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Bioreceptivity of Living Walls: Interactions between Building Materials and Substrates, and Effect on Plant Growth.

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Abstract

Bringing nature into urban areas is largely recognized as one of the multiple benefits of green walls. Among the existing types of living walls, those made from durable building materials have a longer lifespan and require less maintenance than many typical green wall systems. In that context, there is a need to study the bioreceptivity of materials, i.e., their ability to host living organisms. This paper presents a novel method to study the bioreceptivity of materials, by enhancing the biological and physicochemical exchanges in different mixtures of crushed materials and substrates, and by measuring their effect on plant growth. For this experiment, we crushed and sieved four different building materials (3 types of concretes and 1 brick) to increase their contact surface. We then mixed them with substrate with or without compost additions. The mixtures were used as growing media for the cultivation of two wild mural plant species in a glasshouse. Plant growth and the physicochemical evolution of the mixtures were monitored for one year. The study shows the physical and chemical differences between the building materials, their interactions with substrate composition, and their effect on plant growth. Two main results appeared: (i) high pH (>8) was the major constraint against plant growth (ii) compost additions significantly compensated for adverse characteristics of the materials. Assuming that higher plant growth is associated with better bioreceptivity, this experiment introduces a quantitative method that could contribute to the evaluation of the agronomic properties of building materials. The results allow us to make recommendations for Living wall and Technosol design.

Keywords:

Living Wall, Bioreceptivity, Green infrastructure, Glasshouse experiment, Urban Ecosystem, Vertical Greenery Systems (VGS)

1. Introduction

Urban sprawl is today a major driver of the loss of biodiversity across the world (IPBES, 2019), and one means to counteract this is to use building envelopes for enhancing urban biodiversity by greening them (Francis and Lorimer, 2011; Madre *et al.*, 2015). These building envelopes represent from 10 to 50% of the total urban land surface (Darlington, 1981; Grimmond *et al.*, 1991), thus providing a very large surface for vegetation and plant ecosystems. Considering the environmental benefits at the scale of a building (Coma *et al.*, 2017), greening the building envelopes can help mitigate the temperature increase due to global warming in cities, by absorbing solar radiation and cooling through evapotranspiration (Jim and He, 2011). Together with green roofs, green walls might decrease the air temperature in a city up to 11.3 °C on a global scale (Barriuso and Urbano, 2021).

Different types of Vertical Greenery Systems (VGS) exist, and their classification and benefits have been studied over the last decades, as shown by Medl *et al.* (2017) and Auer *et al.* (2019). Green facades refer specifically to any system with climbing plants growing directly on a wall or supported by cables or trellis, while living walls are either based on a continuous felt layer system or based on a soil-cell system (Dunnett and Kingsbury, 2004; Perini *et al.*, 2011; Riley, 2017). Most living walls are designed as non-structural cladding systems made of materials that have a lower longevity than the buildings they are attached to. Furthermore, they often generate high monetary and environmental costs (Ottelé *et al.*, 2011, 2014; Perini and Novi, 2016). One way to reduce maintenance costs is to design living wall systems where plant life is not a separate entity to the building structure but is already included within (Riley *et al.*, 2019). Examples of such living wall

systems which combine greening with building structure include: (i) the bioreceptive designs developed by the BiotA Lab at the Bartlett School of Architecture, UCL (Cruz and Beckett, 2016), (ii) the living wall system based on a new pervious concrete developed by Riley *et al.* (2019), (iii) the bioreceptive concrete panels developed by Mustafa *et al.*, (2021), and (iv) the prototypes of biodiverse wall developed by the architecture firm Chartier Dalix (Figure 1). In all these cases, a substrate for plant growth is directly integrated to the building materials – concrete, brick, stone – throughout the whole wall structure.

Figure 1. Living walls made of building materials: Chartier Dalix, prototypes of “biodiverse” walls made of UHPC concrete (in collaboration with CBC) and of fired clay bricks (in collaboration with the National School of Architecture Paris Malaquais and the Muséum national d’Histoire Naturelle), 2021.



There is a need to better understand how a living wall system works, and namely to fill the lack of knowledge concerning the multiple interactions between the building material and substrate and plants. These interactions raise questions about the long-term sustainability of the system: what kind of interactions occur between a building material and a substrate in a living wall under quasi-permanent moisture? And between the material and plant roots? Can they have an effect on the growth of the plants or the structure of the building in the long term?

Some of these aspects have been studied in different fields, namely in ecology or in bioreceptivity studies. Darlington (1981) and Jim and Chen (2010) linked urban ecology and ecological engineering in studying wall ecology, while Francis (2011) identified the physicochemical characteristics of walls as artificial ecosystems or habitat. Other authors have studied the ability of materials to host living organisms, known as bioreceptivity (Guillitte, 1995): mainly on building stones (Miller *et al.*, 2012), but also on bricks (Guillitte and Dreesen, 1995) or cementitious materials (Sanmartín *et al.*, 2021). Material properties such as porosity, open pore size, roughness, chemical composition, and pH are the main factors influencing the primary bioreceptivity of an inert material (Guillitte 1995; Manso *et al.*, 2014). While several studies have focused on evaluating material bioreceptivity by aging them artificially (Coutinho *et al.*, 2016; Manso *et al.* 2015), others have focused on enhancing bioreceptivity. For instance, some researchers worked on formulating bioreceptive concrete (Manso *et al.*, 2014, Riley *et al.*, 2019, Veeger *et al.*, 2021) by lowering the high pH of cementitious materials which can be detrimental to plant growth. Others have focused specifically on the composition and behavior of organic substrate of green walls (López-Rodríguez *et al.*, 2016; Serra *et al.*, 2017) or of green roofs (Jusselme *et al.*, 2019), without however studying specifically the materials interaction. Some interesting studies of bioreceptivity based on plants (Jim and Chen, 2011) can also be mentioned, as opposed to algae (in-vitro test), making the link between primary and secondary bioreceptivity, and from fresh to weathered materials (Sanmartín *et al.*, 2021).

In recent years, interest has grown in the use of Technosols, which are human-constructed types of soil based on recycled urban materials, for green infrastructure (Abbruzzini *et al.*, 2022; Minixhofer *et al.*, 2022). In that context, some construction materials, such as

crushed concrete or bricks, have been analysed for their agronomic properties (Pruvost *et al.*, 2020).

All these multidisciplinary studies bring essential insights for our research on the interaction of plants or living organisms with building materials and substrate, but they do not precisely treat the off-ground cultivation which is specific to a living wall made of building material. In this work, we propose an original experimental investigation over a 66-week time period of the interactions between the building materials and a plant substrate in a growing mixture module that reproduces the context of a living wall. This is achieved through the quantifying and qualification of the bioreceptivity of the building materials by using them as a growing media, and measuring plant growth as an outcome. As described by Miller *et al.* (2012), bioreceptivity, linked with biodeterioration and biodegradation, is often quantified by biofilm coverage (Guillitte and Dreesen, 1995; Tiano *et al.*, 1995; Tomaselli *et al.*, 2000; Miller *et al.*, 2006; Giannantonio *et al.* 2009) or visual inspection. As mentioned by Sanmartín *et al.* (2021) most of the case studies on bioreceptivity rely on in-vitro (lab-based) tests and the majority of papers has focused on primary bioreceptivity. The strength of our study holds in the fact that it is one of the few to make the link between primary and secondary bioreceptivity (before and after weathering the materials). Additionally, we perform our experiment in conditions that are closer to a 1:1 scale situation, even though they remain controlled in the greenhouse. Last, we compare four different materials that have never been compared all together in the same experiment.

In this experiment, higher plant growth is assumed to be associated with higher bioreceptivity. Our hypothesis is that the characteristics of building materials, known as

intrinsic factors of bioreceptivity (Sanmartín *et al.*, 2021) could alter the substrate properties and affect the availability of nutrients and water for the plants. Similarly, the substrate composition, plant growth and water supply, known as the extrinsic factors of bioreceptivity (Sanmartin *et al.*, 2021), could in turn influence the characteristics of building materials.

The aim of this work was therefore to study the bioreceptivity of building materials, by measuring a certain number of factors which might influence germination and plant growth over time, such as material characteristics, pH level, the stability of materials/substrate mixture properties regarding their composition, organic matter level, bulk density, or nutrients availability. In terms of applications, the aim of the study is to inform the design of living walls and other green infrastructure in relation to the choice of materials that are more bioreceptive to plants.

It should be noted that this experiment focuses specifically on the bioreceptivity of materials and on material/substrate/plant interactions, therefore it leaves out other parameters in living walls such as vertical plant growth. In such context, plant geotropism and nutrient availability can significantly affect individuals. The two plants selected for the experiment are mural plants known to be adapted to vertical growth.

