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

V. Serra[a], [*], L. Bianco[a], E. Candelari[a], R. Giordano[b], E. Montacchini[b], S. Tedesco[b], F. Larcher[c], A. Schiavi[d]

[a] TEBE Research Group, Energy Department, Politecnico di Torino, C.so Duca degli Abruzzi 24, Torino, Italy
[b] Department of Architecture and Design, Politecnico di Torino, Viale Pier Andrea Mattioli 39, Torino, Italy
[c] Department of Agricultural, Forest and Food Sciences, Università degli Studi di Torino, Largo P. Braccini 2, Grugliasco, Torino, Italy
[d] INRIM – National Institute of Metrological Research, Strada delle Cacce 91, Torino, Italy

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0-abstract (max 200 words)

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

1- Introduction

Urban greening provides ecosystem services, and the role of green areas for the well-being of citizens is acknowledged throughout the world [1]. The positive effects of urban vegetation are also important at the built environment microclimatic performance level, due to climate change and pedestrian thermal comfort reasons [2]. The urban environment is characterized by particular conditions, in terms of light, water and nutrient supply, as well as particular temperature and pollution regimes. These aspects can represent a drawback for the development of plants and trees, especially if the purpose is to create urban greening with high aesthetic performances. Nevertheless, green roofs and green walls are the best examples of the extreme relationship between nature and technology in urban greening [3].
Outdoor vegetation applied to the building envelope has proved to be able to positively improve the performances of buildings and urban environmental quality [4]. The subject of green infrastructures is related to various topics – such as buildings, plants, substrates and technology - and its impact on buildings and the city should be considered multidisciplinary, since it covers various aspects, such as energy performance, acoustics, air quality and environmental aspects [5]. Furthermore, different solutions can be

adopted, and different effects can be pointed out for each of them, nevertheless, a lack of a common terminology has been found in literature [6]. Among the various types of green façades, Living wall systems (LWS), are known to be expensive technological systems in which the choice of the right plant and its management are crucial for client satisfaction. However, only a few xerophytic and well adapted species are able to survive spontaneously on vertical surfaces [7,8].
A recently published research has summarized the last 23 works on the subject, between 1988 and 2015, and has introduced the term vertical greenery system (VGS) [9]. A sub-category of VGS is the vertical greenery modular system (VGMS), where a modular technological box is designed in order to provide a good site for rooting, as well as a suitable amount of water and nutrients for the plants to grow.
This kind of technological solution is able to provide different beneficial effects: during the cooling season, thanks to the shading effect of the leaves and the evapotranspiration of the plants, the entering loads are lowered [10], while, during the heating season, it can contribute to reducing heat losses and improving surface thermal resistance, because of the wind reduction in the vicinity of the wall [11,12], to increasing the sound insulation of the wall [13,14] and reducing the environmental impact of the buildings [15–17]. At an urban level, VGSs are able to filter pollution [18], to sequester CO_2 [19], to reduce urban sound propagation [20–22], to give a pleasant aesthetical aspect to a building, to improve the bio-diversity [23] and to mitigate the urban heat island effect (UHI) [24,25].
The species used in outdoor living walls vary to a great extent, depending on the location, on the exposure to the sun and wind and on the height of the building [26]. Studies on the use of edible species, evergreen perennials and Mediterranean shrubs have been performed in Sweden and in Italy [27 and 28]. Apart from these studies, very little research has been focused on the analysis of the substrate [26,29] or on the role of the growing media on root and aboveground plant growth [30]. A synthesis table of the different parameters that influence the energy performance of greenery on energy consumption has been reported in a review paper (table 4 in [31]). For these reasons, the interest in this kind of technology, applied to vertical walls, has been growing in the last few years, and the biomimetic principles of plants have been studied in order to inspire new façades based on adaptive performances [32].
In this framework, a research project on a novel Vertical Greenery Modular System (VGMS) has been carried out in Turin (North West Italy, Lat. 45° N). The developed system has been investigated experimentally by evaluating different kinds of vegetation species, substrates and technological systems. A multidisciplinary approach has been used, by a mixed work group composed of partners with different skills, to optimise the performance of the VGMS prototypes. The first experimental results, which were only related to thermal aspects, were published in Bianco et al. [12]. The entire project is presented in this paper. First, details are given on the design phases, which were followed in a cascade process. The methodologies that were adopted and the results that were obtained, through lab and long-term in-field monitoring, related to the biometric, thermal, acoustic and mechanical performances, are then discussed, and the technological issues that have arisen are mentioned.

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

GRE_EN_S (GREen ENvelope System) is the acronym of an EU research project that was aimed at designing, prototyping and monitoring an innovative VGMS, constituted by modular boxes, covered with vegetation, made of recycled/natural materials and characterised by a high energy/environmental performance.
The adopted process was aimed at optimising the performance and the technical/economic viability of the system, considering the manufacturing, on-site assembling and maintenance stages.
The challenge of this project was to design an advanced LWS, that would be highly performing from the energy, acoustic and agronomic points of view, and which would be easy to install and maintain and, at the same time, be cost effective. Given the modularity of the façade, this LWS is a Vertical Greenery Modular System (VGMS). As far as the high energy efficiency is concerned, both the operational energy (heating and cooling demand reduction) and the embodied energy were taken into account. A key factor was the low

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

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

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

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

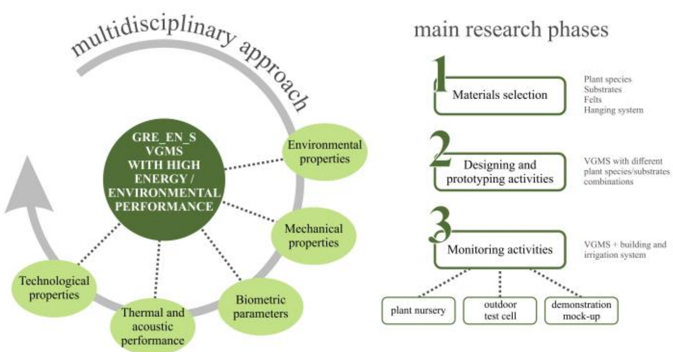

Fig. 1. Sketch of the GRE_EN_S project methodology: a multidisciplinary approach from the technology to the performance

2.1 Selection of the VGMS features and materials

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

Each "Product_datasheet" was divided into two-parts:

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

The “material cards” were characterized according to a Life Cycle Approach [33]. Each “material card” included environmental information about: the country of origin and the availability of the materials on the local market (in order to assess the transportation impact); the embodied energy and carbon dioxide equivalent emissions (to evaluate the depletion of the energy sources and the related climatic changes); the end of life scenarios (to assess the recycling potential); environmental labeling (when available). On the whole, 35 material cards were developed from the large amount of information that was available in databases and software [34].
The “Product datasheet” and “Material cards” provided detailed knowledge about both the technological connections and the most suitable materials to be used in GRE_EN_S VGMS.
The above-mentioned databases proved to be useful tools for the subsequent phase, related to the design and manufacturing of the prototypes.

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

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

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

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

After two prototypes had been proposed, both of which showing some problems from the technological point of view, a third prototype was developed, and was then fully characterised through extensive experimental activities. This third prototype (Fig. 2) was made up as follows: 1) aluminium alloy was used as the frame 2) a polypropylene monofilament double geomat-grid was used as anchorage for the roots; 3) a growing medium, based on standard substrate felt-pad wastes and coconut peat, was inserted 4) a recycled polypropylene material and a nonwoven viscose fabric were used as UV resistant and water absorption layers, respectively.

