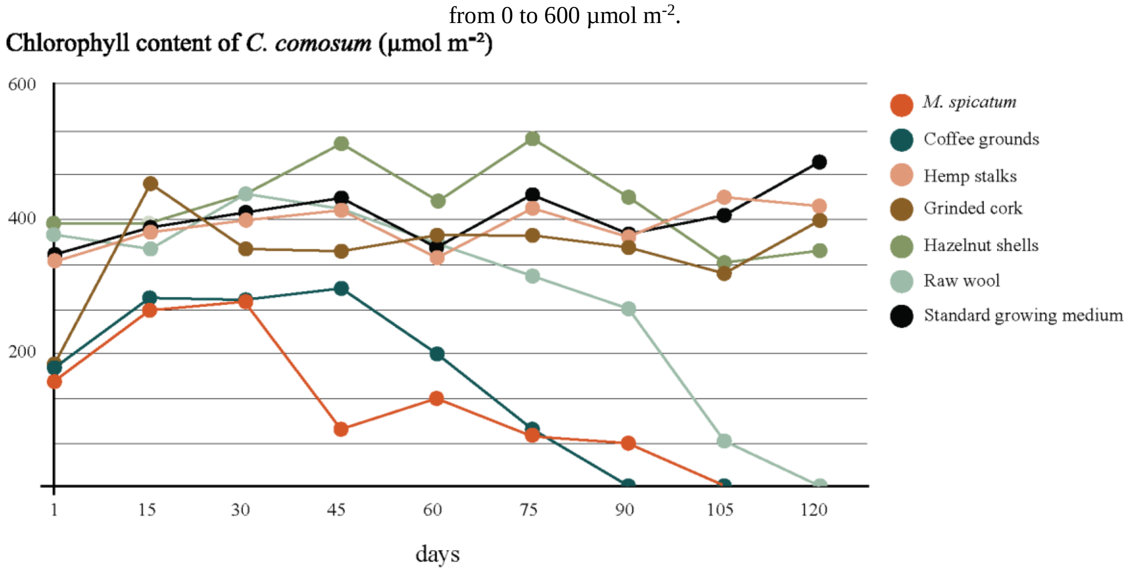


Figure 3. Chlorophyll content trends in *S. wallisii* with the seven growing media. The x axis represents the days and the eight measurement days are reported. The y axis reports the chlorophyll content registered ranging from 0 to 1500 µmol m^{-2}.

