Monitoring and evaluation of a Modular Green Wall: *The Utilization of a Vertical Living Wall for Urban Re-generation, its Environmental and Health Implications*

Master of science in Building and Architecture Engineering, School of Architecture Urban Planning Construction Engineering (AUIC)

Master Thesis

By

Deeba Qadir
Student ID: 939988
Supervisor: Prof. Carlo Andrea Castiglioni
Co-supervisor: Ing. Giovanni Barbotti
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ABSTRACT

The aim of this thesis is to investigate the environmental viability of a Vertical Green Wall System installed at the Politecnico di Milano's Buildings 9 and 10, ItalMesh Srl in the Italian province of Brescia, and Cyprus's Institute. All these sites were designated as Case Study 1 (Politecnico di Milano building 9), Case Study 2 (Politecnico di Milano building 10), Case Study 3 (Nicosia, Cyprus) and Case Study 4 (Brescia, ItalMesh headquarter) respectively. For Case Study 1 and Case Study 2 inside the Politecnico di Milano campus, the monitoring techniques involved the in-situ analysis by the use of instruments and the data interpretation from the sensors: AirCare Pro located internally and externally to the panel and ARPA located in the Milano Pascal Citta' Studi region. For Case Study 3 and Case Study 4, the data interpretation was carried out from AirCare Pro sensors located internally and externally to the panel. The study aims to evaluate the effects of a Living Wall System (LWS). The continuous monitoring of temperature, humidity and sound is done to understand the role of a Living Wall on improving the environmental quality. The Particulate Matter (PM) 2.5 and 10, carbon dioxide concentration (CO_2), indoor air quality (IAQ) and Volatile Organic Compound (VOC) were monitored to keep an eye on the air quality. The research is a component of Zero Gravity Eden, a green building project by ItalMesh that transforms stretched and painted metal mesh into a true vertical garden. These are green walls, which are used to wrap buildings to improve their insulation, energy efficiency, and aesthetics. The study also compared the particulate matter (PM 2.5 and PM 10) data collected by sensors (AirCare) for case studies 1 and 2, as well as the sensor installed in the Milano Pascal Citta' Studi region (ARPA). The comparisons helped to foretell how the Living Walls will aid in the removal of dangerous airborne particles. Furthermore, the measurements of air temperature, relative humidity and particulate matter were done manually by the use of portable sensors. Lastly, the research does suffer from certain limitations mostly owing to the limited availability of data. Nevertheless, the same may be considered as an agenda for future research work. Therefore, in this circumstance, a sustainable method is required. The installation of low-impact development (LID) systems or Green Infrastructures (GI), such as Green Walls, offers a creative solution. These environmentally friendly methods could perhaps lessen the effects of climate change while helping to partially recreate the pre-urbanized environment by bringing vegetation back into urban areas.

Keywords: *Sensors, Living Wall System (LWS), Zero Gravity Eden, energy efficiency, Green Infrastructure (GI)*

ABSTRACT IN ITALIANO

Lo scopo di questa tesi è quello di indagare la fattibilità ambientale di un sistema di pareti verdi verticali installato presso gli edifici 9 e 10 del Politecnico di Milano, ItalMesh Srl nella provincia italiana di Brescia e l'Istituto di Cipro. Tutti questi siti sono stati designati rispettivamente come Case Study 1 (Politecnico di Milano edificio 9), Case Study 2 (Politecnico di Milano edificio 10), Case Study 3 (Nicosia, Cipro) e Case Study 4 (Brescia, sede ItalMesh). Per il Case Study 1 e il Case Study 2 all'interno del campus del Politecnico di Milano, le tecniche di monitoraggio hanno previsto l'analisi in-situ mediante l'utilizzo di strumenti e l'interpretazione dei dati provenienti dai sensori: AirCare Pro posizionato internamente ed esternamente al pannello e ARPA posizionato in la regione Milano Pascal Città Studi. Per Case Study 3 e Case Study 4, l'interpretazione dei dati è stata effettuata dai sensori AirCare Pro situati all'interno e all'esterno del pannello. Lo studio si propone di valutare gli effetti di un Living Wall System (LWS). Il monitoraggio continuo di temperatura, umidità e suono è fatto per comprendere il ruolo di un Living Wall nel migliorare la qualità ambientale. Il particolato (PM) 2,5 e 10, la concentrazione di anidride carbonica (CO2), la qualità dell'aria interna (IAQ) e i composti organici volatili (COV) sono stati monitorati per tenere d'occhio la qualità dell'aria. La ricerca è una componente di Zero Gravity Eden, un progetto di bioedilizia di ItalMesh che trasforma la rete metallica tesa e verniciata in un vero e proprio giardino verticale. Si tratta di pareti verdi, che vengono utilizzate per avvolgere gli edifici per migliorarne l'isolamento, l'efficienza energetica e l'estetica. Lo studio ha anche confrontato i dati di particolato (PM 2.5 e PM 10) raccolti dai sensori (AirCare) per i casi di studio 1 e 2, nonché il sensore installato nella regione Milano Pascal Città Studi (ARPA). I confronti hanno aiutato a prevedere come i Living Walls aiuteranno nella rimozione di pericolose particelle sospese nell'aria. Inoltre, le misurazioni della temperatura dell'aria, dell'umidità relativa e del particolato sono state effettuate manualmente mediante l'uso di sensori portatili. Infine, la ricerca soffre di alcuni limiti dovuti principalmente alla limitata disponibilità di dati. Tuttavia, lo stesso può essere considerato come un'agenda per futuri lavori di ricerca. Pertanto, in questa circostanza, è necessario un metodo sostenibile. L'installazione di sistemi di sviluppo a basso impatto (LID) o Infrastrutture Verdi (GI), come Green Walls, offre una soluzione creativa. Questi metodi rispettosi dell'ambiente potrebbero forse ridurre gli effetti del cambiamento climatico, contribuendo nel contempo a ricreare parzialmente l'ambiente pre-urbanizzato riportando la vegetazione nelle aree urbane.

Parole chiave: Sensori, Living Wall System (LWS), Zero Gravity Eden, efficienza energetica, Green Infrastructure (GI)

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1 INTRODUCTION

Urban expansion and resource use are growing at an unsustainable rate, producing serious societal and environmental consequences. Climate change, health difficulties, the loss of natural ecosystems, and the increasing danger of natural catastrophes are just a few of the numerous issues we face, prompting a feeling of urgency in restoring nature in constructed areas (Olubunmi, Xia, & Skitmore, 2016). Nature-based solutions (NBS) are effective mitigation strategies that aid in the resolution of these problems. These solutions are carefully developed based on a thorough grasp of how nature works, allowing for urban regeneration. Rain gardens, street trees, urban drainage systems, green roofs, and green walls are examples of NBS solutions that, when combined, may create synergies, and address many concerns (European Commission, 2015).

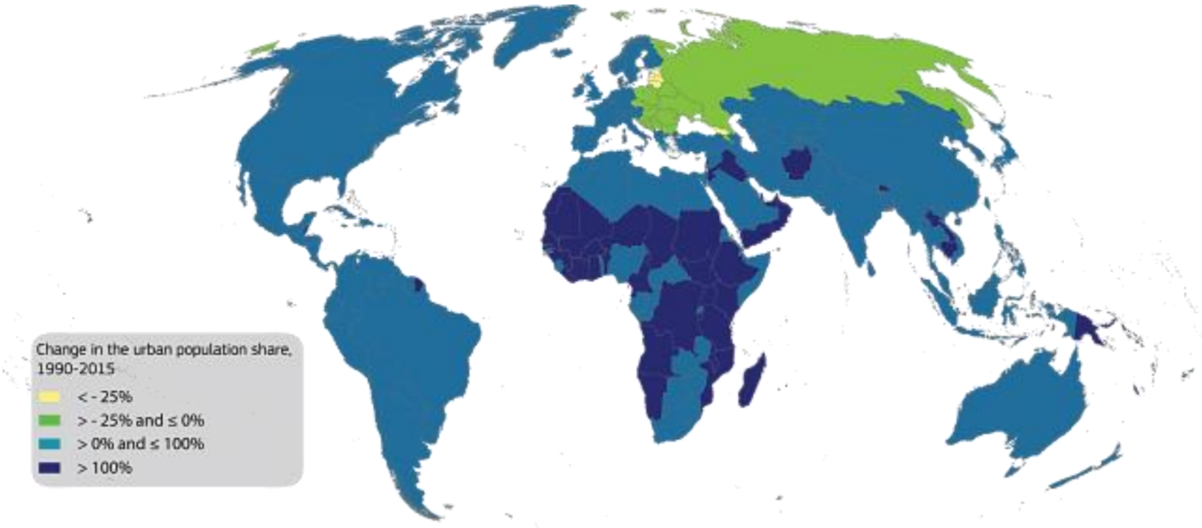


Figure 1:European Union releases global atlas of urbanization

In May 2011, the European Union started a biodiversity strategy to halt biodiversity loss in Europe by 2020 (Figure 1). The strategy is built around six mutually supportive targets which address the main drivers of biodiversity loss. Another target aims to ensure that by 2020, ecosystems and their services are enhanced by establishing Low Impact Development Systems (LID) or Green Infrastructure (GI) and restoring at least 15% of degraded ecosystems (https://ec.europa.eu). It recognises that GI and LID systems can make a significant contribution to the biodiversity loss and all the desired objectives can be met through the nature-based solutions. Two of the most important concerns of our day are the implications of unrestrained urbanization and climate change. The combined significant increase in urban heat island effect (Figure 2), air and water pollution, urban floods, ecosystem loss, as well as human health and well-being, may be regarded the key environmental difficulties generated by these challenges on a worldwide scale.