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

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

a b c

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

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

<u>Vegetal species</u>

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

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

- *Bergenia cordifolia* L.: a species that had not been tested previously on living walls and is characterized by large, thick greenish-purple coloured leaves and pink flowers. This is also a low maintenance hardy species.
- *Heuchera* hybr. ‘Red purple’: a species with medium sized leaves and a bronze – dark purple colour, which requires higher maintenance and can be affected by pests.

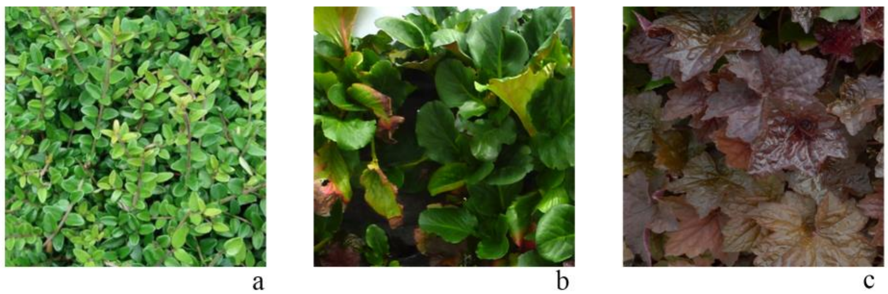

Fig. 4. Plant species: Lonicera nitida (left), Bergenia cordifolia (centre), Heuchera hybr. ‘Red purple’ (right).

Substrates

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

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	

Irrigation system

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

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

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

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

2.3.1 The plant nursery activities

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


a b

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

2.3.2 The outdoor test cell activities

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

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

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

2.3.3 Real-scale demonstration mock-up

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

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

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

The demonstration mock-up structure was prefabricated and supplied by one of the project partners. The demonstration building module envelope with the VGMS was constituted by: plasterboard (1.2 cm), an XPS panel (5 cm), an XPS panel (3 cm), an air cavity (5 cm) and a VGMS module (4 cm). The reference building walls were constituted by: plaster (1.2 cm), an XPS panel (8 cm), an XPS (Extruded Polystyrene Foam) panel (3 cm), an air cavity (5 cm) and the wooden cladding (1.8 cm). The two assemblies had different insulation thicknesses which, on the basis of the previous results obtained on the test cell, would have made the thermal transmittance of the two vegetated and non-vegetated walls equivalent, thus fulfilling the U-value limit imposed by national regulations for the climate in Turin. The location of the demonstration mock-up structure was based on previous studies that took into account various environmental aspects, such as the orientation and prevailing wind. The demonstration building was thus located in an area with an east-west axis orientation, in order to study both the foliage development and the thermal performance under extreme conditions (North vs. South Façade; summer time vs. winter time in temperate climates). The indoor environment temperature was only controlled during the heating season, by means of radiators, while the indoor temperature was free running during the cooling season.

Fig. 7. Demonstration mock-up.

3- GR_EN_S performance characterisation

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

Table 2. Synthesis of the VGMS characterisation.

Parameter	Test	Specimen	Aims
LCA		*Lonicera nitida* + 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 (*Lonicera nitida*, *Bergenia cordifolia* and *Heuchera* 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 (*Lonicera nitida*, *Bergenia cordifolia, Heuchera* hybr. 'Red Purple') + SS+SF50+ GMS module	Acoustic sound absorption
Acoustic performance	Demonstration mock-up	*Lonicera nitida*, *SS*	Sound insulation
Thermal performance	Test cell + Demonstration mock-up	*Lonicera nitida*, *Bergenia cordifolia* and *Heuchera* hybr. SS +SF50	Equivalent thermal conductance and transmittance / Surface temperature and air cavity temperature – daily energy for heating – indoor air temperature

3.1 Life Cycle Assessment (LCA) of the adopted materials

As mentioned in section 2.1, an LCA was adopted as a decision-making tool for the GRE_EN_S development (or for the prototyping implementation) and as a strategic tool for both the energy and raw material optimization and for the greenhouse emission reduction, with particular reference to CO_2 equivalent (CO_2eq) emissions [33].
A 100 year Global Warming Potential (kg CO_2eq) time-horizon was assumed as the environmental effect in order to assess the interaction between the modular box in its off-site construction and climate change.
The environmental characterization was conducted considering the LCA standard (ISO 14040 2006) [35].
The analysis was basically performed, according to the design stage, using secondary data (generic data from the literature or from the databases mentioned in section 2.1). Although these simplifications affected the accuracy and applicability of the LCA results, they were adopted in order to quickly identify the potential environmental effects. LCA was employed in the research project with the aim of finding an ecological way of improving the building-system design and minimizing the environmental burdens in the production stages (upstream and manufacturing processes: from cradle-to-gate). LCA was assumed as a decision-making tool for the GRE_EN_S development system and as strategic tool for both the energy and raw material optimization and for the greenhouse emission reduction, with particular reference to CO_2 equivalent (CO_2eq) emissions [36].
The functional unit (F.U.), the boundary and the cut-off rules are listed and described in Table 3.

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.

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

Table 4. Data Inventory (reference scenario)

Material	**Weight [kg/m^2]**
Lonicera 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

As far as the allometric equation used to predict the *Lonicera nitida* biomass is concerned, the carbon content and the dioxide credit contained within the wood were calculated. The biomass was estimated as 2.66 kg/m^2 (and was assumed as a negative value in the CO2 eq. balance).Two scenarios were analysed. In the first, 100% of raw materials (reference scenario) was taken into account in the data inventory, while a recycling rate (30%) for the aluminium alloy and polypropylene, that is, both the fibre and geomat, was assumed in the second data inventory (recycling scenario). Moreover – according to the research goals – the potting soil mixture was engineered in the recycling scenario by replacing SAP with recycled nylon-based felts. The thus developed potting soil reduced the total SAP amount by half. The considered recycled blend was: 50% of raw soil; 15% of SAP; 15% of recycled felt; 15% of coco-coir; 5% of peat moss. The difference in weight (kg/m^2) of the raw materials and recycled materials was negligible, with reference to F.U. (< 0. 05 kg per F.U.)

<u>Results</u>

The total GWP100 for the reference scenario was calculated as 55.98 kg CO_{2eq} /m^2. The total GWP100 for the recycling scenario was 20.45 kg CO_{2eq} /m^2, which is about one third of the value determined in the reference scenario. In both scenarios, the credits due to the *Lonicera* biomass and viscose fabric were remarkable, and they amounted to 13.13 kg CO_2eq /m^2 (Fig. 8).
Aluminium alloy showed the most impact on climate change: 60.00 kg CO_2eq /m^2 (standard reference scenario) and 27.00 kg CO_2eq /m^2 (recycling scenario), respectively.
As a general rule, even the recycled fibre and geomat-grid polypropylene-based material were characterized by a reduction in GWP 100 (the difference accounted for about 1.3 CO_2eq kg/m^2). However, such a reduction was less remarkable than the GWP100 decrease for aluminium.
The small amount of potting soil analysed for both scenarios did not significantly affect the CO_2eq emissions. Nevertheless, the comparison between the two blends highlighted the importance of replacing SAP with recycled felts. The growing medium manufactured with SAP had a five times higher GWP100 (0.10 kg CO_2eq /m^2) than the recycled one (0.02 kg CO_2eq /m^2).