2. Materials and Methods

2.1. Study location and climate

A living wall module experiment at the scale of pots, with a randomized block design with drip irrigation, was installed in a covered and unheated greenhouse in the Arboretum of Versailles-Chèvreloup in France (48°50'07.9"N 2°05'57.4"E). The greenhouse was

subjected to a temperate climate, without dry season and with warm summer, “Cfb” according to the Köppen climate classification (Peel *et al.*, 2007). The interior of the greenhouse was protected from rainfall, but influenced by seasonality, including sunlight, air temperature and occasional wind. The experiment was conducted for 66 weeks, from July 2020 (summer) to October 2021 (fall) with the daily mean maximum temperature from 16.3 to 26.7 °C in August 2020, and the minimum temperature from 1.1 to 6.4°C in January 2021.

2.2. Initial Substrates and Building Materials

2.2.1. Initial Substrates

The substrate used was a commercially available one designed for semi-intensive roof greening (Reference: "I.D. Flore SP" from Le Prieuré Vegetal i.D.), which presents optimal characteristics of permeability, water retention and stability over time (Appendices, Table A.1). A second substrate was made by adding 50% of green compost (organic matter of plant origin) to this horticultural substrate, in order to study to what extent organic matter additions could stimulate plant growth. We will refer to these two substrates as “Substrate with Compost Additions” and “Substrate without Compost Additions”.

2.2.2. Building Materials

The main material of our study was concrete, the most common building material in many countries due to its low cost. In addition to this cement-based material, a second material, fired clay brick, was chosen for comparison because of its interesting water retention properties. Concrete, and in particular the cement it requires, has a negative environmental impact (Zabalza Bribián *et al.*, 2011; Barcelo *et al.*, 2014). In some cases,

this impact could be mitigated by the expansion of concrete living walls (Riley *et al.*, 2019), which have a positive environmental impact in urban areas.

We tested four types of materials:

- “C25 Concrete”, with CEM II A 32.5 cement (water cement w/c ratio of 0.6); C25 is a widespread ordinary building concrete, but with a high pH that can be detrimental to plant growth
- “Low-pH Concrete” with a sulfoaluminous clinker (Andac *et al.*, 1995; Desbois *et al.*, 2010)
- “UHPC Concrete”, an Ultra-High-Performance Concrete of class C150 (Toutlemonde *et al.* 2018; Resplendino, 2014). The material was developed in CEMEX laboratory from formulae already tested in the past. The UHPC is made of a CEM I 52.5 cement, and silica fume. We also added superplasticizers adapted to very low w/c of the order of 0.17% (dry extract) of cement mass. Its very low permeability limits the physico-chemical exchanges with the substrate, thus avoiding potential negative interaction. Another advantage of UHPC is that its structural properties could be interesting for the construction of living walls with complex morphology
- Crushed “Fire Clay Brick” from the trade (Reference: Les Terres Cuites D’Aizenay, “Brique pilée (chamotte) 40 kg”).

The main constraint was to obtain short-term results representative of long-term behavior. To this end, the building materials were crushed in order to enhance the specific area in contact with the substrate, and thus, to accelerate their physico-chemical exchanges.

We used the following crushing and sieving protocol: the building materials were first crushed in a jaw crusher to obtain aggregates which were afterwards sieved to obtain a

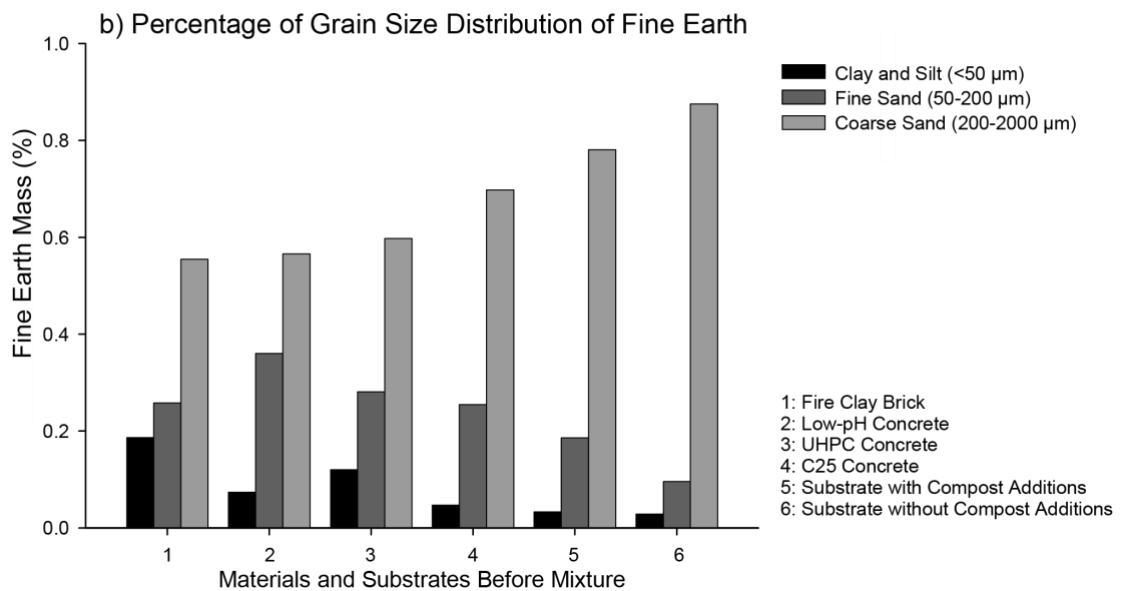
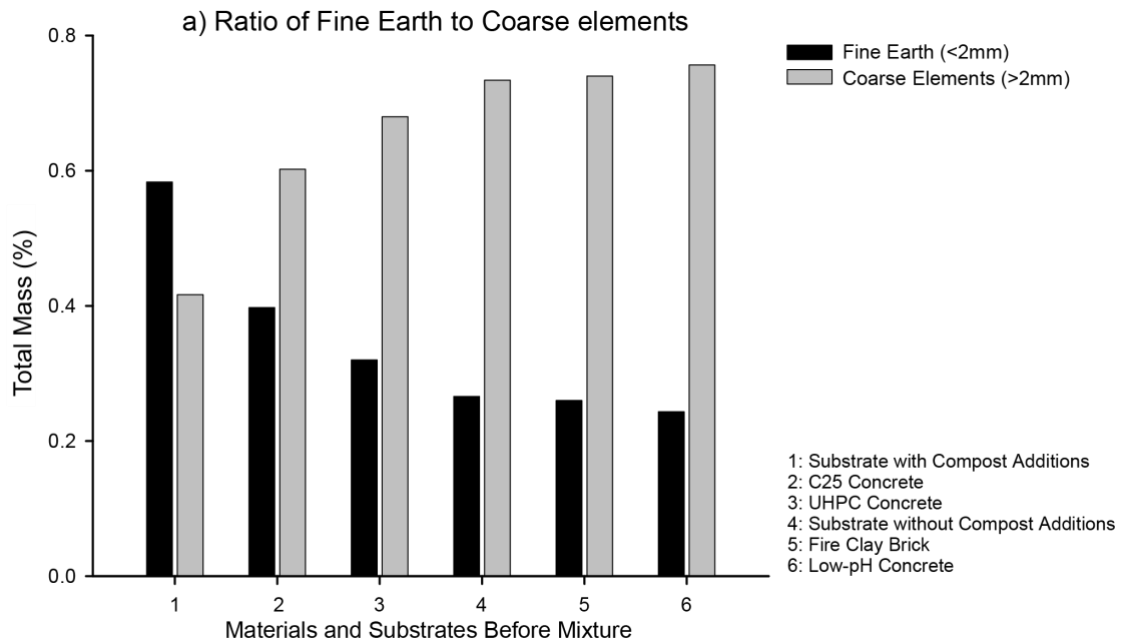
granulometric spectrum equally distributed among 4 size fractions: < 0,63 mm, 0,63-1mm; 1-4 mm and >4mm (Appendices, Figure A.1).

