

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

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1 **Experimenting growing media through local bio-resources valorisation:** 2 **a design-oriented approach for living walls**

3 3 4 4 **Abstract**

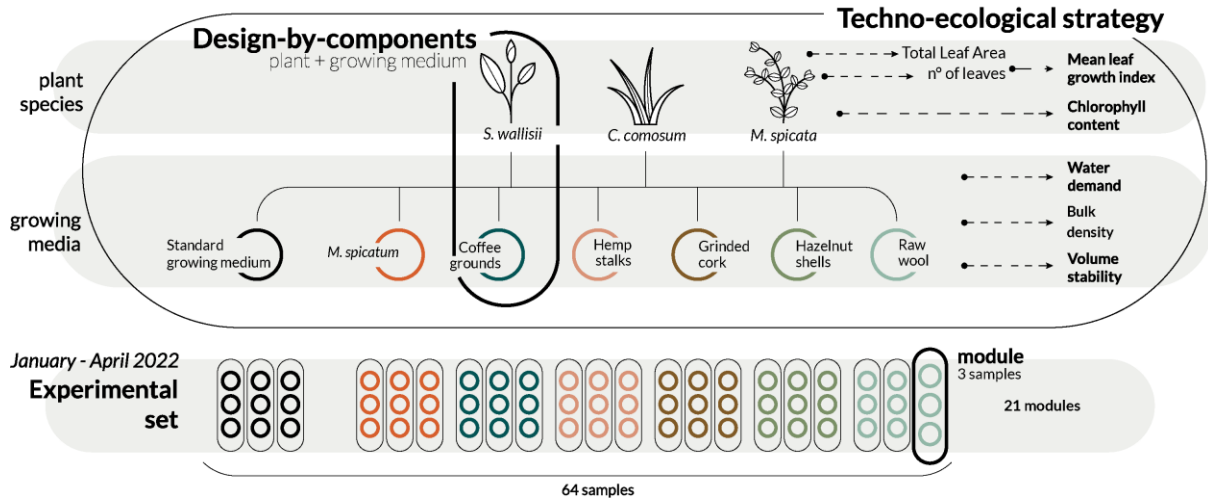
5 5 In the context of densely populated urban areas, vertical greenery systems are gaining momentum for their role in
6 6 reintroducing nature and enhancing buildings sustainability. Despite this trend, the absence of a standardised
7 7 methodology for designing sustainable vertical greenery systems and guidelines for selecting appropriate growing
8 8 media for this technology are two crucial gaps in academic research. This study addresses this by testing six
9 9 alternative growing media derived from local bio-resources (dried *M. spicatum*, hazelnut shells, coffee grounds,
10 10 hemp stalks, grinded cork, and raw sheep wool) and comparing them with a standard growing medium. The
11 11 experiment was conducted over 120 days, monitoring the health and growth of three plant species - *C. comosum*,
12 12 *S. wallisii*, and *M. spicata*. Innovative tools, such as a multi-criteria matrix and the Mean Leaf Growth Index, were
13 13 introduced to assess sustainability and plant development. The findings highlight promising outcomes for hazelnut
14 14 shells-based, hemp stalks-based, and grinded cork-based growing media, showcasing their lightweight and stable
15 15 attributes compared to standard growing medium and assuring good plants health and growth. In contrast, raw
16 16 sheep wool-based, *M. spicatum*-based, and coffee grounds-based growing media present challenges in plant health
17 17 and growth, despite interesting attributes concerning lightweight and low water demand. This research contributes
18 18 to shaping a design-by-components strategy for more sustainable vertical greenery systems, emphasizing the
19 19 crucial role of circular bio-resources in nature-based technological innovations.
20 20

21 21 **Keywords:** organic substrates, laboratory experiment, design-by-components, plant health and growth,
22 22 techno-ecological evaluation
23 23

24 **Highlights**

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

31 **Graphical Abstract**



32
33

34 1. Introduction

35 The increasing urbanisation trend causes critical environmental and social issues that compromise
36 human well-being and challenge the sustainability of cities. Urban greening is a fundamental strategy
37 that can drastically improve the liveability of current congested cities (Musa et al., 2022) and is often
38 adopted to mitigate these critical issues through *nature-inspired* strategies (Dorst et al., 2019). In the
39 framework of urban greening, vertical greenery systems (VGSs), well known as green walls, are useful
40 technology to green densely populated cities and make buildings more sustainable (Douglas et al.,
41 2021). Green walls are space-efficient systems that support the growth of plants on vertical surfaces,
42 and they present a wide range of technical solutions such as green façades and living walls (Manso &
43 Castro-Gomes, 2015). Green façades consist in the use of climbing plants growing directly on a wall or
44 indirectly on a support system (Vox et al., 2018). Instead, living walls are more complex systems that
45 provide a more uniform vegetation coverage, but they usually require frequent maintenance
46 (Gunawardena & Steemers, 2019, 2020). Living walls consist of a supporting structure attached to the
47 wall that contains growing medium and vegetation, usually classified into modular or continuous
48 systems (Perini et al., 2013). VGSs provide multiple environmental and social benefits to human into
49 the built environment (Goel et al., 2022) such as the improvement of air quality (Pettit et al., 2019;
50 Srbinovska et al., 2021), the increase of urban biodiversity (Madre et al., 2015), the reduction of noise
51 pollution, the mitigation of urban heat island effect (Susca et al., 2022), and the improvement of human
52 well-being (Chung et al., 2022). VGSs are multifunctional nature-based solutions that “protect,
53 sustainably manage, and restore natural and man-made ecosystems in order to effectively and adaptively
54 address societal challenges, and to simultaneously benefit people and nature” (IUCN, 2020). However,
55 there are no specific indications to design and produce VGSs in a sustainable way and to reduce their
56 impact on the environment.

