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1 **A novel vertical greenery module system for building envelopes: the results and outcomes of a**
2 **multidisciplinary research project**

3
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14
15 **Keywords** Vertical greenery modular system, Green wall, Green façade, Living wall system, Energy
16 performance, Environmental performance, LCA, Acoustic performance, LAI, Vegetation species, Building
17 envelope.

18
19 **0-abstract (max 200 words)**

20 Vegetation in architecture can be considered a proper design strategy that is aimed at improving not only
21 the performances of buildings, but also the outdoor climate. Different technological solutions have been
22 proposed over the years to cover buildings with vegetation, i.e. green roofs, green walls and green balconies.
23 A particular typology of green wall, which has recently been gaining high consensus among designers, is
24 the vertical greenery modular system (VGMS). The positive impact of this type of technology on the
25 performance of buildings is related to several factors, such as the façade orientation, the use of the building,
26 climatic conditions, the type of plants, the substrates and wall assemblies, as well as mechanical and
27 technological issues. A multidisciplinary approach is therefore needed, and different skills have to be joined
28 together right from the early design phase in order to optimize and balance all the aspects that are involved.
29 In this framework, a research project has been carried out in Turin (North West Italy), with the aim of
30 developing a novel VGMS, constituted by a modular box covered with vegetation, made up of
31 recycled/natural and highly performing materials from the energy/environmental point of view. After the
32 design phase, the actual performance of the VGMS was assessed, through laboratory and long-term in field
33 monitoring, and at the same time, the technological issues, biometric parameters, and the acoustic, thermal
34 and mechanical aspects were investigated.

35
36 **1- Introduction**

37 Urban greening provides ecosystem services, and the role of green areas for the well-being of citizens is
38 acknowledged throughout the world [1]. The positive effects of urban vegetation are also important at the
39 built environment microclimatic performance level, due to climate change and pedestrian thermal comfort
40 reasons [2]. The urban environment is characterized by particular conditions, in terms of light, water and
41 nutrient supply, as well as particular temperature and pollution regimes. These aspects can represent a
42 drawback for the development of plants and trees, especially if the purpose is to create urban greening with
43 high aesthetic performances. Nevertheless, green roofs and green walls are the best examples of the extreme
44 relationship between nature and technology in urban greening [3].

45 Outdoor vegetation applied to the building envelope has proved to be able to positively improve the
46 performances of buildings and urban environmental quality [4]. The subject of green infrastructures is
47 related to various topics – such as buildings, plants, substrates and technology - and its impact on buildings
48 and the city should be considered multidisciplinary, since it covers various aspects, such as energy
49 performance, acoustics, air quality and environmental aspects [5]. Furthermore, different solutions can be

50 adopted, and different effects can be pointed out for each of them, nevertheless, a lack of a common
51 terminology has been found in literature [6]. Among the various types of green façades, Living wall systems
52 (LWS), are known to be expensive technological systems in which the choice of the right plant and its
53 management are crucial for client satisfaction. However, only a few xerophytic and well adapted species
54 are able to survive spontaneously on vertical surfaces [7,8].

55 A recently published research has summarized the last 23 works on the subject, between 1988 and 2015,
56 and has introduced the term vertical greenery system (VGS) [9]. A sub-category of VGS is the vertical
57 greenery modular system (VGMS), where a modular technological box is designed in order to provide a
58 good site for rooting, as well as a suitable amount of water and nutrients for the plants to grow.

59 This kind of technological solution is able to provide different beneficial effects: during the cooling season,
60 thanks to the shading effect of the leaves and the evapotranspiration of the plants, the entering loads are
61 lowered [10], while, during the heating season, it can contribute to reducing heat losses and improving
62 surface thermal resistance, because of the wind reduction in the vicinity of the wall [11,12], to increasing
63 the sound insulation of the wall [13,14] and reducing the environmental impact of the buildings [15–17]. At
64 an urban level, VGSs are able to filter pollution [18], to sequester CO₂ [19], to reduce urban sound
65 propagation [20–22], to give a pleasant aesthetical aspect to a building, to improve the bio-diversity [23]
66 and to mitigate the urban heat island effect (UHI) [24,25].

67 The species used in outdoor living walls vary to a great extent, depending on the location, on the exposure
68 to the sun and wind and on the height of the building [26]. Studies on the use of edible species, evergreen
69 perennials and Mediterranean shrubs have been performed in Sweden and in Italy [27 and 28]. Apart from
70 these studies, very little research has been focused on the analysis of the substrate [26,29] or on the role of
71 the growing media on root and aboveground plant growth [30]. A synthesis table of the different parameters
72 that influence the energy performance of greenery on energy consumption has been reported in a review
73 paper (table 4 in [31]). For these reasons, the interest in this kind of technology, applied to vertical walls,
74 has been growing in the last few years, and the biomimetic principles of plants have been studied in order
75 to inspire new façades based on adaptive performances [32].

76 In this framework, a research project on a novel Vertical Greenery Modular System (VGMS) has been
77 carried out in Turin (North West Italy, Lat. 45° N). The developed system has been investigated
78 experimentally by evaluating different kinds of vegetation species, substrates and technological systems. A
79 multidisciplinary approach has been used, by a mixed work group composed of partners with different skills,
80 to optimise the performance of the VGMS prototypes. The first experimental results, which were only
81 related to thermal aspects, were published in Bianco et al. [12]. The entire project is presented in this paper.
82 First, details are given on the design phases, which were followed in a cascade process. The methodologies
83 that were adopted and the results that were obtained, through lab and long-term in-field monitoring, related
84 to the biometric, thermal, acoustic and mechanical performances, are then discussed, and the technological
85 issues that have arisen are mentioned.

86 **2- The GRE_EN_S project methodology: a multidisciplinary approach from the technology to the** 87 **performance**

88 GRE_EN_S (GREen ENvelope System) is the acronym of an EU research project that was aimed at
89 designing, prototyping and monitoring an innovative VGMS, constituted by modular boxes, covered with
90 vegetation, made of recycled/natural materials and characterised by a high energy/environmental
91 performance.

92 The adopted process was aimed at optimising the performance and the technical/economic viability of the
93 system, considering the manufacturing, on-site assembling and maintenance stages.

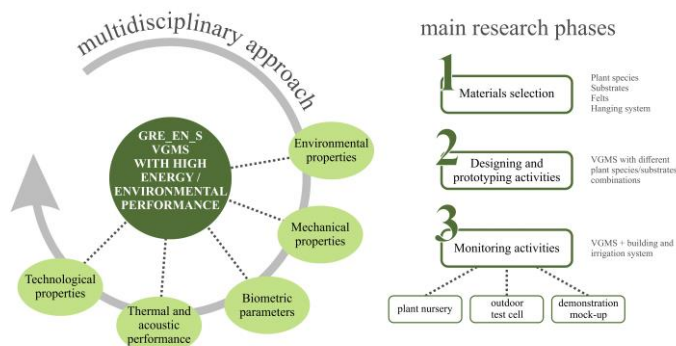
94 The challenge of this project was to design an advanced LWS, that would be highly performing from the
95 energy, acoustic and agronomic points of view, and which would be easy to install and maintain and, at the
96 same time, be cost effective. Given the modularity of the façade, this LWS is a Vertical Greenery Modular
97 System (VGMS). As far as the high energy efficiency is concerned, both the operational energy (heating
98 and cooling demand reduction) and the embodied energy were taken into account. A key factor was the low

99 environmental impact of the chosen materials and of the developed system. The project was carried out by
 100 a multidisciplinary group of researchers (from the Department of Architecture and Design and the
 101 Department of Energy – at the Politecnico di Torino, from the Department of Scienze Agrarie, Forestali e
 102 Alimentari (DISAFA) - at the University of Turin and from INRiM, Torino) in co-operation with small local
 103 companies with expertise in modular prefabricated construction, waste material recycling and natural
 104 textiles for plant growth (CEIT, 13 Ricrea, Safi-tech, respectively).

105 A complete picture of the project is given in this paper, as presented in Fig. 1. The design phase, its
 106 implementation in a VGMS prototype and the main results obtained during the experimental campaign are
 107 presented. A multiscale approach was adopted. The new technology was investigated from a complete
 108 perspective, and at two different scales: at the material/component level and at the system level. The
 109 experimental activity was thus carried out in a laboratory, in an outdoor test cell facility and in a full scale
 110 demonstration mock-up.

111 The main results, which were presented and discussed in the different sections of the work, were aimed at:

- 112 - driving the decision during the VGMS design phase with a Life Cycle Assessment (LCA) of the
 113 considered materials (section 3.1);
- 114 - characterising mechanical performance of the technological support in the laboratory (section 3.2)
 115 to identify the limits and potentials of the textile that was to be adopted (durability and mechanical
 116 resistance aspects vs hydraulic conductivity, which had to be guaranteed in order to ensure the
 117 biological functions of the plants);
- 118 - evaluating the biometric parameters of the plants, the influence of different plant species and
 119 substrates in both the plant nursery and in outdoor applications (test cell and demonstration mock-
 120 up) (section 3.3) to test their adaptability to the real application conditions;
- 121 - assessing the acoustic performance (section 3.4.1 and 3.4.2) and the thermal behaviour (section 3.5)
 122 of the VGMS at the system/building level, for different plant species and substrates;
- 123 - highlighting the technological issues that arose during the prototyping and installation (section 3.6).



124
 125
 126 *Fig. 1. Sketch of the GRE_EN_S project methodology: a multidisciplinary approach from the technology*
 127 *to the performance*

128
 129 **2.1 Selection of the VGMS features and materials**

130 In order to produce a suitable design and make the manufacturing of the GRE_EN_S module possible, two
 131 types of preliminary analyses were performed, and two related databases were developed. The former was
 132 carried out in order to conduct a comparative analysis of the different kinds of VGMS. Several parameters
 133 were considered and collected in detailed “Product_datasheets”. The latter was developed in order to select
 134 suitable materials, and the data was then inserted into “Material cards”.

135 Each “Product_datasheet” was divided into two-parts:

- 136 - Part 1 – “Technical data and performance data” section, which provided information on the
- 137 technical features, materials and product performances (sizing, weighing, water consumption, plant
- 138 species, plant number per square meter, type of substrate, etc.).
- 139 - Part 2 – “General information” section, which provided information on the architectural design
- 140 solutions, as well as detailed drawings and pictures taken of the selected buildings. Such information
- 141 was useful to obtain a better understanding of the morphological aspects (such as the technological
- 142 integration of the various features with the building envelope etc.). Records on the location were
- 143 also included, in which information about the manufacturing site was provided (Italy, Europe, non-
- 144 European Countries).

145 The “material cards” were characterized according to a Life Cycle Approach [33]. Each “material card”
 146 included environmental information about: the country of origin and the availability of the materials on the
 147 local market (in order to assess the transportation impact); the embodied energy and carbon dioxide
 148 equivalent emissions (to evaluate the depletion of the energy sources and the related climatic changes); the
 149 end of life scenarios (to assess the recycling potential); environmental labeling (when available). On the
 150 whole, 35 material cards were developed from the large amount of information that was available in
 151 databases and software [34].

152 The “Product datasheet” and “Material cards” provided detailed knowledge about both the technological
 153 connections and the most suitable materials to be used in GRE_EN_S VGMS.

154 The above-mentioned databases proved to be useful tools for the subsequent phase, related to the design
 155 and manufacturing of the prototypes.

156

157 2.2 Details on the design, prototyping and materials of the GRE_EN_S VGMS

158 The design of the VGMS is presented in this section, and the manufacturing phases, the material selection
 159 and the fixation system are described.

160 VGMS design and implementation in prototypes

161 A first selection of suitable environmentally friendly materials and building system connections was made
 162 on the basis of the product database and the material cards. The materials that were originally selected were
 163 evaluated by the companies themselves, on the one hand in terms of availability on the local market, and on
 164 the other in terms of manufacturability in accordance with their production technologies. The need to meet
 165 the workability and environmental requirements led to a limited final number of materials, which were
 166 eventually picked and tested on the prototypes.