2.2.3. *Granulometry*

A granulometric analysis was performed separately on 800 ml samples (about 1.2 kg) of the four crushed materials (3 concretes and 1 fireclay brick) and of the two types of substrates (with and without compost additions). The sieving was realized at iEES soil physics laboratory in IRD campus, Bondy, France. Four granulometric fractions were determined: Clay and Silt (<50 μm); Fine Sand (50-200 μm) and Coarse Sand (200-2000 μm) (Figure 2a). The fraction of fine earth elements (<2 mm) and coarse elements (>2 mm) of the total mass were also determined (Figure 2a). All the crushed materials had more than 80% of particles in mass >50 μm . Nevertheless, significant differences remained after the above-mentioned homogenization. Crushed Brick had the highest ratio of particles <50 μm (19% in mass while the others had in average less than 6%) and Low-pH Concrete had the highest ratio of 50-200 μm particles (36% while the others had in average less than 22%) (Figure 2b).

The ratio of fine earth to coarse elements, sorted in ascending order in Figure 2a, also showed difference between the different materials and substrates. Brick and Low-pH Concrete had about 25% of <2mm elements, while for the UHPC concrete and the C25 Concrete had about 30 to 40%. The substrate without compost additions had about 27% of <2mm while with compost additions, it reaches about 58%.

Figure 2. a) Ratio of Fine Earth (<2mm) to Coarse elements (>2mm) of the 6 materials and substrates before mixture, sorted in ascending order: 1. Substrate with Compost Additions. 2. C25 Concrete. 3. UHPC Concrete. 4. Substrate without Compost Additions. 5. Fire Clay Brick. 6. Low-pH Concrete. b) Percentage of the grain size distribution of Fine Earth of the 6 materials and substrates before mixture in 3 fractions: 1. Clay and silt (<50 μm). 2. Fine Sand (50-200 μm). 3. Coarse Sand (200-2000 μm). (1 column fitting image. B&W)



2.3. Preparation of Growing Media Mixtures

The crushed and sieved building material were mixed with the substrate following an apparent volume ratio of 17 % material (331 cm³ corresponding to a mass between 344 and 466 g / pot) and 83 % substrate (1656 cm³) in order to fill 2 L pots.

Eight growing mixtures were obtained from the combination of the 4 building materials and 2 substrate types.

In a reference living wall made of brick (Figure 1), using detailed 3D drawings, the contact surface area of the bricks with the substrate was estimated to 3.8.10⁴ cm², for a total volume of 0.34.10⁶ cm³. The surface/volume ratio was therefore 0.1 cm⁻¹.

In the case of our crushed materials, we had 340 cm³ of material in each 2 L pot. If we consider in a lower bound approximation that the material particles are 2-mm diameter spheres, we obtain about 9.10⁵ particles, corresponding to a surface of approximately 10⁴ cm². The surface/apparent volume ratio was therefore 10⁴ cm²/340 cm³ = 29.4 cm⁻¹. The ratio for the experiment is thus at least multiplied by 300 compared to the reference living wall.

2.4. Experimental design

The experiments were carried out on the model Living Wall modules consisting of the growing media mixtures prepared in 2 L plastic pots equipped with individual controlled drip-irrigation, sown with two different plant species: *Cymbalaria muralis* and *Campanula rotundifolia*. These are two wild mural and indigenous plants referenced by the National Botanical Conservatory of the Paris Basin and were chosen because they are known to grow on walls, and have different ecological traits, namely their sensitivity to

soil pH. The *Campanula* is acidocline ($5,0 < \text{pH} < 5,5$) whereas the *Cymbalaria* is perbasophile ($7,5 < \text{pH} < 8,0$) (eFlore encyclopedia on Tela Botanica).

The combination of the 8 growing media mixtures and the 2 plant species give rise to 16 different modules (Table 1). Ten replicates of each of these 16 combinations were prepared to obtain enough data for statistical analysis, i.e. a total of 160 pot modules were studied.

Table 1. Composition of the 16 combinations between 4 types of materials (C25 Concrete, Low-pH Concrete, UHPC Concrete and Brick), 2 types of substrates (With and without compost additions), and 2 plant species (*Campanula rotundifolia* and *Cymbalaria muralis*). The nomenclature is also used in the Appendices Table A.4. (1 column fitting. B&W)

Plants	<i>Campanula rotundifolia</i>	<i>Cymbalaria muralis</i>	<i>Campanula rotundifolia</i>	<i>Cymbalaria muralis</i>
Materials	Substrate without compost additions	Substrate without compost additions	Substrate with compost additions	Substrate with compost additions
C25 Concrete	C1	C5	C9	C13
Low pH Concrete	C2	C6	C10	C14
UHPC Concrete	C3	C7	C11	C15
Brick	C4	C8	C12	C16

The 160 pots were randomly distributed on a 12 m² table among 10 different blocks (Appendices, Figure A.2), under a covered unheated greenhouse in the Arboretum of Versailles-Chèvreloup in France (Figure 3). The spatial randomization of the experiment allows to avoid that external parameters such as irrigation and microclimate differences

bias the results. The pots were spaced to avoid edge effects, and a statistical check was made at the end of the experimentation to ensure this point.

Cultivation was monitored for 66 weeks. All modules received the same maintenance, which consisted of manual watering by daily sprinkling for the first weeks after the sowing in July 2020. Afterwards, an automated drip system was used for the rest of the experiment duration (1 dripper/pot). The amount of supplied water was regulated by an irrigation controller according to the climate. It was initially set at 5min/48h (134 cm³/pot) and then increased to 15 min/24 h (500 cm³/pot) during summer droughts. The controller was then switched off for several weeks during freezing periods in wintertime. Each dripper was manually regulated during the monitoring. Spontaneous species were removed from the pots whenever they were noticed.

Figure 3. Photography of the experiment installation under the greenhouse in Arboretum Versailles-Chèvreloup, July 2021. (1 column fitting image. Color)



2.5 Data collection and analysis

2.5.1. Monitoring of Plant Growth

In order to quantify the bioreceptivity of the substrates, we focused on plant growth parameters, and assumed that better growth is associated with better bioreceptivity. The study consisted of 66 weeks of monitoring after seeding in July 2020 (from summer to fall of the following year). 6 surveys were made at week number 16, 23, 35, 46, 52 and 66 after the beginning of the experimentation. At each survey, we measured the diameter (cm) and height (cm) of each of the 160 plants. When the plant stems grew out of the pot, we counted them as part of the total plant diameter and arranged them manually to avoid an edge effect between the pots. A systematic photographic follow-up was carried out to complement the survey and to help data check (Appendices, Figure A.3). At the end of the experimentation, while constituting the samples for soil analysis, roots weight fresh biomass (g) and whole plant fresh biomass (g) were measured for each germinated pot separately. For each plant, the Root/Shoot ratio was calculated as root weight divided by aboveground part weight.

In week 46, in May 2021, when the temperature increased rapidly after the cold season, the irrigation system wasn't regulated. 19 pots were counted as "dead", which means that their plants, mostly *Cymbalaria muralis*, were damaged by drought. These pots and the last observations for this species were discarded for the statistical analysis to avoid bias due to the incident.

In addition to the plant characteristics survey, the germination rate was calculated at the end of the experiment, with the following formula: Germination rate = The number of germinated seeds divided by the total number of seeds multiplied by 100.

2.5.2. Physicochemical Properties of the Mixtures

The physicochemical analysis of the initial and final states (before and after cultivation) of the growing media mixtures was undertaken by SADEF laboratory (Aspach-le-Bas, France). For the final state testing at the end of the experimentation, for each of the 16 growing media mixtures, sampling was made after mixing all the replicates of the same mixture, after discarding the pots that did not germinated.

The analysis of the growing media was grouped in 3 sub-sets:

1. Physical properties: pH KCl (NF ISO 10 390), Volumetric Retention Capacity (aqueous extract 1/1.5), Dry Density (aqueous extract 1/1.5);
2. Agronomic characteristics: pH H₂O (aqueous extract 1/5 NF EN 13652), Total Nitrogen (N) (NF EN 13652), Organic Matter (LOI NF EN 13652), Organic Carbon (C) (LOI), C/N ratio, CEC (Metson NF EN 13652);
3. Water extraction of water-soluble nutrients: phosphorus (P₂O₅), Potassium (K₂O), Magnesium (MgO) Calcium (CaO) (NF EN 13652 aqueous extract 1/5 + ICP-AES).

2.5.3 Statistical Analysis

We first looked at the percentage of pots that germinated for each plant over the duration of the experience for each growing medium mixture, by material and with or without compost additions. We then looked at the effect of the growing media mixtures on growth performance (plant height and diameter). For that purpose, we kept in the analysis only observations where growth was measured to be positive, and we removed observations of plants after they died.

We first computed descriptive statistics (means and standard errors) by date. We looked at the means of plant growth (diameter and height), by material, and substrate

composition (with or without compost) for each plant species. These graphs showed the week-by-week effect of growing media mixtures on plant growth measures over the 6 observations during the 66 weeks of monitoring.