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

80 and Mannan and Al-Ghamdi (2022) confirmed in their work the importance of considering
1 81 environmental impacts for the selection of materials and recommended for the first time the use of
2 82 organic growing media as a fundamental aspect for a sustainable design of VGSs. Particularly, Chàfer
3 83 et al. (2021a) in their comparative LCA between different typologies of VGSs suggested the application
4 84 of sustainable strategy for growing media (e.g. recycled growing media) to drastically decrease the total
5 85 environmental impacts of the whole system. Reyhani et al. (2022) highlighted the high influence of
6 86 some of the most commonly used artificial and inorganic growing media on the whole environmental
7 87 assessment of VGSs. In their work LCA was applied for the first time as a guiding tool for the design
8 88 of sustainable VGSs, suggesting the replacement of impactful artificial growing media with more
9 89 sustainable organic ones. Nevertheless, as highlighted by Chàfer et al. (2021b), material research and
10 90 optimisation for VGSs is still a major gap of research in literature. Particularly, studies on sustainable
11 91 growing media experimentation are very few. Nevertheless, relevant studies conducted by Parada et al.
12 92 (2021), Manríquez-Altamirano et al. (2020) and Manríquez-Altamirano et al. (2021) sustained that the
13 93 careful design, scientific evaluation and production of bio-resources-based growing media are pivotal
14 94 strategies for sustainable urban greening projects. In its review Koviessen et al. (2023) strongly
15 95 advocates the urgency of finding alternative substrates through the circular use of local by-products and
16 96 waste to be applied in specific nature-based-solutions and how this strategy can boost the green
17 97 transition of contemporary cities. As stated by Toboso-Chavero et al. (2021), besides the chemical,
18 98 physical and biological properties of growing media and general economic aspects, now environmental
19 99 sustainability is gaining importance in the selection of growing media. Vandecasteele et al. (2023)
20 100 sustains that developing new blends using renewable resources represents the next frontier in advancing
21 101 the sustainability of soilless horticulture. Some studies emphasised the use of organic materials as
22 102 constituents of alternative growing media such as composts, bark, wood residues and coconut coir
23 103 (Barrett et al., 2016; Gruda, 2019), generally amended to inorganic ones such as perlite, vermiculite,
24 104 calcined and expanded clay (Sabatino, 2020). In particular, circular economy has been applied for the
25 105 creation of sustainable growing media derived from industrial by-products or from agricultural,
26 106 industrial and urban organic waste (Raviv, 2013). Nevertheless, De Lucia et al. (2021) and Rivas-
27 107 Sánchez et al. (2017) are the only works that tested an agricultural by-product, such as rice husk, as
28 108 sustainable growing media for VGSs.

37
38 109 Nevertheless, the effectiveness of a growing medium in supporting plant growth is the most important
39 110 aspect to be considered to assess growing media efficacy. An alternative growing medium is promising
40 111 if it must ensure plant growth equal to or greater than the regular one (Leiber-Sauheittl et al., 2021).
41 112 Non-destructive methods adopted to assess plant growth are preferred to destructive ones thanks to the
42 113 opportunity to preserve plants and repeat measurements during the experiment (Hilty et al., 2021). Leaf
43 114 length and width, number of leaves, plant or stem height, length, volume and density of roots are
44 115 parameters usually measured to assess the growth of plant biomass (Furbank & Tester, 2011).
45 116 Moreover, leaf length and width can be used for the determination of the Total Leaf Area (TLA)
46 117 (Koyama & Smith, 2022), and these three parameters can be used to define the growth rate (Charles et
47 118 al., 2011). Other studies measure chlorophyll content through a specific instrument that provides on-
48 119 site information about plant health in a non-destructive way (Brown et al., 2022; Gottardini et al., 2014).
49 120 Applying circular economy and sustainable design thinking, the present work develops an experimental
50 121 campaign on different bio-resource-based growing media to be applied to VGSs, using organic waste
51 122 and by-products from the Piedmont Region (Italy). The main challenge of this work is that no protocols
52 123 have been defined to test the sustainability of a growing media. So, evaluation criteria for sustainable
53 124 VGSs growing media were set as follows. The work of (Alexander & Bragg, 2014) was followed to
54 125 define a multi-criteria matrix to evaluate and compare the sustainability of the alternative growing
55 126 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 & Vigandò, 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

173 as an alternative growing medium but it didn't reach any significant result (Dannehl et al., 2015). While
174 hemp stalks, the woody part of the plant stalk, is mainly used in the building sector as sound-absorbent
175 material (Cavallaro, 2015). Many studies (Woznicki et al., 2021, Escobar-Avello et al. 2023) have
176 shown good results using growing media based on wood fibres which are characterised by high total
177 porosity and air holding capacity (Maher et al., 2008) For this reason, this study tested hemp stalks as
178 an abundant and promising valuable by-product at local scale. For the present work the hemp stalks
179 were collected from a hemp farm located in Carmagnola, in the centre of the Piedmont Region (30km
180 from Turin).

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

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

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

211 Piedmont is the leading Italian region concerning wine production, from cultivation to sales (ISTAT,
212 2023c). Many wine shops and wine bars are widely diffused in the region, especially in bigger urban
213 centres (Regione Piemonte, 2021). In this framework, cork stoppers are often disposed of as waste
214 instead of treated as a resource for new supply chains. Indeed, cork presents an interesting hygroscopic
215 feature that can be helpful in vertical greening application because it supports the thermos-hygrometric
216 balance (Contreras et al., 2022). Moreover, Martinez et al. (2013) obtained promising results using a

217 cork-rice husk-based thin layer as a growing medium. Used cork stoppers were collected from two
218 winery shops in the city centre of Turin.

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

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

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

243 3. The experiment: materials and methods

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

251 3.1. Experiment preparation

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

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

263 3.1.1 Growing media preparation

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

271
272 Hazelnut shells were shredded using an electric milling machine (YM221230879, AATAY) in order to
273 obtain shell shreds of 0,5 -1 cm of length and avoid the rotting of plant roots caused by possible water
274 retention in the shell cavity after irrigation. Cork stoppers were grinded with a standard blender with
275 inox steel blades (CB-410, Horet) obtaining cork granulate of 0,3 - 1 cm of length. On the other hand,
276 fronds of *M. spicatum* required the longest pre-treatment process. After their collection from Po River,
277 fronds have been dried at room temperature (17±2 °C) for one week and then grinded with the standard
278 blender obtaining a powder-like material composed of particles ranging from 0,01 cm to 0,3 cm.

280 3.1.2 Phytotoxicity of growing media

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

293
294 (formula 1)

$$295 \quad \text{SG\%} = (\text{number of seeds germinated}) / (\text{number of total seeds}) \%$$

297 3.1.3 Physical and chemical characteristics of growing media

298 Physical characteristics of growing media was assessed by considering Dry Bulk Density (D) (g cm⁻³),
299 Total Porosity (TP) (%) and Water Holding Capacity (WHC) (%). D was measured for each growing
300 media following the method of Rai et al. (2017). This is a pivotal parameter for VGSs growing media
301 since it can strongly affect the weight of the entire system influencing the design of the anchoring system
302 (Dede et al., 2019). In fact, the use of lighter growing media would allow a lighter structural system.
303 Thus, growing media D is an important information in the design of a VGS in order to decrease weight
304 and need of materials.

305 TP was assessed for each growing media following the method of Landis (1990), while WHC was
306 determined following the Keen Raczkowski box method by Govindasamy et al. (2022).

307 The pH and Electrical Conductivity (EC) (µS/cm) were assessed to characterise chemical properties of
308 the alternative growing media (concentration of 1:2,5) following procedures in Castro Garibay et al.
309 (2019).