167

168 *Fig. 2. Manufacturing of the final prototype. Fig. 2a) Outer layer of the VGMS (recycled polypropylene).*
 169 *Fig. 2b) Placement of the inner layer (growing medium) of the VGMS. Fig. 2c) Modular box of the VGMS*
 170 *with pockets where the plants were to be inserted.*

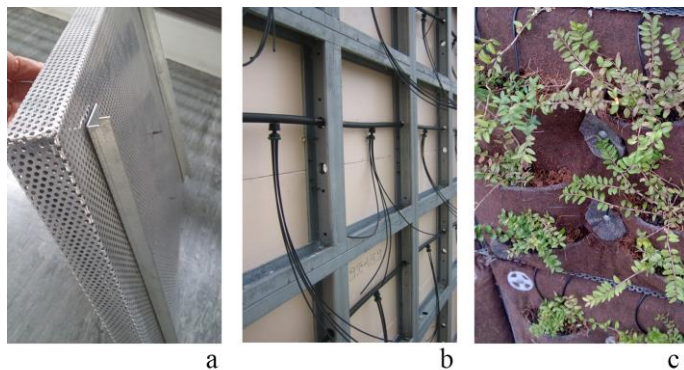
171 After two prototypes had been proposed, both of which showing some problems from the technological
 172 point of view, a third prototype was developed, and was then fully characterised through extensive

173 experimental activities. This third prototype (Fig. 2) was made up as follows: 1) aluminium alloy was used
174 as the frame 2) a polypropylene monofilament double geomat-grid was used as anchorage for the roots; 3)
175 a growing medium, based on standard substrate felt-pad wastes and coconut peat, was inserted 4) a recycled
176 polypropylene material and a nonwoven viscose fabric were used as UV resistant and water absorption
177 layers, respectively.

178 The selection of the materials was carried out on the basis of the LCA results (see section 3.1). In order to
179 assess the environmental burdens of the materials, and to choose those with the lowest energy and
180 environmental impact, the Embodied Energy (EE) and the Embodied Carbon (EC) indicators were
181 considered as being the most effective in the design stage.

182 Six pockets were cut out of each modular box to house the substrates and one plant each. The VGMS was
183 studied and set up in order to be hung on a metal frame connected to the wall with inserts and anchorages
184 placed on rubber thermal breaks (Fig. 3). These reverse assembling connections make it possible for the
185 modular box to be substituted, in the case of plant disease.

186



187

188 *Fig. 3. The reverse assembling connections made up of metal brackets for the anchorage of the modular*
189 *box to the metal frame (left); the metal frame with the integrated irrigation system (centre); the modular*
190 *box with plants (right).*

191 Once the modular box features had been determined, a further research was conducted, focusing on reducing
192 the environmental effects of some of the originally selected materials, such as: aluminum alloy; plastic
193 materials; Super Absorbent Polymers (SAP). Two scenarios were characterized. The former -
194 standard/reference scenario – referred to the primary raw materials used to manufacture the modular box;
195 the latter - recycling scenario – referred to the secondary raw materials that were used (see section 3.1).
196 Some important assumptions (e.g. plant species; composition of the growing medium etc.) were made for
197 the comparative analysis, according to the results that were reached related to the choice of plants and to the
198 experimental test that had been carried out in the nursery , and which are discussed hereafter.

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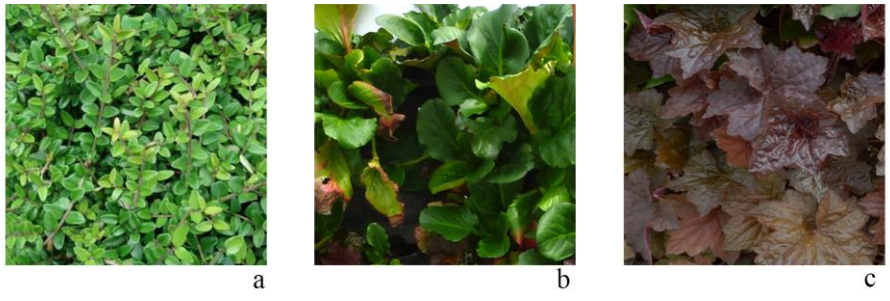
200 Vegetal species

201 Three evergreen and perennial shrub species were selected for the prototypes, on the basis of research that
202 had been carried out previously by the partners DISAFA (Fig. 4):

- 203 - *Lonicera nitida L.*: a common species for living walls with small leaves (1 cm – 1.5 cm) and small white
204 flowers. This species is able to provide a good cover effect, and should preferably be adopted in sunny
205 exposition conditions; it needs to be pruned once a year and requires only limited maintenance.

206 - *Bergenia cordifolia* L.: a species that had not been tested previously on living walls and is characterized
 207 by large, thick greenish-purple coloured leaves and pink flowers. This is also a low maintenance hardy
 208 species.

209 - *Heuchera* hybr. 'Red purple': a species with medium sized leaves and a bronze – dark purple colour,
 210 which requires higher maintenance and can be affected by pests.
 211
 212



213
 214 *Fig. 4. Plant species: Lonicera nitida (left), Bergenia cordifolia (centre), Heuchera hybr. 'Red purple'*
 215 *(right).*

216 Substrates

217 Starting from a standard substrate, named SS (registered by Reviwall®), composed of coconut fibre+hydro-
 218 retainers+mycorrhizae, different solutions were investigated and a material that was able to reduce the
 219 weight of the system, and act like hydro-retainer, was added to the growing material. Chair felt pads and
 220 viscose, derived from a local industrial residue, were added to the standard substrate for this purpose. Six
 221 alternative substrates were evaluated, and their compositions are reported in Table 1.
 222

223 *Table 1. Description of the tested substrates.*

Substrate name	Composition	
SS	coconut fibre+hydro-retainers+mycorrhizae	
SF50	50% coconut fibre + 50% shredded felt	
SF50B	50% coconut fibre + 50% shredded felt, with layers of whole felt as the structural tissue	
SF100	100% shredded felt	
SSV	SS + Viscose layer	
SF50V	SF50 + Viscose layer	

225

226 Irrigation system

227 An automatic irrigation system was integrated and used during the experimental activity, as described in
228 sections 2.3.1, 2.3.2 and 2.3.3.

229 A micro-drip was provided for each level of the green modules. During the summer season, the modules
230 were irrigated every 2 hours for 2 minutes, while no irrigation was provided to the plants during the winter
231 season.

232 **2.3 Nursery, test box and demonstration building as tools for the performance assessment**

233 As far as the performance assessment of the VGMS realized within the GRE_EN_S project is concerned,
234 extensive monitoring campaigns were carried out in Turin (North West Italy, Cfa, sub continental temperate
235 climate, according to the Köppen climate classification). Different measurements were performed: in a
236 nursery, to assess the biometric parameters; in a laboratory, to test the mechanical and acoustical properties
237 of the materials used as supports or as growing media; in an outdoor test cell, to identify the best
238 configuration of species and substrates, as far as the technological, agronomical and thermal performance
239 issues were concerned; in a demonstration mock-up, in order to confirm the previous results and to test the
240 behaviour of the VGMS in a full-scale application.

241 **2.3.1 The plant nursery activities**

242 One important phase of the project was the testing of different combinations of species and substrates to
243 decide which should be adopted in the VGMS. The use of alternative and eco-compatible inert materials to
244 replace coconut fibre in living wall media was evaluated. The previously described evergreen and perennial
245 shrub species were compared in order to choose the most suitable combination plant-substrate. As explained
246 in the next 3.3 paragraph a randomized trial was assessed (Fig. 5). The species were chosen on the basis of
247 their low maintenance costs (low water and pruning requirements) and pest resistance in a Northern Italian
248 urban context [28].

249



250

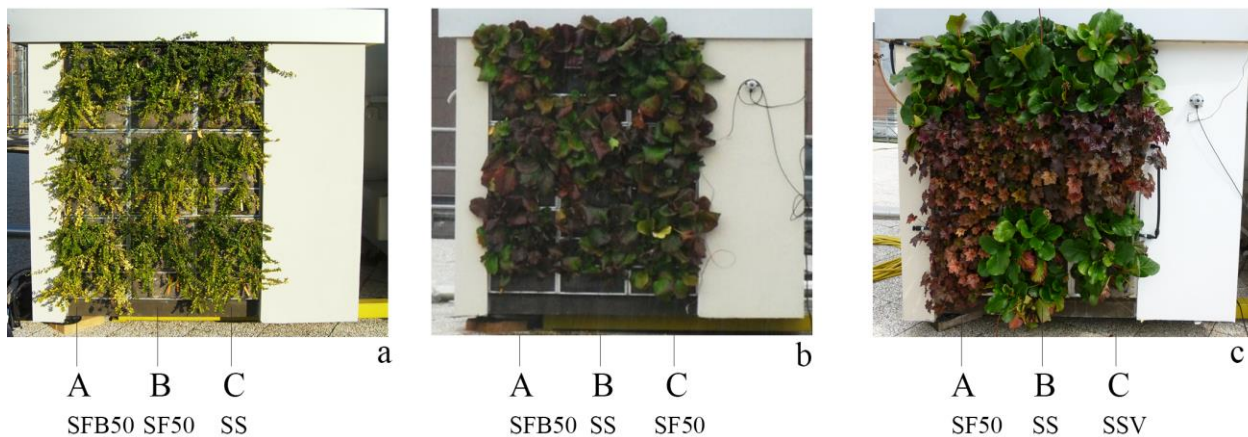
251 *Fig. 5. Examples of the experimental trials in the nursery: left) trial 1 with Lonicera nitida and Bergenia*
252 *cordifolia; right) trial 2 with Lonicera nitida and Heuchera hybr 'Red purple'.*

253

254 **2.3.2 The outdoor test cell activities**

255 In order to easily evaluate and compare the different VGMS prototypes and species/substrate combinations,
256 an ad-hoc outdoor test cell (2 x 1.8 x 1.8m) was built on the rooftop of the Energy Dept. (Politecnico di

257 Torino). This cell allowed the agronomical and thermal performance of the vegetated module to be assessed
 258 after being exposed to real boundary conditions, as well as data to be collected through a continuous long-
 259 term monitoring. The test cell had a South facing wall (2x1.8m), divided into two parts: one part of the wall
 260 was covered with VGMS, constituted by nine vegetated modules, and the other conventionally plastered
 261 part, was considered as the reference wall. The green wall was equipped with 9 VGMS, arranged in 3 lines
 262 with 3 modules each (Fig. 6). The measured data were only recorded for the central modules, in order to
 263 avoid boundary effects. The test cell was made with a conventional 20 cm thick envelope (described in
 264 Table 1 of [12]), with a thermal transmittance of 0.3W/(m² K), in accordance with the current national and
 265 regional standard related to energy efficiency in buildings. As shown in Fig. 6, different plants species, that
 266 is, *Bergenia cordifolia*, *Lonicera nitida* and *Heuchera* hybr. ‘Red Purple’, and different substrates were
 267 tested. The letters A, B and C were used to name the columns of the different substrates of the VGMS.
 268 During the winter period, the indoor temperature in the test cell was kept constant by means of an oil
 269 radiator, while no temperature control system was present during the summer season. The test cell was
 270 equipped with a monitoring system that continuously recorded data on the temperatures, heat fluxes and
 271 solar radiation (for more details see Bianco et al. [12]). An automatic irrigation system was installed to water
 272 the plants.



274 Fig. 6. Outdoor test cell with *Lonicera nitida* (left), *Bergenia cordifolia* (centre) and *Heuchera* hybr. (right). The
 275 positions of the different substrates are indicated.

276

277 2.3.3 Real-scale demonstration mock-up

278 After one year of measurements in the test cell, a real-scale demonstration mock-up (2.5m x 4 m x 2.9 m)
 279 was set up in Turin. This demonstration structure consisted of two separate building modules, as shown in
 280 Fig. 7:

281 -VGMS building module, with the three façades covered completely with the specifically developed novel
 282 VGMS (the entrance, with a glass door, was on the west façade);

283 - reference building module, which was finished with wood cladding, and represented the benchmark.

284 The demonstration mock-up structure was prefabricated and supplied by one of the project partners. The
 285 demonstration building module envelope with the VGMS was constituted by: plasterboard (1.2 cm), an XPS
 286 panel (5 cm), an XPS panel (3 cm), an air cavity (5 cm) and a VGMS module (4 cm). The reference building

287 walls were constituted by: plaster (1.2 cm), an XPS panel (8 cm), an XPS (Extruded Polystyrene Foam)
 288 panel (3 cm), an air cavity (5 cm) and the wooden cladding (1.8 cm). The two assemblies had different
 289 insulation thicknesses which, on the basis of the previous results obtained on the test cell, would have made
 290 the thermal transmittance of the two vegetated and non-vegetated walls equivalent, thus fulfilling the U-
 291 value limit imposed by national regulations for the climate in Turin. The location of the demonstration
 292 mock-up structure was based on previous studies that took into account various environmental aspects, such
 293 as the orientation and prevailing wind. The demonstration building was thus located in an area with an east-
 294 west axis orientation, in order to study both the foliage development and the thermal performance under
 295 extreme conditions (North vs. South Façade; summer time vs. winter time in temperate climates). The indoor
 296 environment temperature was only controlled during the heating season, by means of radiators, while the
 297 indoor temperature was free running during the cooling season.