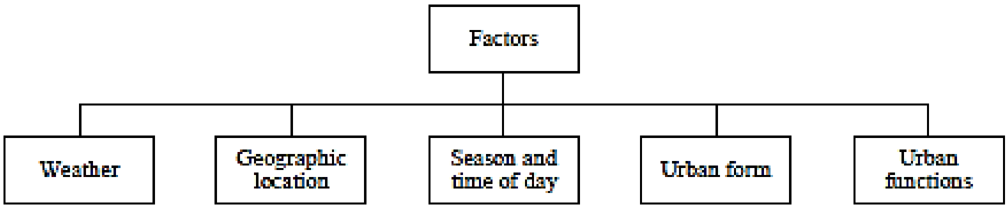


Figure 2: Factors affecting the formation of Urban Heat Island

These consequences can only be addressed by an innovative, sustainable, and environmentally oriented strategy, which, while distinct from one another, are intimately linked (Figure 3). As a result, practically all governments throughout the world are increasingly focused on promoting initiatives that encourage the development of sustainable cities and societies. In this regard, implementing nature-based solutions such as Low Impact Development systems (LID) or Green Infrastructures (GI) (wiki.sustainabletechnologies.ca) which reintroduce vegetation in highly urbanized zones, can restore pre-development conditions and mitigate climate change and urbanization impacts, providing multiple benefits at multiple scales, is a promising strategy.

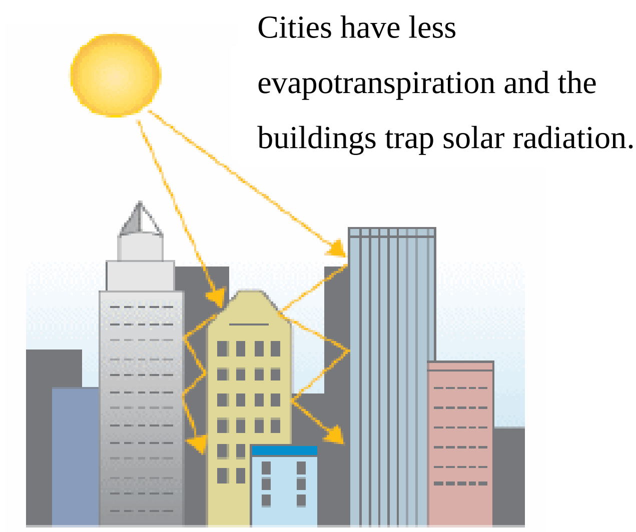


Figure 3 :Absorption of sunlight by buildings in cities *(Public Health Notes, 2018)*

Among different systems that are considered to mitigate these problems, green wall techniques, also known as vertical greening or greenery systems, vertical garden, bio-walls, and so on, can be considered as a sustainable strategy. This strategy can be achieved by using spaces otherwise unused, able to obtain beneficial effects from the building to the urban scale. Specifically, at building scale, by optimizing the benefits of plants species, they can be considered passive design solutions which improve thermal comfort both in winter and summer, thereby reducing energy demand for heating and cooling. In addition, the implementation of a green wall increases the value of the real estate and allow sound insulation; while at urban scale, these systems can enhance air quality, urban biodiversity, mitigate urban heat island effect. They also represent a control source of stormwater management at urban catchment scale. Moreover, from a social point of view, the implementation of vegetation on facades improves cities image and wellbeing, favouring the fruition of them. Given their effectiveness from many points of view, several studies have been carried on these ecologically solutions. In this regard, here we make a comparative analysis from the environmental point of view to present an effect of green wall systems to the current state of art in terms of developed systems (components, materials, and features), design and construction methods, systems benefits; evaluate the main differences, and establish where do we stand in terms of evolution of these techniques and where we are going in terms of new trends and possible future directions.

2 GREEN WALL SYSTEM

2.1 Types and components

The green wall system represents one of the low impact developments (LID) solutions able to increase the green spaces in urban area, aiming at enhancing the aesthetic value of the building and leading several benefits in terms of reduction of the environmental impacts caused by urbanization and climate change. Since with the term “Green Wall System”, we refer to each form of vegetation for facades, the first applications can be found 2500 years ago in the hanging Gardens of Babylon; similar examples were also in the Roman Empire.

Many applications occurred over the centuries, until the 19th century, when these techniques were used in several European and North America cities, as ornamental elements and for thermal purposes (https://iopscience.iop.org). Nowadays, with “Green Wall” we refer to a vegetative system which is, generally, developed along the façade of a building, consisting of different components, and it can be directly attached on the wall or supported by a structure. To better identify the characteristics of the different green wall systems typologies, it is necessary to introduce the general functional elements of this technique, consisting of:

i. Supporting elements
ii. Growing media
iii. Vegetation
iv. Drainage
v. Irrigation.

Based on the features of these elements and on the presence or absence of some of these, the green wall systems can be subdivided into two macro-categories: Green Facades (hereafter named GF) and Living Walls (hereafter named LWs) (Figure 4 and Figure 5). Green facades depend on climbing plants that grow along the wall covering it, while living walls support a variety of plants and help create a uniform growth along the surface (Manso et al., 2015).