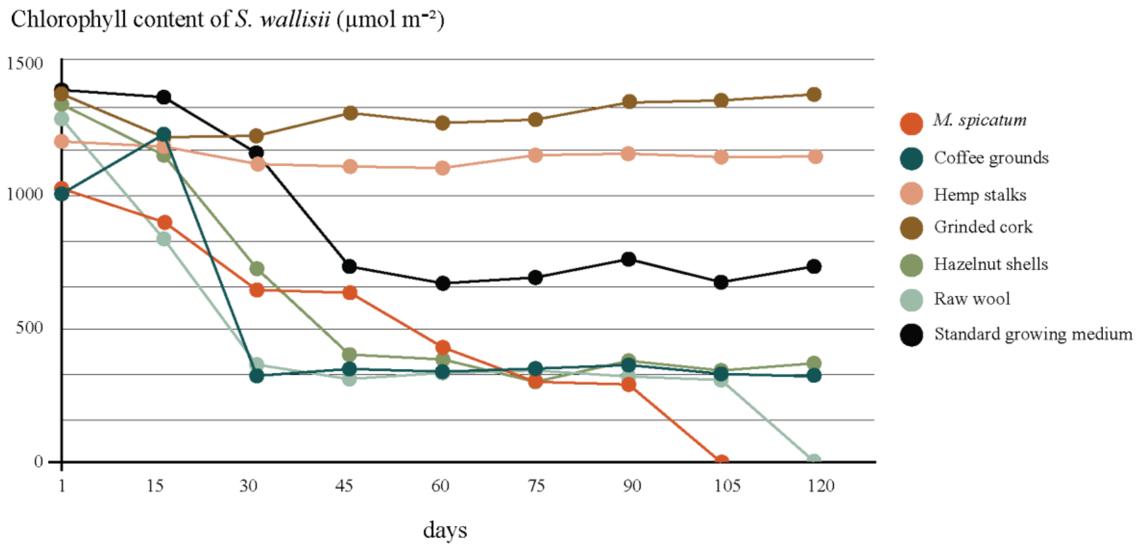
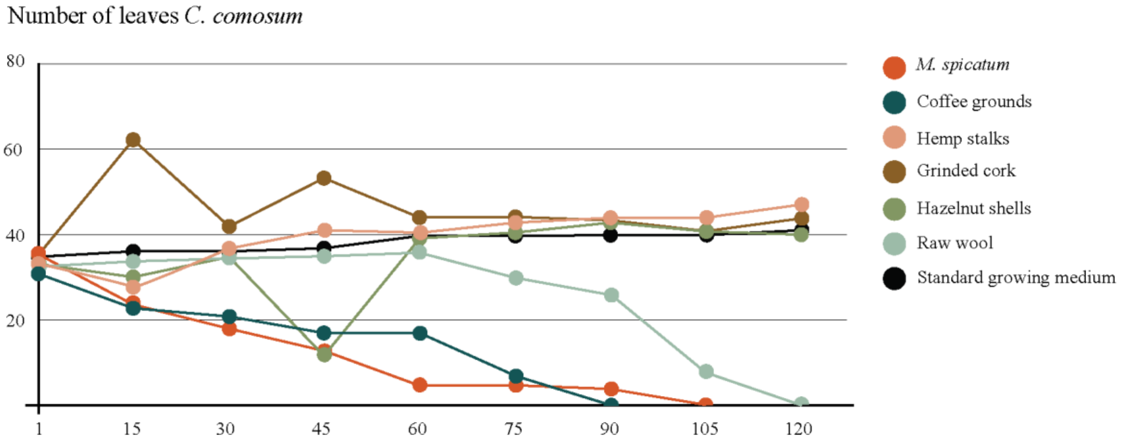

Chlorophyll content of S. wallisii (μmol m-2)
1500
1000
500
0
1
15
30
45
60
75
90
105
120
days
M. spicatum
Coffee grounds
Hemp stalks
Grinded cork
Hazelnut shells
Raw wool
Standard growing medium

Figure 4. Chlorophyll content trends in *M. spicata* with the seven growing media. The x axis represents the days and the eight measurement days are reported. The y axis reports the chlorophyll content registered ranging from 0 to 1250 μmol m^{-2}.



4.4 Plants growth in response to different growing media

The two-way ANOVA analysis reported the consistency of the effect of the seven different growing media on the TLA and number of leaves for all the three plant species. The variance between the seven treatments is significant for both parameters within the three plant species, the growing media and between these two factors ($\alpha < 0,5$). Below results on plants growth are presented considering only the MLGI. It is meant as a consistent value of the plant biomass growth since it combines TLA, number of leaves and their modification in time.

Table 5 presents the MLGI for each growing media and each plant species. All the plants set in *M. spicatum*-based growing media died before the end of the experiment period so they have null MLGI. The same result was obtained for the *C. comosum* with coffee ground-based and raw sheep wool-based growing media, and for the *S. wallisii* with raw sheep wool-based growing media (null MLGI).

C. comosum showed negative MLGI with hemp stalks-based growing medium (-2,68), presenting a decrease in plant biomass. However, it had higher MLGI than standard growing medium (0,49) with grinded cork-based (7,51) and hazelnut shells-based (1,00) growing media. Particularly, *C. comosum* with grinded cork-based had the highest MLGI, more than seven times the standard growing medium one.

S. wallisii presented a negative MLGI only with coffee ground-based growing medium (-3,87). MLGI of S. wallisii with grinded cork-based (4,93), hazelnut shells-based (3,10) and hemp stalks-based (11,00) growing media were higher than the standard growing medium one (2,44). In particular, hemp stalks-based growing media showed an extremely high MLGI, almost five times the standard growing medium.

M. spicata presented positive MLGI for almost all the alternative growing media, with just M-spicatum-based growing medium with null MLGI and raw sheep wool with negative MLGI (-3,37). Thus, almost all the alternative growing media support an increase in plant biomass for M. Spicata. However, although the MLGI with coffee grounds-based (0,06), hemp stalks-based (1,03) and grinded cork-based (1,92) growing media were positive, they are lower than the standard growing medium one (3,52). Only the MLGI with hazelnut shell-based growing media (4,58) was higher than the standard growing medium one.

