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Indoor green walls for improving air quality and human well-being: a case study from a primary school in Turin (Italy)

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ABSTRACT

Indoor green walls (IGWs) are innovative Nature-based Solutions to enhance air quality and thermal comfort in indoor spaces through bio-friendly design. At the same time, they can promote the improvement of human cognitive performance and socio-psychological wellbeing. A case study was developed and implemented in a primary school in Turin (Italy), through a collaborative process involving people from school, municipality, and academia, to prove the environmental and socio-psychological benefits of IGWs, based on impact assessment. The performance of IGW on air quality and human well-being was monitored, showing a positive impact of the IGW on indoor air quality through particulate matter (PM) removal, also highlighting interesting correlations between plant species, PM size fractions and their chemical composition. On the contrary, a low impact on the volatile organic compounds (VOCs) concentration was observed. Regarding the socio-psychological impact, despite the undoubtedly importance of the collaboration between various sectors of the public administration and of the use of IGW as a training tool for students, the impact evaluated by measuring changes in pupils' pro-environmental attitude and behaviour was positive but lower than expected. In conclusion, this real-life case study provides results to be further used for evidence-based decision making about the implementation of IGWs in schools. However, the study also revealed some limitations and barriers in the effective implementation of impact monitoring in living context, such as primary schools. These challenges could provide valuable lessons learned for the implementation of similar projects in the future.

1. Introduction

Nature-based Solutions (NbS) are recognised for their capacity to address biodiversity, climate crises, and other societal challenges, in both urban and extra-urban contexts, by providing multiple benefits and Ecosystem Services (ES) [1]. ES are defined as the benefits that people obtain from nature [2] binding human well-being and natural systems with ecological and economic development, bridging the gap between nature and society [3]. This interconnected relationship between nature and society is crucial for addressing global crises, as a single NbS intervention can contribute to pursuing multiple sustainable development goals [4] and poses NbS at the basis of future transformative changes [5]. However, NbS may cause also ecosystem disbenefits [6]. In urban setting, for example, high-density street trees can create a barrier for the dispersion of air pollutants instead of enhancing their sequestration [7,8]. NbS can also incentivise gentrification with a consequent

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property price increase that could enhance social exclusion [9]. Therefore, as underlined in the evaluation criteria for NbS outlined in the IUCN Global Standard for Nature-based Solutions [10], the success of an NbS action has to pursue the "balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits" (Criterion 6 of the IUCN Global Standard for NbS). On the other side, European Commission (EC) formulated two further definitions of the concept of NbS, arguing that they are solutions inspired and supported by nature that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways [11–13]. It must be based on a holistic approach, in which systems analysis and research are conducted from an inter- and trans-disciplinary perspective. This underscores the need to integrate NbS in policy and regulatory frameworks, indicating a positive shift to a broader NbS research [1]. However, many scientific papers reporting impact monitoring of NbS case studies still focus on single benefits, neglecting the co-benefits.

To foster the development and assessment of multifunctional NbS, the European Union (EU), especially through the Horizon2020 and HorizonEurope funding programmes, promoted the exploration of collaborative approaches involving different sectors of society and research [14]. Attention was put on enhancing collaborative governance models, including co-creation processes [15], considering that the lack of intersectoral collaboration creates bottlenecks in their implementation [16]. Then, polycentric governance structures, which involve a wide range of stakeholders, are believed to be more effective in managing public goods than traditional governance approaches. Among the innovative collaboration models promoted in recent years, Living Labs are defined as a "physical region and interaction space, in which stakeholders form a quadruple helix innovation network collaborate for the creation, prototyping, validating, and testing of new technologies, services, products, and systems in real-life contexts" [17]. The quadruple helix network model should be composed by the end users (citizens, NGOs), the public sector (public agencies, policymakers), the private sector (business companies) and academia [18]. While informative and participative planning can foster acceptance, co-creation is important to reach multiple societal benefits by engaging a wide range of stakeholders during all project stages, including planning, design, implementation, monitoring, evaluation, and maintenance [19]. At the same time, to demonstrate benefits' provision in connection with different ES, researchers with different background should be involved in the NbS monitoring and impact evaluation, which should also be developed according to already established evaluation frameworks, to allow further comparison and improve evidence-based knowledge [10, 20]. However, the dialogue and collaboration among different actors, having each its own perspective and needs, can meet barriers that can hinder the successful completion of the whole NbS life cycle. Furthermore, experiments carried out in real-life contexts, within a public building, such as a school attended by children, may result in some obstacles to the strict application of certain experimental methods and protocols [21].

Among NbS, indoor green walls (IGWs) are an innovative model to apply bio-friendly design for improving human health and well-being [22], and are suitable case studies to test the efficacy of co-creation and co-design process, with a large involvement of local stakeholders, which are essential prerequisites for IGWs to be defined as an NbS [14, 23], as well as to simultaneously monitoring and assessing multiple ES [24].

From the human well-being perspective, previous studies have shown that improving the indoor environment in schools, offices and hospitals through the IGWs implementation is useful to enhance health, education, air quality and indoor microclimate [25]. Contact with the natural element can promote human well-being, both in the form of restorative effects, as well as the promotion of cognitive functions, productivity, mood and stress reduction [26–28]. For instance, when young pupils have a view of green spaces at school, they could have better performance on attention tests and stress recovery [29].

From the environmental benefit side, IGWs can improve air quality due to the concomitant atmospheric CO_2 sequestration, volatile organic compounds (VOCs) adsorption and particulate matter (PM) retention [30,31]. Furthermore, air quality is known to be strictly related to human health [32], since about 250.000 people in Europe die each year for diseases caused by air pollution linked to cardiovascular, respiratory and dermatological systems, while in Italy the numbers reach about 59, 000 cases [33]. VOCs and PM are both known for their negative effect on human health, especially on children who are more vulnerable. VOCs are typical outdoor and indoor airborne pollutants, composed of different chemical compounds, such as aldehydes (and higher aldehydes), benzene, toluene and other aromatic organic compounds. These airborne pollutants are absorbed by plants and subsequently metabolized through a process known as phytodegradation [34]. Several studies [35,36] conducted in laboratory environment showed positive effects of indoor plants in removing some organic pollutants. However, there are also some doubts regarding the effectiveness of these solutions in real contexts [37,38]. On the other side, airborne PM is made up of a complex mixture of solids and liquid droplets, of organic and inorganic origin, suspended on air, and they are removed by plants through wet and dry deposition on leaves [7]. PM organic portion is mainly composed of microorganisms such as bacteria, fungi and viruses, while the inorganic portion can have either natural (i.e., crustal or marine salt) or anthropogenic (i.e., traffic, combustion, etc.) origin [39]. PM is generally classified according to its size as PM_1, $PM_{2.5}$, PM_{10} (i.e. particles smaller than 1, 2.5 and 10 μm, respectively), with harmfulness with decreasing the size [7]. It has been proved by a few studies that PM removal efficiency can be species-depended, as a function of PM size and chemical composition, since the physico-chemical mechanisms driving PM deposition on leaves depends on leaves side characteristics [40–43]. Therefore, a mix of different plant species should be considered to realise an IGW, to maximise PM removal.