310

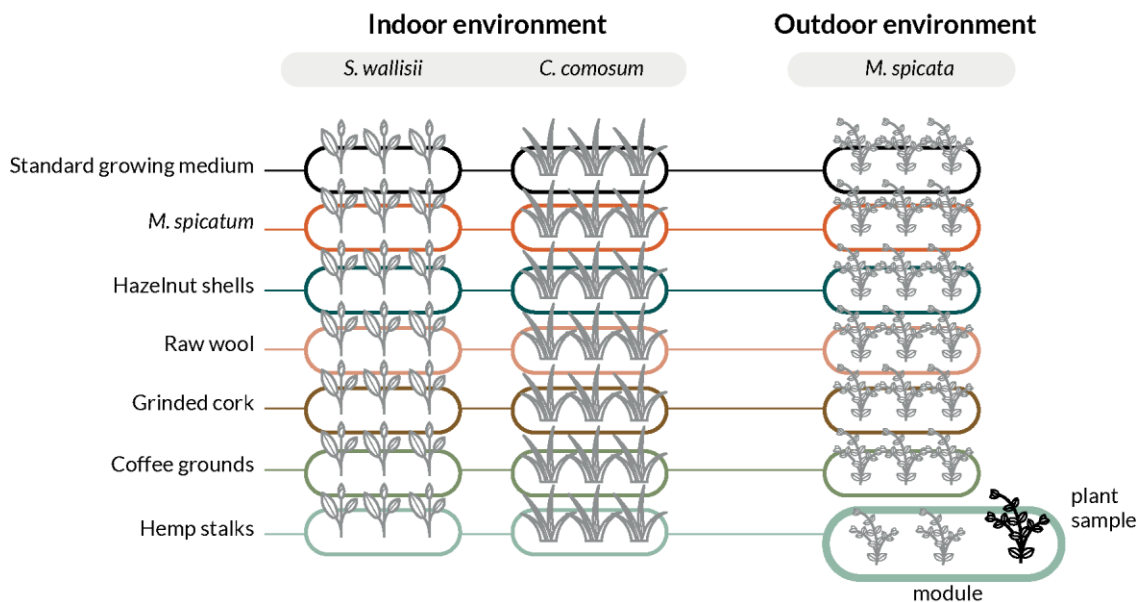
3.1.4 Plant species selection

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

343 *M. spicata* with 500 ml. An average amount of water was defined following the works of Gubb et al.,
1 344 (2018), Gabrys and Fryczkowska (2022) and De Lucia et al. (2021). Liquid fertiliser for ornamental
2 345 plants (NPK 7-5-6 with boron, copper, iron, manganese, molybdenum, zinc, potassium and iron) was
3 346 provided to all pots during the experiment setup through fertigation (20 g of liquid fertiliser in 2 l of
4 347 water).

3.2 Experiment running

350 Specific criteria were measured in order to evaluate the efficiency and sustainability of the six
10 351 alternative growing media in comparison to the one composed by growing medium (control test) for a
11 352 period of 120 days. These criteria were taken into account to obtain an overall description about growing
12 353 media characteristics and plants growth and health. Thus, criteria were divided into two groups: (1)
13 354 those referring to growing media characteristics such as humidity, water demand and volume stability,
14 355 and (2) those referring to the plants growth and health such as number of leaves, Total Leaf Area
15 356 (TLA) and chlorophyll content. Applying a sustainable design perspective, humidity, water demand and
16 357 volume stability were selected as significant information on growing media environmental
17 358 sustainability, defining water use and material duration (Vinci and Rapa, 2019). As established from
18 359 literature, number of leaves and TLA allowed the calculation of plants development, while chlorophyll
19 360 content is a reliable parameter for plant health (Paturkar et al., 2022; Dominici et al., 2021; Kakouei &
20 361 Salehi; 2013).

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

27 364 Water demand (ml per each module) was monitored as a crucial parameter to elucidate on the water
28 365 consumption of each growing media. Watering quantities were added up through the experiment in
29 366 order to obtain the water consumption for each growing media. Soil humidity was measured to regulate
30 367 the irrigation frequency. It was monitored for each of the 21 pots with a 10-point scale manual
31 368 hygrometre (T10 Bodentester, BATOU) every three days. Moreover, volume stability is a fundamental
32 369 parameter to understand the structural stability of a growing medium. More stable is its volume, less
33 370 maintenance and replacement will be required for the growing medium, decreasing waste and economic
34 371 expenses for specialised labour and disposal service. Volume stability (%) was monitored by measuring
35 372 the D of each pot at the beginning and at the end of the experiment.
36 373

3.2.2. Monitoring the plant health: chlorophyll content

41 375 Chlorophyll content (in μmol of chlorophyll per m^2 of leaf) was measured using the optical manual
42 376 metre Apogee Mc-100. Chlorophyll content sampling was performed twice per month since the focus
43 377 of the experiment was the response of plants in the long period, not at daily base (Padilla-Rivera et al.,
44 378 2020). According to Pavlovic et al. (2014) and Liang et al. (19967), chlorophyll content is commonly
45 379 used as an indicator of the plant health since it decreases in plants under stress conditions. The Apogee
46 380 Mc-100 metre is normally used in agriculture to estimate plant health of crops and provide an evaluation
47 381 of the stress condition due to the lack of nutrients, insufficient irrigation and adverse climatic conditions
48 382 (<https://www.apogeeinstruments.com>). The chlorophyll content was measured by sampling three
49 383 randomised leaves for each plant and performing five consecutive measurements per leaf.
50 384

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

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57 388 The assessment of plant growth was performed twice per month by measuring the TLA

389 following the non-destructive method proposed by Dominici et al. (2021). The method consists of
1 390 measuring manually the length and width of leaves (for each plant species) (Zhang et al., 2018) and
2 391 categorising them in four *topos* (or leaves models) based on their average leaf surface. Leaf surface was
3 392 obtained by using an AutoCAD drawing sheet where lengths and widths of each *topoi* were reproduced
4 393 through [Polylines tool] in order to obtain enclosed polyline geometries needed to define the surface
5 394 through [AREA Command]. The TLA is obtain summing the surface of the leaves that composed a
6 395 plant and is expressed by the following formula:
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10 397 (Formula 1)

$$11 398 \quad \text{TLA} = (L_1 \times W_1) + (L_2 \times W_2) + (L_3 \times W_3) \dots + (L_n \times W_n) \text{ (cm}^2\text{)}$$

12 399
13 400
14 401 L: leaf length

15 402 W: leaf width

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17 404 Monitoring the number of leaves informs about the modification of the foliage density over time and it
18 405 gives additional knowledge about the quality of plant growth (Dobrescu et al., 2017).

19 406 The TLA and number of leaves of the three plants contained in a pot (module) were used to define the
20 407 novel Mean Leaf Growth Index (MLGI):
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23 408

24 409 (Formula 2)

$$25 410 \quad \text{MLGI} = (\text{TLA}_f / \text{nl}_f) - (\text{TLA}_i / \text{nl}_i) \text{ (cm}^2\text{)}$$

26 411
27 412 TLA_i : initial total leaf area

28 413 TLA_f : final total leaf area

29 414 nl_i : initial number of leaves

30 415 nl_f : final number of leaves
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34 417 Accordingly, MLGI informed about the development of plants that composed a module of VGS.