Comparison between plants at the same date can be misleading because they had different growth cycles, depending on the date at which they started germinating. To make more robust comparisons, we also averaged growth measures (means and standard errors) by pooling several observations periods: we took the three first observations for *Cymbalaria muralis* to avoid bias due to the irrigation system incident on week 46, and the two last observations for *Campanula rotundifolia* whose stems did not emerge until week 52. Amongst those means, we also used two growth measures performed at the end of the experiment: fresh biomass and root/shoot ratio (Appendices, Table A.2).

Plant diameter, plant height, fresh biomass and root/shoot ratio were statistically analysed by two-way factorial analysis of variances (ANOVAs) for each plant species with materials and compost additions as fixed factors. Regarding the soil parameters, we analysed the difference between the initial state sample (before cultivation) and the final state sample for each treatment. We analysed the change of pH and organic matter levels from initial to final state with ANOVAs, with material and compost additions as fixed factors separately. Tukey's HSD (honestly significant difference) post hoc tests were applied for assessing significance of differences between means for all the analysis.

The periodic data of the plant growth variables were statistically analysed by repeated-measures two-way ANOVAs with type of materials and compost additions as between-subject factors and time as within-subject factor (Appendices, Table A.3). The repeated-measures statistics for the within-subject factor and its interactions with the between-subject factors were adjusted by the Greenhouse–Geisser method whenever the sphericity

assumption was violated as assessed by Mauchly's tests. All analyses were performed with Stata Statistical Software: Release 15.

3. Results

3.1. Germination Rates

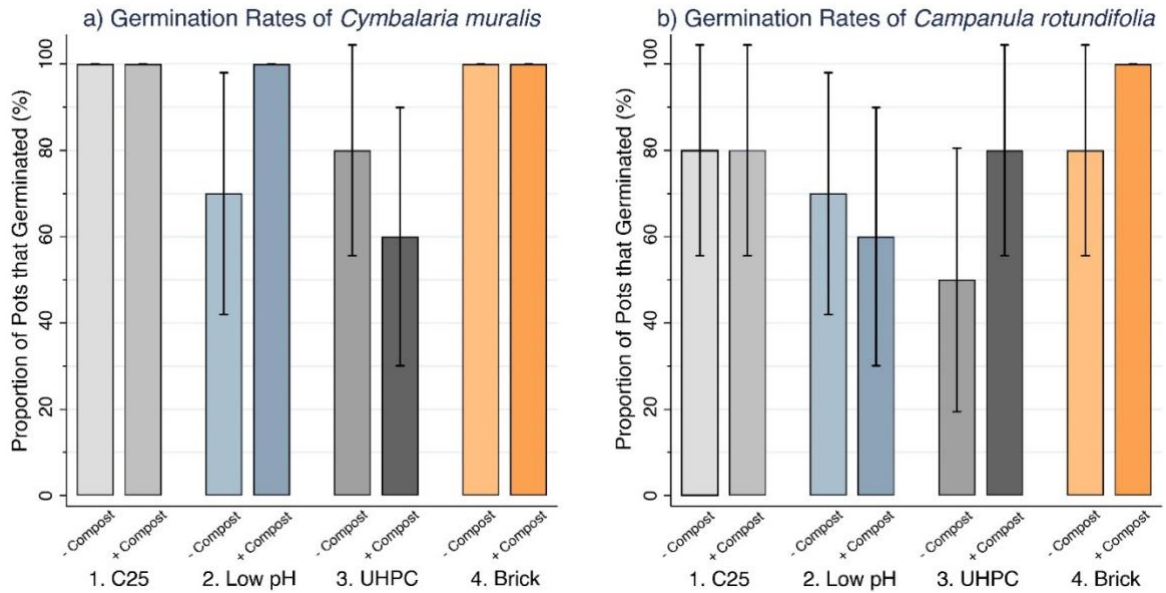
Cymbalaria muralis seeds germinated during the first weeks after seeding while most of *Campanula rotundifolia* seeds germinated six months after seeding. Differences in germination rates at the end of the trial of 66 weeks appeared following the type of material, substrate composition, and plant species (Figure 4).

Germination rates were overall better for *Cymbalaria muralis* than for *Campanula rotundifolia*.

The best results were obtained for both plant species with C25 concrete and brick, with and without compost. UHPC concrete gave the lowest results (less than 70%), regardless of other parameters.

For most of the mixtures, compost additions to the substrate resulted in higher germination rates by 10 to 20%, with 2 exceptions: *Cymbalaria* in UHPC concrete pots and *Campanula* in Low-pH concrete pots.

Figure 4. Germination Rates based on Compost Additions and Materials, for a) *Cymbalaria muralis* b) *Campanula rotundifolia*. In total, 71 out of 80 *Cymbalaria* germinated, and 60 out of 80 *Campanula* germinated. (2 columns fitting image. Color)



W

3.2. Plant Growth

3.2.1 Week-by-week growth

Figures 5 and 6 show the plant growth (height and diameter) measurements, respectively for *Campanula rotundifolia* and *Cymbalaria muralis*, which were carried out after the 6 time periods: weeks 16, 23, 35, 46, 52 and 66 after seeding. Fresh biomass and root/shoot ratio measured at the end of the experiment also provided interesting information on the thriving of the plants: these data are shown in Table A.2 (Appendices), along with the final plant growth data.

There was a noticeable effect of materials on plant growth, independently of the species. Brick material presented the highest plant growth on average for most of the observed parameters and over time, especially for the diameter of the *Campanula* (Figure 6b). On the other hand, UHPC concrete with the substrate without compost additions presented

initially a lower growth compared to the other materials, but at the end of the experiment, pots with UHPC had mostly caught up with the growth of pots with other materials, and they even surpassed it in some cases. For instance, the growth of *Cymbalaria* in pots with UHPC was larger than those grown in other materials, at week 52 with compost additions and at week 66 without compost additions (Figure 5). These same observations were made for the germination rates.

In the first weeks of the experiment plants grown in the mixtures containing C25 concrete had higher growth than those in mixtures containing Low-pH concrete (except on the first observation of *Cymbalaria* with compost). However, by the end of the experiment, the initial difference almost vanished. We noted that these differences are larger for pots without compost additions. We also noted that these differences are larger and more significant for the *Campanula* than for the *Cymbalaria*. We clearly see an effect at week 52 for the *Campanula* whose height increased by about 7 times (Figure 6b), consistent with the observation of late germination for this species. From the week 52 to the week 66, some of the plant growth averages decreased, notably the height of the *Cymbalaria* (Figure 5b). This can be due to the end of one plant life cycle, or it can be due to the drought that occurred at week 46 of the monitoring.

Figure 5. Week-by-week effect of materials on the diameter and height of germinated *Cymbalaria muralis* with or without compost, over 66 weeks of monitoring.

Note: On the 80 samples of Cymbalaria muralis tested (20 for each material), 71 germinated. On the pots without compost additions, we measured 10 samples of C25 Concrete, 7 of Low-pH Concrete, 8 of UHPC Concrete and 10 of Brick. On the pots with compost additions, we measured 10 samples of C25 Concrete, 10 of Low-pH Concrete, 6 of UHPC Concrete and 10 of Brick. Confidence intervals are represented at the 90 percent level. (2 columns fitting image. Color)