298



299

300 *Fig. 7. Demonstration mock-up.*

301

302 **3- GR_EN_S performance characterisation**

303 In order to characterise the VGMS performance, both laboratory measurements and in-field measurements
 304 were carried out, in order to analyse the properties of the system at both the material level and at the
 305 component scale. The different measurements and variables, which are presented in detail in the paper, are
 306 synthetically presented in Table 2. The methodology developed for each topic, the performance metrics
 307 used to analyse the behaviour and the main obtained results are described in the following section. A cascade
 308 process was applied, in which the solutions presenting the poorest performances, from the technological and
 309 agronomic points of view, were discarded. The prototype resulting from the best compromise among the
 310 different investigated aspects was adopted in the demonstration mock-up.

311 *Table 2. Synthesis of the VGMS characterisation.*

Parameter	Test	Specimen	Aims
LCA		<i>Lonicera nitida</i> + Functional Unit - one square meter of modular box	Comparison between reference scenario/standard and

recycling scenario			
Mechanical properties	Laboratory	Polymer-based fibrous materials	Elastic response of the felt support/Air permeability
Biometric parameters	Nursery + test cell + demonstration mock-up	Plants (<i>Lonicera nitida</i> , <i>Bergenia cordifolia</i> and <i>Heuchera</i> hybr. 'Red Purple') + substrates (SS+SF50, SF50B, SF100, SSV, SF50V)	Monitoring of the plant growth and quality of the green cover for different kinds of substrates
Acoustic properties	Laboratory	Plant leaves (<i>Lonicera nitida</i> , <i>Bergenia cordifolia</i> , <i>Heuchera</i> hybr. 'Red Purple') + SS+SF50+ GMS module	Acoustic sound absorption
Acoustic performance	Demonstration mock-up	<i>Lonicera nitida</i> , SS	Sound insulation
Thermal performance	Test cell + Demonstration mock-up	<i>Lonicera nitida</i> , <i>Bergenia cordifolia</i> and <i>Heuchera</i> hybr. SS +SF50	Equivalent thermal conductance and transmittance / Surface temperature and air cavity temperature – daily energy for heating – indoor air temperature

312 3.1 Life Cycle Assessment (LCA) of the adopted materials

313 As mentioned in section 2.1, an LCA was adopted as a decision-making tool for the GRE_EN_S
314 development (or for the prototyping implementation) and as a strategic tool for both the energy and raw
315 material optimization and for the greenhouse emission reduction, with particular reference to CO₂ equivalent
316 (CO₂eq) emissions [33].

317 A 100 year Global Warming Potential (kg CO₂eq) time-horizon was assumed as the environmental effect
318 in order to assess the interaction between the modular box in its off-site construction and climate change.

319 The environmental characterization was conducted considering the LCA standard (ISO 14040 2006) [35].

320 The analysis was basically performed, according to the design stage, using secondary data (generic data
321 from the literature or from the databases mentioned in section 2.1). Although these simplifications affected
322 the accuracy and applicability of the LCA results, they were adopted in order to quickly identify the potential
323 environmental effects. LCA was employed in the research project with the aim of finding an ecological way
324 of improving the building-system design and minimizing the environmental burdens in the production stages
325 (upstream and manufacturing processes: from cradle-to-gate). LCA was assumed as a decision-making tool
326 for the GRE_EN_S development system and as strategic tool for both the energy and raw material
327 optimization and for the greenhouse emission reduction, with particular reference to CO₂ equivalent (CO₂eq)
328 emissions [36].

329 The functional unit (F.U.), the boundary and the cut-off rules are listed and described in Table 3.

330

331 *Table 3. Life cycle assessment assumptions.*

F.U.	1 m ² (= 4 modular boxes)
Boundary	
Boundary in time	Carbon dioxide emissions were considered for a 100 year target (Global Warming Potential 100).
Boundary towards geography	Carbon dioxide emissions were accounted for assuming the Italian electric energy mix as the reference. If this was not possible, the Western European Country energy mix was considered.
Boundaries in the life cycle	Carbon dioxide emissions were accounted for by including the raw material extraction, the raw material refining, the manufacturing of the components and the building-system assembly.
Boundary towards nature	Carbon dioxide credits were accounted for by including the CO _{2eq} content in the shrub biomass and in the cellulose-based fibres.
Cut-off rules	
Water consumption and nutrient needs	Not included. The analysis was carried out on upstream and manufacturing processes.
Transportation	Not included. The material selection was carried out at a regional scale and the environmental impact was considered negligible.
Materials used to hold the system in place	Not included.

332
 333 Potting soil (placed in the pockets), planted vegetation (*Lonicera nitida*) and the material flows required to
 334 product the system were taken into account in the data inventory (Life Cycle Inventory LCI).
 335 As far as carbon dioxide credits are concerned, the calculation was implemented by estimating the shrub
 336 biomass from the basal stem diameters. The biomass below ground (roots) was not included in the
 337 estimation. Table 4 shows the materials that were necessary to build up a square meter of VGMS.

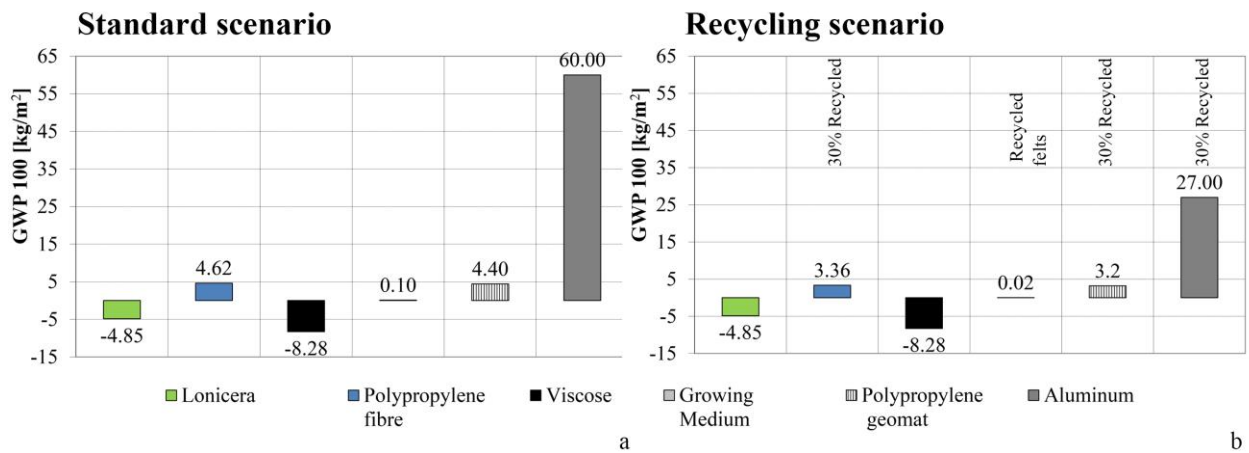
338
 339 *Table 4. Data Inventory (reference scenario)*

Material	Weight [kg/m ²]
<i>Lonicera</i> stems biomass	1.66
Polypropylene fibre	0.53
Non-woven viscose fabrics	1.15
Growing medium (50% of raw soil; 30% of SAP; 15% of coco-coir; 5% of peat moss)	4.2
Polypropylene monofilament geomat-grid	2
Aluminium alloy	3.9

340
 341 As far as the allometric equation used to predict the *Lonicera nitida* biomass is concerned, the carbon content
 342 and the dioxide credit contained within the wood were calculated. The biomass was estimated as 2.66 kg/m²
 343 (and was assumed as a negative value in the CO₂ eq. balance). Two scenarios were analysed. In the first,
 344 100% of raw materials (reference scenario) was taken into account in the data inventory, while a recycling
 345 rate (30%) for the aluminium alloy and polypropylene, that is, both the fibre and geomat, was assumed in
 346 the second data inventory (recycling scenario). Moreover – according to the research goals – the potting soil
 347 mixture was engineered in the recycling scenario by replacing SAP with recycled nylon-based felts. The
 348 thus developed potting soil reduced the total SAP amount by half. The considered recycled blend was: 50%
 349 of raw soil; 15% of SAP; 15% of recycled felt; 15% of coco-coir; 5% of peat moss. The difference in weight
 350 (kg/m²) of the raw materials and recycled materials was negligible, with reference to F.U. (< 0.05 kg per
 351 F.U.)

352
 353 Results

354
 355 The total GWP100 for the reference scenario was calculated as 55.98 kg CO_{2eq} /m². The total GWP100 for
 356 the recycling scenario was 20.45 kg CO_{2eq} /m², which is about one third of the value determined in the
 357 reference scenario. In both scenarios, the credits due to the *Lonicera* biomass and viscose fabric were
 358 remarkable, and they amounted to 13.13 kg CO_{2eq} /m² (Fig. 8).
 359 Aluminium alloy showed the most impact on climate change: 60.00 kg CO_{2eq} /m² (standard reference
 360 scenario) and 27.00 kg CO_{2eq} /m²(recycling scenario), respectively.
 361 As a general rule, even the recycled fibre and geomat-grid polypropylene-based material were characterized
 362 by a reduction in GWP 100 (the difference accounted for about 1.3 CO_{2eq} kg/m²). However, such a
 363 reduction was less remarkable than the GWP100 decrease for aluminium.
 364 The small amount of potting soil analysed for both scenarios did not significantly affect the CO_{2eq}
 365 emissions. Nevertheless, the comparison between the two blends highlighted the importance of replacing
 366 SAP with recycled felts. The growing medium manufactured with SAP had a five times higher GWP100
 367 (0.10 kg CO_{2eq} /m²) than the recycled one (0.02 kg CO_{2eq} /m²).
 368
 369
 370
 371
 372
 373



374
 375 Fig. 8. a) GRE_EN_S Global Warming Potential (target of 100 years) for the reference scenario. b)
 376 GRE_EN_S Global Warming Potential (target of 100 years) for the recycling scenario.

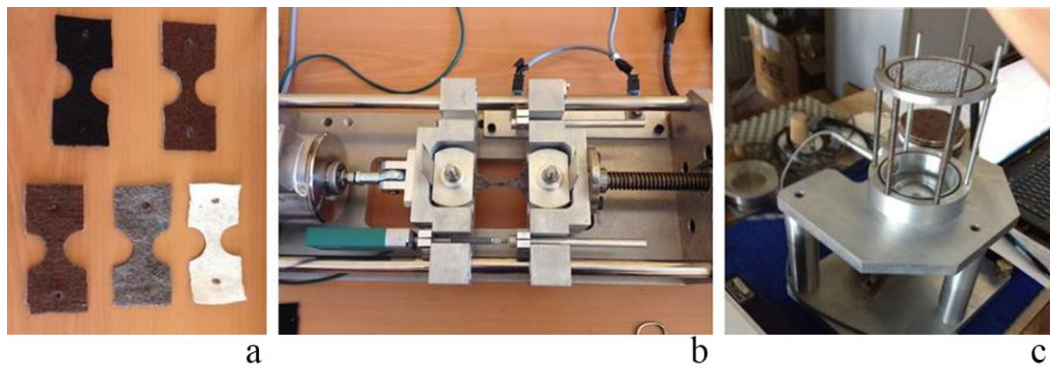
377 3.2 Mechanical properties

378 After a first selection of the materials considered suitable for containing the plants in the VGMS, specific
 379 analyses were undertaken to test other important matters related to the application. In particular, the felts
 380 (view Fig. 2) that were to be chosen had to respond to both durability aspects, connected to the mechanical
 381 properties, and to permeability issues. This layer, which works as a support for the plants, had to ensure, at
 382 the same time, both mechanical strength, to counteract the weight of the whole structure (in vertical
 383 development conditions), and an adequate hydraulic conductivity, to ensure the maintenance of the
 384 biological functions of the plants. Since the goal of the research was to enhance the biometric parameters of
 385 the plants using recycled materials, the mechanical properties of the support were evaluated in order to
 386 optimize the health of the plants and the mechanical structure of the VGMS. The mechanical properties
 387 were thus evaluated on the basis of the elastic response and fluid transport behavior. A description of the
 388 tested materials and the macroscopic physical properties is given in Table 5.