35 418 If the MLGI is higher than 0, it means that the growth of plants followed a positive trend (increasing
36 419 both TLA and number of leaves). If the MLGI is equal to 0, it means that plants didn't grow. While if
37 420 the MLGI is lower than 0, it means that plant growth showed a decreasing trend. If the three plants
38 421 contained in a module died during the monitoring period, the MLGI has been considered null.
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43 423 **3.3 Data analysis**

44 424 A two-way ANOVA was applied to assess the effects of the seven different growing media on
45 425 chlorophyll content and TLA along the monitoring period. Therefore, two different analyses have been
46 426 carried out for the TLA (dependent variable 1) the and the chlorophyll content (dependent variable 2).
47 427 For both analysis plant species and growing media were set as independent variables, respectively with
48 428 three and seven levels. Two hypotheses were defined for each analysis:
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52 430 Null Hypothesis (H_0_1): There are no significant differences in TLA among growing media and
53 431 plant species.

54 432 Alternative Hypothesis (H_a_1): There are significant differences in TLA among growing media
55 433 and plant species.
56
57 434

58 435 Null Hypothesis (H_0_2): There are no significant differences in chlorophyll content among
59 436 growing media and plant species.
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Alternative Hypothesis (Ha₂): 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	<i>Eruca vesicaria ssp. Sativa</i>	<i>Nepeta cataria</i>	<i>Lactuca sativa</i>
Hazelnut shells	90%	90%	100%
Grinded cork	100%	100%	90%
Hemp stalks	100%	90%	100%
<i>M. spicatum</i>	90%	90%	90%
Raw wool	90%	90%	90%
Coffee grounds	90%	90%	90%

TP (Table 2) of all the alternative growing media are lower 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
<i>M. spicatum</i>	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 $\mu\text{S}/\text{cm}$) present a similar value to standard growing medium (400 $\mu\text{S}/\text{cm}$), followed by hazelnut shells-based growing media (743 $\mu\text{S}/\text{cm}$). However, hemp stalks-based (1116 $\mu\text{S}/\text{cm}$), *M. spicatum*-based (4080 $\mu\text{S}/\text{cm}$), raw wool-based (1540 $\mu\text{S}/\text{cm}$) and coffee grounds-based (2340 $\mu\text{S}/\text{cm}$) 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 ($\mu\text{S}/\text{cm}$)
Hazelnut shells	7	743
Grinded cork	7	401
Hemp stalks	6	1116
<i>M. spicatum</i>	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 g cm^{-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 – 2000; 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)		
		<i>C. comosum</i>	<i>S. wallisii</i>	<i>M. spicata</i>	<i>C. comosum</i>	<i>S. wallisii</i>	<i>M. spicata</i>
Raw wool	0,04	40	40	30	1500	1500	2000
<i>M. spicatum</i>	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 ($\alpha < 0,5$).

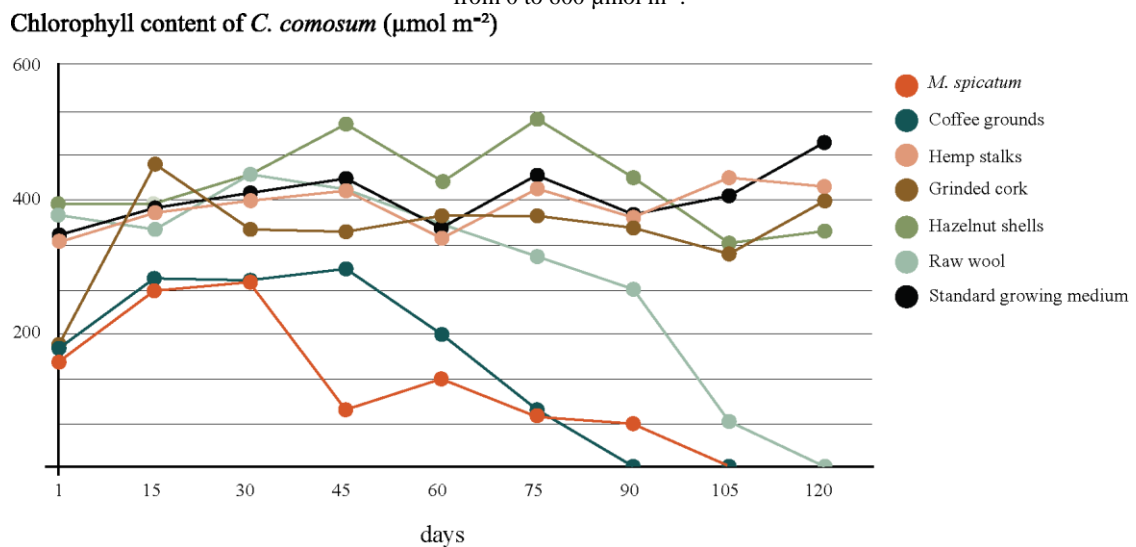
Starting with *C. comosum*, it presented a stable trend of chlorophyll content with hazelnut shells-based, hemp stalks-based, grinded cork-based growing media. Moreover, hazelnut shells-based showed a higher chlorophyll content than standard growing medium for all the experiment period, while hemp stalks-based 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

531 drastically reduced the chlorophyll content from the day 30 of experiment. Coffee grounds-based and
 1 532 *M. spicatum*-based growing media showed a reduction of chlorophyll content from the day 45.

2 533
 3 534 *S. wallisii* presented a decreasing trend of chlorophyll content for almost all growing media, including
 4 535 standard growing medium and this effect is already visible from the day 15 of the experiment period.
 5 536 Only hemp stalks-based and grinded cork-based growing media produced stable trends of chlorophyll
 6 537 content with *S. wallisii*, showing particularly higher values than standard growing medium.
 7 538

8 539 Hazelnut shells-based, grinded cork-based and hemp stalks-based growing media produced stable
 9 540 chlorophyll content trends with *M. spicata* throughout the entire experiment period and present very
 10 541 similar values to standard growing medium. While *M. spicatum*-based, raw sheep wool-based and
 11 542 coffee ground-based growing media produced a drastic reduction of chlorophyll content from the day
 12 543 30 of the experiment. Despite this, it is interesting to note that after the day 45 raw sheep wool-based
 13 544 growing medium showed a slightly but continuous increase of chlorophyll content.
 14 545

15 546 **Figure 2.** Chlorophyll content trends in *C. comosum* with the seven growing media. The x axis represents the
 16 547 days and the eight measurement days are reported. The y axis reports the chlorophyll content registered
 17 548 from 0 to 600 $\mu\text{mol m}^{-2}$.