Table 5. The table shows the TLA_i, TLA_f (cm^2), nF_i, nF_f and the MLGI (cm^2) values of the seven growing media for *C. comosum*, *S. wallisii* and *M. spicata*. MLGI values higher than the reference value of the standard growing medium are highlighted in yellow.

	C. comosum				
	TLA_i (cm^2)	**TLA_f (cm^2)**	**nl_i**	**nl_f**	**MLGI**
M. spicatum	1716,42	0,00	34	0	-
Coffee grounds	1367,17	0,00	31	0	-
Hemp stalks	1450,03	1939,40	33	47	-2,68
Grinded cork	1400,99	2143,49	34	44	7,51
Hazelnut shells	1497,28	1801,33	34	40	1,00
Raw wool	1415,98	0,00	33	0	-
Standard growing medium	**1557,24**	**1844,33**	**35**	**41**	**0,49**
	S. wallisii				
	TLA_i (cm^2)	**TLA_f (cm^2)**	**nl_i**	**nl_f**	**MLGI**
M. spicatum	590,00	0,00	24	0	-
Coffee grounds	1480,00	201,95	26	11	-3,87
Hemp stalks	800,00	2746,64	24	18	11,00
Grinded cork	510,00	536,01	21	16	4,93
Hazelnut shells	450,00	187,72	22	6	3,10
Raw wool	600,00	0,00	29	0	-
Standard growing medium	**560,00**	**330,48**	**23**	**11**	**2,44**
	M. spicata				
	TLA_i (cm^2)	**TLA_f (cm^2)**	**nl_i**	**nl_f**	**MLGI**
M. spicatum	1530,00	0,00	247	0	-
Coffee grounds	1310,00	332,19	301	76	0,06
Hemp stalks	1690,00	2003,59	263	270	1,03
Grinded cork	1590,00	3480,18	224	388	1,92
Hazelnut shells	1200,00	5270,83	210	512	4,58
Raw wool	1090,00	229,10	186	92	-3,37
Standard growing medium	**1160,00**	**3102,40**	**205**	**338**	**3,52**

5. Discussion

The following sections present the results obtained from the physical and chemical characterisation of the growing media (5.1) and their performance according to the selected criteria for VGSs growing media sustainability and support in plant development (5.2).

5.1 Optimising growing media physical and chemical characteristics

Based on the growing media physical and chemical characterization, adding 50% bio-resources to the standard growing medium maintains a consistent pH level suitable for floriculture. TP met acceptable values for all alternative growing media, except coffee grounds-based and *M. spicatum*-based, which barely reached the 50%. While hazelnut shells showed a similar value to standard growing medium, the WHC of the other alternative growing media is exceptionally high, potentially causing plant death despite managed watering based on humidity levels. Notably, lignin-based growing media showed the lowest EC. All alternatives growing media, except hazelnut shells and cork-based ones, had EC values exceeding 1100 µS/cm, anacceptable result for floriculture according to Dewir et al. (2005). Results obtained from the characterisation are promising considering the experimental phase of these alternative growing media.

5.2 Comparative analysis between alternative growing media and the standard growing medium

The following sections discuss the results obtained by each alternative growing media with *C. comosum*, *S. wallisii* and *M. spicata and* compare them with standard growing medium. The results have been proposed in a multi-criteria matrix in order to highlight strength and weakness of each growing media with *C. comosum* , *S. wallisii* and *M. spicata*. Table 3 shows MLGI and chlorophyll content as indicators of plants growth and health, while water demand, 19ensity and volume stability referred to growing media technical performances. The former two criteria describe the efficiency of alternative growing media for herbaceous and ornamental plants, while the other three criteria are useful to assess the sustainability of the growing media. As shown in Table 6, the multi-criteria matrix obtained is a project-oriented tool since it allows easy comparisons between growing media and plant species, highlighting results that exceed the standard growing medium values. (Alexander and Bragg, 2014). Below the performances of each growing medium for each plant species are discussed.