389 *Table 5. Technological supports and macroscopic physical properties of the materials.*

Typology		Thickness <i>L</i> /mm	Density ρ /kgm ⁻³	Porosity ϵ /-
E-1	Polypropylene fibres	4.32	77.9	0.92
I-2	Polypropylene and polyester fibres	1.86	131.4	0.86
E-3	Polyester fibres (calendering of the fibres on the inner side)	5.16	54.6	0.96
I-4	viscose and polypropylene fibres	3.65	54.4	0.97
E-5	Polyester fibres (needle punching of the fibres on the inner side)	5.05	94.5	0.93

390 The experimental techniques involved engineering stress-strain and intrinsic permeability measurements.
 391 Some specimens of the tested materials and the measuring devices used in the characterization are shown
 392 in Fig. 9.



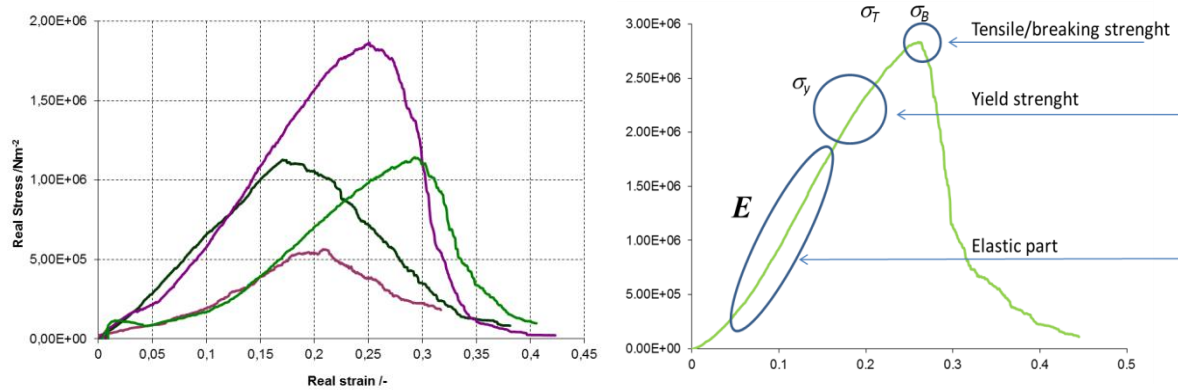
393
 394 *Fig. 9. Specimens of the technological support materials and devices for the stress-strain and permeability*
 395 *measurements.*

396 The mechanical strength of the tested materials was evaluated by conducting uniaxial tension measurements,
 397 until failure was reached at displacement control, as shown in Fig. 10. The background theory and
 398 experimental method are described in [37].

399 The hydraulic conductivity, *K*, a parameter that describes the behaviour of a given fluid as it passes through
 400 the interstitial spaces of a porous material, was determined on the same materials on the basis of the
 401 measurement of intrinsic permeability *k*, using an appropriate measuring procedure [38], in both loaded and
 402 unloaded conditions [39].

403 Results

404 The elastic response of several polymer-based fibrous materials which were used as technological
 405 supports, were investigated on the basis of "stress-strain" measurements and analyses. The mechanical
 406 properties of interest were deduced from the complete experimental stress-strain diagram (Table 6). A
 407 comparison of the stress-strain diagrams of several technological support materials is shown in Fig. 10, as
 408 an example.



409
 410 *Fig. 10. Experimental “stress-strain” diagrams of several technological support materials and evaluation*
 411 *of the mechanical properties.*

412 The typical ductile behavior of the materials was observed, until breaking, during the test. The elastic
 413 modulus E of the tested materials ranged from between 0.3 MPa and 7 MPa, the yield strength values σ_y
 414 ranged from between 0.5 MPa and 3 MPa and the tensile and breaking strength values, σ_T and σ_B , ranged
 415 from between 0.6 MPa and 3 Mpa, respectively. On the basis of these measurements, it was possible to
 416 define the maximum load that could be sustained by the materials that were used as technological supports
 417 of the substrates and plants, after they had been installed vertically.

418 The fluid transport characteristics of the technological supports, evaluated on the basis of the hydraulic
 419 conductivity K , showed data ranging on average from between 10^{-2} and 10^{-3} ms^{-1} (Table 6). These values,
 420 which correspond to the hydraulic conductivity of a soil composed of sand and gravel [40], were adequate
 421 to ensure the quantity of water necessary, the feeding and transpiration as well as an adequate humidity
 422 storage for the plants.

423
 424 *Table 6. Experimental mechanical properties of the technological support materials under investigation.*

	Young's Mod. E [Pa]	σ_y [Pa]	σ_T [Pa]	σ_B [Pa]	Permeability k [m^2]	Hydraulic conductivity K [ms^{-1}]
E-1	$7.0 \cdot 10^6$	$1.0 \cdot 10^6$	$1.1 \cdot 10^6$	$1.1 \cdot 10^6$	$1.24 \cdot 10^{-9}$	$1.53 \cdot 10^{-2}$
I-2	$1.4 \cdot 10^6$	$5.3 \cdot 10^5$	$5.6 \cdot 10^5$	$5.6 \cdot 10^5$	$2.46 \cdot 10^{-10}$	$3.02 \cdot 10^{-3}$
E-3	$2.6 \cdot 10^6$	$3.0 \cdot 10^6$	$5.0 \cdot 10^6$	$4.7 \cdot 10^6$	$4.27 \cdot 10^{-10}$	$5.25 \cdot 10^{-3}$
I-4	$2.5 \cdot 10^5$	$1.6 \cdot 10^6$	$1.9 \cdot 10^6$	$1.4 \cdot 10^6$	$7.19 \cdot 10^{-10}$	$8.84 \cdot 10^{-3}$
E-5	$5.8 \cdot 10^6$	$1.0 \cdot 10^6$	$1.1 \cdot 10^6$	$1.1 \cdot 10^6$	$6.87 \cdot 10^{-10}$	$8.44 \cdot 10^{-3}$

425
 426 **3.3 Biometric parameters**

427 One of the most important aspects that had to be investigated was related to the behavior of the plants, since,
 428 as highlighted in a recent published work by Perez et al 2017 [4], the energy savings of a green façade are
 429 dependent to a great extent on the biometric parameters, that is, on the LAI. The biometric parameters were
 430 thus experimentally assessed in order to:

- 431 - test the suitability of the different species for VGMS applications

- 432 - evaluate the effect of different substrates on the growth of the plants
 433 - find a relationship between the biometric parameters and the thermal performances.

434
 435 As is usual in VGMS arrangements, the initial growing phase was performed in a nursery with small plants
 436 in pots of about 8 cm in diameter. Two experimental trials were performed in a nursery in Moncalieri near
 437 Turin (Italy) (45°00'58'' N, 7°74'15'' E), in which the Reviwall® supporting technology (as patented by
 438 Reviplant Nurseries, Moncalieri, Italy) was modified. The single module was 40 cm width × 50 cm high, it
 439 was hung on metal supports and it was composed as follows: a frame of galvanized aluminum, two layers
 440 of rootable nonwoven synthetic mats, and two geogrids, one under and one above the 100% coconut fiber
 441 substrate. Six pockets were cut out of each panel to house 6 plants.

442 The *Lonicera nitida*, *Bergenia cordifolia* and *Heuchera* hybr. 'Red Purple' ornamental species were grown
 443 vertically in different technical solutions in order to evaluate their suitability for this kind of application.
 444 Each module contained 2.5 l of substrate, and the weight (before irrigation) varied between 1.3 kg and 1.8
 445 kg, depending on the substrate features.

446 Two different trials were performed in the nursery, as described in Table 7. Two species and four different
 447 substrates were compared in each trial (Fig. 11).

448 Starting from a standard substrate composition (SS made of: 100% coconut fibre with hydro-retainers, and
 449 mycorrhizal Inoculum composed of 30/g of *Glumus* spp. Fungal spores), different compositions and
 450 combinations were investigated. It was assumed that the addition of felt and viscose to the substrates would
 451 improve the water retention of the system, and as a result, the growing potentiality of the plant. During trial
 452 1 (Table 7), the SS was compared with alternative substrates with different percentages of coconut fibre and
 453 shredded felt: SF50; SF50B; SF100 (see section 2.2 for details of the composition). In trial 2 (Table 7),
 454 SF50B and SF100 were substituted by two other substrates with a viscose layer (named SSV and SF50V).
 455

456 Table 7. Details of the trials performed in the nursery.

	Plant species	Substrates (ID code)	Period (duration)
Trial 1	1. <i>Lonicera nitida</i> 2. <i>Bergenia cordifolia</i>	1. Standard Reviwall® Substrate composed of coconut fibre+hydro-retainers+mycorrhizae (SS) 2. 50% coconut fibre + 50% shredded felt (SF50) 3. 50% coconut fibre + 50% shredded felt, with layers of whole felt used as structural tissue (SF50B) 4. 100% shredded felt (SF100)	June-November (6 months)
Trial 2	1. <i>Lonicera nitida</i> 2. <i>Heuchera</i> hybr. 'Red Purple'	1. Standard Reviwall® Substrate composed of coconut fibre+hydro-retainers+mycorrhizae (SS) 2. 50% coconut fibre + 50% shredded felt (SF50) 3. SS + Viscose layer* (SSV) 4. SF50 + Viscose layer* (SF50V)	June-November (6 months)

457
 458 Eighteen plants (three modules) were organised randomly within a block for each of the 8 plant-substrate
 459 combinations in each trial. Six blocks, over a total area of 28.8 m², and 144 modules were tested. A
 460 westwards exposure was chosen as it was found to be the worst situation for the plants in the summertime.
 461 The plants were fertirrigated (Mineral soluble fertilizer: N, P₂O₅ e K₂O), adopting the standard procedure,
 462 using Algapark® (Canale d'Alba, Italy) and Criscap® 16-12-23 NPK (Canale d'Alba, Italy).
 463 Five monthly surveys were performed to monitor the plant growth and the quality of the green cover, and
 464 the following were considered:

- 465 - plant height (h) and diameter dimensions (w_1 and w_2);
 466 - plant health, using a SPAD-502 Konica Minolta Chlorophyll Meter (Nieuwegein, The Netherlands) to
 467 perform the *in vivo* measurements of the total chlorophyll content in the plant tissue, and to indirectly
 468 measure the nutritional status of the plant through the SPAD index (Soil Plant Analysis Development).
 469 Any pathological symptoms, such as chlorosis, leaf loss or diseases, were observed and filed [41];
 470 - ornamental value and covering percentage, established by means of photographic surveys.

471
 472 The dimensions were used to calculate the Growth Index (GI) [42] as in Eq. (1):

$$473 \quad GI = \pi \cdot \left\{ \left[(w_1 + w_2) / 2 \right] / 2 \right\}^2 \cdot h \quad \text{cm}^3 \quad (1)$$

474 Measurements were performed on 9 plants chosen randomly during each thesis. At the end of each trial
 475 period, the aerial parts of 9 plants were dried in an oven at 90°C for 4 days, and their dry weight was
 476 determined.

477 Moreover, in order to analyze the interaction between the species and the substrates, the data were subjected
 478 to a one-way analysis of variance in which the data were tested with the Ryan-Einot- Gabriel-Welsh process
 479 [43], using the SPSS statistical package (Version 17.0, SPSS Inc., Chicago IL).

480 In order to analyse the thermal performances, 3 modules were cultivated in the test cell for each substrate
 481 (SS, SF50 and SF50B) of *Lonicera nitida* and *Bergenia cordifolia*, taken from trial 1 [12].

482 The leaf area index (LAI) [44] of six plants was calculated for each combination of species and substrate.
 483 This parameter was of particular interest as far as the cooling potential of the plants was concerned, since it
 484 can be considered as an equivalent shadow index of the plants. The relationship between LAI and the energy
 485 performance of the plants was investigated, and the results are given in section 3.5.

486 In order to measure the LAI, leaves were cut and scanned with an A3 standard scanner, and the free Xnview
 487 scanner software (version 1.98.2/1.70 by Gougelet P., Reims, France) was used. The images were modified
 488 appropriately, and the leaf data (area, perimeter, number) were automatically calculated using the free
 489 ImageJ software (version 1.45m by Rasband W., Bethesda, Maryland, USA).

490 The Leaf Area Index was calculated for one module (LAI_m) using Eq. (2):

$$491 \quad LAI_m = LA_m / A_m \quad (2)$$

492 where LA_m was the total leaf area (mm^2) of the six plants grown in one module, and A_m was the area (mm^2)
 493 of one module.

495 Results

496 Trial 1 – Biometric evaluation of different substrates for *Lonicera nitida* and *Bergenia cordifolia*

497 A synthetic comparison of the main results obtained at the end of the trial 1 is shown in Table 8. The Growth
 498 Index (GI), the dry weight of the aerial parts of the plants, and the SPAD index values for *Lonicera nitida*
 499 and *Bergenia cordifolia* are reported.