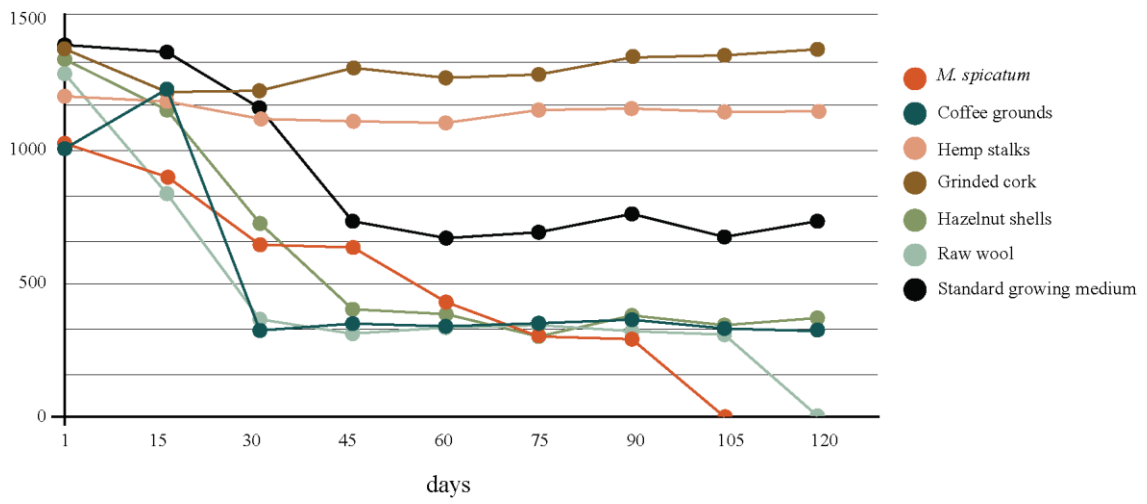


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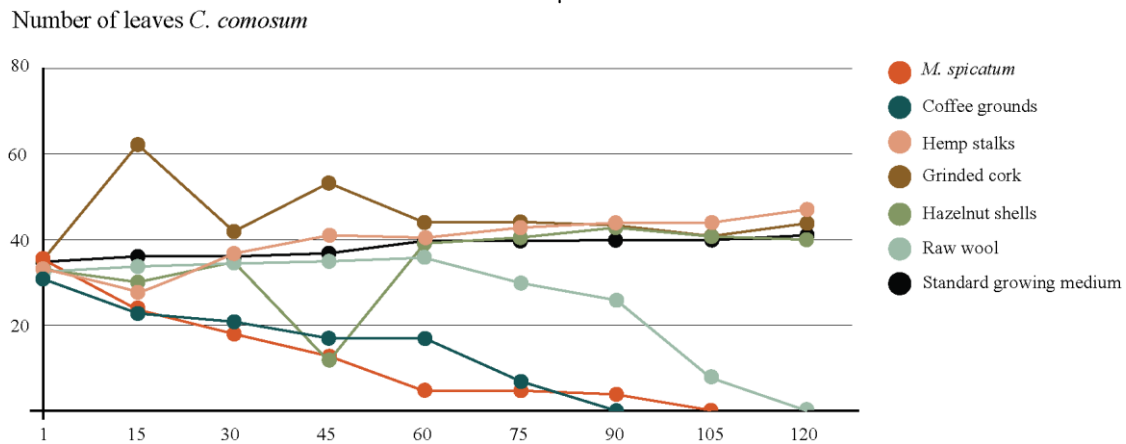
Chlorophyll content of *S. wallisii* ($\mu\text{mol m}^{-2}$)



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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 $\mu\text{mol m}^{-2}$.



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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.

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Table 5 presents the MLGI for each growing media and each plant species. All the plants set in *M. spicata*-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).

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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.

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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.

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M. spicata presented positive MLGI for almost all the alternative growing media, with just *M. spicata*-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.

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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.

	<i>C. comosum</i>				
	TLA_i (cm^2)	TLA_f (cm^2)	nF_i	nF_f	MLGI
<i>M. spicatum</i>	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
	<i>S. wallisii</i>				
	TLA_i (cm^2)	TLA_f (cm^2)	nF_i	nF_f	MLGI
<i>M. spicatum</i>	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
	<i>M. spicata</i>				
	TLA_i (cm^2)	TLA_f (cm^2)	nF_i	nF_f	MLGI
<i>M. spicatum</i>	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

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598 5. Discussion

1 599 The following sections present the results obtained from the physical and chemical characterisation of
 2 600 the growing media (5.1) and their performance according to the selected criteria for VGSs growing
 3 601 media sustainability and support in plant development (5.2).
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6 603 5.1 Optimising growing media physical and chemical characteristics

7 604 Based on the growing media physical and chemical characterization, adding 50% bio-resources to the
 8 605 standard growing medium maintains a consistent pH level suitable for floriculture. TP met acceptable
 9 606 values for all alternative growing media, except coffee grounds-based and *M. spicatum*-based, which
 10 607 barely reached the 50%. While hazelnut shells showed a similar value to standard growing medium, the
 11 608 WHC of the other alternative growing media is exceptionally high, potentially causing plant death
 12 609 despite managed watering based on humidity levels. Notably, lignin-based growing media showed the
 13 610 lowest EC. All alternatives growing media, except hazelnut shells and cork-based ones, had EC values
 14 611 exceeding 1100 $\mu\text{S}/\text{cm}$, an unacceptable result for floriculture according to Dewir et al. (2005). Results
 15 612 obtained from the characterisation are promising considering the experimental phase of these alternative
 16 613 growing media.
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22 615 5.2 Comparative analysis between alternative growing media and the standard growing 23 616 medium

24 617 The following sections discuss the results obtained by each alternative growing media with *C. comosum*,
 25 618 *S. wallisii* and *M. spicata* and compare them with standard growing medium. The results have been
 26 619 proposed in a multi-criteria matrix in order to highlight strength and weakness of each growing media
 27 620 with *C. comosum*, *S. wallisii* and *M. spicata*. Table 3 shows MLGI and chlorophyll content as indicators
 28 621 of plants growth and health, while water demand, density and volume stability referred to growing
 29 622 media technical performances. The former two criteria describe the efficiency of alternative growing
 30 623 media for herbaceous and ornamental plants, while the other three criteria are useful to assess the
 31 624 sustainability of the growing media. As shown in Table 6, the multi-criteria matrix obtained is a project-
 32 625 oriented tool since it allows easy comparisons between growing media and plant species, highlighting
 33 626 results that exceed the standard growing medium values. (Alexander and Bragg, 2014). Below the
 34 627 performances of each growing medium for each plant species are discussed.
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40 629 **Table 6.** Multi-criteria matrix showing results of each growing medium for *C. comosum*, *S. wallisii*
 41 630 and *M. spicata*. Higher values than standard growing medium are highlighted in green.
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	<i>C. comosum</i>				
	MLGI (cm^2)	Chlorophyll c. ($\mu\text{mol m}^{-2}$)	Water demand (ml)	Dry bulk density (g cm^{-3})	Volume stability (%)
<i>M. spicatum</i>	-	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%
	<i>S. wallisii</i>				
	MLGI (cm ²)	Chlorophyll c. (µmol m ⁻²)	Water demand (ml)	Dry bulk density (g cm ⁻³)	Volume stability (%)
<i>M. spicatum</i>	-	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%
	<i>M. spicata</i>				
	MLGI (cm ²)	Chlorophyll c. (µmol m ⁻²)	Water demand (ml)	Dry bulk density (g cm ⁻³)	Volume stability (%)
<i>M. spicata</i>	-	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