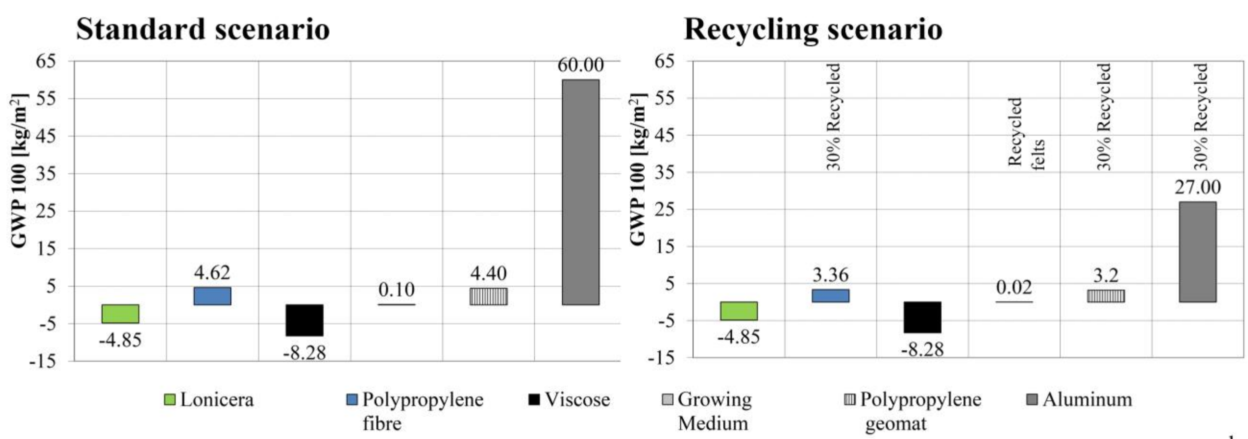

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Fig. 8. a) GRE_EN_S Global Warming Potential (target of 100 years) for the reference scenario. b) GRE_EN_S Global Warming Potential (target of 100 years) for the recycling scenario.

3.2 Mechanical properties

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

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

Typology		Thickness L /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

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

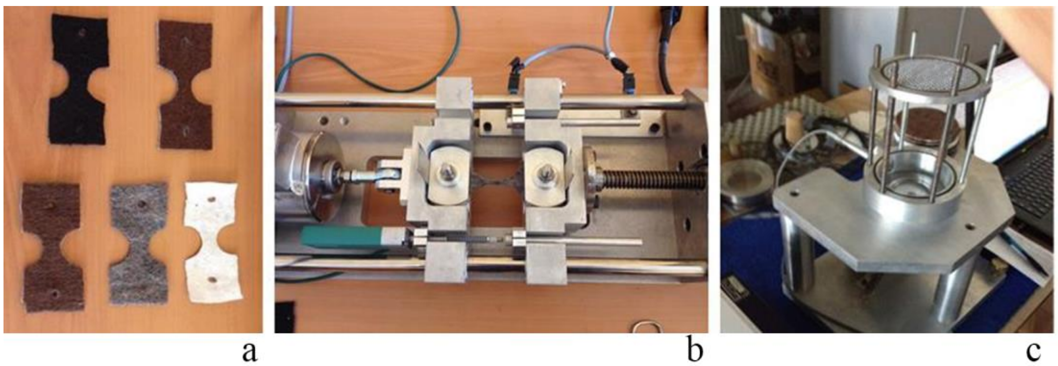

Fig. 9. Specimens of the technological support materials and devices for the stress-strain and permeability measurements.

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

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

<u>Results</u>

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

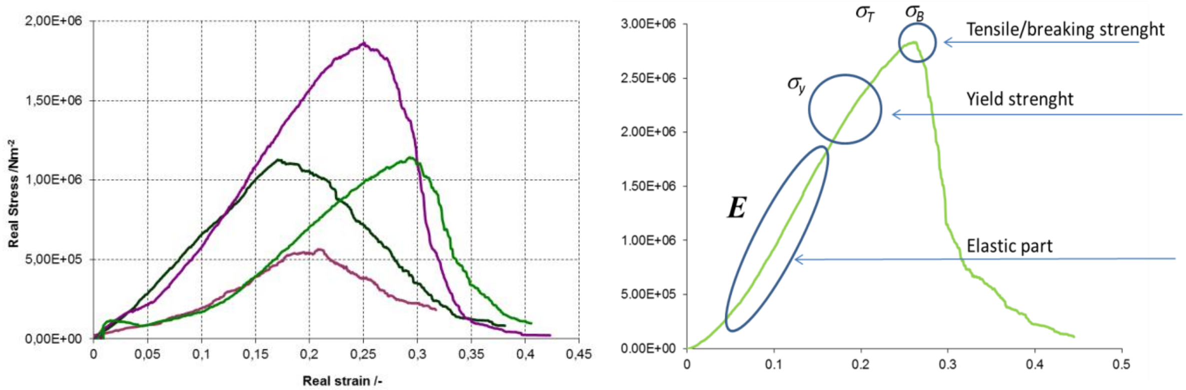

Fig. 10. Experimental "stress-strain" diagrams of several technological support materials and evaluation of the mechanical properties.

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

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

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	$7.0\cdot10^6$	$1.0\cdot10^6$	$1.1\cdot10^6$	$1.1\cdot10^6$	$1.24\cdot10^{-9}$	$1.53\cdot10^{-2}$
I-2	$1.4\cdot10^6$	$5.3\cdot10^5$	$5.6\cdot10^5$	$5.6\cdot10^5$	$2.46\cdot10^{-10}$	$3.02\cdot10^{-3}$
E-3	$2.6\cdot10^6$	$3.0\cdot10^6$	$5.0\cdot10^6$	$4.7\cdot10^6$	$4.27\cdot10^{-10}$	$5.25\cdot10^{-3}$
I-4	$2.5\cdot10^5$	$1.6\cdot10^6$	$1.9\cdot10^6$	$1.4\cdot10^6$	$7.19\cdot10^{-10}$	$8.84\cdot10^{-3}$
E-5	$5.8\cdot10^6$	$1.0\cdot10^6$	$1.1\cdot10^6$	$1.1\cdot10^6$	$6.87\cdot10^{-10}$	$8.44\cdot10^{-3}$

3.3 Biometric parameters

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

- test the suitability of the different species for VGMS applications

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

As is usual in VGMS arrangements, the initial growing phase was performed in a nursery with small plants in pots of about 8 cm in diameter. Two experimental trials were performed in a nursery in Moncalieri near Turin (Italy) (45°00'58'' N, 7°74'15'' E), in which the Reviwall® supporting technology (as patented by Reviplant Nurseries, Moncalieri, Italy) was modified. The single module was 40 cm width × 50 cm high, it was hung on metal supports and it was composed as follows: a frame of galvanized aluminum, two layers of rootable nonwoven synthetic mats, and two geogrids, one under and one above the 100% coconut fiber substrate. Six pockets were cut out of each panel to house 6 plants.
The *Lonicera nitida*, *Bergenia cordifolia* and *Heuchera* hybr. 'Red Purple' ornamental species were grown vertically in different technical solutions in order to evaluate their suitability for this kind of application. Each module contained 2.5 l of substrate, and the weight (before irrigation) varied between 1.3 kg and 1.8 kg, depending on the substrate features.
Two different trials were performed in the nursery, as described in Table 7. Two species and four different substrates were compared in each trial (Fig. 11).
Starting from a standard substrate composition (SS made of: 100% coconut fibre with hydro-retainers, and mycorrhizal Inoculum composed of 30/g of Glumus spp. Fungal spores), different compositions and combinations were investigated. It was assumed that the addition of felt and viscose to the substrates would improve the water retention of the system, and as a result, the growing potentiality of the plant. During trial 1 (Table 7), the SS was compared with alternative substrates with different percentages of coconut fibre and shredded felt: SF50; SF50B; SF100 (see section 2.2 for details of the composition). In trial 2 (Table 7), SF50B and SF100 were substituted by two other substrates with a viscose layer (named SSV and SF50V).