In this study, an heterogeneous team of people from school, local administration, company involved in the IGW implementation, and different research contexts worked in synergy to better disclose benefits and barriers related to the realisation and management of an IGW in a public school, and specifically, to: 1) develop and implement a solid co-design and co-governance strategy, 2) evaluate the impact on pupils' socio-psychological well-being, 3) evaluate the impact in term of air quality improvement; 4) identify strengths and weaknesses with a view to trade-offs, to provide suggestions for future IGW evidence-based implementation.

2. Materials and methods

2.1. Green wall design: location and plant species selection

The case study consisted of an IGW installed inside the building of the primary school I.C. "A. Cairoli" of Turin (long: 45.01668286552169, lat: 7.655621939741015), implemented by the proGIreg Horizon 2020 project. The I.C. Cairoli was selected after a consulting process done in the Mirafiori Sud district to identify the school building able to satisfy basic preconditions, such as the accessibility during the year for the NbS maintenance. The IGW was co-developed through the involvement of key stakeholders and the local community during the environmental education program "*Pareti Verdi a Scuola*'' conceived and implemented by the Department of Environment, Land and Infrastructure Engineering of the Politecnico di Torino, which was carefully described by Comino et al. [44]. The co-design process carefully focused on needs and requirements suggested by municipal officers responsible for the school building and safety risk reduction unit, and the school dean and staff. Focus groups and technical visits were organised to establish and strengthen the collaborative design process between municipality, academia and school staff. At the end of co-design preliminary stages, two modular IGWs of 12 m^2 (3 m height and 4 m wide), for a total surface of 24 m^2 were installed in the school hallway at the ground floor.

The technical solution chosen was the *VP-Modulo* System® modular structure Verde Profilo® [45] consisting of planter boxes in expanded polypropylene foam installed on an aluminium frame anchored to the building wall. The IGW was equipped with an automated dripline fertigation system and a water collection tank placed on the bottom of the structure, and it was composed by the following plant species: *Marantha leuconera* (56 plants), *Chamaedorea elegans* (104 plants), *Pilea peperomioides* (65 plants), *Chlorophytum comosus* (97 plants), *Calathea amabilis* (86 plants), *Calathea ornata* (12 plants) and *Calathea orbifolia* (12 plants). These were pre-planted on IGW modules and then mounted *in-situ* on the aluminium frame. Maintenance of the IGW occurred on a monthly base, including water and fertigation system check, and plant replacement (if needed). However, a systematic monitoring of biomass growth and loss was not performed. The IGW received sunlight according to the natural photoperiod, thanks to the skylight installed on the rooftop of the school hallway. Moreover, a descriptive poster was installed to provide information about its components and functions to school occupants and other external stakeholders. The engagement of local stakeholders continued after the IGW installation thanks to activities of environmental education proposed and organised by the academic partner in collaboration with the I.C. Cairoli school staff (Fig. 1a-b).

2.2. Questionnaires on children pro-environmental attitude and behaviour

Pro-environmental attitude and behaviour questionnaires were developed to track any changes in children's well-being in relation to activities conducted within school environments featuring natural elements. Children between 8 and 12 years of age responded to questions under teachers' supervision and support. Baseline measurement was conducted before the IGW installation (December 2020), and a follow-up survey was performed after one year and a half (May 2022). The analysis was carried out on two classes of the 4th grade of primary school (i.e., 4A and 4B) and two classes of the 5th grade (i.e., 5A and 5B). Quali-quantitative measures were collected on pupils, starting from descriptive information (i.e., age, gender, and class) and then the questionnaire was submitted. It was based on 14 items for assessing environmental attitudes towards nature and of 9 items for assessing environmental behaviour. Items intended to detect children's perceptions, beliefs, and actions regarding nature, sustainability, and environmental conservation. Questions were about the level of concern for the environment, sustainable consumption practices, interest in nature conservation and participation in pro-environmental behaviours such as recycling, reducing energy consumption, and using sustainable transport. In conclusion, an adapted version of "Perceived Restorativeness Scale" (PRS; original validation by Korpela e Hartig [46]), based on a 16-item tool was used to assess perceived restoration provided by a natural environment. The adaptation for children was developed *ad hoc* and involved using a dichotomous response format (yes/no) instead of the Likert scale, represented graphically by "thumbs up" or "thumbs down" emoticons. The English version of the questionnaire text, the descriptive statistics of the collected data and the results of the statistical analysis are reported in the Supplementary Material (Annex SM1, Table SM1, and SM2).