641 medium. Therefore, this feature negatively impacts the practical application of these organic waste
1 642 material for VGS, as it would result in a very close consumption of the bio-resource, making its
2 643 utilization a controversial decision (Six et al., 2016). However, the already mentioned exceptional
3 644 lightweight nature of the *M-spicatum*-based growing medium it's worth to consider the possibility of
4 645 blending it with another material whose characteristics could balance the high WHC of the *M. spicatum*-
5 646 based growing medium. According to these results, it is recommended to use a proportionally lower
6 647 quantity of dried *M-spicatum*.
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10 649 **5.2.2 Coffee grounds-based growing medium**

11 650 As observed in the case of the *M. spicatum*-based growing medium, the low water demand of the coffee
12 651 grounds-based growing medium is due to its high WHC, likely contributing to root rot in most plant
13 652 samples, regardless of the plant species. These findings align with those of Hardgrove & Livesley
14 653 (2016), who noted an increased WHC when coffee grounds were directly added to the soil. Additionally,
15 654 Chrysargyris et al. (2021) highlighted that the addition of coffee grounds reduced the air-filled porosity
16 655 in peat-based growing media, necessitating more moderate and frequent watering to avoid inadequate
17 656 water distribution during irrigation. Although in the conducted study this criticality was addressed
18 657 through an irrigation system guided by recorded humidity levels, the exceedingly high WHC
19 658 nonetheless made its management challenging. Therefore, it seems that the coffee grounds-based
20 659 growing medium may not be a viable alternative to standard growing medium. However, the good
21 660 performance in terms of volume stability suggests the possibility of blending it with other growing
22 661 media to balance the water retention of the coffee grounds. In light of these results, it is recommended
23 662 to use a proportionally lower quantity of coffee grounds.
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29 664 **5.2.3 Hemp stalks-based growing medium**

30 665 Physical characteristics of this alternative growing medium showed better results for most criteria than
31 666 standard growing media. Anyway, hemp stalks-based growing medium showed species-specific results.
32 667 *C. comosum* showed not promising results concerning plant growth performances. This specific result
33 668 may suggest an insufficient supply of nutrients offered by this growing medium for the plant species
34 669 tested. As discussed by Aurdal et al. (2022), wood fibre-based growing media offer physical stability
35 670 but they require additional nutrients. This aspect could negatively affect the growth of *M. spicata*.
36 671 Nevertheless, particularly good outcomes obtained in the plant growth of *S. wallisii* suggest the
37 672 suitability of the hemp stalks-based growing medium for this specific plant species, showing the highest
38 673 results of the MLGI of all samples tested. This result is in line with the low nutrient demand of *S.*
39 674 *wallisii* as highlighted by many studies (Dewir et al., 2005; Mak & Yeh, 2001). Finally, hemp stalks-
40 675 based growing medium is a promising alternative to standard growing medium for *S. wallisii*
41 676 considering the values obtained for all the five criteria of the multi-criteria matrix.
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49 679 **5.2.4 Grinded cork-based growing medium**

50 680 It showed good results regarding growing medium physical characteristics and plant biomass growth,
51 681 specifically for *C. comosum* and *S. wallisii*. In particular, *S. wallisii* showed the highest chlorophyll
52 682 content among all the alternative growing media and this result suggests the suitability of lignin-rich
53 683 materials as growing media amendments for this specific plant species (Graceson et al., 2014). Also
54 684 the high MLGI values for *C. comosum* and *S. wallisii* suggested that the good performance related to
55 685 plant growth can be due to the high porosity of the cork structure (Bozzolo & Evans, 2013), ensuring
56 686 air provision to the rooting system(Liang et al., 1996).
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688 5.2.5 Hazelnut shells-based growing medium

1 689 It had a better effect than standard growing medium on leaves growth in all the three tested plant species,
2 690 though good results for plant growth and health were noticeable only in *C. comosum*. In agreement with
3 691 results obtained by Ekbic et al. (2022), nutrients offered by hazelnut shells are particularly effective at
4 692 chlorophyll production in *C. comosum*. Moreover, the lignin content of this alternative growing medium
5 693 assures a good volume stability, thus a good air provision to the rooting system (Gruda, 2019). This is
6 694 a crucial factor in *C. comosum* growth and health (Rameshkumar, 2018). The matrix shows that hazelnut
7 695 shells-based growing medium required higher watering than standard growing medium showing good
8 696 water drainage. This characteristic also justifies the high performances in *S. wallisii* growth
9 697 (Mashinchian et al., 2017). Nevertheless, considering the water demand shown by *M. spicata* - tested
10 698 in outdoor environment - hazelnut shells-based growing medium required the same water supply than
11 699 standard growing medium suggesting similar water retention .
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16 701 5.2.6 Raw sheep wool-based growing medium

17 702 The performance of this alternative growing medium showed similar trends to those observed with *M.*
18 703 *spicatum*-based growing medium. Data presented in Table 3 indicate that this growing medium is not
19 704 conducive to supporting plant growth. The low water demand implies a high WHC of raw sheep wool-
20 705 based growing medium, potentially leading to root rot in all samples across the three plant species,
21 706 particularly in *C. comosum* and *S. wallisii* samples. Furthermore, the extremely low volume stability of
22 707 this growing medium fails to ensure a consistent structure for rooting systems. The raw sheep wool-
23 708 based growing medium gradually disintegrates into its two components after irrigation, causing a
24 709 separation between the standard growing medium and the raw sheep wool. Therefore, modifications in
25 710 the method of growing media preparation and mixing are imperative to thoroughly assess the potential
26 711 of raw sheep wool as a component for alternative growing media. Since Gabrys and Fryczkowska
27 712 (2022) did not specify the nature of the standard growing medium in their experiment, it could be
28 713 inferred that their positive results were contingent upon either the proportion of standard growing
29 714 medium and raw sheep wool used in their studies or the distinct performance of dust wool owing to its
30 715 unique physical characteristics. Nevertheless, the high lightness of raw sheep wool and its WHC hold
31 716 promise for vertical greening applications, suggesting the potential for mixing it with other materials to
32 717 balance detrimental water retention and stabilize the volume structure. According to the obtained
33 718 results, as for *M.spicatum* and coffee grounds, it is recommended to use a proportionally lower quantity
34 719 of raw sheep wool to undertake further experiments.
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41 720 42 721 6. Conclusions

43 722 The study reveals promising results for hazelnut shells-based and cork-based growing media with *C.*
44 723 *comosum* and *S. wallisii*, as well as hemp stalks-based growing medium with *S. wallisii*, outperforming
45 724 the standard potting soil. These findings position them as potentially sustainable alternatives for VGSs.
46 725 The positive outcomes support the use of lignin-rich materials as amendments for the tested plant
47 726 species, offering crucial insights for exploring similar bio-resources in diverse geographical contexts.
48 727 Notably, grinded hemp stalks emerge as a particularly promising bio-resource, requiring no pre-
49 728 treatment before integration with standard growing media, making it readily applicable for local-scale
50 729 production of sustainable growing mediums. However, all alternative growing media exhibit superior
51 730 volume stability, lightweight and low water consumption compared to the standard growing medium,
52 731 making them intriguing options for creating VGSs with lowered environmental impact.