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

	Plant species	Substrates (ID code)	Period (duration)
Trial 1	*1. Lonicera nitida* *2. Bergenia cordifolia*	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. Lonicera nitida* 2. *Heuchera* 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)

Eighteen plants (three modules) were organised randomly within a block for each of the 8 plant-substrate combinations in each trial. Six blocks, over a total area of 28.8 m^2, and 144 modules were tested. A westwards exposure was chosen as it was found to be the worst situation for the plants in the summertime. The plants were fertirrigated (Mineral soluble fertilizer: N, P_2O_5 e K_2O), adopting the standard procedure, using Algapark® (Canale d'Alba, Italy) and Criscap® 16-12-23 NPK (Canale d'Alba, Italy).
Five monthly surveys were performed to monitor the plant growth and the quality of the green cover, and the following were considered:

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

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

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

Measurements were performed on 9 plants chosen randomly during each thesis. At the end of each trial period, the aerial parts of 9 plants were dried in an oven at 90°C for 4 days, and their dry weight was determined.
Moreover, in order to analyze the interaction between the species and the substrates, the data were subjected to a one-way analysis of variance in which the data were tested with the Ryan-Einot- Gabriel-Welsh process [43], using the SPSS statistical package (Version 17.0, SPSS Inc., Chicago IL).
In order to analyse the thermal performances, 3 modules were cultivated in the test cell for each substrate (SS, SF50 and SF50B) of *Lonicera nitida* and *Bergenia cordifolia*, taken from trial 1 [12].
The leaf area index (LAI) [44] of six plants was calculated for each combination of species and substrate. This parameter was of particular interest as far as the cooling potential of the plants was concerned, since it can be considered as an equivalent shadow index of the plants. The relationship between LAI and the energy performance of the plants was investigated, and the results are given in section 3.5.
In order to measure the LAI, leaves were cut and scanned with an A3 standard scanner, and the free Xnview scanner software (version 1.98.2/1.70 by Gougelet P., Reims, France) was used. The images were modified appropriately, and the leaf data (area, perimeter, number) were automatically calculated using the free ImageJ software (version 1.45m by Rasband W., Bethesda, Maryland, USA).
The Leaf Area Index was calculated for one module (*LAIm*) using Eq. (2):

$$LAI_m = LA_m / A_m \qquad (2)$$

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) of one module.

Results

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

A synthetic comparison of the main results obtained at the end of the trial 1 is shown in Table 8. The Growth Index (GI), the dry weight of the aerial parts of the plants, and the SPAD index values *for Lonicera nitida* and *Bergenia cordifolia* are reported.
The substrates with 50% of shredded felt pads (SF50 and SF50B) induced more lignification in *Lonicera nitida*, and caused the yellowing of leaves (lower SPAD values than SS). SF100 produced significantly different plants from those grown in the other substrates. The *Bergenia* plants grown in SS and SF50 had larger volumes, more leaves (data not shown) and greener leaves than the ones grown in SF50B and SF100 (Fig. 11). In trial 1, the best overall plant health biometric parameters were found for the SF 50B and SS substrates, and for this reason the SF50 and SF100 substrates were not used in trial 2.

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

Substrate	*Lonicera nitida*			*Bergenia cordifolia*		
	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
P	<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

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

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

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

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

Trial 2 – Biometric evaluation of different substrates for *Lonicera nitida* and *Heuchera* hybrida 'Red purple'

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

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

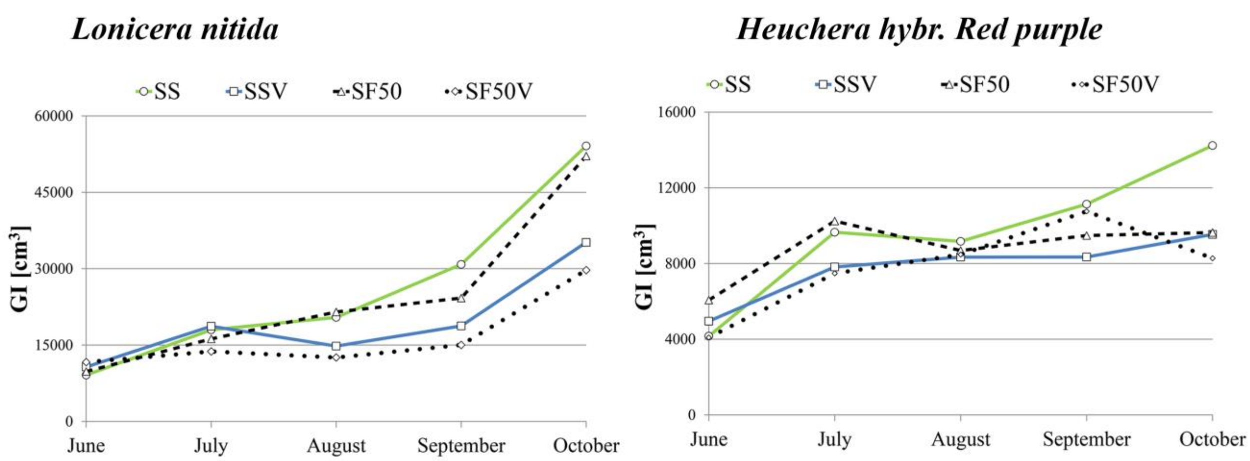

Fig.12.(Left) Growing index (GI) of the Lonicera nitida plants cultivated in the four substrates (Standard, SS; Standard + viscose, SSV; 50% Standard + 50% felt pads, SF50; 50% Standard + 50% felt pads + viscose, SF50V) during trial 2 (June-October). (Right) Growing index (GI) of Heuchera hybr. 'Red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

3.4 Acoustic performance

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

3.4.1 Laboratory characterisation of the acoustical properties

The acoustical performance of the VGMS was evaluated on the basis of the sound absorption, as a function of frequency, in the INRiM laboratory. The experimental techniques involved measuring the standing wave sound fields for small-scale samples, and the diffuse sound fields for large-scale samples.
Small-scale samples (cylinder cores, diameter 50 mm) of different plant leaves were considered, and substrate assemblies were conducted in both dry and wet conditions. The sound absorption coefficient was measured in a Kundt tube, according to the ISO 10534-2 standard [45] and to literature [46]. The sound absorption coefficient, in the 100 Hz to 3800 Hz frequency range, was determined at normal incidence α_0. The measurement provides accurate results [47], even for extremely heterogeneous and anisotropic materials, such as the examined stratigraphy. The technique is based on the measurement of a transfer function between the sound pressure measured by two microphones within the tube, when the tube is excited by a loudspeaker placed at one end, while the specimen is placed at the other end of the tube. The sound absorption coefficient was calculated by quantifying the dissipation of the reflected sound energy *r*, according to Eq. (3):