500 The substrates with 50% of shredded felt pads (SF50 and SF50B) induced more lignification in *Lonicera*
 501 *nitida*, and caused the yellowing of leaves (lower SPAD values than SS). SF100 produced significantly
 502 different plants from those grown in the other substrates. The *Bergenia* plants grown in SS and SF50 had
 503 larger volumes, more leaves (data not shown) and greener leaves than the ones grown in SF50B and SF100
 504 (Fig. 11). In trial 1, the best overall plant health biometric parameters were found for the SF 50B and SS
 505 substrates, and for this reason the SF50 and SF100 substrates were not used in trial 2.

506

507 *Table 8. Growth Index (GI), dry weight and SPAD index of Lonicera nitida and Bergenia cordifolia*
 508 *grown on the different substrates (Standard, SS; 50% Standard + 50% felt pads, SF50; 50% Standard +*
 509 *50% felt pads + felt layer, SF50B; 100% felt pads, SF100) at the end of trial 1.*

Substrate	<i>Lonicera nitida</i>			<i>Bergenia cordifolia</i>		
	GI (cm ³)	Dry weight (g)	SPAD index	GI (cm ³)	Dry weight (g)	SPAD index
SS	27.6 x 10 ³ a*	229.2b	42.6a	13.0 x 10 ³ a	415.7b	47.6
SF50	27.0 x 10 ³ a	282.8a	36.7b	13.5 x 10 ³ a	34.7c	40.2
SF50B	23.5 x 10 ³ b	240.1ab	38.7ab	11.7 x 10 ³ b	428.9ab	40.4
SF100	13.5 x 10 ³ c	150.6c	27.9c	11.3 x 10 ³ b	456.6a	38.2
<i>P</i>	<0.05	<0.001	<0.001	<0.05	<0.001	n.s.

*In each column, means followed by the same letter do not differ significantly according to the Ryan-Einot- Gabriel-Welsh test

510

511 As far as the LAI results are concerned, *Lonicera nitida* showed a lower value than *Bergenia cordifolia*.

512 A higher number of leaves was detected in the *Lonicera nitida* plants grown on the SF50 and SF50B
 513 substrates in the test cell. The LAI of one module was higher in plants grown on SF50 and SF50B than on
 514 SS [12].



515

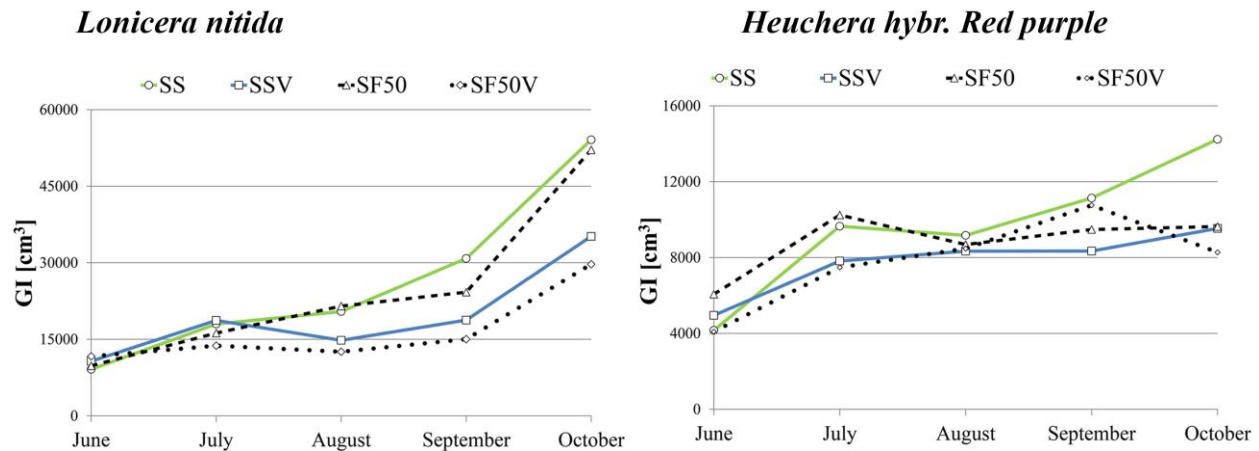
516 *Fig. 11. Comparison of photographs taken from the initial stage (June) to the end of trial 1 (November) of*
 517 *plants grown on the four substrates (Standard, SS; 50% Standard + 50% felt pads, SF50; 50% Standard +*

518 50% felt pads + felt layer, SF50B; 100% felt pads, SF100). *Lonicera nitida* at the top and *Bergenia*
 519 *cordifolia* at the bottom.

520

521 Trial 2 – Biometric evaluation of different substrates for *Lonicera nitida* and *Heuchera hybrida* ‘Red purple’
 522 *Lonicera nitida* and *Heuchera* hybr. ‘Red purple’ were monitored during the second year growing season.
 523 The GI trend of the *Lonicera* and *Heuchera* plants in the different substrates is shown in Fig. 12. The
 524 substitution of coconut fibre with up to 50% of shredded felt pads (SF50) resulted in increased performances
 525 in the *Lonicera* modules. The SS substrate was the best one for the development of the *Heuchera* plants.
 526 The GI results, for both species, suggested that the use of viscose is not so useful (SSV, SF50V). The reason
 527 for this is that the fertirrigation supplied the right amount of water to the plants when needed, without the
 528 necessity of retaining more water in the module. Nevertheless, further research on water run-off should be
 529 carried out in order to reduce the loss of water and nutrients.

530 The SPAD values and dry weight (data not shown) confirmed that the *Lonicera* plants in SS and SF50 had
 531 higher biomasses and were healthy. The *Heuchera* plants, in spite of their high ornamental value (small pink
 532 flowers and red leaves), were found to be too sensitive, and they were also found to be affected by pest
 533 disease; their initial nursery quality was found to be of fundamental importance.



534 Fig.12.(Left) Growing index (GI) of the *Lonicera nitida* plants cultivated in the four substrates (Standard,
 535 SS; Standard + viscose, SSV; 50% Standard + 50%felt pads, SF50; 50% Standard + 50%felt pads +
 536 viscose, SF50V) during trial 2 (June-October). (Right) Growing index (GI) of *Heuchera* hybr. ‘Red
 537 purple’ plants cultivated in the four substrates (Standard, SS; Standard + viscose, SSV; 50% Standard +
 538 50%felt pads, SF50; 50% Standard + 50%felt pads + viscose, SF50V) during trial 2 (June-October).
 539

540 **3.4 Acoustic performance**

541 Once the properties and suitability of the different tested felts/substrates and plant species had been defined,
 542 specific measurements were performed to collect data in order to fully characterise the performance of the
 543 system and to identify the best compromise between the different aspects that were involved. In this
 544 framework, the acoustic performance was evaluated in both a laboratory, at the material/component level
 545 (section 3.4.1), and in the demonstration mock-up, at the system level (section 3.4.2).
 546

547 **3.4.1 Laboratory characterisation of the acoustical properties**

548 The acoustical performance of the VGMS was evaluated on the basis of the sound absorption, as a function
549 of frequency, in the INRiM laboratory. The experimental techniques involved measuring the standing wave
550 sound fields for small-scale samples, and the diffuse sound fields for large-scale samples.

551 Small-scale samples (cylinder cores, diameter 50 mm) of different plant leaves were considered, and
552 substrate assemblies were conducted in both dry and wet conditions. The sound absorption coefficient was
553 measured in a Kundt tube, according to the ISO 10534-2 standard [45] and to literature [46]. The sound
554 absorption coefficient, in the 100 Hz to 3800 Hz frequency range, was determined at normal incidence α_0 .
555 The measurement provides accurate results [47], even for extremely heterogeneous and anisotropic
556 materials, such as the examined stratigraphy. The technique is based on the measurement of a transfer
557 function between the sound pressure measured by two microphones within the tube, when the tube is excited
558 by a loudspeaker placed at one end, while the specimen is placed at the other end of the tube. The sound
559 absorption coefficient was calculated by quantifying the dissipation of the reflected sound energy r ,
560 according to Eq. (3):

$$561 \quad \alpha_0 = 1 - |r|^2 \quad (3)$$

562
563
564 Three prototypes of large-scale VGMS systems (surface areas of 12 m²) were also characterized, in terms
565 of acoustic absorption coefficient, at random incidence α , according to the ISO 354 standard [48]. The
566 method consisted of measuring the sound pressure time decay in a reverberation room, as a function of
567 frequency, with and without the test specimen. The equivalent absorption area of the specimen A_T was
568 calculated from the reverberation time values, according to Sabine's formula, and the sound absorption
569 coefficient of the test specimen was then determined, according to Eq. (4):

$$570 \quad \alpha = A_T / S \quad (4)$$

571 A large-scale VGMS system, which was installed in the INRiM reverberation room (Turin), and a small-
572 scale sample of plants leaves, substrate stratigraphy and the technological supports are shown, in the Kundt
573 tube, in Fig. 13.



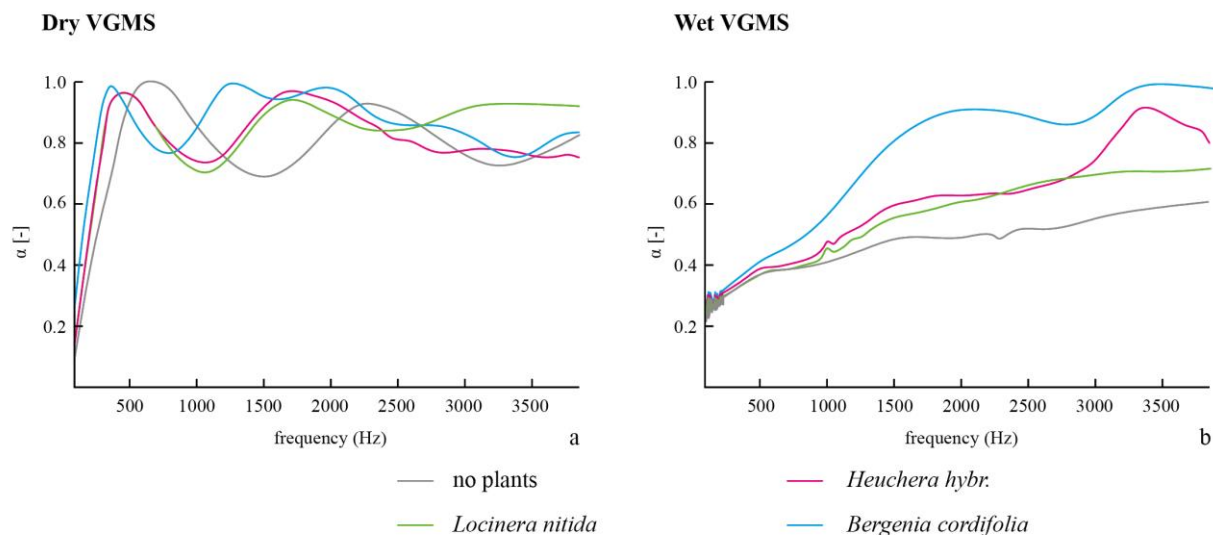
574
575 *Fig. 13. Measurements of the sound absorption coefficient in the diffuse sound field (reverberation room)*
576 *and in the standing wave sound field (Kundt tube).*

577 Three prototypes were tested: VGMS-1 and VGMS-2, which differ according to the type of substrate and
578 fabrics, and the reference VGMS-1, with no plants or substrate. The modules were composed of :

- 579 - **VGMS-1**, an exterior felt covering in polypropylene, soil, a double layer of rootable mat in
580 polypropylene and in polyester, a three-dimensional geogrid in polypropylene, the standard substrate
581 (SS), a three-dimensional geogrid in polypropylene, a double layer of rootable mat in polypropylene
582 and in polyester, and an exterior felt covering in polypropylene.
- 583 - **VGMS-2**, an exterior UV resistant felt covering in polyester, soil, a single layer of woven material in
584 viscose and polypropylene, a three-dimensional geogrid in polypropylene, substrate SF50, a single layer
585 of woven material in viscose and polypropylene, and an exterior UV resistant felt covering in polyester
586

587 Results – Sound absorption coefficient for substrates SS and SF50 and different plant species (*Lonicera*,
588 *Heuchera* and *Bergenia*)

589 The experimental results (Fig. 14) showed that the high values of the sound absorption coefficient α_0 ,
590 between 250 Hz and 3800 Hz, were mainly due to the presence of the substrate. The measurements carried
591 out in dry conditions showed that the presence of different typologies of leaves did not influence the acoustic
592 performances of the VGMS. On the other hand, in wet conditions, the acoustical performances of the VGMS
593 decreased, since the water inside increased the density of the substrate and filled the open pore voids. Fig.
594 14 shows two graphs of the sound absorption coefficient measurements at normal incidence, for the three
595 plant species that were considered, with substrates in dry and wet conditions.