53 732 The presented multi-criteria matrix serves as a foundational description of alternative growing media,
54 733 urging further enrichment with additional properties and preliminary steps for comprehensive
55 734 evaluation and validation. The matrix is aligned with sustainable design thinking and circular
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735 bioeconomy principles. It aims to guide decision-making in the VGS design process and can be adapted
1 736 for various geographical contexts through collaboration between academia and practitioners.
2 737 For what concern the limits of the study, further exploration, suggesting varied material mix
3 738 percentages, are recommended. In particular, chemical and biological tests are deemed necessary for a
4 739 comprehensive characterization of these alternative growing media. Moreover, future studies should
5 740 focus on evaluating nutritional values and other chemical properties to identify key nutrients for plant
6 741 growth and facilitate appropriate fertigation strategies.
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10 743 The study underscores the potential for creating a novel supply chain based on circular bioeconomy
11 744 principles, particularly in the Mediterranean region and other areas abundant in the bio-resources tested.
12 745 It emphasizes the need to prioritize growing media to enhance the sustainability of VGSs and nature-
13 746 based solutions at large, positioning them as increasingly prevalent systems.
14 747 The proposed methodology, integrating sustainable design thinking, circular bioeconomy principles and
15 748 laboratory experimentation, is advocated as a tool to identify sustainable alternatives to standard
16 749 growing media. Regional or national implementation of this strategy requires collaborative efforts
17 750 involving local companies, research centres, universities, architects, and landscape designers to
18 751 establish a sustainable production system for VGSs growing media based on localized bio-resource
19 752 valorisation. At the end, the study suggests conducting an environmental life cycle assessment for each
20 753 growing medium to deepen understanding and guide strategies for further enhancing the sustainability
21 754 of VGS design.
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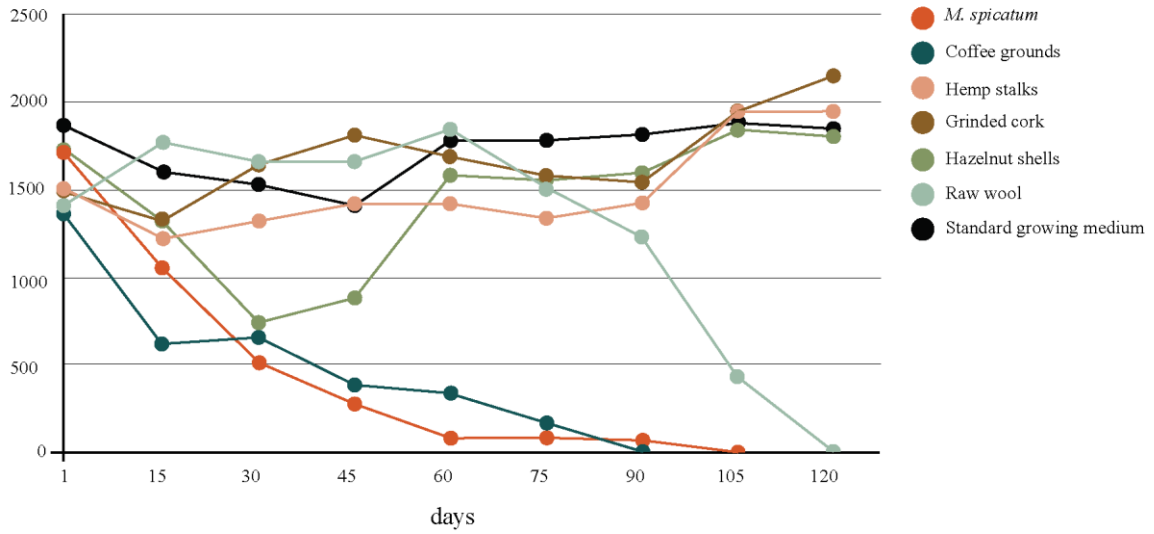
1146 **Supplementary materials**

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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.

TLA of *C. comosum* (cm²)

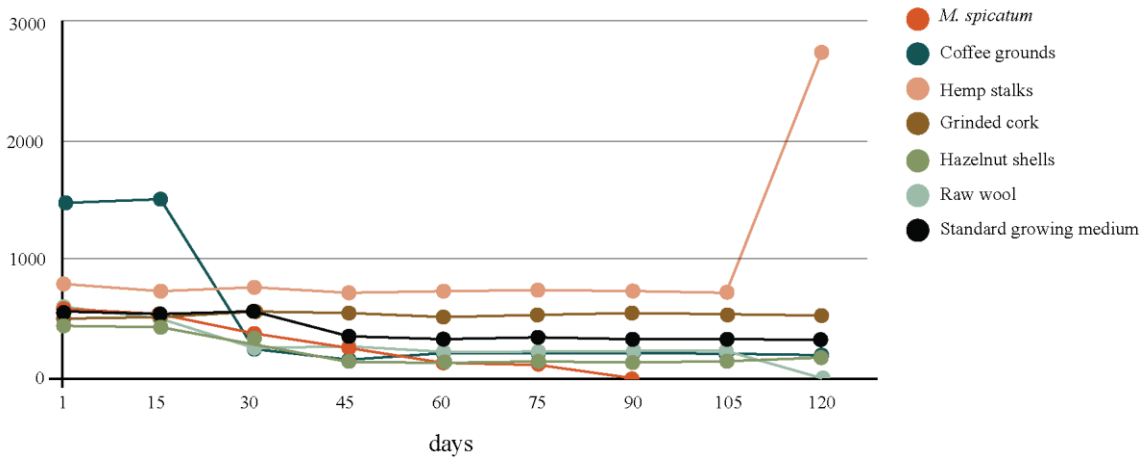


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Supplementary Figure 2. TLA trends in *S. wallisii* with the seven growing media.

The x axis represents the days and the eight measurement days are reported.