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

Three prototypes of large-scale VGMS systems (surface areas of 12 m^2) were also characterized, in terms of acoustic absorption coefficient, at random incidence α, according to the ISO 354 standard [48]. The method consisted of measuring the sound pressure time decay in a reverberation room, as a function of frequency, with and without the test specimen. The equivalent absorption area of the specimen A_T was calculated from the reverberation time values, according to Sabine’s formula, and the sound absorption coefficient of the test specimen was then determined, according to Eq. (4):

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

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

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

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

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

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

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

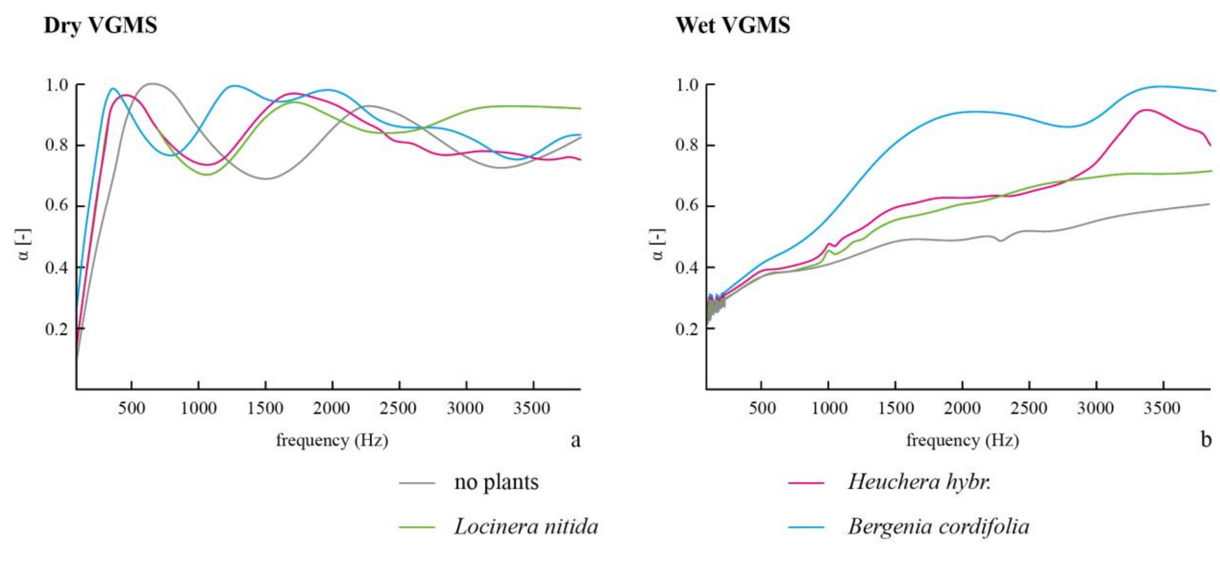

Fig. 14.The sound absorption coefficient (dry and wet conditions) of the VGMS for different vegetal species.

In order to provide an assessment of the sound absorption coefficient of the VGMS under operating conditions, measurement were carried out on different configurations of substrates, technological supports and plant species (*Lonicera nitida, Bergenia cordifolia, Heuchera* hybr. 'Red purple'), in both wet and dry substrate conditions. The values of the sound absorption coefficient were determined at normal incidence α_0 in the Kundt tube.
The three different systems VGMS-1, VGMS-1 without plants and substrate, and VGMS-2, were characterized in terms of sound absorption, as a function of the frequency, that is, between 100 Hz and 5

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

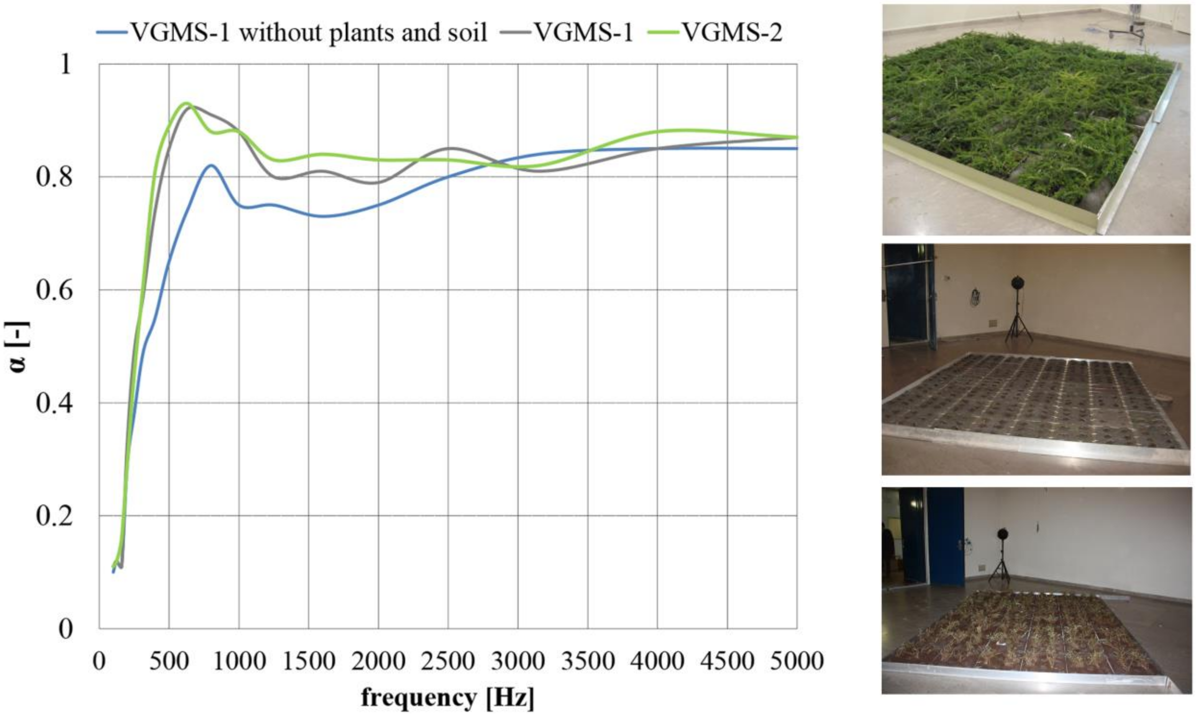

Fig. 15. Experimental sound absorption coefficient results in the reverberation room. The three different prototypes measured in the reverberation room were: VGMS_1, VGMS_1 without plants and soil, VGMS_2 (c).