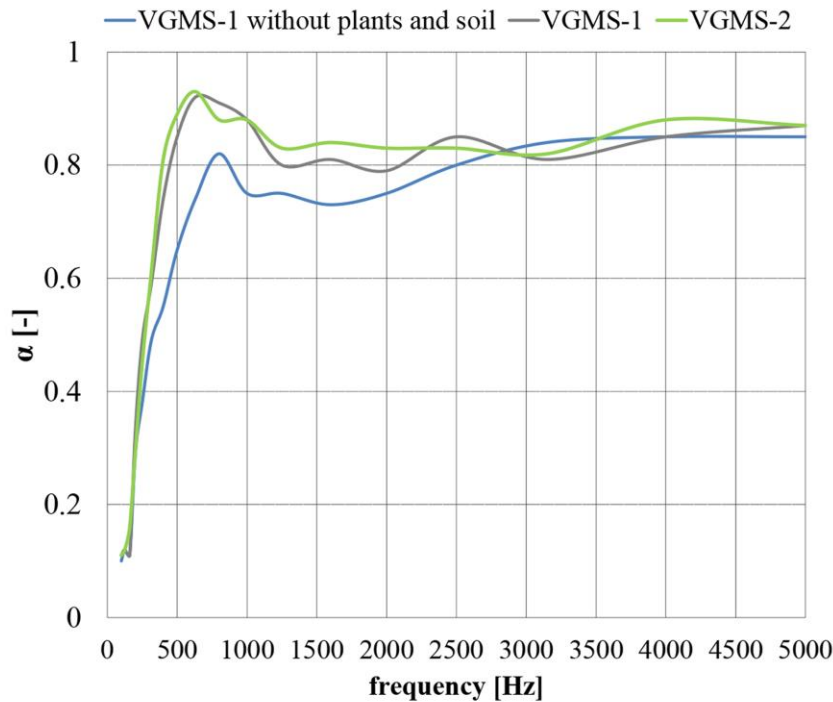


596
597 *Fig. 14. The sound absorption coefficient (dry and wet conditions) of the VGMS for different vegetal*
598 *species.*

599 In order to provide an assessment of the sound absorption coefficient of the VGMS under operating
600 conditions, measurement were carried out on different configurations of substrates, technological supports
601 and plant species (*Lonicera nitida*, *Bergenia cordifolia*, *Heuchera* hybr. ‘Red purple’), in both wet and dry
602 substrate conditions. The values of the sound absorption coefficient were determined at normal incidence
603 α_0 in the Kundt tube.

604 The three different systems VGMS-1, VGMS-1 without plants and substrate, and VGMS-2, were
605 characterized in terms of sound absorption, as a function of the frequency, that is, between 100 Hz and 5

606 kHz, in diffuse sound fields in a reverberation room. As shown in Fig. 15, VGMS-1 and VGMS-2 show
 607 similar sound absorption trends. The influence of the plants can be ascertained by comparing the blue and
 608 green curves relative to VGMS-1. The system without plants did not perform as well as the case with plants,
 609 but the observed differences were small. The obtained results showed that the most important effect, in
 610 terms of sound absorption, was due more to the substrate than to the vegetation.



611
 612 Fig. 15. Experimental sound absorption coefficient results in the reverberation room. The three different
 613 prototypes measured in the reverberation room were: VGMS_1, VGMS_1 without plants and soil,
 614 VGMS_2 (c).

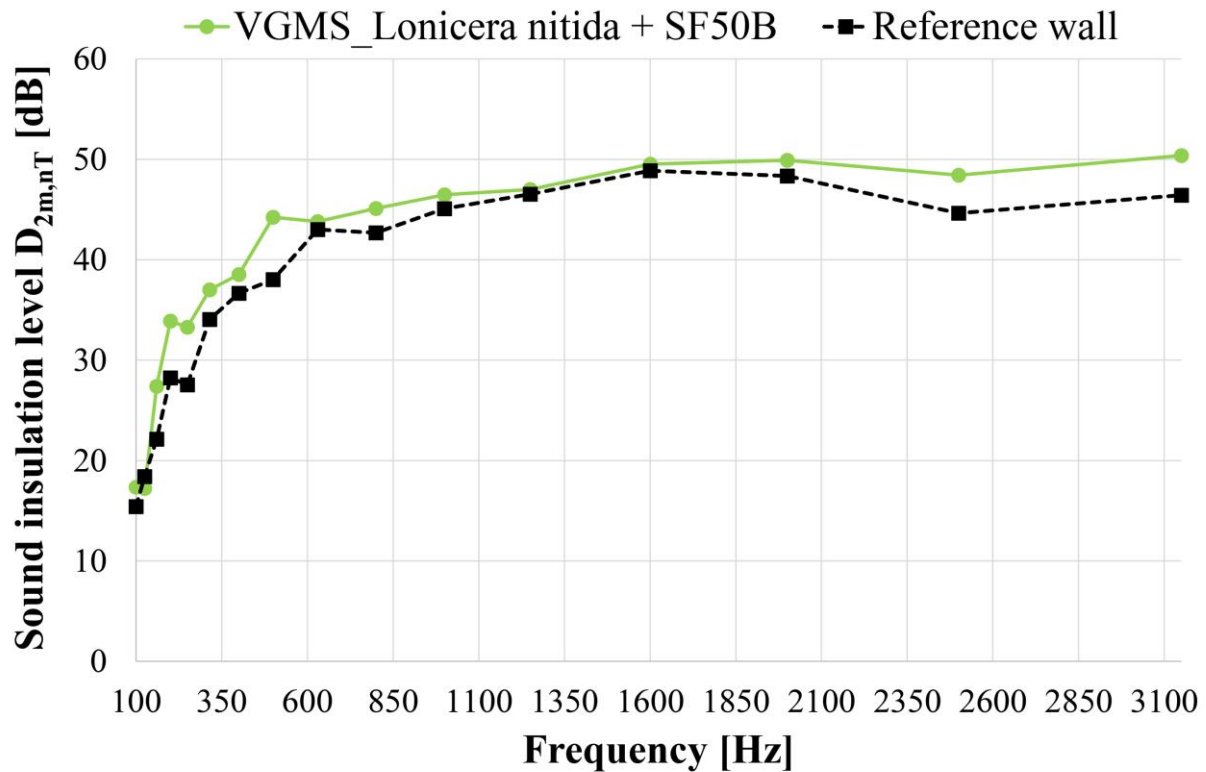
615 3.4.2 Mock-up characterisation

616 In the mock-up, the sound insulation level ($D_{2m,nT}$) for the VGMS façade and for the reference façade of the
 617 demonstration building was experimentally evaluated through the intensimetric method [49]. The sound
 618 insulation level was measured for *Lonicera nitida* with the SF50B substrate. This method allowed the sound
 619 insulation level of the façade to be measured punctually, and the transmitted intensity was measured using
 620 a sound intensity probe (Brüel & Kjær, according to the methodology described in standards [49] and [50].
 621 In this way, it was possible to evaluate the sound insulation level ($D_{2m,nT}$).

622 Results – Sound insulation level of the façade with *Lonicera nitida* grown in the SF50B substrate

624
 625 The measured sound insulation level is plotted in frequency in Fig. 16. It is possible to note that the VGMS
 626 presents higher values than the reference structure for low and high frequencies. However, the values are
 627 similar for the central frequency. An indoor environment reverberation time of 0.5 s (τ_{60}) was measured for
 628 both of the mock-up modules. As far as the aggregated results are concerned, sound insulation levels ($D_{2m,nT}$
 629) of 40 dB and 43 dB were calculated for the reference and the VGMS with *Lonicera nitida*, respectively.
 630 In-situ measurements on the demonstration mock-up showed that the use of VGMS leads to a 3 dB
 631 improvement in the sound insulation level of the façade. It is important to point out that this type of

632 performance can be affected to a great extent by the water content in the substrate, the type of substrate and
 633 the biometric parameters of the vegetation.
 634



635
 636 *Fig.16. Sound insulation level of VGMS Lonicera nitida + SF50B and the reference technology.*

637 **3.5 Thermal performance**

638 The characterisation of the thermal performance of the VGMS had two main goals:
 639 - to provide data on the thermal behaviour of this unconventional envelope technology, under real boundary
 640 conditions, during the heating and cooling seasons;
 641 - to investigate the influence of different species and different substrates on the thermal behaviour of the
 642 wall.
 643

644 The measurements were conducted to characterise the VGMS at the component scale, and to perform
 645 comparative analyses of different solutions. The thermal transmittance/conductance and the increase, due
 646 to the leaves, in the external surface resistances were assessed for the winter performance. Given the absence
 647 of an HVAC system, which would have been able to maintain the indoor temperature during the summer
 648 season, it was not possible to measure any dynamic parameters, such as the periodic thermal transmittance
 649 or thermal lag. Nevertheless, it is important to stress that, in this kind of system, which is characterised by
 650 a thin and light substrate and, as a consequence, by reduced evapotranspiration effects, the dynamic thermal
 651 behaviour that characterises other types of vegetated envelope (i.e green roofs) is not so significant. Aspects
 652 related to the reduction in the external surface temperature and in the indoor air temperature, due to the
 653 presence of the VGMS, were instead investigated in the cooling season.

654 Two different experimental campaigns were thus set up: one on the outdoor test cell (section 2.3.2) and the
 655 other on the demonstration mock-up (section 2.3.3). An extensive and continuous measurement campaign
 656 was carried out for both of the experimental activities. The measurement equipment consisted of

657 thermocouples, heat fluxes and a weather station connected to a data-logger, which recorded data every 15
 658 min. All the instruments were previously calibrated or verified in the laboratory in order to guarantee the
 659 following uncertainties, using the/a 95 % confidence limit: ± 0.3 °C for the temperature measurements and
 660 ± 5 % for the heat fluxes, as declared by the manufacturers (with a nominal sensitivity of $50 \mu\text{V}/\text{W}/\text{m}^2$). For
 661 the sake of brevity, only some details are reported concerning the measurement methodology, which is
 662 described in detail in [12].

663 During the heating season, the experimental data that were collected were used to calculate the equivalent
 664 thermal conductance (C^* Eq. 5) and transmittance (U^* in Eq. 6) of the VGMS and of the reference wall,
 665 according to standard [51]. The average value of the heat flux was divided, according to equations 5 and 6,
 666 on the basis of the difference in the surface and air temperatures (indoor and outdoor) to calculate the thermal
 667 equivalent conductance and the transmittance, respectively. The difference between the inverse ratio of U^*
 668 and C^* allowed the sum of the indoor and outdoor surface resistances to be calculated (Eq. 7).

$$669 \quad C^* = (\overline{\dot{Q}/A}) / \Delta t_s \quad [\text{W}/(\text{m}^2\text{K})] \quad (5)$$

$$670 \quad U^* = (\overline{\dot{Q}/A}) / \Delta t_{air} \quad [\text{W}/(\text{m}^2\text{K})] \quad (6)$$

$$671 \quad R_{si} + R_{se} = 1/U^* - 1/C^* \quad [(\text{m}^2\text{K})/\text{W}] \quad (7)$$

672
 673 The influence of the plant species and of the substrates was investigated during the heating season; the trend
 674 of the surface and air cavity temperatures was observed. The aggregate daily energy values (Eq. 8) for
 675 heating (only negative heat fluxes were considered) were calculated as follows:

$$676 \quad E_{24} = \int_{24:00}^{00:00} (\dot{Q}/A)(\tau) d\tau \quad [(\text{Wh})/\text{m}^2] \quad (8)$$

677
 678 During the cooling season, the presence of vegetation consistently affected the surface temperatures, as was
 679 observed when the VGMS and the reference technology were compared. The influence of the ventilated
 680 cavity was also analysed. The indoor air temperatures were compared in the different rooms (one vegetated
 681 and the other with wooden cladding) at the building level (demonstration mock-up), in free floating
 682 conditions.

684 Results: VGMS – winter performance

685 The equivalent thermal conductance and transmittance were assessed for the two experimental campaigns,
 686 and the results are reported in Table 9.

687 The test cell results showed lower thermal transmittance and conductance for the VGMS than the reference
 688 wall, which indicates a reduction in heat losses due to the presence of the vegetated module.