Table 6. Multi-criteria matrix showing results of each growing medium for *C. comosum*, *S. wallisii* and *M. spicata*. Higher values than standard growing medium are highlighted in green.

	C. comosum				
	MLGI (cm^2)	**Chlorophyll c. (µmol m^{-2})**	**Water demand (ml)**	**Dry bulk density (g cm^{-3})**	**Volume stability (%)**
M. spicatum	-	113,1	1800	0,25	50%
Coffee grounds	-	142,6	1800	0,42	70%
Hemp stalks	-2,68	397,4	3000	0,29	85%
Grinded cork	7,51	372,9	2400	0,3	90%
Hazelnut shells	1,00	426,6	3600	0,48	85%

Raw wool	-	278,2	1500	0,04	40%
Standard growing medium	0,49	411	3300	0,52	70%
	S. wallisii				
	MLGI (cm^2)	**Chlorophyll c. (μmol m^{-2})**	**Water demand (ml)**	**Dry bulk density (g cm^{-3})**	**Volume stability (%)**
M. spicatum	-	399,5	1800	0,25	50%
Coffee grounds	-3,87	449,3	1800	0,42	70%
Hemp stalks	11,00	1139,1	3000	0,29	85%
Grinded cork	4,93	1297,2	2400	0,3	90%
Hazelnut shells	3,10	507	3600	0,48	85%
Raw wool	-	351,8	1500	0,04	40%
Standard growing medium	2,44	847,4	3300	0,52	70%
	M. spicata				
	MLGI (cm^2)	**Chlorophyll c. (μmol m^{-2})**	**Water demand (ml)**	**Dry bulk density (g cm^{-3})**	**Volume stability (%)**
M. spicatum	-	429,2	2000	0,25	40%
Coffee grounds	0,06	641,3	1500	0,42	70%
Hemp stalks	1,03	840,1	3500	0,29	75%
Grinded cork	1,92	858,7	3000	0,3	90%
Hazelnut shells	4,58	830,9	3500	0,48	80%
Raw wool	-3,37	722,8	2000	0,04	30%
Standard growing medium	3,52	891,7	3500	0,52	70%

5.2.1 *M. Spicatum*-based growing medium

This growing medium showed an exceptionally low water demand, a phenomenon explicable by the concurrently high measured WHC. However, this characteristic likely led to root rot in all three plant species. Additionally, the combination of the high WHC and the lightweight and inconsistent nature of the crushed *M. spicatum* may be responsible for the poor volume stability of this growing medium. Since it showed lower volume stability than standard growing medium, using the *M. spicatum*-based growing medium would require more frequent replacement of material compared to standard growing medium. Therefore, this feature negatively impacts the practical application of these organic waste material for VGS, as it would result in a very close consumption of the bio-resource, making its utilization a controversial decision (Six et al., 2016). However, the already mentioned exceptional lightweight nature of the *M-spicatum*-based growing medium it's worth to consider the possibility of blending it with another material whose characteristics could balance the high WHC of the *M. spicatum*-based growing medium. According to these results, it is recommended to use a proportionally lower quantity of dried *M-spicatum*.

5.2.2 Coffee grounds-based growing medium

As observed in the case of the *M. spicatum*-based growing medium, the low water demand of the coffee grounds-based growing medium is due to its high WHC, likely contributing to root rot in most plant samples, regardless of the plant species. These findings align with those of Hardgrove & Livesley (2016), who noted an increased WHC when coffee grounds were directly added to the soil. Additionally, Chrysargyris et al. (2021) highlighted that the addition of coffee grounds reduced the air-filled porosity in peat-based growing media, necessitating more moderate and frequent watering to avoid inadequate water distribution during irrigation. Although in the conducted study this criticality was addressed through an irrigation system guided by recorded humidity levels, the exceedingly high WHC nonetheless made its management challenging. Therefore, it seems that the coffee grounds-based growing medium may not be a viable alternative to standard growing medium. However, the good performance in terms of volume stability suggests the possibility of blending it with other growing media to balance the water retention of the coffee grounds. In light of these results, it is recommended to use a proportionally lower quantity of coffee grounds.