3.4.2 Mock-up characterisation

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

<u>Results – Sound insulation level of the façade with *Lonicera nitida* grown in the SF50B substrate</u>

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

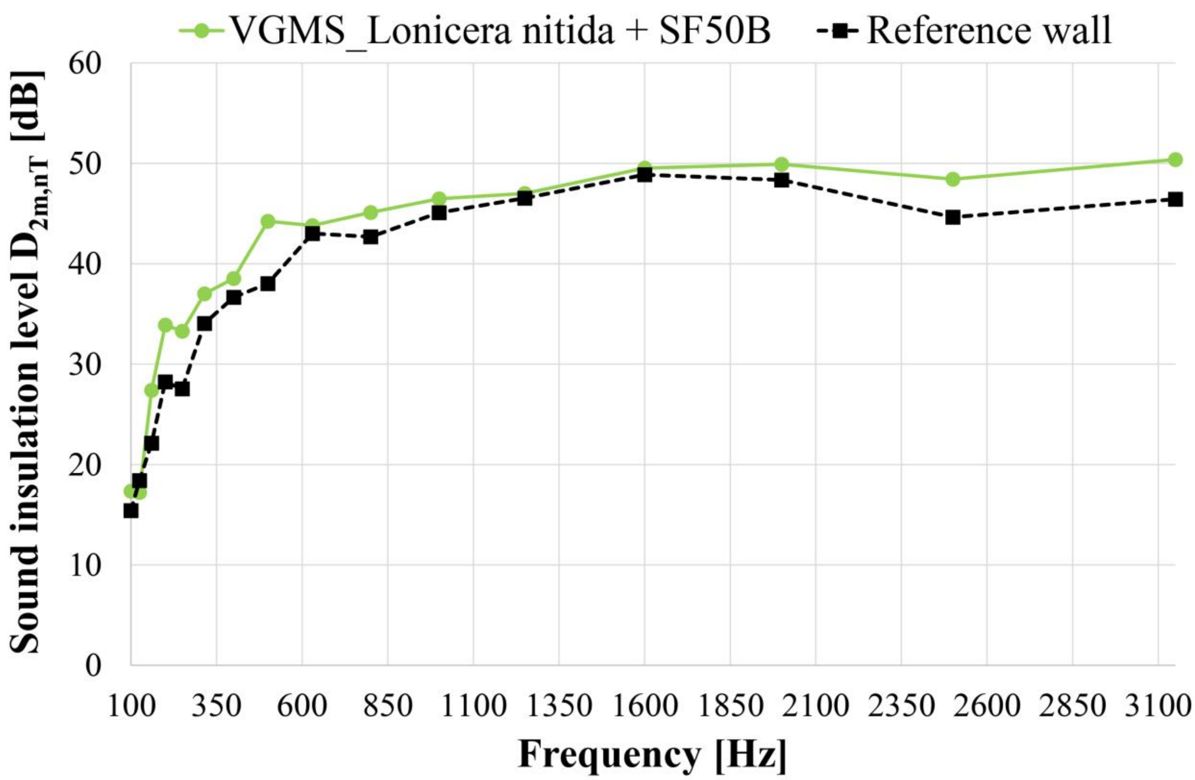

Fig.16. Sound insulation level of VGMS <u>*Lonicera nitida*</u> *+ SF50B and the reference technology.*

3.5 Thermal performance

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

The measurements were conducted to characterise the VGMS at the component scale, and to perform comparative analyses of different solutions. The thermal transmittance/conductance and the increase, due to the leaves, in the external surface resistances were assessed for the winter performance. Given the absence of an HVAC system, which would have been able to maintain the indoor temperature during the summer season, it was not possible to measure any dynamic parameters, such as the periodic thermal transmittance or thermal lag. Nevertheless, it is important to stress that, in this kind of system, which is characterised by a thin and light substrate and, as a consequence, by reduced evapotranspiration effects, the dynamic thermal behaviour that characterises other types of vegetated envelope (i.e green roofs) is not so significant. Aspects related to the reduction in the external surface temperature and in the indoor air temperature, due to the presence of the VGMS, were instead investigated in the cooling season.
Two different experimental campaigns were thus set up: one on the outdoor test cell (section 2.3.2) and the other on the demonstration mock-up (section 2.3.3). An extensive and continuous measurement campaign was carried out for both of the experimental activities. The measurement equipment consisted of

thermocouples, heat fluxes and a weather station connected to a data-logger, which recorded data every 15 min. All the instruments were previously calibrated or verified in the laboratory in order to guarantee the following uncertainties, using the/a 95 % confidence limit: ±0.3 °C for the temperature measurements and ±5 % for the heat fluxes, as declared by the manufacturers (with a nominal sensitivity of 50 μV/W/m^2). For the sake of brevity, only some details are reported concerning the measurement methodology, which is described in detail in [12].
During the heating season, the experimental data that were collected were used to calculate the equivalent thermal conductance (C* Eq. 5) and transmittance (U* in Eq. 6) of the VGMS and of the reference wall, according to standard [51]. The average value of the heat flux was divided, according to equations 5 and 6, on the basis of the difference in the surface and air temperatures (indoor and outdoor) to calculate the thermal equivalent conductance and the transmittance, respectively. The difference between the inverse ratio of U* and C* allowed the sum of the indoor and outdoor surface resistances to be calculated (Eq. 7).

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

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

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

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

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

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

Results: VGMS – winter performance

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

The test cell results showed lower thermal transmittance and conductance for the VGMS than the reference wall, which indicates a reduction in heat losses due to the presence of the vegetated module.
The comparison between the *Lonicera nitida* and *Bergenia cordifolia* results revealed no significant differences. Even though these species are characterised by different LAI, it does not seem to have affected the results to any great extent.
The results obtained in this set of measurements were used to define the insulation thickness that was to be adopted in the mock-up in order to obtain the same thermal transmittance (0.30 W/m^{2}K, as required by the national regulations). The presence of the vegetated module was estimated to be equivalent to 3 cm of XPS (see the description in section 2.3.3).The measurements carried out in the mock-up instead demonstrated an overestimation of the contribution of the vegetation (0.29 W/m^{2}K vs 0,26 W/m^{2}K). Nevertheless, it is important to highlight that the air cavity between the wall and the vegetated module was thicker in the mock-up than in the first prototype adopted in the test cell. It was actually decided to enlarge the cavity to increase the ventilation of the green façade in order to avoid an overheating effect during the night, due to the presence of a still warm cavity, as observed during the test cell measurement campaign. However, this

ameliorative strategy made the winter behaviour worse since the thermal buffer provided by the gap behind the vegetated substrate was reduced, as described hereafter.

Moreover, when the measured conductance and transmittance were compared, it was possible to determine the surface resistance values for both envelopes. Higher values were registered for the VGMS than for the reference wall, for both the test cell and the demonstration mock-up. The difference between the VGMS and the reference wall was 0.42 vs 0.31 (m^2K)/W for the test cell (plastered wall) and the difference was 0.42 (m^2K)/W vs 0.15 (m^2K)/W for the demonstration mock-up (wood cladding). It is in fact possible to state that the presence of vegetation on a façade noticeably increases the thermal resistance of the surface, compared to a standard wall. Since the resistance of the internal surface is the same (identical room, same temperature and control system), the difference can be attributed to the presence of vegetation, which is able to reduce the wind speed and significantly decrease the convective heat exchange between the wall itself and the external environment.

These findings suggest that even if plants and leaves can act as a shading device for the designed VGMS during winter and reduce the absorbed solar gain transferred to the wall they do contribute positively to the reduction in heat losses through the wall. This is due to both the surface thermal resistance increase and the creation of a thermal buffer between the wall and the vegetated module, as discussed hereafter. It is also possible to state that the use of evergreen species, which can reduce the maintenance cost of the façade, does not negatively affect the VGMS performance during the winter season.

Table 9. Equivalent thermal conductance and transmittance for the outdoor text cell and demonstration building. Results of the Lonicera nitida and Bergenia cordifolia species.