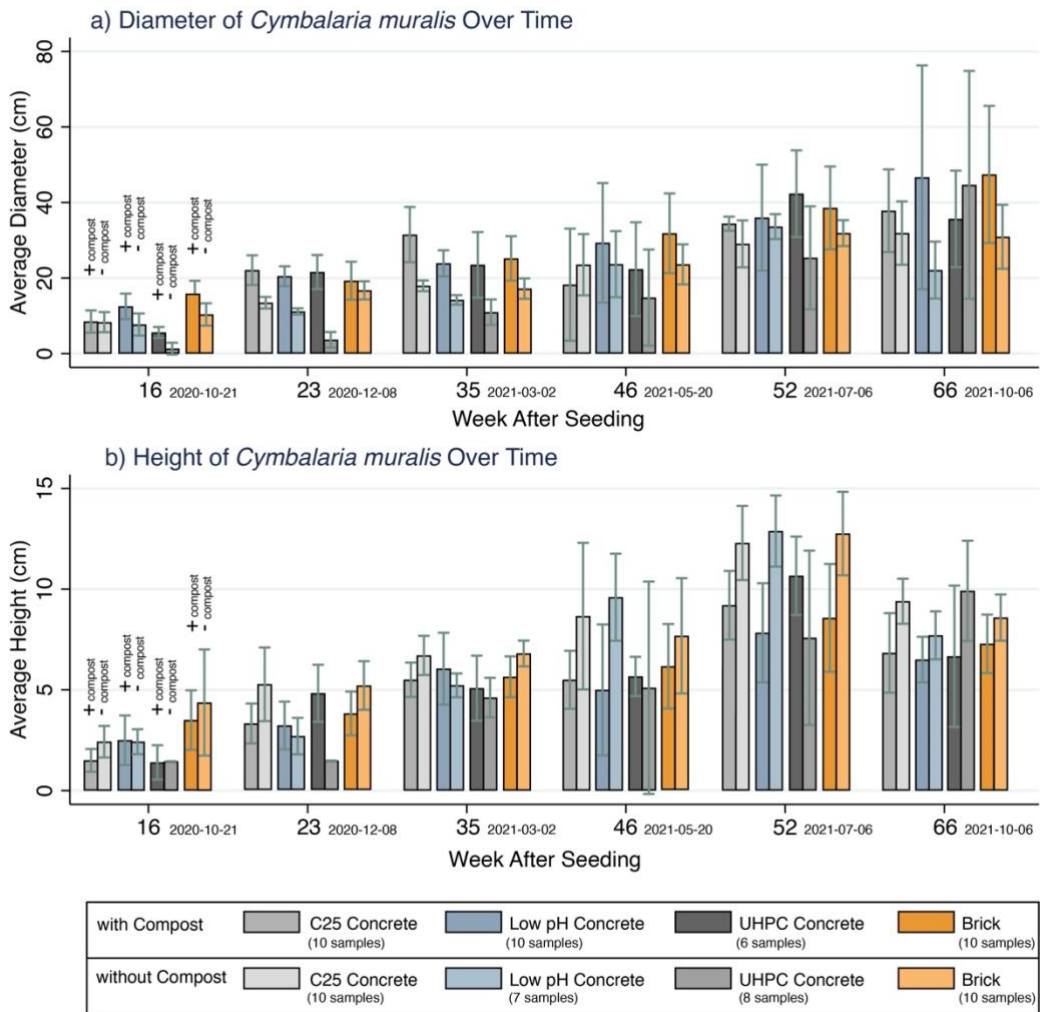
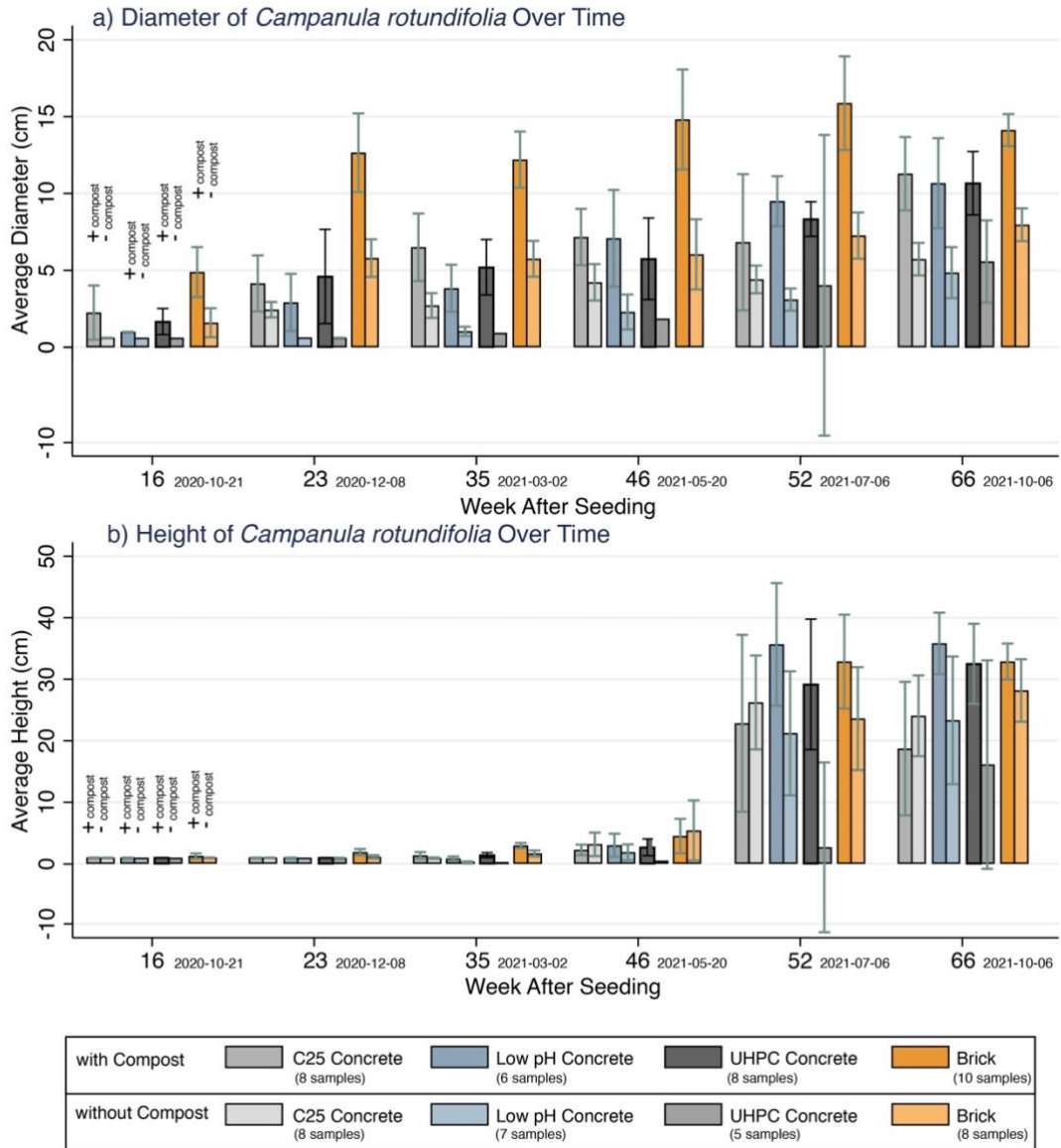


Figure 6. Week-by-week effect of materials on the diameter and height of germinated *Campanula rotundifolia* with or without compost, over 66 weeks of monitoring.

Note: On the 80 samples of Campanula rotundifolia tested (20 for each material), 60 germinated. On the pots without compost additions, we measured 8 samples of C25 Concrete, 7 of Low-pH Concrete, 5 of UHPC Concrete and 8 of Brick. On the pots with compost additions, we measured 8 samples of C25 Concrete, 6 of Low-pH Concrete, 8 of UHPC Concrete and 10 of Brick. Confidence intervals are represented at the 90 percent level. (2 columns fitting image. Color)



3.2.1 Effects of Materials and Compost

The repeated measures statistics on plant growth data confirmed that the building material had a significant influence on plant growth variables independently of time, whereas for compost the effect is time-dependent, with one exception on the *Campanula* diameter (Appendices, Table A.3).

Plant diameter and height (over the experiment) and fresh biomass (end of experiment) were significantly affected both by materials and compost additions for the two plant species (Table 2). Interactions material x compost affected plant growth significantly in some cases: the height of *Cymbalaria*, and the height and diameter of *Campanula* (Table 2).

Compost additions were mostly associated with higher plant growth, but not always significantly. Compost additions affected plant growth positively and significantly in the following cases: for the height of *Cymbalaria* in low-pH and UHPC concrete pots and their fresh biomass in UHPC pots (Figure 7); and for the diameter of *Campanula* in low-pH and brick pots, and their height in UHPC pots (Figure 8).

The differences between materials effects on plant growth were more important for mixtures without compost additions. However, they are not significant, apart from the difference between UHPC and brick pots. Indeed, the diameter and fresh biomass of both plant species were significantly higher in brick pots in comparison with UHPC pots that presented lower growth. Significant interactions appeared between the UHPC concrete and compost additions, in which plants grew as much as in other treatments (Figures 7 and 8).

Regarding the Root/Shoot ratio at the end of the experiment, higher values were obtained for the pots without compost additions, with one exception for the *Campanula* in UHPC

mixtures without compost (Figure 8d). The low-pH mixtures Root/Shoot ratio is slightly larger than the other mixtures ratio. This effect of low-pH concrete is also noticeable in the average height of the *Campanula* (Figure 8b), an acidocline plant that grows vertically.