5.2.3 Hemp stalks-based growing medium

Physical characteristics of this alternative growing medium showed better results for most criteria than standard growing media. Anyway, hemp stalks-based growing medium showed species-specific results. *C. comosum* showed not promising results concerning plant growth performances. This specific result may suggest an insufficient supply of nutrients offered by this growing medium for the plant species tested. As discussed by Aurdal et al. (2022), wood fibre-based growing media offer physical stability but they require additional nutrients. This aspect could negatively affect the growth of *M. spicata*. Nevertheless, particularly good outcomes obtained in the plant growth of *S. wallisii* suggest the suitability of the hemp stalks-based growing medium for this specific plant species, showing the highest results of the MLGI of all samples tested. This result is in line with the low nutrient demand of *S. wallisii* as highlighted by many studies (Dewir et al., 2005; Mak & Yeh, 2001). Finally, hemp stalks-based growing medium is a promising alternative to standard growing medium for *S. wallisii* considering the values obtained for all the five criteria of the multi-criteria matrix.

5.2.4 Grinded cork-based growing medium

It showed good results regarding growing medium physical characteristics and plant biomass growth, specifically for *C. comosum* and *S. wallisii*. In particular, *S. wallisii* showed the highest chlorophyll content among all the alternative growing media and this result suggests the suitability of lignin-rich materials as growing media amendments for this specific plant species (Graceson et al., 2014). Also the high MLGI values for *C. comosum* and *S. wallisii* suggested that the good performance related to plant growth can be due to the high porosity of the cork structure (Bozzolo & Evans, 2013), ensuring air provision to the rooting system(Liang et al., 1996).

5.2.5 Hazelnut shells-based growing medium

It had a better effect than standard growing medium on leaves growth in all the three tested plant species, though good results for plant growth and health were noticeable only in *C. comosum*. In agreement with results obtained by Ekbic et al. (2022), nutrients offered by hazelnut shells are particularly effective at chlorophyll production in *C. comosum*. Moreover, the lignin content of this alternative growing medium assures a good volume stability, thus a good air provision to the rooting system (Gruda, 2019). This is a crucial factor in *C. comosum* growth and health (Rameshkumar, 2018). The matrix shows that hazelnut shells-based growing medium required higher watering than standard growing medium showing good water drainage. This characteristic also justifies the high performances in *S. wallisii* growth (Mashinchian et al., 2017). Nevertheless, considering the water demand shown by *M. spicata* - tested in outdoor environment - hazelnut shells-based growing medium required the same water supply than standard growing medium suggesting similar water retention .

5.2.6 Raw sheep wool-based growing medium

The performance of this alternative growing medium showed similar trends to those observed with *M. spicatum*-based growing medium. Data presented in Table 3 indicate that this growing medium is not conducive to supporting plant growth. The low water demand implies a high WHC of raw sheep wool-based growing medium, potentially leading to root rot in all samples across the three plant species, particularly in *C. comosum* and *S. wallisii* samples. Furthermore, the extremely low volume stability of this growing medium fails to ensure a consistent structure for rooting systems. The raw sheep wool-based growing medium gradually disintegrates into its two components after irrigation, causing a separation between the standard growing medium and the raw sheep wool. Therefore, modifications in the method of growing media preparation and mixing are imperative to thoroughly assess the potential of raw sheep wool as a component for alternative growing media. Since Gabrys and Fryczkowska (2022) did not specify the nature of the standard growing medium in their experiment, it could be inferred that their positive results were contingent upon either the proportion of standard growing medium and raw sheep wool used in their studies or the distinct performance of dust wool owing to its unique physical characteristics. Nevertheless, the high lightness of raw sheep wool and its WHC hold promise for vertical greening applications, suggesting the potential for mixing it with other materials to balance detrimental water retention and stabilize the volume structure. According to the obtained results, as for *M.spicatum* and coffee grounds, it is recommended to use a proportionally lower quantity of raw sheep wool to undertake further experiments.

6. Conclusions

The study reveals promising results for hazelnut shells-based and cork-based growing media with C. comosum and S. wallisii, as well as hemp stalks-based growing medium with S. wallisii, outperforming the standard potting soil. These findings position them as potentially sustainable alternatives for VGSs. The positive outcomes support the use of lignin-rich materials as amendments for the tested plant species, offering crucial insights for exploring similar bio-resources in diverse geographical contexts.