Outdoor Test cell	**Equivalent thermal conductance** C* [W/m^2K]		**VGMS**	**Reference**
		Lonicera nitida	0.22	0.63
		Bergenia cordifolia	0.21	0.57
	Equivalent thermal transmittance U* [W/m^2K]		**VGMS**	**Reference**
		Lonicera nitida	0.17	0.40
		Bergenia cordifolia	0.17	0.39
Demonstration Building	**Equivalent thermal conductance** C* [W/m^2K]		**VGMS**	**Reference**
		Lonicera nitida	0.33	0.26
	Equivalent thermal transmittance U* [W/m^2K]		**VGMS**	**Reference**
		Lonicera nitida	0.29	0.25

Two different days with similar boundary conditions were selected during the winter season to perform a comparison between two species: *Bergenia cordifolia* and *Heuchera hybr.* (the measurements were carried out for one species at a time). The daily heating energy, calculated with equation 8, and the boundary conditions of the two selected days are plotted in Fig. 17. It was possible to make a direct comparison of the two, since the boundary conditions were very similar, as confirmed by the very similar energy transmitted values through the reference wall, that is, of -153.9 Wh/m^2 and -151 Wh/m^2, respectively. The energies calculated for the VGMS were significantly smaller and very similar: -53.3 Wh/m^2 for the VGMS with *Heuchera* hybr. and 55.7 Wh/m^2 for the VGMS with *Bergenia cordifolia*. The two analysed species had different LAI values, as mentioned in the section dealing with the biometric parameters (section 3.3 – the results of trial 1), but, as observed previously when considering the very similar thermal transmittance values of *Lonicera nitida* and *Bergenia cordifolia,* it did not seem to affect the overall thermal behaviour to any great extent.

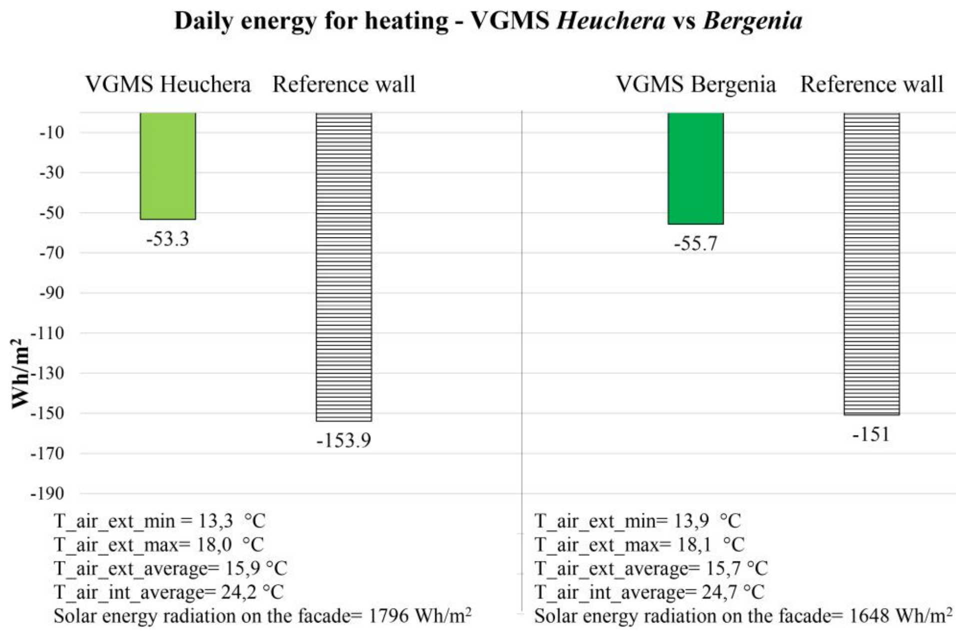

Fig. 17. Winter season, comparison between the Heuchera hybr. (left) and Bergenia cordifolia (right).

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

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

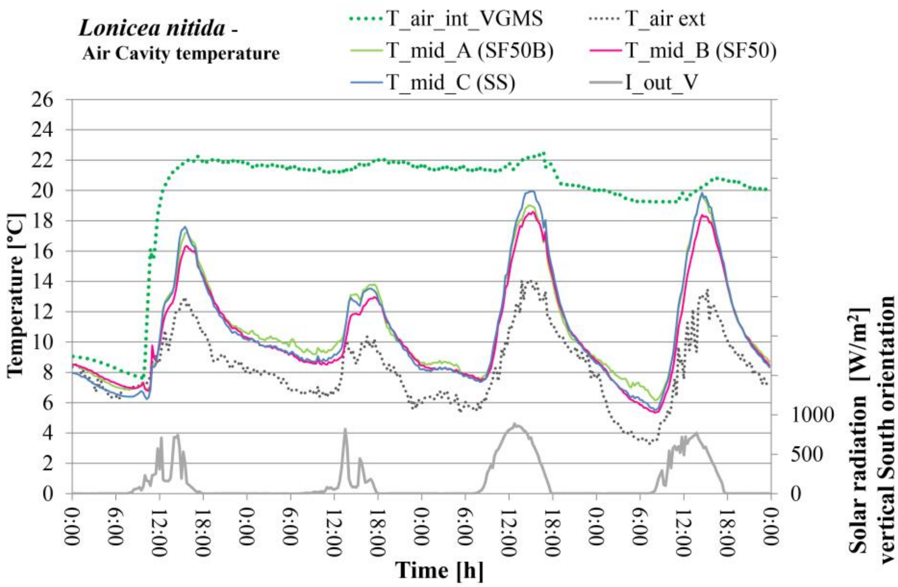

Fig. 18. Air cavity temperature T_mid (between the VGMS and the wall) of the 3 substrates A, B, C with Lonicera nitida

Results: VGMS – summer performance

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

The outdoor surface temperature was measured on both a south exposed façade (VGMS versus plastered wall) and on a north exposed façade (VGMS vs wood cladding).
The peak temperature difference between the VGMS with *Lonicera nitida* and the reference plastered wall was found to be 23°C on a sunny summer day, due to the evapotranspiration process. The experimental results were, as expected, the same for SS and SF50, even though they were characterised by different LAI values.
As far as the demonstration mock-up is concerned, a reduction in temperature was also observed between the VGMS (*Lonicera nitida)* and the wood cladding, both of which only received diffuse solar radiation. As can be seen in Fig. 19, the reference external surface temperature (T_se_R) was close to the external air temperature, while the external surface temperature measured for the VGMS (T_se_VGMS) with *Lonicera nitida* was about 6.5°C lower.
A reduction in the external surface temperature is very important at the urban level, as it can help to mitigate urban heat island effects. Nevertheless, it is important to stress that the actual contribution that could be observed is closely connected to the urban morphology, and ad-hoc studies need to be performed to better quantify this aspect.