Figure 7. Box-plot diagrams for Diameter (cm), Height (cm), Fresh Biomass (g) and Root/Shoot Ratio of *Cymbalaria muralis*. Letters show comparison of the plant growth means per growing medium mixtures (4 materials, with or without compost) at the 90 percent level. The means of two treatments labelled with at least one same letter (a, b, or c) are not considered statistically different from each other. Different letters indicate significant ($P < 0.1$) differences between treatments. The box indicates the median (inner line) with 50% of observations; the bars indicate the upper and lower quartiles. (2 columns fitting image. Color)

Note: Compost additions are mostly associated with better plant growth, but not significantly, apart from the UHPC. Significant interactions appear between the UHPC concrete and compost.

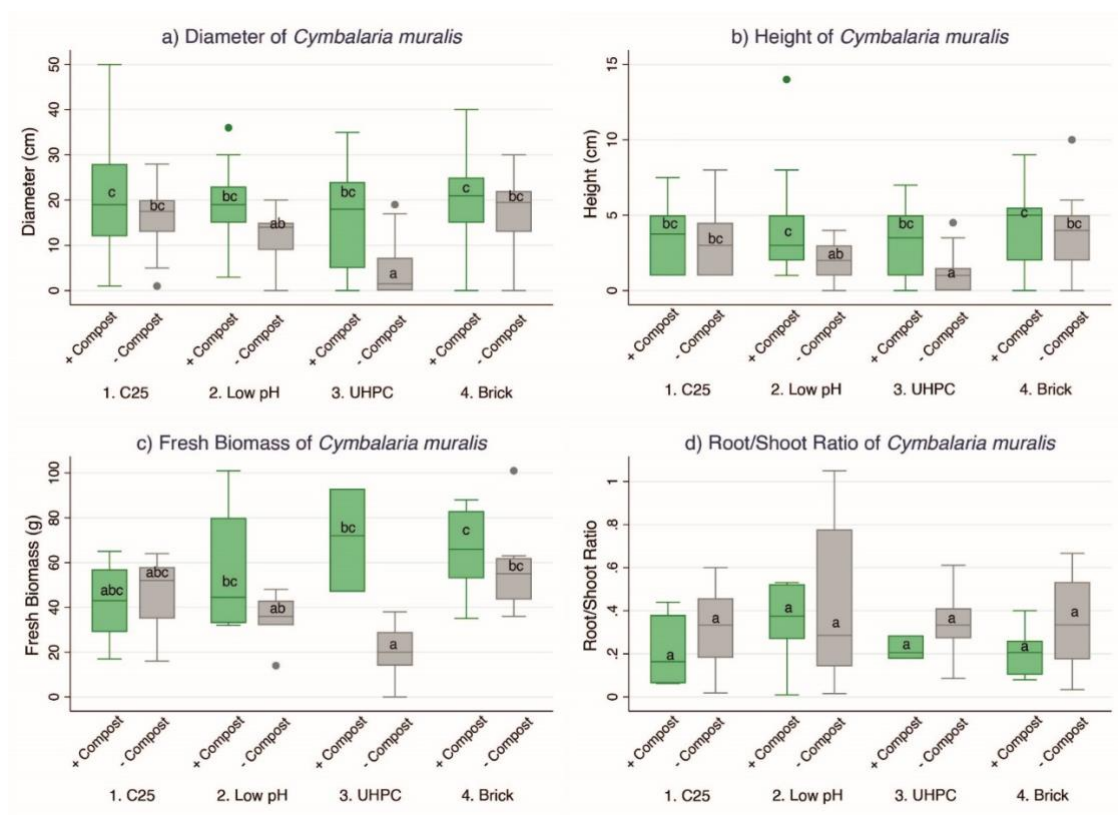


Figure 8. Box-plot diagrams for Diameter (cm), Height (cm), Fresh Biomass (g) and Root/Shoot Ratio of *Campanula rotundifolia*. Letters show comparison of the plant growth means per growing medium mixtures (4 materials, with or without compost) at the 90 percent level. The means of two treatments labelled with at least one same letter (a, b, or c) are not considered statistically different from each other. Different letters indicate significant ($P < 0.1$) differences between treatments. The box indicates the median (inner line) with 50% of observations; the bars indicate the upper and lower quartiles. (2 columns fitting image. Color)

Note: Compost additions are mostly associated with better plant growth, but not significantly. Compost additions are significantly associated with bigger diameter for the pots with Brick, and bigger heights for the pots with UHPC and Low-pH concretes. The mixture Brick with compost is significantly associated with the biggest diameter.

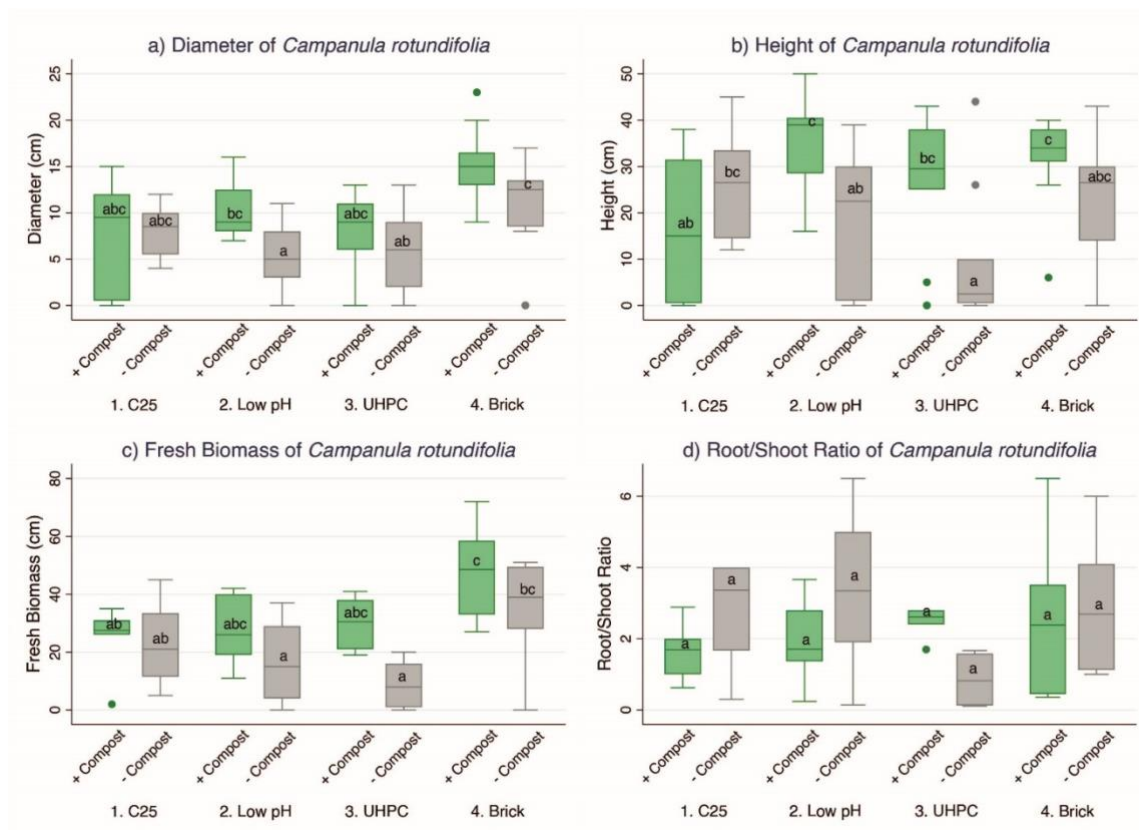


Table 2. *F*-values and associated *P* levels resulting from two-way factorial ANOVAs for diameter, height, fresh biomass and root/shoot ratio of *Campanula rotundifolia* and *Cymbalaria muralis* subjected to 8 combinations of materials and compost additions*. (2 columns fitting. B&W)

	Diameter of <i>Cymbalaria</i>	Height of <i>Cymbalaria</i>	Fresh Biomass of <i>Cymbalaria</i>	Root/Shoot Ratio of <i>Cymbalaria</i>	Diameter of <i>Campanula</i>	Height of <i>Campanula</i>	Fresh Biomass of <i>Campanula</i>	Root/Shoot Ratio of <i>Campanula</i>	<i>Degree</i> <i>of</i> <i>freedom</i>
Material	8.57 (<i>P</i> =0.0000)	3.95 (<i>P</i> =0.0091)	2.63 (<i>P</i> =0.0618)	0.89 (<i>P</i> =0.4518)	12.68 (<i>P</i> =0.0000)	4.12 (<i>P</i> =0.0083)	8.15 (<i>P</i> =0.0002)	0.86 (<i>P</i> =0.4696)	3
Compost	24.17 (<i>P</i> =0.0000)	17.37 (<i>P</i> =0.0000)	11.97 (<i>P</i> =0.0012)	3.12 (<i>P</i> =0.0846)	10.81 (<i>P</i> =0.0014)	12.16 (<i>P</i> =0.0007)	9.91 (<i>P</i> =0.0029)	0.49 (<i>P</i> =0.4887)	1
Material × Compost	1.94 (<i>P</i> =0.1245)	2.56 (<i>P</i> =0.0559)	3.76 (<i>P</i> =0.0173)	0.05 (<i>P</i> =0.9857)	2.64 (<i>P</i> =0.0533)	6.70 (<i>P</i> =0.0003)	1.00 (<i>P</i> =0.4020)	1.99 (<i>P</i> =0.1294)	3

ANOVAs, analysis of variance.