Notably, grinded hemp stalks emerge as a particularly promising bio-resource, requiring no pre-treatment before integration with standard growing media, making it readily applicable for local-scale production of sustainable growing mediums. However, all alternative growing media exhibit superior volume stability, lightweight and low water consumption compared to the standard growing medium, making them intriguing options for creating VGSs with lowered environmental impact.

The presented multi-criteria matrix serves as a foundational description of alternative growing media, urging further enrichment with additional properties and preliminary steps for comprehensive evaluation and validation. The matrix is aligned with sustainable design thinking and circular bioeconomy principles. It aims to guide decision-making in the VGS design process and can be adapted for various geographical contexts through collaboration between academia and practitioners.

For what concern the limits of the study, further exploration, suggesting varied material mix percentages, are recommended. In particular, chemical and biological tests are deemed necessary for a comprehensive characterization of these alternative growing media. Moreover, future studies should focus on evaluating nutritional values and other chemical properties to identify key nutrients for plant growth and facilitate appropriate fertigation strategies.

The study underscores the potential for creating a novel supply chain based on circular bioeconomy principles, particularly in the Mediterranean region and other areas abundant in the bio-resources tested. It emphasizes the need to prioritize growing media to enhance the sustainability of VGSs and nature-based solutions at large, positioning them as increasingly prevalent systems.

The proposed methodology, integrating sustainable design thinking, circular bioeconomy principles and laboratory experimentation, is advocated as a tool to identify sustainable alternatives to standard growing media. Regional or national implementation of this strategy requires collaborative efforts involving local companies, research centres, universities, architects, and landscape designers to establish a sustainable production system for VGSs growing media based on localized bio-resource valorisation. At the end, the study suggests conducting an environmental life cycle assessment for each growing medium to deepen understanding and guide strategies for further enhancing the sustainability of VGS design.

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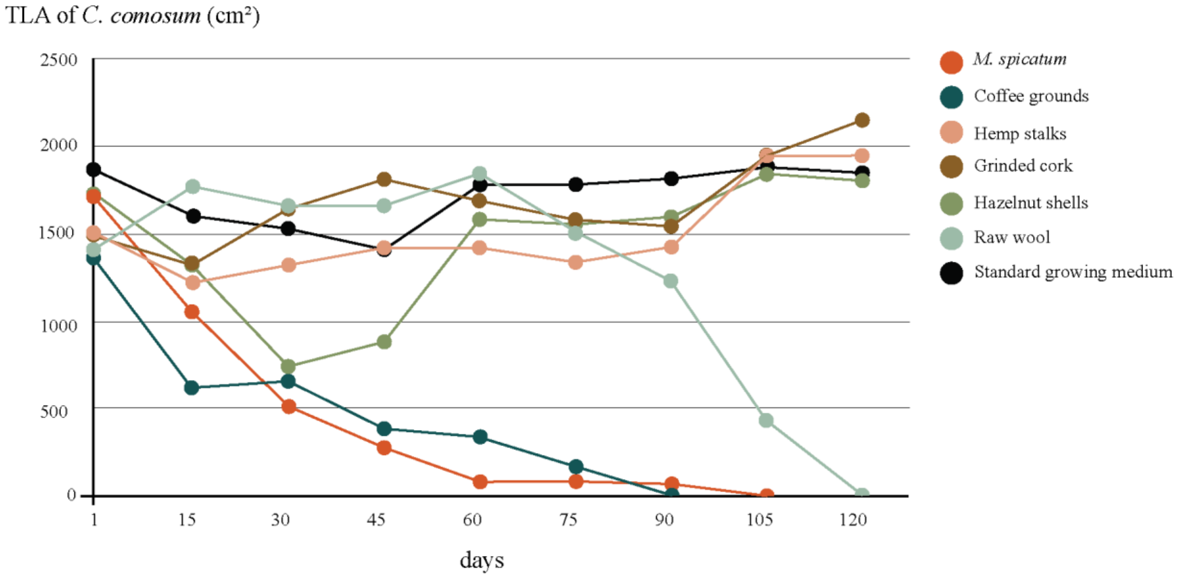
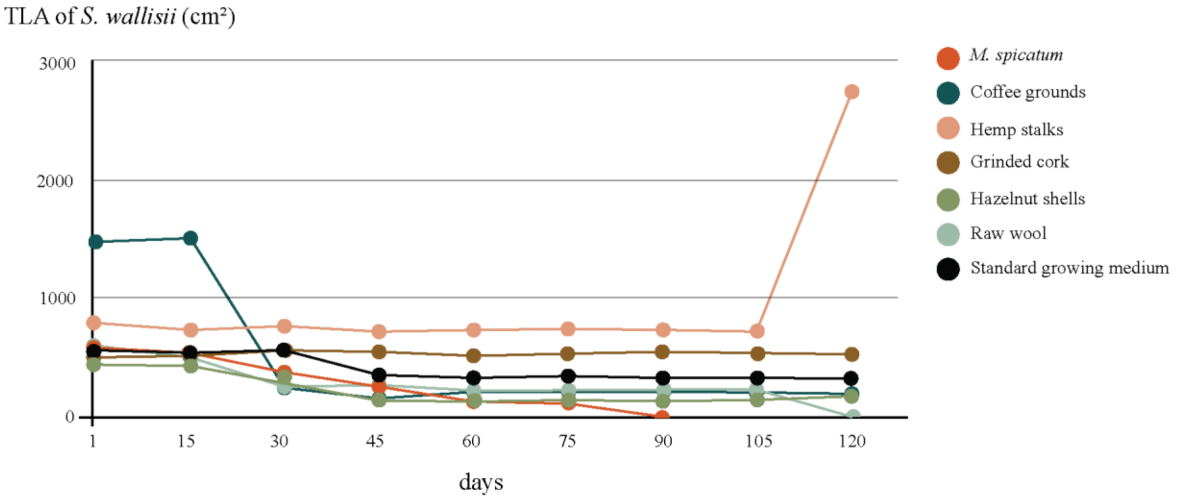
Supplementary materials