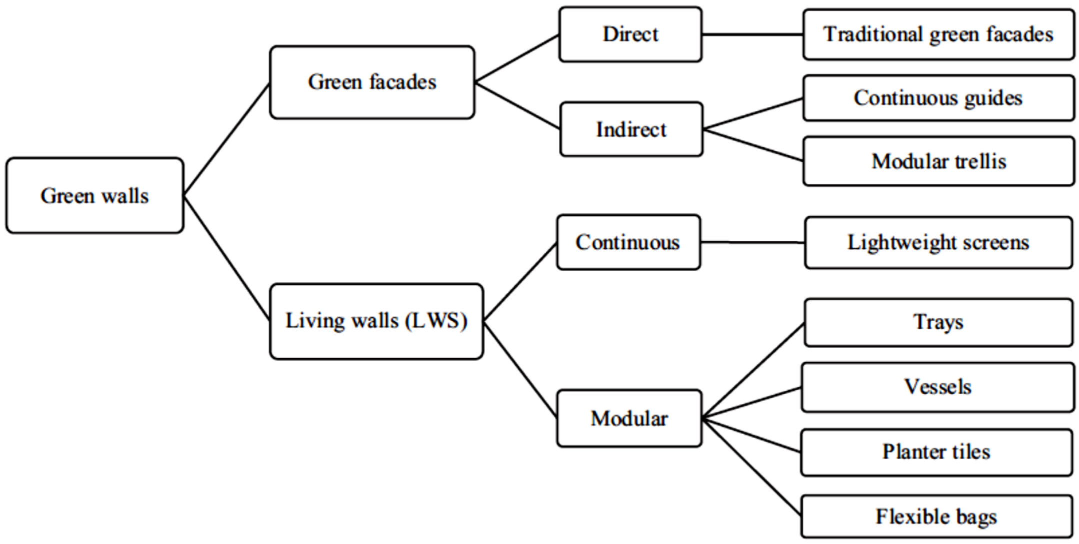


Figure 4 : Green Wall System Classification *(Manso et al 2015)*

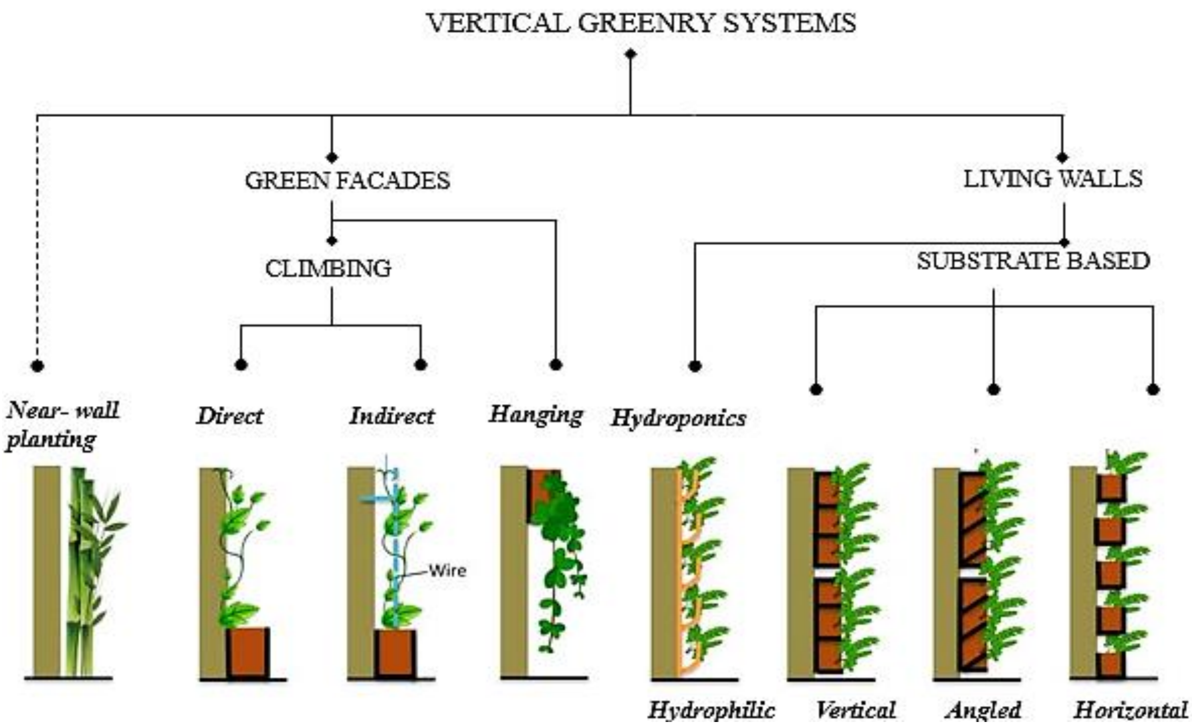


Figure 5: Classification Of Green Wall System (*Ottelle, 2011*)

2.2 Green facades (GF)

The Green Facades (GF) are characterized by a low systemic technology, few constituent elements, and a limited level of integration between plants and walls. They are light, easy to install and, generally, aimed at supporting the natural development of plants, mainly climbing plants, that can have evergreen foliage or deciduous, and reach until 25 m of height, taking, however, some years for the full coverage of the wall.

Figure 6 :Applying of Direct Green Facade on Bratislava Slovakia building *(Pixabay, 2016)*

The green facades can be differentiated into direct GF and indirect GF systems (Figure 6 Figure 7). The plants are directly connected to the wall in the first scenario, whereas indirect GF provide a structural support for vegetation development, often comprising of continuous or modular guides (tensile cables, stainless steel, grids, etc.). This support structure has various advantages, including preventing plants from dropping, creating an air gap between the building's surface and the flora, and increasing the system's resilience to natural forces such as rain, wind, and snow. Moreover, for both systems, in case of very tall buildings or lack space at the base of the building, it is possible to use special boxes, placed at intermediate heights.

Figure 7: Example of indirect Green façade *(Best Design Gallery 2012)*

2.3 Living Wall Systems (LWS)

The Living Walls (LW), allowing the rapid coverage by vegetation of high building, represent a more recent innovation than the green facades. These types of green wall can use a wide variety of plants species (grasses, perennial plants, shrub, succulent, and so on), selected according to the climate condition, the drought tolerance, the root development, and specifically combined to achieve aesthetic effects. Based on their application method, the LW systems can be continuous or modular. More in detail, the continuous LW do not require a substrate of soil, but the plants grow in lightweight and absorbent screens, as a fabric layer (i.e., felt), cut to form pockets. This layer is connected to different layers (permeable, flexible and root proof screens), supported by a base panel, directly attached to a supporting structure, consisting of a frame indirectly fixed to the wall. These types of systems are mainly based on hydroponic technique. The water supply is generally guaranteed by an irrigation system installed at the top of the structure, while the permeable layer ensures the uniform distribution of water and nutrients.

On the other hand, the modular LW are characterized by pre-vegetated panels with specific supporting elements (vessels, trays, flexible bags, planter tiles) in which the plants grow. The growing media consists in an organic and/or inorganic substrate, which present a good retention capacity, and where the roots can proliferate.

Modular flexible bags living wall (Figure 8) is made of flexible plastic material filled with growing media and the plants are inserted into them, these bags can be attached individually to the wall or in modular form (Deutsch-Aboulmahassine et al., 2009).

Figure 8: Modular Flexible Bags Living Walls *(Home Grown 2010)*

Modular planter tiles living wall consists of a flat back that they are installed by it on the wall of the building where it can be glued to the wall vertically or installed by mechanical machining, and a front part is to farming plants individually (Figure 9). These tiles are connected to each other by juxtaposition and are made of light materials such as plastic or ceramics (Bribach et al., 2012).

Figure 9: Modular Planter Tiles Living Walls *(Urban Gardens, 2015)*

Modular vessels living wall (

Figure 10) are made of polymeric materials, it is characterized by the possibility of installing a group of plants in separate elements and each element contains a type of plants in a row, it gives a special character to the wall of the building (Deutsch-Aboulmahassine et al., 2009).

Figure 10: Modular Vessels Living Walls (*Gardenista 2014)*

Modular trays living wall consists of a set of modules, each of which contains interlocked system on the sides to enable bonding. These modules are made of lightweight materials such as plastic or metal sheets like stainless steel, these modules have a front cover that prevents the fall of plants. It can be attached to the wall of the building in a horizontal or vertical frame through hooks or mounting brackets located on the back surface (Kmieć, 2015)

Figure 11: Grid of Trays ***(Plantups, 2016)***

Figure 12: Example of Modular Tray Living Wall ***(Plantscape, 2016)***

The irrigation system, according to the configuration of the supporting elements, is generally installed between the panels, and the water is drained through the panels for the entire facade and collected on the bottom. For tiny walls, there is a type of irrigation called manual irrigation that uses a mobile tank on wheels and the person responsible for the green wall to water the plants (Medl et al., 2018). Both modular and continuous LWS require irrigation systems to deliver water to the plants. To promote the growth of plants, fertilizers and plant nutrients can be added to irrigation water. To avoid tube lockage, the irrigation system may also include a filter system (Manso et al, 2015).

Due to its specific feature the Modular LWs provide greater seeding depth than the continuous ones and allow easy maintenance in terms of replacing plant species. By comparing the two main categories (GF and LW), in terms of installations cost, it is detected that although the LW require much more materials than the GF and, therefore, the costs are higher, they offer several benefits during the maintenance process. In fact, in case of unexpected problems, the LWs panels can be easily replaced, or it is possible to provide a more rapid renewal of vegetation. While, the direct GF present the advantage to not require a supporting structure, but the disadvantage to employ a long period to cover the entire wall. The use of a supporting structure offers the benefits to have a space between the system and the wall, which could be used for insulation or maintenance purposes.

3 LITERATURE SURVEY

3.1 What is a Living Wall System (LWS)?

A living wall is a particular type of vertical greenery system where a vertical surface is covered in greenery with plants of regular growth rather than scattered or haphazard development (Manso and Castro-Gomes 2015; Riley 2017). Living walls provide flexibility in plant selection and remove application restrictions on higher floors of the building (Charoenkit and Yiemwattana 2016). The plants growing on the substrate are supplied with the necessary nutrients and water by a vertical irrigation system that is attached to the walls (Giordano et al.2017). The substrate can be soil or an artificial growing media as rockwool, cock-coir, perlite, felts, peat chunks, peat moss, coconut fibres, and foam (Gunawardena and Steemers 2020), among others (Ottele et al. 2011), (Rakhshandehroo et al. 2015).

Living walls can be implemented using soil-based systems or hydroponic systems (Ottele et al. 2011; Rakhshandehroo et al. 2015). Living walls typically include low shrubs, perennial flowers, ferns, grasses, and small herbaceous species (Charoenkit and Yiemwattana 2017). There are two types of living walls: continuous and modular systems (Charoenkit and Yiemwattana 2016; Manso and Castro-Gomes 2015). A thin screen and felts make up the continuous system (Manso and Castro-Gomes 2015) and felts (Weerakkody 2018). It is termed as Mat system, invented by Patrick Blanc (Weerakkody 2018). The installation is done on-site, where plants are plugged into the support skin (screen or felt) (Gunawardena and Steemers 2020). Trays, containers, planter tiles, and flexible bags are all part of the modular system. The plants can grow uniformly thanks to this machinery (Manso and Castro-Gomes 2015). It is possible to construct modular systems on-site and attach them to structural frames (Weerakkody 2018). It can be prepared off-site and brought to the location for assembly because it is made up of discrete units (Gunawardena and Steemers 2020).

Living walls serve as biofilters and environmentally friendly air conditioners (Rakhshandehroo et al. 2015). They provide environmental, social, and economic benefits (Charoenkit and Yiemwattana 2016, Rahkhandehroo et al. 2015), as well as decreased energy and water use (Riley 2017, Cortes et al. 2021) and improved mental health (Muahram et al. 2019). Additionally, they facilitate social contact and assist in reversing the loss of collective memory, identity, and image (Felasari and Peng 2012) (Okesli and Gurcinar 2012).