*Significant (*P*<0.1) values in bold character.

3.3 Physicochemical Properties of the Mixtures: soil evolution of growing media

Soil analysis was carried out on the growing media at the initial state, before cultivation, and at the final state, at the end of the experiment (Appendices, Table A.4).

3.3.1 Change in Physical Properties

In the initial state, the mixtures presented high differences in soil pH levels depending on the material and substrate composition (Table A.4). However, all mixtures had an alkaline pH, above or equal to 8. This made the growing media rather adverse in respect to the species cultivated, particularly for the mixtures containing concrete (pH between 9 and 11). In the final state, we observed a general decrease of pH levels which reached a value of 8 for most mixtures and for both plant species (Table A.4). Mixtures containing brick, which had a relatively lower pH level in their initial state did not change significantly. The change from initial to final pH in brick and in low-pH concrete were significantly different from the ones in C25 and UHPC concretes (Figure 9a), with a higher decrease in pH observed in the latter materials. Regarding compost, the changes of soil pH were not significantly different for pots with and without compost additions (Figure 9c).

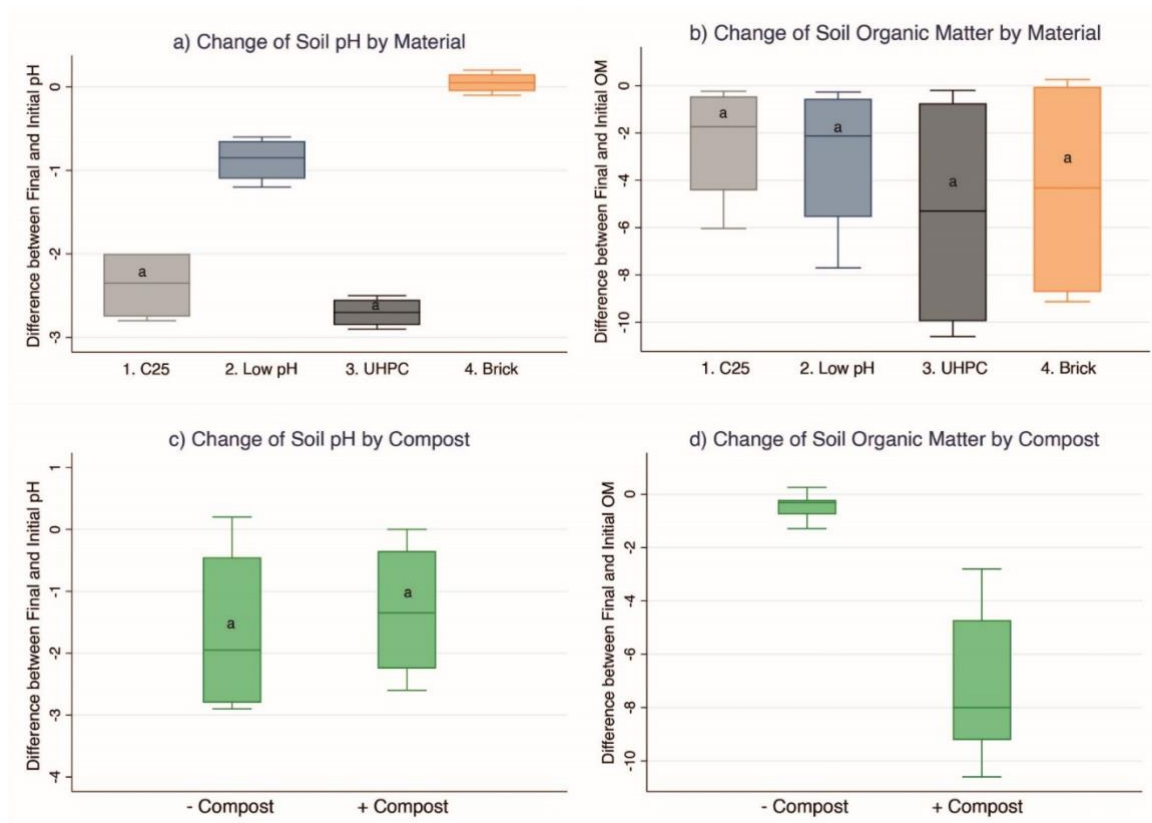
Concerning the other physical properties, we observed a higher water retention for mixtures with compost (Appendices, Table A.4), while the bulk dry density was higher for mixtures without compost additions. However, no significant change was noted between initial and final states for these parameters.

3.3.2 Change in Agronomic Characteristics

As expected, the addition of compost increased the initial level of organic matter (OM) and carbon (C) within the mixtures (Appendices, Table A.4). Since better plant growth is usually associated with high initial organic matter content, this corroborates the overall better plant growth results with compost (Figure 8a-b). Over time, the level of organic matter decreased significantly in comparison with the mixtures without (Figure 9d). In the absence of compost, the initial content of organic matter remained stable (Figure 9b). The same trends were also observed for Nitrogen content.

The Cation exchange capacity (CEC), corresponding to the ability of the mixtures substrates to supply nutrients to the plants, was generally relatively low in materials without compost additions (Table A.4). For the mixtures with UHPC concrete or brick and without compost addition, the initial state presented a high CEC. This was linked to the larger proportion of fine mineral particles, which increased the exchange surface area of the construction materials. Compost additions in the mixtures containing these relatively fine-grained materials raised the CEC corresponding both to the larger surface of mineral and organic particles.

Figure 9. Change in Soil pH and in Soil Organic Matter (LOI) by Material (a), (b), and by Compost additions (c), (d), from initial state (week 1) to final state (week 66). Different letters indicate significant ($P < 0.1$) differences between treatments. The box indicates the median (inner line) with 50% of observations; the bars indicate the upper and lower quartiles. (2 columns fitting image. Color)



3.3.3 Change in Water Extracted Elements

Most of the water extracted elements (CaO, K₂O, MgO) decreased from initial to final states. This corresponded both to consumption by the plants and to lixiviation by water percolating through the mixtures. However, the share between the part absorbed by plants and the part lost at the bottom of the pots could not be estimated. The high CaO content corresponded to the high carbonate content of mixtures containing concrete, the maximum values being obtained in the Low-pH concrete mixture. For all the mixtures containing concrete, the CaO content was divided by more than two between the initial

and the final state. For all mixtures, we also observed a very large decrease of potassium (K₂O) content which reached very low values at the end of the experiment.

Trends were not so clear for MgO content. In the initial state, Low-pH concrete presented the highest MgO content, corresponding to the composition of the sulfoaluminate clinker, but this level decreased in the final state, especially in the presence of compost. It is likely that MgO is principally leached and not extracted by plants. Indeed, organic matter contained in the mixtures increased the solubility of MgO which was present in the building material. For the other mixtures, there was no significant effect as the amounts of magnesium were lower in the initial mixtures.

4. Discussion

In this work, we aimed to quantify and qualify the bioreceptivity of materials by using them as growing media for cultivation, assuming higher bioreceptivity is associated with higher plant growth. The studied intrinsic factors of bioreceptivity included pH, density, and chemical composition, while extrinsic factors were interactions with substrate composition (contact surface between materials and substrate) and cultivation with two different plant species. Note that surface roughness, which is one of the intrinsic factors of bioreceptivity, was modified by crushing the materials for the purpose of the study. Amongst these factors, we could thus add the modified morphology of the crushed materials, measured by their granulometry. An important result of our analysis is that bioreceptivity is driven by these factors, but also by their interactions.

The results confirmed that one of the most important intrinsic factors is material pH. This is shown by the fact that the *Cymbalaria*, a calcicole species, has higher germination rates and plant growth performance than the *Campanula*, an acidocline species, which grew

later in the experiment, when pH levels of the growing media had reached lower levels. Over time all materials became more bioreceptive (secondary bioreceptivity), but the pH mixtures remained at a level of 8, which is still basic. Regarding density and chemical composition, it is difficult to link them with plant growth performance as there is no clear pattern of correlation in the physicochemical analysis.