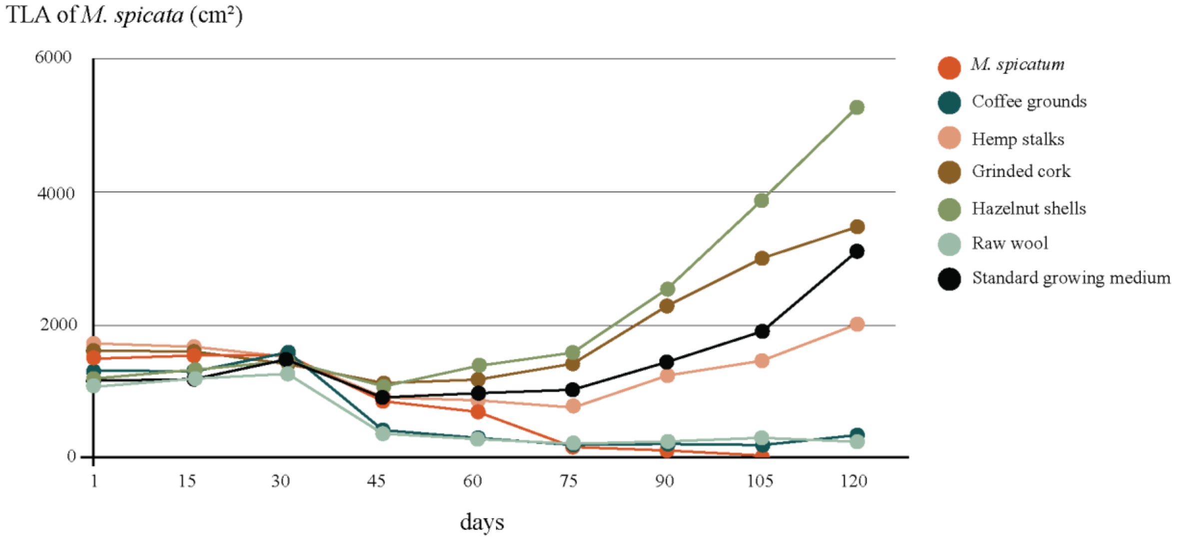
Supplementary Figure 1. TLA trends in *C. comosum* with the seven growing media. The x axis represents the days and the eight measurement days are reported.