3.2 Evolution

The human tendency to alter physical environment has transformed the ways in which they live while in close contact with vegetation. The Neolithic era is an example of that, and proofs are available that there has been a relationship between greenery and humankind (Zeybek 2020). In the twenty-first century, an increasing number of people are moving to densely populated cities and living in a compact man-made physical environment (Muahram et al. 2019), as the result of rapid urbanization and globalization. This impact has affected city climate (Ghazalli et al. 2018), pollution levels (Ghazalli et al. 2018), per capita green space (Xia et al. 2021), mental health (Elsadek et al. 2019), and much more. Apart from the environmental impact, the impact on the social environment is also noticeable (Anguluri and Narayanan 2017). Recognizing such an impact on the environment, people are putting in efforts to make cities future-ready and liveable. Governments and citizens have started stressing the need for greenery in cities. Greenery contributes to active surroundings and encourages outdoor activities (Wu et al. 2020; Xia et al. 2021).

According to A Pattern Language book (1977), the streets do not offer much reassurance for outdoor activities as most of the space is tied down by cars and a lot of spaces within the right of way are underutilized due to poor street design. To provide the opportunity for social interaction, we require space for sheltered walks, arcades and paths which are dedicated to pedestrian movement as well as provide physical comfort while walking or resting. Such places invite visitors locally as well as globally. Places which offer such opportunities in the urban streetscape are relatively limited. Social interaction has the characteristic that it only takes place when conditions are optimal with a minimum chance of hindrances, inconveniences, and disadvantages (Gehl 1989). Time spent in social interactions is a trigger for memories and the comfortable physical environment is a catalyst to the same (Stoltz and Grahn 2021).

However, all these venues, which encourage social interaction take up space and in the competitive world of real estate economics, there is rarely a leeway provided for green spaces in urban centres without incurring drastic costs (Boulton et al. 2018). Vertical surfaces in the form of bare walls remain the only space that can be utilized for providing greenery economically (Collins et al. 2017). By installing Living walls on bare walls, we can make cities green, sidestepping the issue of scarcity of spaces (Charoenkit and Yiemwattana 2017). Like urban level street greenery and parks, living walls provide multiple benefits (Charoenkit and Yiemwattana 2017).

3.3 Environmental benefits

Indirectly or directly, all industries contribute to pollution levels in the form of greenhouse gases, pollutants, and noise, which have an impact on locals' health and way of life. 92% of people globally, according to the World Health Organization in 2014, resided in areas with poor air quality (Weerakkody 2018). Plants are known to absorb carbon dioxide and enhance air quality (Li et al. 2015). The effects of pollution will be lessened when more trees are planted. An average car can filter its emissions for about 4,000 kilometres (2500 miles) per year through a tree (Muahram et al. 2019). One to three tonnes of oxygen can be produced each day by a square kilometre of trees (Muahram et al. 2019). By way of illustration, living wall systems can trap 50–70% of their total carbon in their substrate, which is capable of capturing carbon at a rate of 3–4 kg/cm2 (Charoenkit and Yiemwattana 2016). The negative impact of industry can be observed by considering the example of the COVID-19 pandemic. In places including Beijing, Bengaluru, Delhi, Lima, Mumbai, Rome, and Wuhan, industries were shut down during the initial COVID-19 outbreak, and urban air quality considerably improved as a result (Kumari and Toshniwal 2020). They observed reductions in PM2.5 of 20 to 34.2%, PM10 of 23.7 to 47.3%, and NO2 of 31.6 to 64.5%. (Kumari and Toshniwal 2020).

Different substrates are available for the installation and growth of plants on living walls' vertical surfaces. In a 2010 study on the thermal impact of living walls carried out at Singapore's Hort Park, Alex Yong Kwang Tan describes these types of living walls. Nine parts, eight vertical green systems, and a control wall made comprised a vertical surface (a bare wall). These typologies are based on various systems, such as mixed, inorganic, and soil-type substrates combined with modular, felt, moss-tile, and framed planter types. Table 1 defines these eight categories of vertical greenery systems (Perez et al. 2014; Wong et al. 2010).

Table 1: Eight categories of vertical greenery systems (*Perez et al. 2014*; *Wong et al. 2010*).

	System typology	Description	Plant size
1	Living wall – Modular panel, vertical interface, mixed substrate	Combination of 2 systems: the versicell-based and ‘plug-in’ slot planter system. Versicell planters have drainage cells with selected mixture of green roof and soil planting media wrapped in geotextile membrane while the slotted planters are mainly planter cages system	Small to medium
2	Green façade – Modular trell	Climber plants in planters forming green screens across mesh panels on the wall	Climber plants
3	Living wall – Grid and modular, vertical	Plant panels embedded within stainless steel mesh panels inserted into fitting frames.	Small
4	Living wall – Modular panel, vertical interface, inorganic substrate	Employed the Parabienta system with a patented growing medium (composite peat moss) as a planting media inlay. The peat moss panel encased in a stainless-steel cage is hung onto supports lined with integrated irrigation	Small
5	Living wall – Planter panel, angled interface, green roof substrate	This system uses a UV-treated plastic as a moulded base panel with integrated horizontal planting bays.	Small
6	Living wall – Framed mini planters, horizontal interface, soil substrate	individual mini planters placed and secured onto stainless steel frame.	Small
7	Living wall – Vertical moss-tile, vertical interface, inorganic substrate	Patented ceramic tiles shipped with pre-grown moss species. Suitable for creating tiling designs	Small, custom-grown on tiles
7a	Living wall – Flexible mat tapestry, horizontal interface, soil substrate	Lightweight panel comprising 2 layers of moisture retention mats secured onto a supporting grating or mesh. Plants slotted and pre-grown in between mats. Suitable for flat and curved surfaces. Allows ease of change.	Small to medium
8	Living wall – Plant cassette, horizontal interface, soil substrate	Use of planters to hold wider variety of plant types and of larger sizes. Planters are secured onto the wall through hinges. Lightweight growing medium is used.	Small to medium large

According to the results of the testing, these devices lowered the surface's temperature by up to 11.58°C. The best results were obtained using the Living wall system 3 (grid and modular, vertical interface, and mixed substrate) (Perez et al. 2014; Wong et al. 2010). Due to the evapotranspiration phenomena, which can burn through 680 kWh of heat per cubic meter of water, this reduction is made achievable (Perez et al. 2014). The Hort Park experiment demonstrates that different types of living walls can help lower surface temperatures and that system typology can influence how much of a temperature decrease occurs.

Living walls can lower a building's internal temperature by up to 10°C by reducing the heat flux, or the amount of heat that is transported indoors through hard surfaces (Radi et al. 2019). In the summer, it has been demonstrated that a lush green wall can reflect or absorb up to 80% of the sun's rays (Muahram et al. 2019). With these advantages, living walls can enhance human wellbeing while addressing problems like global warming and climate change. By 2020, 189 nations will have ratified the Paris Agreement, which aims to combat global climate change. The agreement's primary goals are to lower global greenhouse gas emissions, stabilise global temperatures, and transition to a low-carbon economy (Agreement n.d.).

3.4 Energy consumption pattern

Modern cities are concrete jungles, and the urban heat island effect has increased as the volume of concrete has increased (Anguluri and Narayanan 2017; Verma and Raghubanshi 2018; Widiastuti et al. 2018). The amount of surface area that absorbs and holds onto heat from sunlight has increased due to unplanned urban expansion. As a result, the temperature rises, increasing the energy required to cool the interiors (Anguluri and Narayanan 2017; Verma and Raghubanshi 2018; Widiastuti et al. 2018). In the long run, cooling the interiors raises the ambient temperature, creating a vicious cycle. This vicious loop is broken by living walls. They generate a microclimate for the building and its environs as well as lower the internal temperature (Hunter et al. 2014; Teixeira 2021). They lessen the requirement for air conditioning (Pérez-Urrestarazu et al. 2016; Davis et al. 2016). According to research, heat is blocked and a temperature differential of up to 10ºC is felt when insulation, greenery, and shading are installed. According to (Radic et al. 2019), living walls serve as a heat buffer and can cut energy consumption by up to 20%.

In a study conducted in Vancouver, Canada, the energy consumption of a structure with living skins (green cover) was contrasted with that of a standard building. The Energy-10 software was used to simulate the energy performances of both structures. According to the simulation, a regular building uses roughly 100 MWh of energy for cooling, in contrast to a living skin building, which uses no energy at all. Comparing the usual building's annual energy use to that of the living skin one, the typical building uses 747.46 MWh while the live skin one uses 677.24 MWh. The living skin building uses 70.22 MWh, or 9.3% less energy, annually (Roehr and

Laurenz 2008). Researchers advise using solar panels to power the hydroponic systems that create living walls that act as carbon sinks to further reduce energy use.