2.3. Air pollutants monitoring

The concentration of VOCs, aldehydes and nitrogen dioxide was detected in two sampling campaigns. The first air sampling was performed before IGW installation, from 11/12/2020 to 18/12/2020, while the second one was after IGW installation, from 22/01/2021 to 29/01/2021, a short time later to limit the seasonal outdoor air pollution differences. The list of VOCs included: formaldehyde, acetaldehyde, propionaldehyde, isovaleraldehyde, valeraldehyde, methyl tert-butyl ether (MTBE), benzene, toluene, ethylbenzene, o,m,p xylene, styrene, isopropylbenzene, n-propylbenzene, 1,2,4-trimethylbenzene, dichloromethane, chloroform, 1,1,1-trichloroethane, 1,2-dichloroethane, carbon tetrachloride, 1,2-dichloro-propane, trichloroethylene, tetrachloroethylene, ethyl-tert-butyl ether, acetone, methyl-ethyl ketone, ethyl acetate, 1-methoxy-2-propyl acetate. Two different types of sampling were performed: active and passive collections. Active collections consisted in single measures of some hours, carried out on a tripod at 1,5 m high by the ARPA technicians. Otherwise, passive collections were collocated in an elevated position not to be accessible to the pupils, and they reached data for some days. Data were collected in two measurement points in proximity to the IGW in the school hallway (called hallway point 1 - HP1 and hallway point 2 - HP2). Two control points were also selected for the same experimental measurements: the indoor control point (ICP) was located around 20 m far from the IGW, on the lower floor of the school; the outdoor control point (OCP) was located close to the school entrance. At each sampling point, aldehydes were actively sampled with *vial Supelco LpDNPH10*, applying the *NIOSH 2016* and *NIOSH 2018* sampling and analysis protocols. Aldehydes concentration in the air was carried out by active sampling using adsorbent cartridges (*Supelco LpDNPH10*) made of silica coated with 2,4 - dinitrophenylhydrazine (DNPH). The aldehydes trapped in the cartridge were analysed in the laboratory by liquid chromatography (HPLC). The other VOCs and nitrogen dioxide have been sampled with radiello® passive samplers for one week, by applying the sampling and the analysis method of *Salvatore Maugeri IRCCS Foundation* (respectively pages D1-D6: 2003 - updated 2007 and pages F1-F2: 2003). The radiello® passive sampler consists of a radially symmetric diffusive sampler in which a specific cartridge for the pollutant to be detected is inserted. VOCs retained during exposure were analysed in the laboratory by solvent extraction and instrumental determination using gas chromatography and mass spectrometry (GC–MS). Regarding nitrogen dioxide, it was determined in the form of nitrite ions using the ion chromatography technique. The concentrations of the monitored pollutants were expressed in ug/m^3 and normalised to standardised conditions of temperature (25 °C) and pressure (1013 mbar). The full lists of the measured

Fig. 1. a) IGWs installed in the school hallway and b) pupils during an activity related to IGW.

compounds and collected data are reported in the Supplementary Material (VOCs and nitrogen dioxide can be found in Table SM3 and SM4, respectively). To further support the concentration values measured by passive samplers at the OCP, these latter have been compared with the concentration measured on an hourly base by the ARPA Piemonte station in Turin "TO-Lingotto" [47].

Removed PM physico-chemical characterization was conducted on a species-specific base, by analysing sampled leaves by scanning electron microscopy coupled with energy-dispersed X-ray spectroscopy (SEM/EDX), according to the protocol validated by Baldacchini et al. [48]. Leaves were collected by five plant species in the IGW, selected focusing on their capability of improving indoor air quality [49,50]: *C. orbifolia, C. elegans, C. comosum, M. leuconeura,* and *P. peperomioides.* Leaves were sampled in two different sampling campaigns, conducted in October 2021 (Time 1) and October 2022 (Time 2), to evaluate changes on leaf deposited PM quantity and quality after one year of continuous exposure in the school environment. Time 1 is intended as the baseline measure. Leaves have been sampled from the same plants, at the two times. Obtained results gave information about leaf deposited particles density (number of particles/mm^2), chemical composition (W % of each chemical element for each plant species) and load of PM removed for unit area (μg/cm^2). A Phenom ProX (Phenom-World, The Netherlands) scanning electron microscope was used, equipped with an X-ray analyser and charge-reduction sample holder suited for biological samples. Samples were taken from three individuals of the same species (replicates) in random points of the IGW. Both the adaxial (AD) and abaxial (AB) sides of each leaf sample were examined. For the analyses, a portion of approximately 1 × 1.5 cm^2 from each leaf was fixed to the head of the carbon-based stub (PELCO Tabs, Ted Pella, Inc.), with the AD or the AB side facing upwards, after being cleaned with compressed air. For PM size analysis and particle count, SEM images were performed with an incident electron energy of 5 keV to limit side charging. Ten random images, each covering an approximate area of 150 × 150 μm^2 (1024 × 1024 pixels), were taken for each sample. Images were analysed using Gwyddion open-source software [51]. By applying a colour threshold-based grain analysis [52,53], the number of particles and the aerodynamic diameter (diameter of equivalent sphere) of each particle were determined. Particles with an equivalent diameter (d_{eq}) comparable to the size of a single pixel (0.146 μm) were excluded, resulting in a lower cutoff diameter of about 0.3 μm. Particles with a d_{eq} larger than 10 μm were also excluded, resulting in a final data set composed by $PM_{0.3–10}$ particles. For the elemental analysis of leaf deposited particles, ten images with a lateral size of 50 μm (1024 × 1024 pixels) per each sample were acquired at an electron voltage of 15 kV. From each image, ten particles were randomly selected, totalling 100 particles per leaf sample. The d_{eq} for each particle was determined by averaging their two main Feret diameters [54], as measured with ImageJ software [55]. Using the dedicated Phenom Pro Suite software, the corresponding EDX spectrum for each particle was obtained by positioning the laser beam at the particle centre [53]. The elemental composition of the PM in each leaf sample n was estimated by calculating the weighted volume percentage (W %xn) of each element x across the selected particles i of sample n, as outlined in Eq. (1) [41]. For each sample n, W %xn was obtained by multiplying the relative percentage of each element x in each particle i (Cxi, as determined by the EDX software) by the particle volume Vi = 4/3 π $(deq/2)^3$. The relative volumes occupied by each element in all analysed particles were then summed and normalised by the total volume of the EDX-analysed particles for sample n [48]. Finally, the PM mass per unit leaf area of each sample n (Mn; μg/cm^2) was estimated by multiplying the W %xn of each element by the corresponding elemental atomic mass per volume amx, and by the total volume Vn of the particles imaged in the ten 150×150 μm^2 images of the same sample n, normalized by the total imaged area An (Eq. (2)):

$$W\%xn = \frac{\sum_i Cxi * Vi}{\sum_i Vi} \quad (1)$$

$$Mn = \sum_x * \frac{W\%xn * Vn * amx}{An} \quad (2)$$

Based on the PM_{10} load per unit leaf area results, the total leaf deposited PM_{10}wt on the IGW in one year was then roughly estimated as the difference between the leaf deposited PM_{10}wt on the IGW at the two times. These values were calculated by considering the size of the IGW (24 m^2), assuming that similar IGW fractions are occupied by the five selected species (resulting in 48.000 cm^2 per species), and taking into account the tridimensionality of the plants by multiplying the PM_{10} load at leaf level by the species specific Wall Leaf Area Index (WLAI) [56] (see Table SM5 in Supplementary Materials) as:

$$IGW\ accumulated\ PM_{10}\ (\mu g) = PM_{10}\ load\ \left(\frac{\mu g}{cm^2}\right) \times 48000\left(cm^2\right) \times WLAI$$