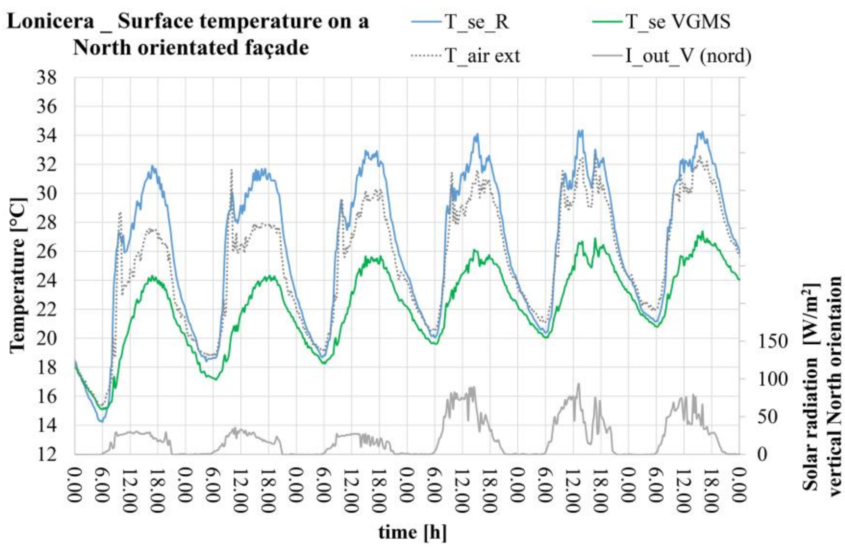

Fig. 19. Demonstration building with Lonicera nitida. Comparison of the external surface temperature between the reference wall (T_se_R) and the VGMS wall (T_se_VGMS) both of which are north oriented.

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

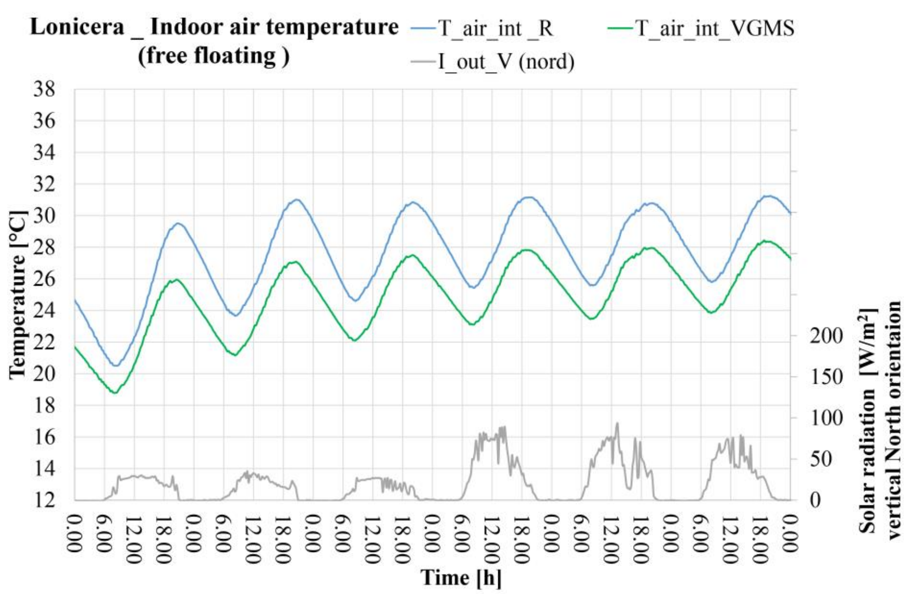

Fig. 20. Demonstration building, with Lonicera nitida. Comparison of the indoor air temperature between the room with the reference technology (wooden cladding T_air_int_R) and the room with the VGMS (T_air_int_VGMS). Measurements conducted in free floating conditions.

3.6 Technological issues

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

Manufacturing stage: this was mainly focused on the system workability requirements and the availability of material on the Piedmont market in order to minimise the environmental impacts and reduce the material intensity. The materials and semi-finished products were obtained from suppliers located within a maximum distance of 70 km from the site chosen for the assembly (CEIT-Asti). Furthermore, the assembly of the components that were tested during the prototyping activities led to the identification of the manufacturing phases, currently done by hand, which could be implemented in an industrialized process, for example, the cutting of the felts and the mixing of the growing medium. Some activities, such as the insertion of the plants into the pockets can only be done by hand. Six hours/man was required during the prototyping activities to produce 1 m^2 of LWS. It was assumed that the industrialization of some processes could reduce the preparation times by 50%, with a consequent reduction in the production costs.

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

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

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

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

Table10. GRE_EN_S costs.

Stages	***Costs***
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 (*Lonicera nitida, Bergenia cordifolia, Heuchera* hybr.).

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

4- Discussion and conclusions

VGMS, Vertical Greenery Modular Systems, are able to provide several benefits to buildings. The complete and multidisciplinary results of a research project (GRE_EN_S) on VGMS are presented in the paper. From the design phase of the VGMS to the complete characterisation of the technology, the decisions were supported by analyses and experimental results. The VGMS and the plant species were subjected to extensive monitoring campaigns in a nursery, in a test cell and in a demonstration mockup in Turin (North West Italy, Cfa, temperate sub continental climate, according to the Köppen climate classification). The aim of the research was to design a new VGMS and to evaluate different kinds of vegetation species, different substrates and technological systems characterised by a low embodied energy. The process started with an LCA, which allowed the raw materials to be selected and the importance of addressing the choice towards a recycled aluminum frame for the technological support of the module to be highlighted. The mechanical test allowed the suitability of the felts to be tested in order to guarantee sufficient mechanical strength to support the weight of the roots and also an adequate permeability to ensure a sufficient water level for the plants. A biometric analyses allowed the response of different plants (*Lonicera nitida*, *Bergenia cordifolia* and *Heuchera* hybr. 'Red purple') to be evaluated under vertical conditions, and the interaction between different vegetal species and substrates to be tested. The results have shown that the right combination of plant species and substrates can significantly improve the VGMS performances and improve the quality of the green covering. As far as VGMS maintenance is concerned, the use of evergreen shrubs permits the number of interventions a year to be limited, but a an appropriate design and integrated automatic irrigation system must be programmed carefully. As much as 50% in volume of alternative recycled materials, such felt pads and viscose, can be used in the VGMS substrate; this helps to improve the water retention, and to facilitate root development and plant anchorage in the module. An acoustic analysis demonstrated that the system acts well as a sound insulation system, and its high sound absorption could be exploited to reduce the urban canyoning effect. Thermal performance analyses showed interesting effects that were found during both the heating and cooling seasons. The tested walls with VGMS showed good thermal transmittance values, and the external surface temperature of the VGMS during the cooling season, which was much lower than that of the reference technology, highlighted the importance of this solution at an urban level, as it was able to efficiently counteract the urban heat island effect. No particular differences were noticed, in terms of heating performance, when different substrates and vegetal species with different LAI (*Lonicera, Bergenia* and *Heuchera*) were compared. The results of a real-scale application of VGMS in the demonstration mock-up highlighted the potentiality of VGMS to reduce the indoor air temperature during the summer period by as much as 4°C, in comparison to the reference technology in a free floating condition.

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

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Nomenclature

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

Greek symbols

α	Sound absorption coefficient for random incidence	[-]
α_0.	Sound absorption coefficient for normal incidence	[-]
Δ	difference between the indoor – outdoor temperatures	
$\Delta\sigma$	incremental stress	[Nm^{-2}]
$\Delta\varepsilon$	incremental strain	[-]
μ	dynamic viscosity	[Pa s]
ρ	density	[$kg \cdot m^{-3}$]
σ_y	yield strength	
σ_T	tensile strength	
σ_B	breaking strength	
τ_{60}	reverberation time	[s]

Acronyms

GMS	Green Module System
GRE_EN_S	GREen ENvelope System
LCI	Life Cycle Inventory
LWS	Living Wall Systems
R	referring to the reference technology
SAP	Super Absorbent Polymer
SF	substrate with felt
SPAD	Soil Plant Analysis Development
SS	standard substrate
SSV	standard substrate and viscose layer
VGMS	Vertical Greenery Modular System

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