3.5 Vegetation

The right vegetation will depend on the climate, the features of the building, and the surroundings where the green wall will be placed. The systems under analysis reveal several issues with vegetation lifetime. A low-cost method of vertical greening is the use of climbing plants. Evergreen or deciduous foliage are the two basic forms that these plant species might have. There is a noticeable visual difference throughout the year as deciduous plants shed their leaves in the fall while evergreen plants keep their leaves all year. Root climbers and adhesive-suckers are two examples of climbing plants that can sustain themselves by clinging to a vertical surface. Other climbing plants can be supported by a structure so that they can grasp on to it (e.g., twining vines, leaf–stem climbers, leaf climbers and scrambling plants). They have historically been used to wrap the outer walls of tiny buildings in Germany and France. In pergolas, vines were frequently planted to provide shade for the building envelope in hot summer temperatures (Dunnett N et al. 2008). It's crucial to keep in mind that climbing plants have some growth restrictions. Some species reach heights of 5 or 6 m, 10 m, and even 25 m (Dunnett N et al. 2008), and it takes them around 3–5 years to cover their entire area (AA. VV 2008).

According to the acquired foliage density after one year of development, a study conducted in the Mediterranean Continental climate compared the development of numerous climbing plants, both perennials (Hereda helix, Lonicera japonica) and deciduous (Parthenocissus quinquefolia, Clematis). Parthenocissus quinquefolia, popularly known as Virginia creeper, was shown to provide more foliage density, although none of the chosen species could completely cover the surface after a year. As with Clematis, which was impacted by summer weather, several species also have difficulty adapting to the climatic conditions, which include high temperature changes throughout the year and little rainfall (Perez G et al. 2011). With the aid of plant species, living wall systems enable the production of novel aesthetical concepts for green walls that explore the use of patterns, differences in colour and texture, foliage forms and density, vitality, and growth. Incorporating shrubs, grasses, and numerous perennials into green walls is now possible thanks to these methods, provided their watering and fertilizer requirements are considered.

The growth of a greater variety of plants, in various stages of development, including grown plants, cuttings, or seeds, is made possible by hydroponic systems (Patrick Blanc 2011). According to the intended aesthetic effect, vegetation is chosen in these situations (Koumoudis S. 2011), necessitating the proper watering and nutrients for a healthy plant growth. According to the creative intents for a particular structure, it is crucial to analyse the development, colour, blooming, foliage, and global plant composition of the plants (e.g., building framing in the urban context, advertisement of a particular company, or marking distinction of a certain building or interior space). However, to achieve sustainability goals, vegetation must have low watering requirements (for example, employ native plants) and be adapted to the local exposure circumstances (for example, sun, semi-shade, or shade) (e.g., wind, rainfall, heat, drought, and frost). Succulent carpets can be used in place of perennial plants and shrubs in green walls, which is a recent example of modular LWS. The usage of succulents, which are drought tolerant plant species, minimizes the demand for irrigation (Bruse M et al. 1999). In addition to being low maintenance, these plant type help reduce system weight. Succulent carpets, on the other hand, take on the illusion of a flat vegetated surface, which is intriguing in small walls. Due to the range of colours and textures that perennials and shrubs might incorporate, they can be used to create more ornate landscapes on bigger areas.

A Japanese system (Fukuzumi Y 1996) also serves as an example of how to use specific bushes on sloping surfaces (e.g., Juniperus chinensis, Juniperus conferta, Euonymus Fortunei, Cotoneaster, Cotoneaster Horizontal, Vitex rotundifolia). Green walls have the potential to significantly reduce the environmental impact of food production and distribution, especially in metropolitan areas where there is a scarcity of land for cultivation (AA. VV 2008). As part of new green wall concepts, vegetables and aromatic herbs could be incorporated into continuous or modular living wall systems, as planters (Taber S. 2011) or vessels (Deutsh-Aboulmahassine E. 2009), to increase the system's usefulness to building occupants.

3.6 Drainage and Irrigation

Gravity controls the excess fluid drainage in green walls. Geotextiles are used in continuous and modular LWS to promote drainage along the permeable membrane while limiting the growth of roots. To optimize drainage and water excess reuse to the modules below, modular trays make use of the overlap of modules and materials. The bottom of a modular system can be concave, sloped, perforated, or composed of a porous or absorbent substance for better drainage (Laurence and Sabin 2016). Other vessel examples include the use of a filter material applied at the bottom of the module vessels (Deutsh-Aboulmahassine E 2009) (for example, inoculated sand or another method to purify rainwater, remove toxins and heavy metals) or a granular inert filler (Jetson Green 2013) that encourages drainage and the growth of roots. For better aeration and the evacuation of excess moisture from the substrate, some examples of modular systems additionally mention the insertion of grooves or holes on the sides and back face of modules (Koumoudis S 2011).

The type of system, the plants employed, and the climatic conditions all affect how much irrigation is required. An irrigation system is important for LWS and modular green facades in order to supply the plants with the water they need to grow. To enhance the growth and vitality of the vegetation, irrigation water can be treated with nutrients, fertilizers, minerals, phosphates, amino acids, or hydroponic materials. The installation of a continuous irrigation line at the top creates the water supply for LWS. At the top of the structure, a Continuous LWS irrigation system is placed and connected to the main irrigation system. The permeable screen enables the homogeneous distribution of water and nutrients along the surface in the case of continuous LWS. Some trays shaped modular LWS have a recess at the top face of the module where the irrigation tubing can be inserted. The trays have several holes in the recess for gravity-watering the growing media (Urriola H 2011, Laurence and Sabin 2016, Sichello C 2010). To allow extra water to irrigate the modules below, drainage holes are placed in the bottom of trays.

The irrigation tubes and connectors can be made from a variety of materials, including silicone, rubber, plastics, and thermoplastic piping. They can also have a variety of outputs, including drip, sprinkler, holes, and pipes, and can be distributed and intensified to meet the needs of the plant. To avoid blockage, the irrigation system may also have a filter system. Additionally, several LWS discuss ways to reduce the consumption of treated water. There are techniques such as rainwater recovery from building roofs (Koumoudis S. 2011), reusing the water collected in the drainage system (Bindschedler P et al. 2011), and monitoring water supply needs through the installation of sensors (Laurence and Sabin 2011), which control the level of the collecting water tank, the timing of irrigation, and the weather (e.g., quantity of Other LWS, whether continuous (Corradi 2009 and Bribach C 2011) or modular (Taber S 2011 and Huet P 2010), also relate to the installation of a gutter in the system base, recovering any excess water, storing it, and returning it to the irrigation system. Utilizing sensors to measure the amount of nutrients needed in the growing medium is another tactic. This may be crucial to reduce nutrient consumption and meet the needs of the plant, rainfall, humidity, temperature, atmospheric pressure).

3.7 Installation and Maintenance

When it comes to installation costs, green walls with climbing species are more economical, but their plant diversity is constrained. Some climbing plants need support as they grow to make sure they cover the entire surface. The impact of climbing plants spreading out along the surface is substantially reduced when plants are installed at various heights, and this also makes it possible to replace struggling plants. To reduce installation, maintenance, and replacement issues, a growing number of modular LWS are being introduced to the market.

For wall maintenance or plant replacement, certain modular systems allow for the individual disassembly of each module (Lee A et al. 2010, Yap T et al. 2011). To make the transportation and application processes simpler, several modular pieces can also be nested inside of one another. Continuous LWS may create vegetated surfaces with a greater range of plant species and can be lighter than modular LWS. It has a density of about thirty plants per square meter and weighs less than 30 kg/m2 (Blanc P 2011). But since continuous LWS are frequently hydroponic systems that need a constant supply of water and nutrients, they have a negative impact on sustainability and raise maintenance costs because they require more irrigation.

Each green wall system has unique qualities, with benefits and drawbacks based on their aesthetic potential, price, and maintenance requirements, which are summarized in (Table 2). The choice of the most appropriate system is closely tied to the characteristics of the building (such as orientation, accessibility, and height) and the climate (e.g., sun, shade and wind exposure, rainfall). Consequently, it's critical to comprehend how they differ in composition and their primary traits. (Table 3).