When calculating the amount of PM accumulated by GWs, several authors suggested adapting the concept of Leaf Area Index (LAI) used for tree and crop species, represented by the one-sided green leaf area per unit ground surface area (LAI = leaf area / ground area, m^2/m^2) [57], to the concept of WLAI [56,58]. WLAI is measured as the ratio between the one-side leaf area and the vertical surface area projected onto the GW. To calculate the WLAI of the species, we used the method proposed by Tomson et al. [56], considering the number of leaves on a vertical GW surface area equal to a 25 cm^2 quadrat. For species with an average leaf area smaller than the quadrat, such as *C. elegans, C. comosum* and *P. peperomioides*, we followed the same method, while for species with a leaf area larger than the quadrat, such as *C. orbifolia* and *M. leuconeura*, we adapted Tomson's method by considering a leaf area equivalent to the quadrat, a maximum of 25 cm^2. The WLAI results obtained are as follows: *C. orbifolia* (2), *C. elegans* (2.5), *C. comosum* (8), *M. leuconeura* (2), *P. peperomioides* (1.5).

2.4. Statistical analysis

Statistical data analyses for questionnaires results were conducted utilising R software (R Core Team, 2020). The descriptive statistics employed in the analysis comprised the computation of means and standard deviations for age, pro-environmental attitude, and behaviour, restoration, as well as the frequency distribution of gender. To explore the potential effect after the IGW implementation on pro-environmental attitude and behaviour across classes, repeated measures ANOVAs were conducted separately for each class group, after verifying that the assumptions of sphericity and homoscedasticity were met.

For VOC concentration analyses, due to the limited number of single measurements (no replicated measures were available apart from the two replicates close to the IGW), only a correlation analysis between the concentration values was performed by using *STATISTICA Release 7* © software.

Regarding PM removal results, PM density, size distribution and load analyses were conducted by using Excel. A principal component analysis (PCA) was performed through *STATISTICA Release 7* © to analyse the correlation between plant species and physico-chemical PM characteristics. Data from three replicates per species were used as input cases and single elemental concentrations elements with a W % higher than 0.1 % were used as input variables, as well as the relative content of ultrafine ($PM_{0.2–1}$) and coarse PM ($PM_{2.5–10}$). Contrary, trace elements, such as anthropogenic elements, with a percentage W % <0.1 %, were not considered because of the reduced representativeness. *OriginPro 8.5* © was used for data visualisation.

3. Results and discussion

3.1. Socio-psychological benefits and lessons learned: challenges, barrier and future directions

The co-design process adopted a bottom-up approach to promote an active role of stakeholders and school occupants. The multifunctional IGW was co-designed between stakeholders and school members to improve the quality of the indoor space by enhancing the aesthetic perception of interiors through the introduction of the natural elements. At the same time, the IGW improved community wellbeing as "soft benefits" by promoting positive social relations among pupils, teachers, school staff and parents, and by providing environmental educational opportunities. The IGW project, in fact, was used by schoolteachers and staff as an educational tool, according to the model of the living lab. Twenty meetings were organised between January and December 2021, involving 150 students (age 6–10), by adopting a play-based learning approach that alternate theoretical lectures with experiential activities and games involving the interaction with plants and introducing the concept of ecological literacy, also known as "ecoliteracy" [59,60]. During meetings, students had the opportunity to learn some aspects related to the interaction between humans and nature, the alienation from nature, and the importance of re-naturalization processes within cities. In addition, during the learning activities, pupils were divided in small groups to foster the peer-to-peer dialogue and were asked to express and communicate their point of view and emotional perceptions.

Questionnaires on pupils' pro-environmental attitude and behaviour were submitted before and after the IGW installation and the described activities related to environmental education program. Results from descriptive analyses based on the monitoring and evaluation of four school classes (4A, 4B, 5A,5B) are reported in Supplementary Materials (Table SM1 and SM2). They considered the following aspects: age, gender, pro-environmental attitude, pro-environmental behaviour and restoration. The results obtained from the repeated measures ANOVA reveal no significant difference between the baseline and follow-up assessments concerning pro-environmental attitude and behaviour, except for class 5A. Notably, within class 5A, there is a considerable increase observed in the total score for pro-environmental behaviour after IGW implementation, suggesting a positive effect of the IGW within this class. Despite the current scientific literature shows limited studies published on green walls in a school setting, the realisation and monitoring of this project allow to learn several lessons that will be useful for the future NbS implementations. First, the reduced participation of children in educational activities related to the restriction caused by Covid-19 negatively affected the result. In fact, only a few activities set out in the program were carried out on time and in the prescribed manner. For this reason, some difficulties were also found in the coordination of the environmental education activity with the monitoring campaigns. Moreover, the IGW implementation demonstrated a significant positive impact observed only in specific class groups. This suggests that the failure to achieve the desired results may also be due to the methods used to assess learning. Many students, in fact, showed a certain sensitivity towards environmental sustainability issues, and this is probably due to the education they received from their families. In recent years, in fact, children show greater sensitivity to environmental protection and nature than previous generations. This condition may have contributed to the reduced impact on socio-psychological well-being. Consequently, potential difficulty in its implementation is the variability in response across different classes, indicating the need for tailored approaches. At the same time, bureaucratic barriers increased the difficulties, because a public primary school is a very strictly controlled environment, and all the activities conducted involving young students must be done with respect to specific requirements. On the other side, among positive aspects, interest, motivation and collaboration between different stakeholders was necessary for the coordination of the project steps. The creation of an active community with a strong sense-of-place able to support IGW installation, monitoring and continuing activities of the living lab, was one of the most important project's challenges. Additionally, to promote educational, social and cultural activities after the end of the proGIreg Horizon2020 program [61], the I. C. Cairoli opened his spaces to host additional activities for people from the local community of Mirafiori district. Therefore, some open days have been organised to show the living lab and the IGW to other interested stakeholders with the aim to replicate the case study in other schools or public and private buildings.