One important result is that brick had a better performance both in terms of germination rates and plant growth, regardless of compost additions and plant species. This confirms our analysis regarding pH as brick presented the lowest pH at the start of the trial. However, this is also explained by its better porosity.

On the other hand, UHPC concrete presented the lowest bioreceptivity performance. This is explained by two observations. Firstly, the UHPC concrete was the material with the highest pH (pH = 12.6) which influenced the high pH-level of growing media mixtures (pH = 11). This result is also explained by the intrinsic properties of the building material. UHPC concrete contains anhydrous grains that are usually embedded in the very dense cement matrix. In the experiment, the process of crushing and cultivation exposed these grains to contact with water. When hydrated, these clinker particles release lime (Ca(OH)_2) that is detrimental to plants. However, over time, these elements are leached, and so their negative impact on plant growth eventually decreased. UHPC concrete presents a very low permeability. In a living wall application, the effect associated with the release of lime would probably only appear in a very long run, or if the wall gets damaged.

The addition of compost stimulated plant growth, by increasing the level of organic matters of the mixtures, and hence their biological activity, and by contributing to the structuration of the substrate providing better water retention. This phenomenon is quite

common and very well documented in agronomical studies (Estévez-Schwarz *et al.*, 2009), and our findings mean that those agronomical observations can be transferable in a vertical greenery system made of building materials.

On the one hand, it was also found that compost additions compensated to a certain extent the negative effect of material, especially for the UHPC and Low-pH concretes. In this study, the interaction of these materials with organic matter was one determinant factor in quantifying their bioreceptivity. On the other hand, the results also showed that in the pots without compost, the plants could grow without any significant decrease of the organic matter content of the mixtures. This indicated that for lower initial organic matter content, the primary production of the plants through their photosynthesis might compensate the consumption by microbial activity. Nevertheless, these results were associated with lower plant growth and hence probably lower microbiological activity. However, we can suppose that the decay of roots might contribute to maintaining the organic matter content in the mixture and change this equilibrium. At the end of the trial, although the organic matter content was still at least twice larger in the pots with compost additions than in the pots without compost addition, the initial content was divided by two.

This configuration with compost additions was not at equilibrium compared to the ones without compost additions: it questions the necessity of providing compost to the system, which could be associated with more maintenance in the long run.

One should note that the equilibrium also depended on the amount and the nature of the organic matter additions. In the case of the vertical garden, Lopez-Rodriguez *et al.* (2016) showed that the addition of 12.5% of conifer-bark compost or 25% organic material by

volume should be the optimal amount to sustain healthy plant growth while reducing substrate compaction.

Beecham and Razzaghmanesh (2015) observed that a higher organic matter content is associated with a larger loss of nutrients. The optimal organic matter content must therefore be considered very carefully (Grard, 2015).

For the pots containing UHPC concrete or Brick material without compost additions, the initial state presented a higher CEC. This can be attributed to the higher content of fine particles of clay and silt size particles in those materials which increased the exchange surface for nutrients as shown for brick in other studies (Rokia *et al.*, 2014). Indeed, in the final state, their CEC mostly decreased, probably due to the leaching of these fine particles. Regarding the pots with Low-pH and C25 concretes, the compost additions increased their CEC significantly.

The levels of water extractions of nutrients (MgO, K₂O and CaO) indicated the differences between the chemical compositions of the materials as one of the intrinsic bioreceptivity factors. The concrete, with carbonates, contributed to the level of calcium. The Low-pH concrete (in the presence of compost) particularly contributed to the highest levels of minerals, which were however subsequently reduced at the end of the experiment, especially in the case of Potassium. It is very likely that part of this loss corresponded to plant uptakes. Nevertheless, we may hypothesize that a large amount was also leached by water percolation through the pots after irrigation.

The results helped to characterize the bioreceptivity of the materials, in comparing their effect on plants significantly, and brought insights for further explorations. Indeed, the agronomical properties of materials, such as studied in Technosols (Pruvost *et al.*, 2020), constitute an important intrinsic factor of their bioreceptivity. While more and more living

walls are based on construction materials, the bioreceptivity can be considered as an important critical design factor amongst those classified by Jim (2015). The Water percolation, related to the substrates' porous structure, was responsible for organic matter and nutrient leaching, and influenced considerably the germination rates, growth and the physicochemical change between initial and final state. All materials had a significant structure of coarse elements, which goes with a large macro-porosity (Fiès, 1971). Furthermore, the fine particles are very likely to be lixiviated by the percolation of a rapid flow of water between the coarse elements. The removal of fine particles can be associated with a beneficial decrease of the pH and a detrimental leaching of nutrients which have antagonistic effects whose outcome on plant growth may be difficult to anticipate. In this experiment it appeared that the effect on pH overcame the effect on nutrients. The leaching of elements can be detrimental to a wall structure, as studied for stone monuments, in which the leaching of calcite induced by weathering decreases their mechanical strength (Tiano *et al.*, 1995). Overall, the alteration of building materials by organic matter with regard to decalcification and lixiviation must be further studied in the context of living wall design. Bertron *et al.* (2007) showed the degradation of cement pastes by organic acids resulted in a poor mechanical resistance of the materials. They recommended reducing the amount of CaO in order to improve the durability of cement materials in an acid environment.

On the one hand, the results confirmed that the bioreceptivity is defined by the structure of the material as intrinsic factors (porosity, open pore size) which are either favorable or detrimental to plant growth. On the other hand, the interaction of the materials with water flows through them, resulting in the leaching of constitutive elements, could be categorized as a new extrinsic factor influencing bioreceptivity.

5. Conclusion

This experiment on living wall materials, modeled at the scale of the pot, led to interesting results in the study and comprehension of the interactions between building materials and substrate, and of their effect on plant growth. It helped to qualify and quantify the bioreceptivity of building materials by testing their agronomic properties in a new way with significant outcomes. This physicochemical characterization represents an important factor for Vertical Greenery Systems (VGS) design and their architectural applications in terms of materials choice and substrate composition. Based on these results, the use of brick and concrete materials in living wall applications is realistic, but the harmful effect of pH level on plant growth must be controlled. More specifically, the release of lime by the hydrated clinker particles of concrete, more observable with the UHPC, which is detrimental to plant, must be compensated. For the design of a living wall, these observations must also be crossed with other parameters such as verticality that influence plant growth, nutrient leaching as well as substrate compaction.

This research allows us to make a few agronomic recommendations for living wall design. The pH level is one of the most important factors determining bioreceptivity. In our study, as all the mixtures present pH levels of 8 or higher, our first recommendation is to choose plants that are adapted to this alkaline environment, such as *Cymbalaria muralis*. It is also recommended to choose building materials with lowest pH level, or with low permeability so that their alkaline properties do not affect the substrate pH. Brick material, with its lower pH level, is associated with higher plant growth. However, at the end of the trial, the pH is stabilized around 8 for all germinated pots. This stabilization shows that this initial detrimental parameter may not influence the system in the long

term. This result is also of interest in the design of Technosol as it demonstrates the viability of using building materials in growing media mixtures for the long term.

The addition of compost is beneficial for plant growth, and it compensates to a certain extent the detrimental effects the materials can have on plant growth. However, the plants in pots without compost additions were still able to grow without a noticeable decay of initial organic matter content. Our second recommendation is hence to choose the right amount of organic matter amendments in substrate composition, providing good agronomical and structural characteristics to favor plant growth, while aiming for the equilibrium of the system in the long run. Amongst the water-soluble nutrients, we found that a big part of the potassium was eliminated by percolation during the trial. This points at the importance of planning potassium amendments.

There are beneficial and harmful effects on the sustainability of the living system. Soluble nutrients are rapidly removed by plant uptakes and by water percolation, and this would be largely favoured in a vertical system. The water-supply is very harmful to the stability of the system as it favors percolation, which is the first cause of nutrient leaching. Further investigations with longer experiments are needed to quantify the role of water percolation in a vertical greenery system. The building materials can however provide some of these water-soluble nutrients and mineral elements, but this can be to the detriment of the wall structure as part of the wall is consumed and evacuated over time. At the scale of a wall, this equilibrium, and more precisely the mechanisms which alter the building materials, is more complicated and should be further studied.

Finally, although concrete and fire clay brick were chosen for this study because of their strength and application in construction, their manufacture has a high environmental impact (due to firing and resource use). Regarding material choice, there is a trade-off

between their economic and their environmental costs. Other building materials such as stone should be considered in living wall applications, for their high bioreceptivity and lower environmental impact.

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