Table 2: Comparison of Green Wall Systems: Advantages and Disadvantages

SYSTEM	CATEGORY	SUBCATEGORY	ADVANTAGES	DISADVANTAGES
GREEN FACADES	Direct Greening	Traditional Green Facades	No materials involved (support, irrigation) Low environmental burden Low cost	Limited plant selection Slow surface coverage Surface deterioration Maintenance problems
	Indirect Greening	Continuous Guides	Vegetation development Low water consumption	Limited plant selection Slow surface coverage Scattered growth along the surface
		Modular trellis	Lightweight support Controlled irrigation Plants replacement	Limited plant selection High environment burden High installation costs
LIVING WALLS	Continuous systems	Felt pockets vertical gardens	Uniform growth Flexible and lightweight Increased variety of plants Uniform water and nutrients	Complex implementation High water & nutrients usage Frequent maintenance
	Modular systems	Trays	Easily disassembled Increased variety of plants Controlled irrigation	Complex implementation Heavier solutions High installation costs
		Planter tiles	Increased variety of plants Attractive design of modules	Limited space for root growth Surface forms limited to tiles dimension
		Flexible bags	Adaptable to sloped surfaces Aesthetic potential	Heavier solutions due to growing media High installation costs

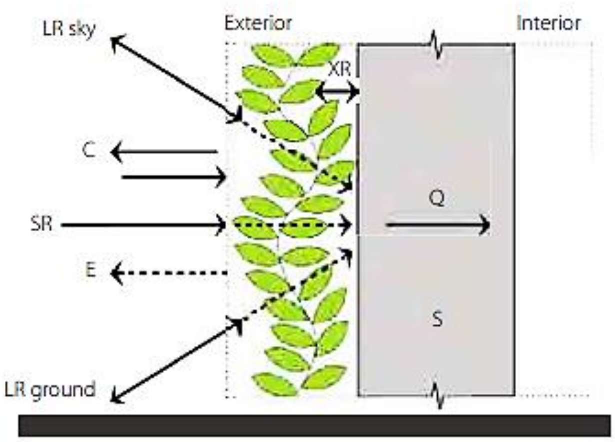
Table 3: Summary of Green Wall Systems composition

SYSTEM REQUIREMENTS	GREEN FACADES	CONTINUOUS LIVING WALL SYSTEM	MODULAR LIVING WALL SYSTEM
SUPPORT	Cables, ropes, nets, wood, plastic, glass fibre	Geotextile felts	Galvanised steel, stainless steel, polymers, and ceramics
GROWING MEDIA	Ground soil or vessels filled with substrate	-	Substrate mixture including organic and inorganic compounds
VEGETATION	Climbing plants	Shrubs, grasses, and perennials	Shrubs, grasses, perennials, and succulent plants
DRAINAGE	Vessels with inferior holes	-	Lateral and inferior holes
IRRIGATION	Drip line inside vessels	Drip line on top of wall	Drip line on top of each module

4. VARIOUS CASE STUDIES ON GREEN WALL SYSTEMS

Implementing Green Walls as a Natural Based Solution is an innovative and effective approach of "attacking" urban life difficulties, which have now been embraced by practically all developed and developing countries. To have a broader understanding of the roles, capabilities, operations, and benefits of Green Wall Systems, some case studies from various locations were analysed and evaluated. One of the most important aspects influencing the design of green walls is the local climate. The feasibility of different types of green walls and plant species will depend on the air temperature, relative humidity, wind speed, solar radiation, cloud cover, and monthly precipitation.

To assess the effects of a green wall on building thermal performance and possible energy savings, it is crucial to comprehend the energy balance of a vegetated wall and the various thermal-physical processes. The schematic design below depicts the energy balance and heat flows via a building façade covered in a layer of plants (Irina Susorova et al) (Figure 13). Convection to and from the façade, evapotranspiration from the plant layer, heat storage in the façade material, and heat conduction through the façade are all considered in the energy balance of a plant-covered façade. Incoming solar radiation, infrared radiative exchange between the façade and sky, ground, and vegetation layer, as well as convection to and from the façade are also considered.



SR	*Shortwave radiation*
LR	*Longwave radiation*
XR	*Plant-wall radiative exchange*
C	*Convection*
E	*Evapotranspiration*
Q	*Conduction through the façade*
S	*Heat storage in façade material*

Figure 13: Energy Balance of Vegetated Façade

4.1 Implementation of Green Wall Systems in Genoa, Italy

The National Institute of Social Insurance (Istituto Nazionale di Previdenza Sociale) (Figure 14) is in Genoa's Sestri Ponente district in north of Genoa, Italy (Magliocco and Perini 2015).

Figure 14: Istituto Nazionale di Previdenza Sociale- Living Wall System Installation

Main features:

- The green facade was installed in the last century in October and November 2014 on the south wall of the building.
- Building structure comprised of concrete pillars and beams.
- The facade is exposed to solar radiation several hr/days in summer and 1–2 hr/day during winter.
- *Climate of the region*: Mediterranean, with mild, rainy winter and hot, sunny summer.
- *Green wall system:* Living wall system.
- *Vegetation:* The living wall system consists of a mat planted with different plant species (climbing plants, shrubs, evergreens). The mat contains an aggregate mix and is composed of two layers of special geotextile.
- *Irrigation system:* The system is irrigated with a drip line in each module and is designed primarily to use recycled condensate water from a network of air conditioning units.

4.2 Implementation of Green Wall in Melbourne Australia

Council House 2 is the municipal offices of the City of Melbourne opened in October 2006. It was the first six-star rated green building in Australia (Figure 15). The building has nine storey and supports a semi-extensive green roof and green wall (Rayner et al., 2010).

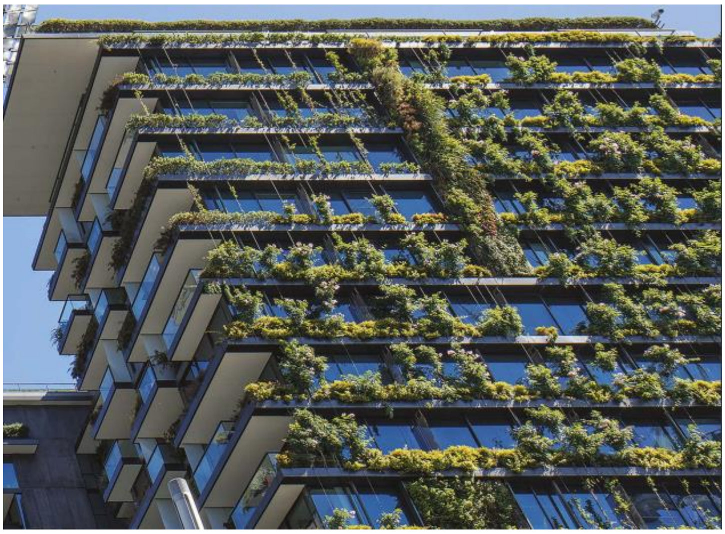


Figure 15: Application of the Green Wall on Council House 2 (CH2) of Melbourne

Main features

- The façade consists of 90 moulded black plastic containerized planters.
- The planters placed on small balconies on the north side of building.
- Each planter 0.3m * 0.97m at the surface, 0.89m in depth, volume 260 L.
- Steel cable x-tend mesh trellis, 1m in width (150mm aperture size) was built behind and above the planters, forming a vertical screen the full height of the building.
- *Green wall system*: Modular living wall
- *Climate of the region*: Temperate subtropical oceanic, with mild winters and pleasantly warm summers.
- *Vegetation:* One hundred and sixty-four plants from five taxa were planted: Clematis aristata, Kennedia nigricans, Kennedia rubicunda, Pandorea pandorana and Trachelospermum jasminoides. A total of 60.9% of plants were classified as 'failed' due to death or poor cover values. Pest infestation and stress symptoms were particularly prevalent in surviving Kennedia spp. of the five plants used in the project,

only Pandorea pandorana had low rates of failure (6.2%). Across all species the greatest rates of failure were in the lower levels and eastern sides of the building.

- *Irrigation System*: Sub-irrigation system encompassing as small cistern at the base (100 mm depth), controlled by a foot valve connected to the weather supply. Each cistern houses vertical, inverted cone-like ‘columns’ rising upwards in the substrate and filled with Hydrocell™ flakes to form a capillary irrigation ‘wick’ into the container proper.

4.3 Application of green wall systems in Berlin, Germany

The first urban research endeavour in Berlin was the Paul-Lincke-Ufer initiative (Figure 16). A 100-year-old apartment complex was the first target of the renovation, which started in 1984. On the facades and at garden level, Parthenocissus tricuspidata (Boston ivy) and other climbers were cultivated in planters (Köhler, 2008).

Figure 16 : Apartment Building in Berlin, Germany (Paul-Lincke-Ufer)

Main Features:

- The project comprised of the restoration of a 100-year-old apartment building.
- After approximately 10 years, Boston ivy had completely covered the exterior of the old apartment building, *Parthenocissus tricuspidata.*
- The ground-based climber species had reached the gutter at the edge of the roofs during the survey, which took place over a 10-year period.
- *Climate of the region:* Moderately continental with chilly winters, with average lows around 0 °C (32 °F), and moderately warm summers, with average highs of 24 °C (75 °F) during the day.

- *Green Wall System:* Green facade
- *Vegetation*: For the little inner courtyard to have as much flora as possible, hanging planter boxes and Boston ivy were planted.

4.4 Applications of Green Wall Systems in Different Climates

The research of green walls is largely influenced by the climate. The impacts of greenery on urban temperature are more pronounced in hotter and drier climates. When both the walls and the roofs of an urban structure are green, it can help to lower temperatures in humid conditions. The greening of surfaces helps absorb more solar radiation, which lowers the temperature further.