3.2. Environmental benefits: volatile organic compounds (VOCs)

The concentration of most of the measured VOCs resulted below the limit of detection at each sampling point, before and after the IGW installation. This is shown for propionaldehyde, isovaleraldehyde, valeraldehyde, methyl tert-butyl ether (MTBE), styrene, isopropylbenzene, n-propylbenzene, dichloromethane, chloroform, 1,1,1-trichloroethane, 1,2-dichloroethane, 1,2 dichloropropane, trichlorethylene, ethyl *tert* butyl ether and 1 methoxy 2 propyl acetate. For the remaining VOCs (formaldehyde, acetaldehyde, benzene, toluene, ethylbenzene, o,m,p xylenes, 1,2,4-trimethylbenzene, carbon tetrachloride, tetrachlorethylene, acetone, methyl ethyl ketone, ethyl acetate) and for the nitrogen dioxide, the average concentration values measured at the two sampling points close to the IGW (HP1 and HP2), before and after the implementation, are compared with the single values observed at the indoor (ICP) and outdoor (OCP) control points in Fig. 2.

First, it should be noted that some compounds have higher concentrations outdoor than indoor (such as toluene, benzenes and xylenes), while others show an opposite behaviour (such as aldehydes, chlorine compounds, acetone, ethyls and nitrogen dioxide). This may be due to the presence of internal sources of VOCs, which in some cases cause higher indoor concentrations. In addition to anthropogenic sources, such as paints, fuels, solvents and sprays [62], human sources should also be considered. People emit VOCs through breathing and skin emissions, and this phenomenon can be observed in crowded places, such as an office or a school classroom [63].

The average concentration values measured close to the IGW (HPav) are lower after implementation than before for almost all the compounds, except for nitrogen dioxide. However, a correlation analysis showed that the averaged concentration values close to the IGW (HPav) are mostly correlated with the surrounding indoor concentration (ICP, $r = 1.00$, $p < 0.05$ for both pre and post) and with the outdoor concentration (OCP, $r = 0.98$ and $r = 0.99$, $p < 0.05$, for pre and post, respectively), not depending on the presence of the IGW. Moreover, the difference between the average concentration close to IGW (HPav) and the ICP remained almost constant (such as for benzene, 0.2 $\mu g/m^3$) or slightly decreased as for toluene (0.4 $\mu g/m^3$ before IGW implementation and 0.3 $\mu g/m^3$ with IGW) and ethylbenzene (0.2 $\mu g/m^3$ before IGW implementation and 0.1 $\mu g/m^3$ with IGW). Notably, only the indoor concentration of acetaldehyde didn't correlate with the outdoor one: while this latter remained stable over time, the indoor concentrations decreased, both close and far from the IGW.

Compared to other studies [64] in which the presence of an IGW produced a significant difference in VOCs concentration between before and after the installation of the IGW, we may argue that in the present case study a few additional difficulties, mainly related to the usage of the site, reduced the impact. For instance, in the study period the school was subjected to public health rules related to the Covid 19 pandemic: hallway windows were always open and strong ventilation was required; this probably improving the indoor with the outdoor air mixing, reducing the IGW effect. In addition, the IGW was placed in a large hallway, and this probably further reduced indoor accumulation phenomena. Furthermore, the post installation measurements were conducted when the plant were still far from their full growth. These limitations must be considered such as lessons learned for the future projects. Further potential improvement could be also suggested in the

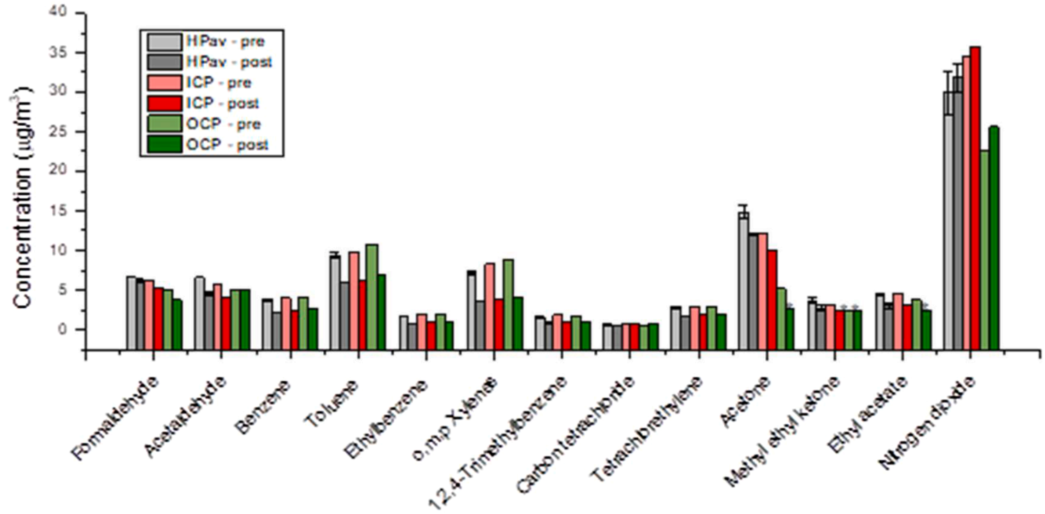

Fig. 2. Active sampled concentration of aldehydes, passive sampled concentration of other Volatile Organic Compounds (VOCs) and of nitrogen dioxide as measured before and after the IGW installation (December 2020 and January 2021) at the 3 sampling points: hallway point average (HPav; i.e. the average between hallway points 1 HP1 and hallway point 2 HP2), indoor control point (ICP), and outdoor control point (OCP). Columns with an asterisk represent values below the limit of detection.

IGW design in terms of plant species. Indeed, it was documented that the efficiency of VOCs removal varies depending on the plant species: the use of plants with a large leaf side area should be preferred to maximize the presence of stomata, structures that are essential for regulating gas exchanges, including VOCs [65], and it is also important to consider that gas exchanges can be affected by biochemical characteristics of the cuticle [49].

3.3. *Environmental benefits: monitoring of leaf deposited particulate matter (PM)*

SEM images of the AD and AB leaf sides of the five species present in the IGW are shown in Fig. 3, together with standard pictures of the corresponding plants. The five species have different macro and micro morphological traits of their leaves. The PM particles are evident on both AD and AB sides of each species, as the brightest spots.