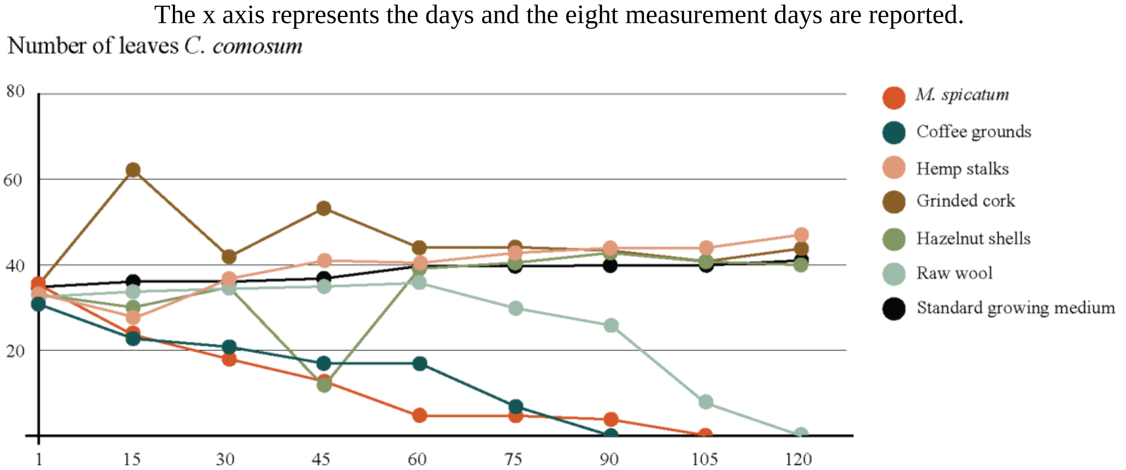
Supplementary Figure 2. TLA trends in *S. wallisii* with the seven growing media. The x axis represents the days and the eight measurement days are reported.



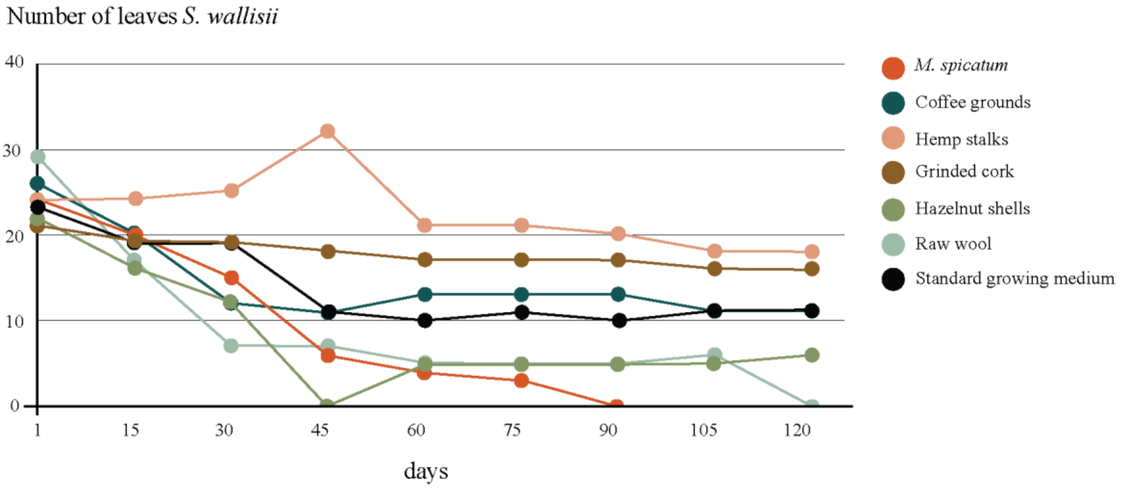
Supplementary Figure 3. TLA trends in *M. spicata* with the seven growing media.
The x axis represents the days and the eight measurement days are reported.



Supplementary Figure 4. Number of leaves trends in *C. comosum* with the seven growing media.
The x axis represents the days and the eight measurement days are reported.



Supplementary Figure 5. Number of leaves trends in *S. wallisii* with the seven growing media. The x axis represents the days and the eight measurement days are reported.



Supplementary Figure 6. Number of leaves trends in *M. spicata* with the seven growing media. The x axis represents the days and the eight measurement days are reported.