Therefore, the efficiency of the green wall as well as temperature reduction increases in hotter and drier climates. The annual savings from this level of temperature reduction can be substantial. Without raising the relative humidity of the interior air, the LWS makes the relative humidity in the air layer close to the wall surface more stable. (Zarandi and Pourmousa, 2018). Regarding the potential of vertical greening systems in terms of energy conservation in buildings, the significant influence of weather conditions must be considered.

Additionally, it is necessary to ascertain how the environment affects a building's thermal efficiency as well as how the weather affects plant development and physiological reactions. Thus, weather conditions will also have an impact on the thermal behaviour of vertical greenery systems, which will ultimately alter the outcomes.

Numerous studies advise using the Köppen Climate Classification System to take the climate into proper consideration while designing vertical green systems. (Pérez et al., 2014). The Köppen Climate Classification System, period (1980-2016) is displayed in Figure 17. The present-day map (1980–2016) is derived from an ensemble of four high-resolution, topographically corrected climatic maps. The future map (2071–2100) is derived from an ensemble of 32 climate model projections, by superimposing the projected climate change anomaly on the baseline high-resolution climatic maps

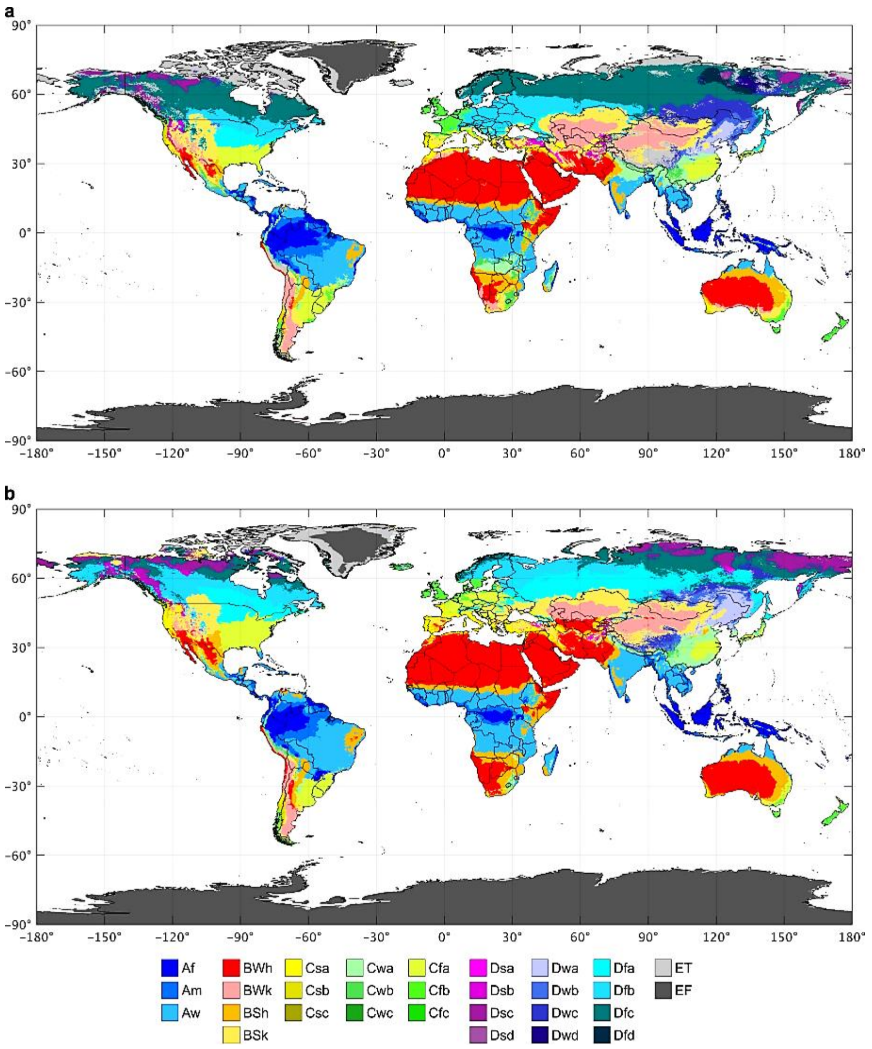


Figure 17: Part (a) shows the present-day map (1980–2016) and panel (b) the future map (2071–2100). The colour scheme was adopted from (*Peel et al.21.*)

5 IMPLEMENTATION OF A LIVING WALL SYSTEM

Before designing a green façade or a living wall, the characteristics of the site should be well studied and analysed as they would affect the cost, feasibility, and the success of the project. Thus, the site analysis phase includes climatic conditions (wind orientation, rainfall, solar radiation, temperature and humidity and micro-climatic conditions), weight loading, existing structures and areas, accessibility, and nearby vegetation. Green wall systems vary in their design and construction. Generally, there are main components that are required to be present in green wall systems and there are important design principles that should be well considered in installing green walls as follows: plant selection, growing medium, water supply, waterproof layer, wall protection, supporting structures and components, shading and light and installed sensors.

5.1 Guidelines and Standards for Installation of the Living Wall System (LWS):

Green facades meet the interest of many kinds of stakeholders both public and private sector. Currently, there are no international technical standards for LWS, despite some policies and guidelines have been developed in several EU countries to encourage green façade construction. The Italian standard UNI 11235:2015 provides technical information in the field of LWS design and construction. The standard encourages innovative and responsible LWS design.

CEN/TC 350 – "Environmental sustainability of construction works" was used as general framework. With reference to the notion of building life cycle the CEN/TC 350 is one of the main standard available in order both to assess the sustainability aspects of new and existing construction works. The CEN standard includes as reference method the ISO 14040:2006 - Life Cycle Assessment (LCA) and describes a harmonized methodology for assessing the environmental performance of buildings and the life cycle cost performance. Further the standard intends to assess those aspects related to health and comfort of a building.

Each environmental requirement is associated to a set of references and assessment tools; on the one hand standardized tools and rules; on the one other new tool fit for LWS characteristics. For example, to assess the indoor air quality ProMo_TC and ProMo _IAQ, described in the paragraph 2.1, are assumed as a reference.

Overall, 40 requirements were identified: 12 associated with manufacturing stage, 4 with on-site assembling stage, 18 with use and maintenance stages, 6 with final disposal stage (Table 2 of standard). Examples of Environmental Requirements:

MANUFACTURING
Reducing the number, the weight and the thickness of materials and elements Maximizing the use of low environmental impact materials Maximizing the use of products with a plurality of functions Maximizing the use of products with a similar expected life (…)
ON-SITE ASSEMBLING
Maximizing the use of easy-assembling connections Maximizing the use of easy-installing products Maximizing the use of integrated and operable devices for water, fertigation and electrical needs (…)
USE AND MAINTENANCE
Selecting plant species with low maintenance needs Maximizing the use of products characterized by easy-transportation, construction and maintaining Selecting products with high environmental performance: thermal, acoustic, indoor air quality (…)
END OF LIFE
Maximizing the use of products based on reverse assembling technologies Maximizing the use of reusing/recycling products (…)

Furthermore, the standard proposal describes requirements and materials related to the design process (e.g., data concerning the framework for LWS anchorage, the growing medium, the vegetation, the irrigation system, etc.). Technological details for a proper LWS design are even encompassed.

The standard also identifies general strategies for proper installation.

A detailed maintenance plan is part of the proposal. In particular, the standard highlights the need to drawing up (by manufacturer) a use and maintenance guide, according to LWS typology. The guide is aimed at maintaining the efficiency of LWS over a long period. The guide provides technical advice concerning: the frequency of maintenance; the maintenance of plant species (regular pruning, remove foliage wastes, etc.); the maintenance of the irrigation devices (check of nutrient levels, growing medium moisture content). The proposal can be assumed as a significant basis for broader research to develop a new national technical standard to measure the LWS performance.

5.1 Monitoring sites and conditions:

5.1.1 The case of Green Panels - Politecnico di Milano Campus, Italy

Figure 18: Green Panels- Politecnico di Milano Campus, Milan, Italy

ItalMesh is an Italian company pioneering in the processing of panels made with extended mesh and perforated metal sheets for architectural solutions. The panels produced can be used for outdoor applications, such as facades and sunscreens, fences, and balustrades. Zero Gravity

Eden is a green project by ItalMesh in support of sustainable architecture where expanded and painted metal mesh turns into a veritable vertical garden. These are green walls, designed to cover buildings to optimise their insulation and energy efficiency as well as improving their appearance. This patented product includes an automatic watering system and can host many different vegetable species, which have been selected to resist the local climate. They range from ornamental plants to herbs or even vertical kitchen gardens. In collaboration with the Politecnico di Milano (Figure 18), patented zero gravity panels were installed inside the University centre (Building 9 and Building 10) to test the benefits of the environmental impact of green walls in a metropolitan city of Milan and specifically around the University premises.