To evaluate the amount of PM removed by the IGW in one year, the density, size distribution and chemical composition of the PM particles deposited on leaves of each species in October 2021 (Time 1) and in October 2022 (Time 2) were measured (see Figure SM1 and SM2 in Supplementary Materials). By combining these data, the load of leaf deposited PM per each plant species and each size fraction, was obtained as per Baldacchini et al. [50], at the two Times (Fig. 4). The PM load is higher for the coarse ($PM_{2.5\text{–}10}$) and lower for the ultrafine fraction ($PM_{0.2\text{–}1}$), despite the opposite trend is observed in particle density (see Figure SM1), as expected [49]. In Time 1, which should be considered the baseline value, all the species have a total PM_{10} load of about 4 $\mu g/cm^2$. In Time 2, four species show a significant increase of the PM load, ranging 8–13 $\mu g/cm^2$, except for *M. leuconeura,* whose PM load is not significantly increased with respect to the baseline value.

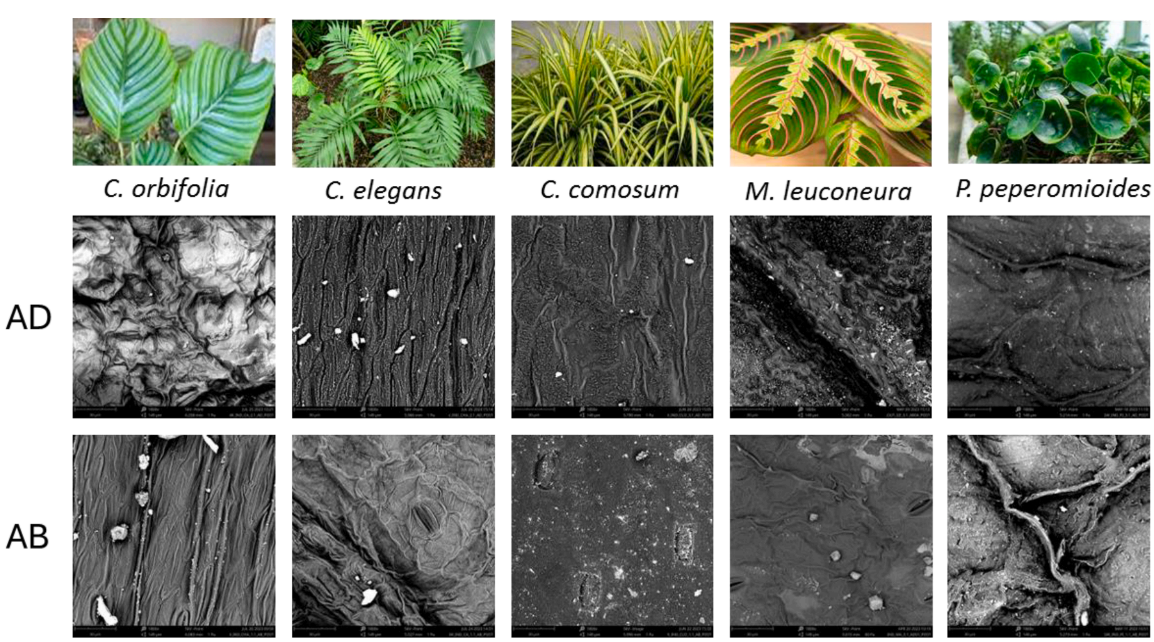

Fig. 3. Pictures of the five plant species and the corresponding Scanning Electron Microscopy images of the adaxial (AD) and abaxial (AB) sides, acquired in back-scattering, by using an incident electron energy of 5 keV, having a lateral size of 149 µm.

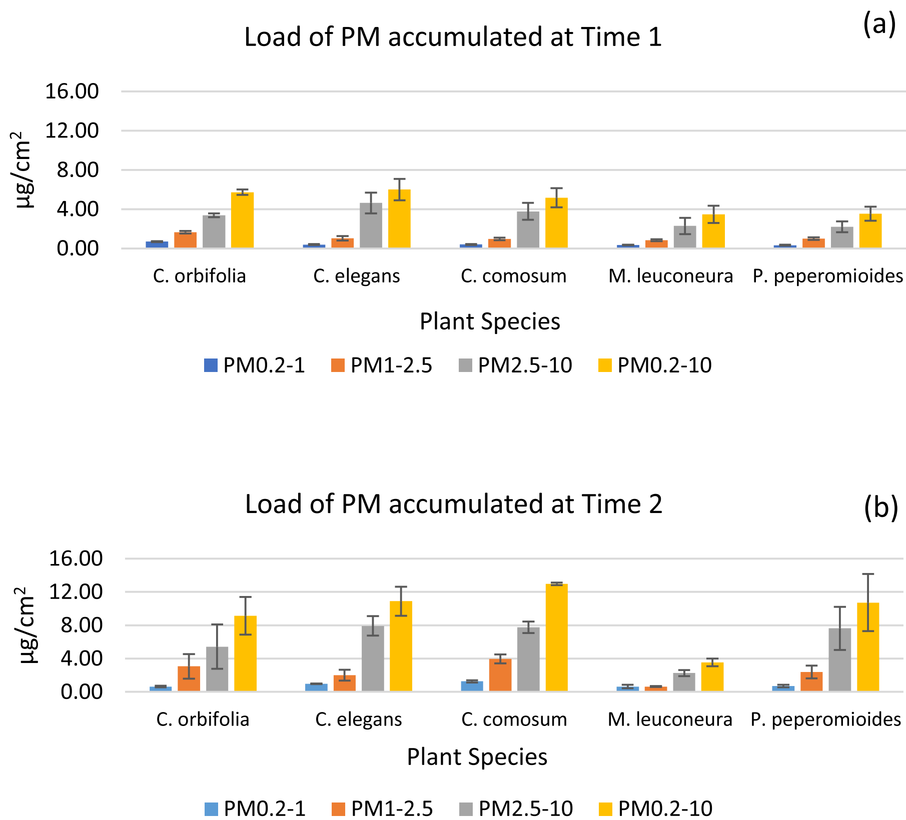

Fig. 4. Load of PM accumulated on the leaves of the different plant species in the Indoor Green Wall, for the 3 PM size fractions $PM_{0.2–1}$ – $PM_{1–2.5}$ – $PM_{2.5–10}$, and for total PM_{10}. Leaves have been collected in October 2021 (Time 1, a) and in October 2022 (Time 2, b).