TLA of *S. wallisii* (cm²)



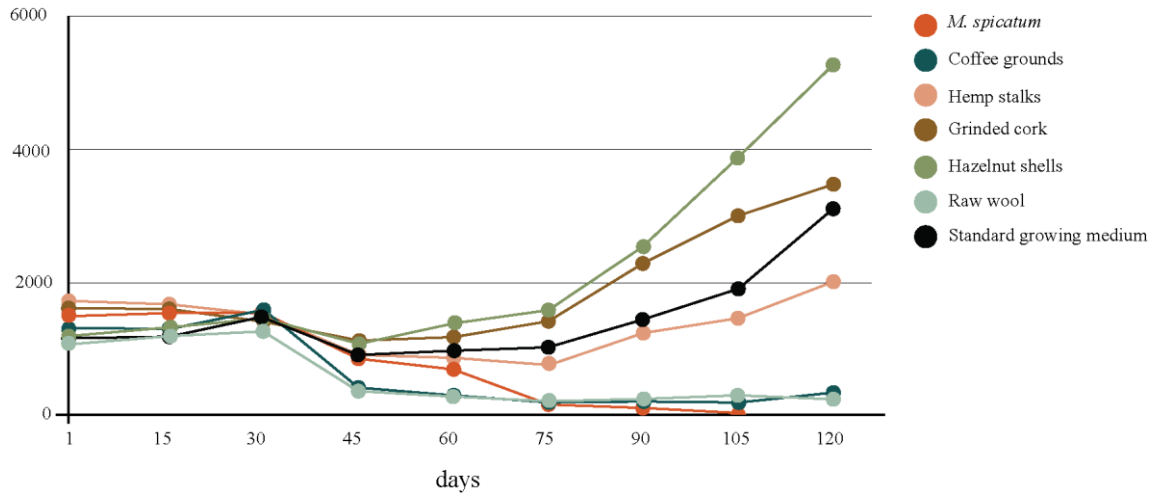
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Supplementary Figure 3. TLA trends in *M. spicata* with the seven growing media.

The x axis represents the days and the eight measurement days are reported.

TLA of *M. spicata* (cm²)

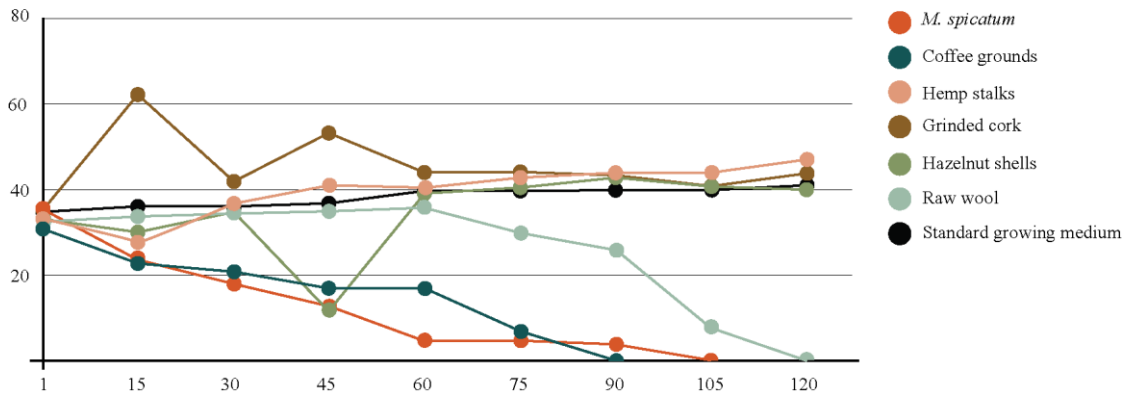


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Supplementary Figure 4. Number of leaves trends in *C. comosum* with the seven growing media.

The x axis represents the days and the eight measurement days are reported.

Number of leaves *C. comosum*



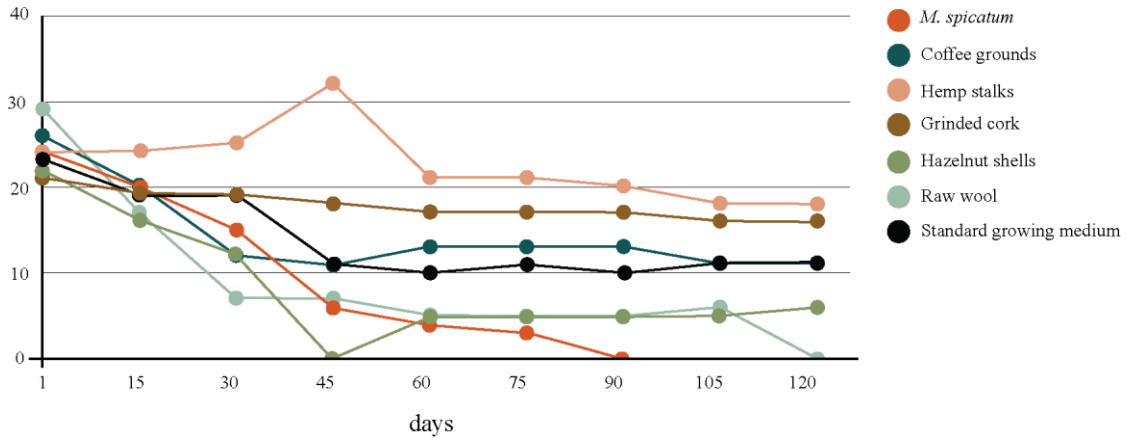
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Supplementary Figure 5. Number of leaves trends in *S. wallisii* with the seven growing media.

The x axis represents the days and the eight measurement days are reported.

Number of leaves *S. wallisii*

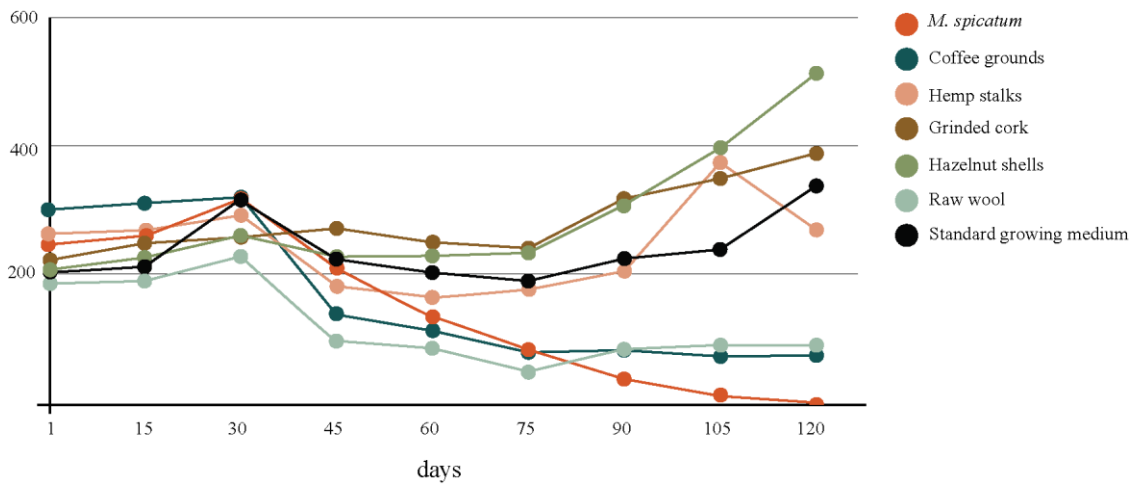


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Supplementary Figure 6. Number of leaves trends in *M. spicata* with the seven growing media.

The x axis represents the days and the eight measurement days are reported.

Number of leaves *M. spicata*



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