689 The comparison between the *Lonicera nitida* and *Bergenia cordifolia* results revealed no significant
 690 differences. Even though these species are characterised by different LAI, it does not seem to have affected
 691 the results to any great extent.

692 The results obtained in this set of measurements were used to define the insulation thickness that was to be
 693 adopted in the mock-up in order to obtain the same thermal transmittance ($0.30 \text{ W}/\text{m}^2\text{K}$, as required by the
 694 national regulations). The presence of the vegetated module was estimated to be equivalent to 3 cm of XPS
 695 (see the description in section 2.3.3). The measurements carried out in the mock-up instead demonstrated an
 696 overestimation of the contribution of the vegetation ($0.29 \text{ W}/\text{m}^2\text{K}$ vs $0.26 \text{ W}/\text{m}^2\text{K}$). Nevertheless, it is
 697 important to highlight that the air cavity between the wall and the vegetated module was thicker in the mock-
 698 up than in the first prototype adopted in the test cell. It was actually decided to enlarge the cavity to increase
 699 the ventilation of the green façade in order to avoid an overheating effect during the night, due to the
 700 presence of a still warm cavity, as observed during the test cell measurement campaign. However, this

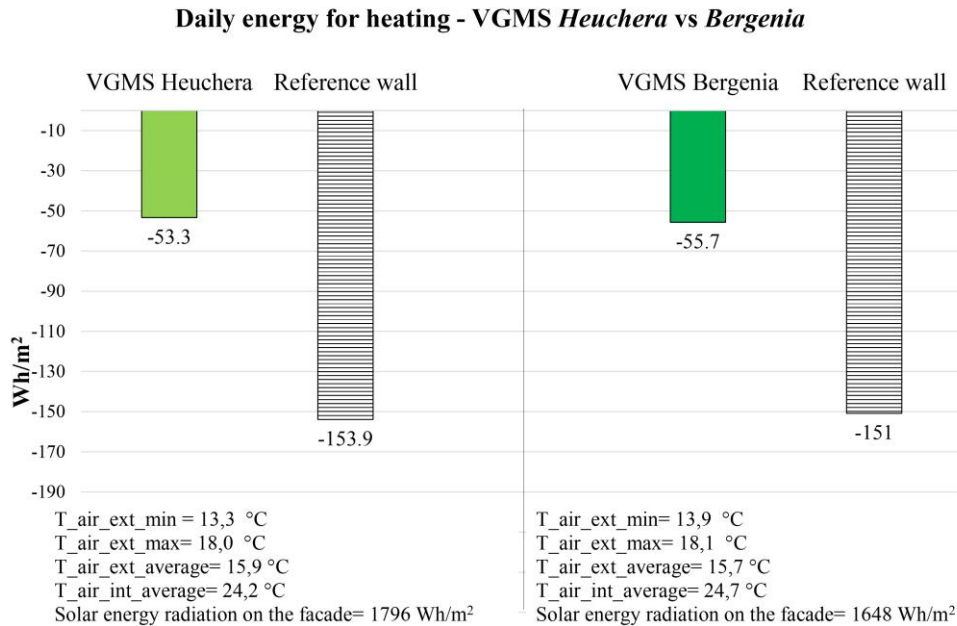
701 ameliorative strategy made the winter behaviour worse since the thermal buffer provided by the gap behind
 702 the vegetated substrate was reduced, as described hereafter.
 703 Moreover, when the measured conductance and transmittance were compared, it was possible to determine
 704 the surface resistance values for both envelopes. Higher values were registered for the VGMS than for the
 705 reference wall, for both the test cell and the demonstration mock-up. The difference between the VGMS
 706 and the reference wall was 0.42 vs 0.31 (m²K)/W for the test cell (plastered wall) and the difference was
 707 0.42 (m²K)/W vs 0.15 (m²K)/W for the demonstration mock-up (wood cladding). It is in fact possible to
 708 state that the presence of vegetation on a façade noticeably increases the thermal resistance of the surface,
 709 compared to a standard wall. Since the resistance of the internal surface is the same (identical room, same
 710 temperature and control system), the difference can be attributed to the presence of vegetation, which is able
 711 to reduce the wind speed and significantly decrease the convective heat exchange between the wall itself
 712 and the external environment.
 713 These findings suggest that even if plants and leaves can act as a shading device for the designed VGMS
 714 during winter and reduce the absorbed solar gain transferred to the wall they do contribute positively to the
 715 reduction in heat losses through the wall. This is due to both the surface thermal resistance increase and the
 716 creation of a thermal buffer between the wall and the vegetated module, as discussed hereafter. It is also
 717 possible to state that the use of evergreen species, which can reduce the maintenance cost of the façade,
 718 does not negatively affect the VGMS performance during the winter season.

719
 720 *Table 9. Equivalent thermal conductance and transmittance for the outdoor test cell and demonstration*
 721 *building. Results of the Lonicera nitida and Bergenia cordifolia species.*

Outdoor Test cell		Equivalent thermal conductance C* [W/m²K]	VGMS	Reference
		<i>Lonicera nitida</i>	0.22	0.63
		<i>Bergenia cordifolia</i>	0.21	0.57
		Equivalent thermal transmittance U* [W/m²K]	VGMS	Reference
		<i>Lonicera nitida</i>	0.17	0.40
		<i>Bergenia cordifolia</i>	0.17	0.39
Demonstration Building		Equivalent thermal conductance C* [W/m²K]	VGMS	Reference
		<i>Lonicera nitida</i>	0.33	0.26
		Equivalent thermal transmittance U* [W/m²K]	VGMS	Reference
		<i>Lonicera nitida</i>	0.29	0.25

722
 723 Two different days with similar boundary conditions were selected during the winter season to perform a
 724 comparison between two species: *Bergenia cordifolia* and *Heuchera hybr.* (the measurements were carried
 725 out for one species at a time). The daily heating energy, calculated with equation 8, and the boundary
 726 conditions of the two selected days are plotted in Fig. 17. It was possible to make a direct comparison of the
 727 two, since the boundary conditions were very similar, as confirmed by the very similar energy transmitted

728 values through the reference wall, that is, of -153.9 Wh/m^2 and -151 Wh/m^2 , respectively. The energies
 729 calculated for the VGMS were significantly smaller and very similar: -53.3 Wh/m^2 for the VGMS with
 730 *Heuchera* hybr. and 55.7 Wh/m^2 for the VGMS with *Bergenia cordifolia*. The two analysed species had
 731 different LAI values, as mentioned in the section dealing with the biometric parameters (section 3.3 – the
 732 results of trial 1), but, as observed previously when considering the very similar thermal transmittance values
 733 of *Lonicera nitida* and *Bergenia cordifolia*, it did not seem to affect the overall thermal behaviour to any
 734 great extent.
 735

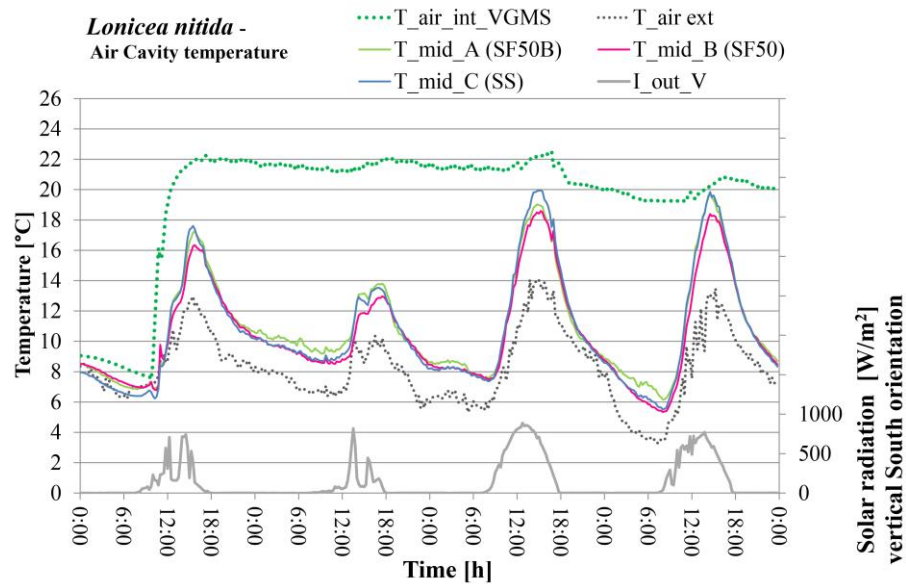


736
737

738 *Fig. 17. Winter season, comparison between the *Heuchera* hybr. (left) and *Bergenia cordifolia* (right).*

739 The presence of an air gap behind the vegetated module, as previously mentioned, can significantly affect
 740 the VGMS behaviour. Therefore, the air cavity temperature between the wall and the green module was
 741 analysed for the three VGMS modules for cloudy and sunny winter days, as shown in Fig. 18. During the
 742 day and the night, the air cavity temperatures was higher than the external temperature ranging from between
 743 about 2°C and 6 °C, which shows that the VGMS improved the thermal performance of the entire structure
 744 and that the vegetated substrate layer created a thermal buffer which increases the insulation features of the
 745 module.

746 In order to evaluate the influence of different substrates on the global thermal behaviour of the VGMS, the
 747 air temperatures were measured in the cavity behind the three A, B and C modules, which were characterised
 748 by the SS, SF50B and SF50 substrates, respectively (see the substrate description reported in Table 1 and
 749 the position of the substrates in the test cell reported in Fig. 6). As can be seen in Fig. 18, it was possible to
 750 observe a very similar profile, which indicates that the presence of the recycled material in the substrates
 751 did not improve the insulation level, as expected. These findings were in line with the results of the thermal
 752 conductivity measurements of the different substrates, carried out by means of a hot plate in the Energy
 753 Dept. [12].
 754



755
756 Fig. 18. Air cavity temperature T_{mid} (between the VGMS and the wall) of the 3 substrates A, B, C with *Lonicera*
757 *nitida*

758 **Results: VGMS – summer performance**

759 Unfortunately, the measurements in the summer season were carried out in free floating conditions, and it
760 was therefore not possible to obtain consistent data related to the heat fluxes crossing the façades. Given the
761 high thermal resistance of the envelope, which was necessary to comply with the U-value limits stated in
762 the current regulations, the measured heat fluxes were too low to provide significant data. Nevertheless, it
763 was possible to assess the effect of the VGMS on the reduction of the external surface temperature and on
764 the indoor air.

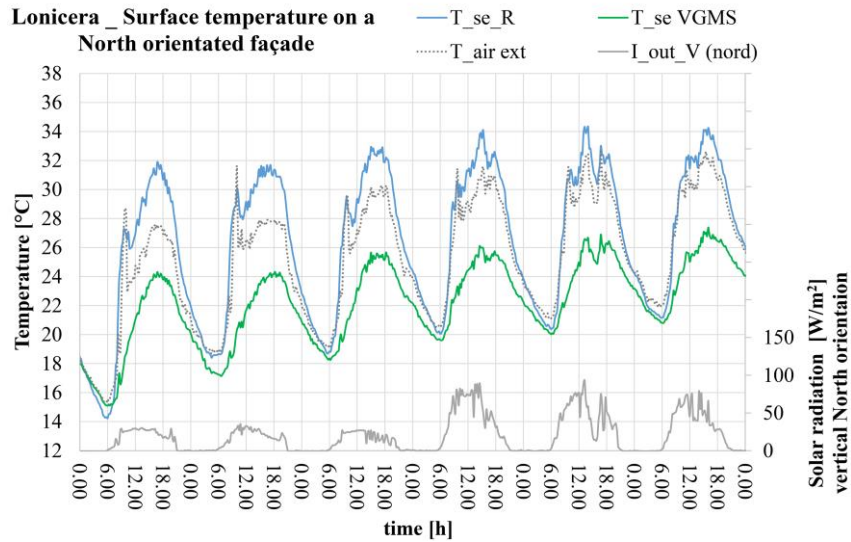
765
766 The outdoor surface temperature was measured on both a south exposed façade (VGMS versus plastered
767 wall) and on a north exposed façade (VGMS vs wood cladding).

768 The peak temperature difference between the VGMS with *Lonicera nitida* and the reference plastered wall
769 was found to be 23°C on a sunny summer day, due to the evapotranspiration process. The experimental
770 results were, as expected, the same for SS and SF50, even though they were characterised by different LAI
771 values.

772 As far as the demonstration mock-up is concerned, a reduction in temperature was also observed between
773 the VGMS (*Lonicera nitida*) and the wood cladding, both of which only received diffuse solar radiation. As
774 can be seen in Fig. 19, the reference external surface temperature (T_{se_R}) was close to the external air
775 temperature, while the external surface temperature measured for the VGMS (T_{se_VGMS}) with *Lonicera*
776 *nitida* was about 6.5°C lower.