Specifically, PM_{10} load increases from 6.0 ± 1.1 to 10.9 ± 1.7 µg/cm^2 for *C. elegans* (+82 %), from 5.7 ± 0.3 to 9.0 ± 2.2 µg/cm^2 for *C. orbifolia* (+58 %), from 5.1 ± 1.0 to 13.0 ± 0.1 µg/cm^2 for *C. comosum* (+155 %), and from 3.6 ± 0.7 to 10.7 ± 3.5 µg/cm^2 for *P. peperomioides* (+197 %).

It is worth noting that, during the study time, the effectiveness of PM accumulation was species-specific and the relative increase in leaf deposited PM ranged from almost 0 in *M. leuconeura* to about 200 % for *P. peperonioides*. Several studies observed a similar behaviour, for both tree and herbaceous species, and it was mainly attributed to physical mechanisms related to plant leaf macro and micro-morphological traits [32,41,43]. On the other side, a lower number of studies recently highlighted that species-specific PM deposition on leaves can be also related to the PM particles' chemical composition [42,66].

The PM_{10}wt removed by the IGW in one year was then estimated as the difference between total PM_{10}wt accumulated at Time 2 and at Time 1, and it corresponds to about 4.42 g (0.184 g/m^2 per year, equal to 18.4 µg/cm^2 per year, at the wall level). Specifically, the PM_{10}wt removed by the five species per unit wall area ranges from a minimum of 0.12 µg/cm^2 for *M. leuconeura* to a maximum of 62.4 µg/cm^2 for *C. comosum*, while *C. orbifolia* accumulated 6.8 µg/cm^2, *C. elegans* accumulated 12.0 µg/cm^2 and *P. peperomioides* accumulated 10.8 µg/cm^2 of PM_{10}. We can compare these results with those obtained by Tomson et al. [55] by eight species in an outdoor GW (OGW) close to a busy road, which were observed accumulating (as a mean value over three sampling periods of different days) from a minimum of 2.6 µg/cm^2 (*O. vulgare*) to a maximum of 13.1 µg/cm^2 (*H. helix*) of PM_{10} at wall level per day. Our results, being evaluated on a yearly base, seems to underestimate IGW performance with respect to what observed by Tomson et al. [56]. However, it should be considered that IGW are exposed to lower atmospheric PM concentrations than OGW and are sheltered from rain, which particularly affects PM accumulation and has been shown to reach saturation after approximately 26 days [67]. However, the species-specific accumulation rate is confirmed also by our experiment.

To further disclose this aspect, and to provide more insights into the species-specific affinity between leaf sides and PM particles, which could be relevant for the future implementation of more efficient IGW, we have performed a PCA. In this PCA, the plant species (3 replicates per species) are the cases and the relative weighted percentages W % of the elements and the percentage of particles in the ultrafine (i.e., PM_1) and coarse (i.e., $PM_{2.5–10}$) fractions are the input variables. The PCA has been performed by using data from leaf deposited PM both at Time 1 (Fig. 5a-b) and at Time 2 (Fig. 5c-d) to disclose potential differences in the species-specific PM accumulation. Notably, the two Times mainly differ by the fact that before Time 1 (i.e., before the IGW setting) the plants were exposed to different PM sources and environmental conditions, while for one year before Time 2 the plants were exposed to the same air pollutants, withsin the same site.

Fig. 5a and 5c show the factor coordinates of variables, i.e. the projection of the two most discriminant components over the input variables, at the two Times. Fig. 5b and 5d show the factor scores of the cases. In Time 1, the most discriminant component PC1 represents the 30.2 % of the total variance, and PC2 represents the 18.2 %. In Time 2, the most discriminant component PC1 represents the 29.9 % of the total variance, and PC2 represents the 27.2 %, thus the total variance explained by the first two PCs increased by about 10 %. In both cases, a high relative concentration of coarse particles results to be correlated with a high concentration of those elements referred to as "crustal components" (Si, Al, Mg and Fe, positive PC1 and mainly PC2 values). This set of chemical elements belong to the mineral dust aerosol group derived by soil and crustal rock disintegration, and for this reason they usually have a coarse size [68]. Also, in both cases, a high concentration of ultrafine particles results being correlated with a high concentration of ionic species and Ca (negative PC1 values and mainly negative PC2). This correlation may reflect the influence of common emission sources, such as the water used to irrigate the plant, from which the inorganic ions originate. In addition, other ultrafine particles can be originated by

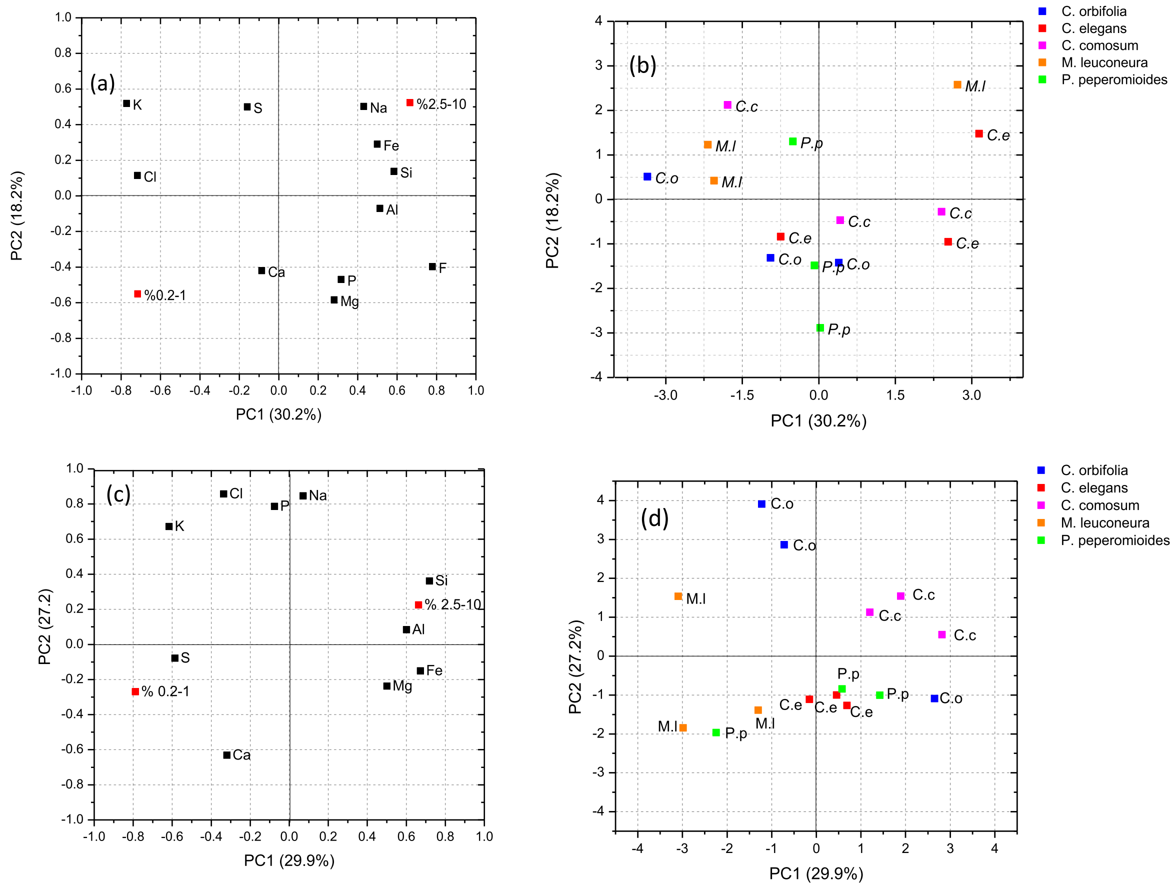

Fig. 5. Factor coordinates of variables (a-c) and factor scores of the cases (b-d) related to three replicates per species plotted in the bi-dimensional plane defined by PC1 and PC2, at Time 1 (October 2021; a, b) and at Time 2 (October 2022: c, d).

vehicular traffic and industrial processes, which simultaneously release both ultrafine particles and inorganic ions into the atmosphere [69].

However, the bidimensional plots of the factor scores of the cases as a function of PC1 and PC2 (Fig. 5b and 5d) are very different. Indeed, any clear clustering of the species is observed at Time 1 (as expected, due to the different exposures of the plants before the IGW setting), while a clear clustering is observed at Time 2 (demonstrating that, when exposed to the same atmosphere, within the same environment, plant species may have different affinities towards different PM types). In particular, *C. comosum* and *M. leuconeura* show a good clustering of their three replicates, indicating a strong affinity towards coarse PM composed by Si and Al, and towards ultrafine PM mostly composed by S, Ca and K, respectively. *C. elegans* replicates clustered in the central area of the bidimensional plot suggesting that particles of different types are present on its leaves. For *C. orbifolia* and *P. peperomioides*, the clustering concern only two replicates of three, and this could indicate a preferentially adsorption on these species of ultrafine PM mostly composed by Cl, P, and K, and of coarse PM, mostly composed by Fe and Mg, respectively.

Similar results were obtained previously by other studies, which found a correlation between the amount of PM accumulated and the micromorphological characteristics of the leaves [32,43,40], as well as a specific affinity of the species depending on the chemical elements [42,53]. However, some studies [42,70] were conducted in active GW systems, where the circulating air flow maximises PM deposition on leaf surfaces. Active GWs are closed and controlled systems where microclimatic parameters, air flow velocity and PM concentration can be controlled in real time. For these reasons, these systems are a useful tool for furthering the study of the physical-chemical dynamics that regulate PM deposition on leaves and for determining the effectiveness of PM removal by GWs and by the individual species. Having more information on the PM removal performance of different plant species can be very useful for the design of indoor and outdoor GWs in urban environments. In conclusion, choosing the species best suited to removing PM from different sources and with specific physical-chemical characteristics will make it possible to promote NbS implementations in line with specific air pollutant targets, thus maximising the impact of GWs on improving air quality.

4. Conclusion

This study can be considered an example of collaborative processes between different stakeholders (school, municipality, company and academia), in which cooperation occurred both in the NbS implementation and impact monitoring. Although stakeholders involved came from different backgrounds, co-creation process was carried out successfully and with respect for the professionalism and the opinions of all those involved, starting from the children. The IGW was designed to pursue social and environmental benefits and proved to be a useful educational tool for school students and an interesting research tool for scientists and technicians. However, despite the undoubted high value in terms of strengthening of social cohesion and awareness raising of the co-creation process and related didactical activities, a lower-than-expected impact has been measured by a socio-psychological survey, likely due to the starting different levels of environmental awareness (sometimes already high) shown by the involved pupils; therefore, an analysis based on approaches tailored to the specific characteristics of each class group would have been more appropriate. At the same time, also the effect on indoor VOCs concentration was lower than expected, likely due to the constraints imposed by the school structure and public health rules, which hindered to perform the evaluation in the best conditions. Indeed, assessing air quality mitigation by air concentration measurements requires to adhere to precise monitoring and evaluation protocols that not always are applicable in real-life context. Thus, when evaluating NbS impact, it can be required to use less standard but more suitable experimental approaches. Indeed, by using SEM/EDX evaluation of the PM particles deposited on leaves collected by the IGW at two times, we have been able not only to evaluate to total PM uptake by the IGW, but also to get insights about the species-specific PM deposition affinity that can be useful for the future implementation of evidence-based IGW design.

NBS impacts and implications

Our study highlights the multiple impacts and implications of Nature-based Solutions (NbS) within the built environment. The indoor green wall improved air quality by reducing particulate matter (PM) and volatile organic compounds (VOCs), and also generated social benefits by fostering environmental awareness and supporting students' well-being. Moreover, the participatory co-design process demonstrated that community involvement is essential for the acceptance and the success of green infrastructure, offering valuable lessons for future NBS implementations in urban contexts.

CRediT authorship contribution statement

Alessandro Campiotti: Writing – original draft, Investigation, Formal analysis, Data curation. **Elisabetta Ricciardi:** Writing – original draft, Formal analysis, Data curation. **Giuseppina Spano:** Writing – review & editing, Methodology, Investigation. **Laura Dominici:** Writing – original draft, Methodology. **Elena Comino:** Writing – review & editing, Methodology. **Roberto Riggio:** Writing – original draft, Investigation, Formal analysis, Data curation. **Francesco Pitasi:** Writing – original draft, Investigation, Formal analysis, Data curation. **Laura Ribotta:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Silvia Barbero:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Giovanni Sanesi:** Supervision, Project administration, Funding acquisition. **Chiara Catalano:** Writing – review & editing, Supervision. **Carlo Calfapietra:** Supervision, Project administration, Funding acquisition. **Chiara Baldacchini:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2025.100280.

Data availability

Data will be made available on request.

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