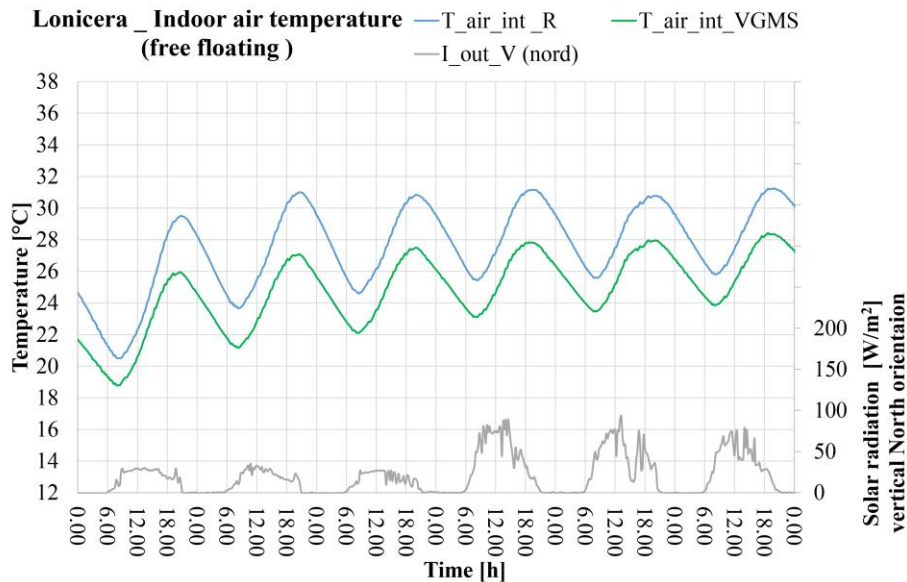
777 A reduction in the external surface temperature is very important at the urban level, as it can help to mitigate
778 urban heat island effects. Nevertheless, it is important to stress that the actual contribution that could be
779 observed is closely connected to the urban morphology, and ad-hoc studies need to be performed to better
780 quantify this aspect.

781



782
 783 Fig. 19. Demonstration building with *Lonicera nitida*. Comparison of the external surface temperature between the
 784 reference wall (T_{se_R}) and the VGMS wall (T_{se_VGMS}) both of which are north oriented.

785 During the summer season, in free floating conditions, the indoor air temperature in the two mock-up
 786 modules was measured. It is possible to note, in Fig. 20, that the indoor temperature of the module with
 787 three façades covered with VGMS was always lower than the reference module (with the wood cladding
 788 finishing). The peak indoor air temperature was reached, in both modules, in the evening, but the indoor air
 789 temperature of the module covered with the VGMS was always lower than the reference module. The
 790 maximum difference in the indoor air temperature between the two modules was about 4°C, and was
 791 measured during the peak hours. This finding was confirmed for the entire cooling season, and a repetitive
 792 trend was observed. This result shows the potentiality of VGMS to reduce the cooling load, and to avoid
 793 the necessity of installing HVAC systems to maintain the indoor temperature within the comfort range.
 794



795
 796 Fig. 20. Demonstration building, with *Lonicera nitida*. Comparison of the indoor air temperature between the room
 797 with the reference technology (wooden cladding $T_{air_int_R}$) and the room with the VGMS ($T_{air_int_VGMS}$).
 798 Measurements conducted in free floating conditions.

799 **3.6 Technological issues**

800 The following technological issues emerged from the monitoring activities that were carried out over a
801 period of three years. Particular attention was paid to the development of the prototypes, in particular as far
802 as the manufacturing, on-site assembling and maintenance stages were concerned.

803 *Manufacturing stage:* this was mainly focused on the system workability requirements and the availability
804 of material on the Piedmont market in order to minimise the environmental impacts and reduce the material
805 intensity. The materials and semi-finished products were obtained from suppliers located within a maximum
806 distance of 70 km from the site chosen for the assembly (CEIT-Asti). Furthermore, the assembly of the
807 components that were tested during the prototyping activities led to the identification of the manufacturing
808 phases, currently done by hand, which could be implemented in an industrialized process, for example, the
809 cutting of the felts and the mixing of the growing medium. Some activities, such as the insertion of the
810 plants into the pockets can only be done by hand. Six hours/man was required during the prototyping
811 activities to produce 1 m² of LWS. It was assumed that the industrialization of some processes could reduce
812 the preparation times by 50%, with a consequent reduction in the production costs.

813 *On-site assembling stage:* this was mainly focused on easy and quick-assembling procedures. GRE_EN_S
814 LWS is made up of light modular boxes with reverse assembling connections and the possibility of fast
815 installation. The modular boxes are also pre-vegetated in nurseries, and therefore already provide an
816 aesthetic effect. On the whole, these features allow 16 man hours per 25 m² of installed wall to be achieved,
817 which is equivalent to the work of 2 installers per day.

818 *Maintenance stage:* this was mainly focused on minimizing the water needs and the number of prunings per
819 year. The irrigation system was equipped with a control unit which regulates the solenoid valves; the
820 selected plants required a reduced number of prunings and had limited water needs. As it is possible to see
821 in Fig. 21, one year after its installation the VGMS presented a flourishing aspect.
822



823
824 *Fig. 21. Demonstration building, one year after plantation (Environment Park, Turin, Italy)*

825 Moreover, the costs were analysed in relation to the stages described above (Table 10) and similar LWSs
826 available on the market were compared (Table 11).
827

828 Table 10. GRE_EN_S costs.

<i>Stages</i>	<i>Costs</i>
Manufacturing	Reused and recycled materials; reduced acquisition costs of the raw materials.
On site installing	Reduced installation costs, due to the developed building system (modular boxes that are easy to carry, install, and disassemble).
Maintenance	Reduced maintenance costs, due to the limited water requirements (2 l/h m ²) and to the limited number of yearly prunings (2 prunings /year) necessary for the monitored species (<i>Lonicera nitida</i> , <i>Bergenia cordifolia</i> , <i>Heuchera</i> hybr.).

829

830 Table 11. GRE_EN_S and LWSs. Comparison of the systems on the market.

	GRE_EN_S	Similar LWSs available on the market
Price	400 €/m ²	€750 /m ²
Thickness	3.5-10 cm	10-20 cm
Weight	18 kg/m ²	> 50 kg/m ²

831

832 4- Discussion and conclusions

833 VGMS, Vertical Greenery Modular Systems, are able to provide several benefits to buildings. The complete
 834 and multidisciplinary results of a research project (GRE_EN_S) on VGMS are presented in the paper. From
 835 the design phase of the VGMS to the complete characterisation of the technology, the decisions were
 836 supported by analyses and experimental results. The VGMS and the plant species were subjected to
 837 extensive monitoring campaigns in a nursery, in a test cell and in a demonstration mockup in Turin (North
 838 West Italy, Cfa, temperate sub continental climate, according to the Köppen climate classification). The aim
 839 of the research was to design a new VGMS and to evaluate different kinds of vegetation species, different
 840 substrates and technological systems characterised by a low embodied energy. The process started with an
 841 LCA, which allowed the raw materials to be selected and the importance of addressing the choice towards
 842 a recycled aluminum frame for the technological support of the module to be highlighted. The mechanical
 843 test allowed the suitability of the felts to be tested in order to guarantee sufficient mechanical strength to
 844 support the weight of the roots and also an adequate permeability to ensure a sufficient water level for the
 845 plants. A biometric analyses allowed the response of different plants (*Lonicera nitida*, *Bergenia cordifolia*
 846 and *Heuchera* hybr. ‘Red purple’) to be evaluated under vertical conditions, and the interaction between
 847 different vegetal species and substrates to be tested. The results have shown that the right combination of
 848 plant species and substrates can significantly improve the VGMS performances and improve the quality of
 849 the green covering. As far as VGMS maintenance is concerned, the use of evergreen shrubs permits the
 850 number of interventions a year to be limited, but an appropriate design and integrated automatic irrigation
 851 system must be programmed carefully. As much as 50% in volume of alternative recycled materials, such
 852 felt pads and viscose, can be used in the VGMS substrate; this helps to improve the water retention, and to
 853 facilitate root development and plant anchorage in the module. An acoustic analysis demonstrated that the
 854 system acts well as a sound insulation system, and its high sound absorption could be exploited to reduce
 855 the urban canyoning effect. Thermal performance analyses showed interesting effects that were found

856 during both the heating and cooling seasons. The tested walls with VGMS showed good thermal
 857 transmittance values, and the external surface temperature of the VGMS during the cooling season, which
 858 was much lower than that of the reference technology, highlighted the importance of this solution at an
 859 urban level, as it was able to efficiently counteract the urban heat island effect. No particular differences
 860 were noticed, in terms of heating performance, when different substrates and vegetal species with different
 861 LAI (*Lonicera*, *Bergenia* and *Heuchera*) were compared. The results of a real-scale application of VGMS
 862 in the demonstration mock-up highlighted the potentiality of VGMS to reduce the indoor air temperature
 863 during the summer period by as much as 4°C, in comparison to the reference technology in a free floating
 864 condition.

865 LCA analyses, a mechanical test, and biometric, acoustic and thermal results have made it possible to fully
 866 and reliably characterize the GRE_EN_S performance, with the result that a data set that covers different
 867 aspects was obtained. Even though VGMS are expensive solutions, they can provide multiple services in
 868 the urban context. The use of VGMS could facilitate the spread of this kind of greening over the next few
 869 years. A relevant output of the project is its interdisciplinary and multiscale approach, which does not allow
 870 a unique and best solution to be identified, but rather a set of data that designers could efficiently combine
 871 by adopting different materials/species/technical solutions, according to the goals and expected results
 872 (aesthetic value, energy saving, noise reduction, money sparing, ...).

873
 874 **Acknowledgments**
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 877 Reviplan, Ricrea and Safitech. The Authors would like to thank P. Taricco and F. Bronuzzi for their help
 878 with the acoustic measurements and Mr. Secondino Lamparelli for providing the nursery plants.

879
 880 **Nomenclature**

881	A_m	area of one module	$[mm^2]$
882	A_T	equivalent sound absorption area	$[m^2]$
883	C^*	equivalent thermal conductance	$[W/(m^2K)]$
884	$D_{2m,nT}$	sound insulation level of the façade	$[dB]$
885	E	elastic module	$[Nm^{-2}]$
886	E_{24}	daily energy for heating	$[(Wh)/m^2]$
887	GI	growing index	$[cm^3]$
888	GWP	Global Warming Potential	$[kg CO_{2eq}]$
889	h	plant height	$[m]$
890	K	hydraulic conductivity	$[ms^{-1}]$
891	k	intrinsic permeability	$[m^2]$
892	LA_m	Leaf Area per module	$[mm^2]$
893	LAI_m	Leaf Area Index per module	$[-]$
894	\dot{Q}/A	Specific heat flux	$[W/m^2]$
895	r	reflected sound energy	$[-]$
896	R_{si}	indoor surface resistance	$[(m^2K)/W]$
897	R_{se}	outdoor surface resistance	$[(m^2K)/W]$
898	S	surface area	$[m^2]$
899	t_s	surface temperature	$[°C]$
900	t_{air}	air temperature	$[°C]$
901	U^*	equivalent thermal transmittance	$[W/(m^2K)]$
902	w	plant diameter	$[m]$

903			
904	<i>Greek symbols</i>		
905	α	Sound absorption coefficient for random incidence	[-]
906	α_0	Sound absorption coefficient for normal incidence	[-]
907	Δ	difference between the indoor – outdoor temperatures	
908	$\Delta\sigma$	incremental stress	[Nm ⁻²]
909	$\Delta\varepsilon$	incremental strain	[-]
910	μ	dynamic viscosity	[Pa s]
911	ρ	density	[kg·m ⁻³]
912	σ_y	yield strength	
913	σ_T	tensile strength	
914	σ_B	breaking strength	
915	τ_{60}	reverberation time	[s]
916			
917	<i>Acronyms</i>		
918	GMS	Green Module System	
919	GRE_EN_S	GREen ENvelope System	
920	LCI	Life Cycle Inventory	
921	LWS	Living Wall Systems	
922	R	referring to the reference technology	
923	SAP	Super Absorbent Polymer	
924	SF	substrate with felt	
925	SPAD	Soil Plant Analysis Development	
926	SS	standard substrate	
927	SSV	standard substrate and viscose layer	
928	VGMS	Vertical Greenery Modular System	
929			

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