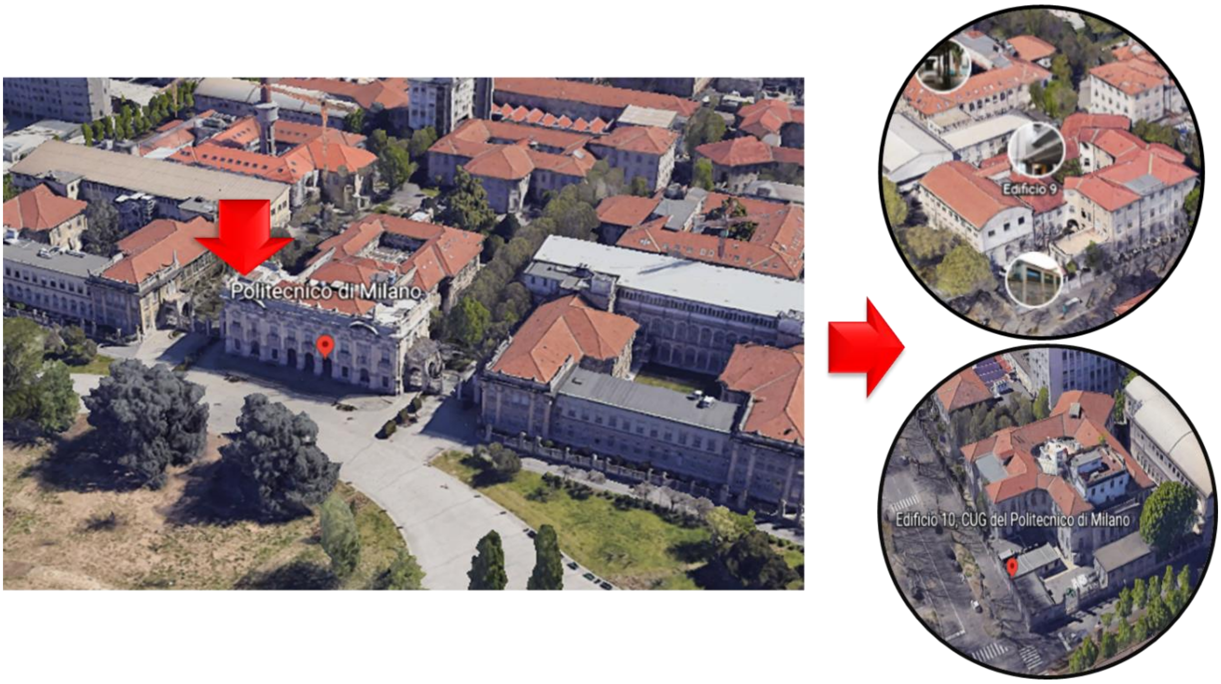


Figure 19: Panels installed in Building 9 and Building 10

The environmental impacts of the Living Walls, installed in Politecnico di Milano campus, to be considered are the meteorological data (relative humidity, air temperature, light intensity), health related data (PM2.5, PM10, Air Quality Index, noise pollution).

The Green Panels are located at the Building 9 and Building 10 (Figure 19) of the Politecnico di Milano campus. Both the buildings are facing South. The university is in Milan, a metropolitan city in the Lombardy region, Italy (45^{0}27'51.1344" N, 45^{0}27'51.1344" E). Based on the Italian meteorological data, in Milan the summers are warm and humid, the winters are very cold, and it is partly cloudy year-round. Over the course of the year, the temperature typically varies from 31^0F to 85^0F and is rarely below 23^0F or above 92^0F.

ItalMesh has installed metal meshes in the Politecnico di Milano campus, turning facade and wall of building 9 and building 10 into a green vertical suspended garden. The meshes have an integrated irrigation systems that allows the cultivation of any plant species. The vertical suspended garden installed also known as Zero Gravity Eden is designed to cover the structure in such a way, optimizing its performance and giving it an unmatched aesthetic impact (Figure 20).

Figure 20: Metal meshes by ItalMesh

Properties of Zero Gravity Eden Modules:

- *Patented fastening system:* Zero Gravity Eden is equipped with a patented fast and modular fastening system, which makes it possible to cover the entire facade of any building.

- *Different green species:* Green is selected in order to resist local climate. Their range can be wide: from ornamental plants to bushes or even vertical kitchen gardens.

- *Automatic Watering System:* With Wi-Fi connection to the local weather station, to give the plants the right amount of water.

- *Sustainability*: Zero Gravity Eden consists of 100% recyclable aluminium meshes. It is also a sustainable solution because excess water can be collected and recycled to water the plants.

Benefits of Zero Gravity Eden Modules:

- *Thermal insulation*: Zero Gravity Eden insulates the building, as it won't let the heat out in winter and won't let it in, in summer. It guarantees a remarkable energy saving

- *Soundproofing:* As natural thermal insulators, the plants will reduce the impact of noise. So, Zero Gravity Eden can be used to soundproof the building. Noise reduction is reinforced by panels width, which reaches 20 cm.

- *Greener Environment:* Green facades increase urban greenery, with many environmental benefits such as lowering summer temperature and climatic winter mitigation.

- *Phyco-physical wellbeing:* Zero Gravity Eden contributes to physical wellbeing, thanks to the natural purification function of the air guaranteed by plants. And don't forget the psycho wellbeing that is felt by the human body when it lives in a green environment.

- *Unmatched aesthetic impact*: With its 100% green design Made in Italy, Zero Gravity Eden turns buildings into great scenic impact architectures.

- *Durability:* Zero Gravity Eden has been designed and tested to last. The best professionals select the most suitable plants, those that can best adapt to the local climate.

- *Easy Modular Installation:* The vertical garden patented ItalMesh is delivered ready to use. So, it can be easily installed and removed, also thanks to its modular composition. Possibility of product storage for later use.

- *Customisable Sizes*: Zero Gravity Eden consists of customizable single units, which size can be adjusted to suit any need.

- *Maintenance and Cleaning:* Zero Gravity Eden modules are practical and fast to maintain and clean.

- *Versatility*: For 1/3 of the starting cost, all the plants can be replaced with a brand-new vertical garden, to begin a new life cycle.

5.1.2 The case of Brescia, ItalMesh Headquarter

Brescia, a city and commune in northern Italy's Lombardy region, few miles from the lakes of Garda and Iseo, it is located at the base of the Alps. Brescia has a mid-latitude humid subtropical climate, as defined by the Köppen climatic classification (Cfa). Its average annual temperature is 13.7 °C (57 °F), with daytime highs of 18.2 °C (65 °F) and lows of 9.1 °C (48 °F). June, July, and August are the warmest months, with highs ranging from 27.8 °C (82 °F) to 30.3 °C (87 °F). Low temperatures in December, January, and February range from 1.5 °C (29 °F) to 0.6 °C (33 °F), making them the coldest months.

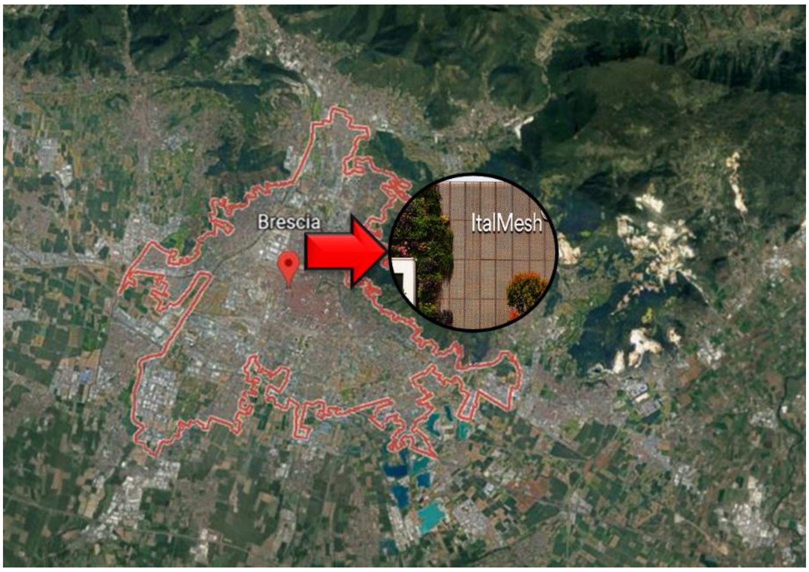


Figure 21: ItalMesh Headquarter, Brescia Italy

Along with establishing green panels at the Politecnico di Milano, the ItalMesh headquarters (Figure 21) have just put new Zero Gravity Eden panels on the facade of their offices, to observe nature develop luxuriantly even in an area surrounded by manufacturing firms. The project entails the complete reconstruction and cladding of the Montirone corporate facade. Aluminium expanded metal meshes from the Siena 150 model (Figure 22) and panels from the Zero Gravity Eden vertical garden were used for this intervention. With an eye toward eco-sustainability and environmental preservation, the impact of vertical green and expanded metal offers the industrial structure elegance and dynamism. In fact, the vertical garden modules guarantee thermal and acoustic insulation as well as a significant reduction of CO_2.

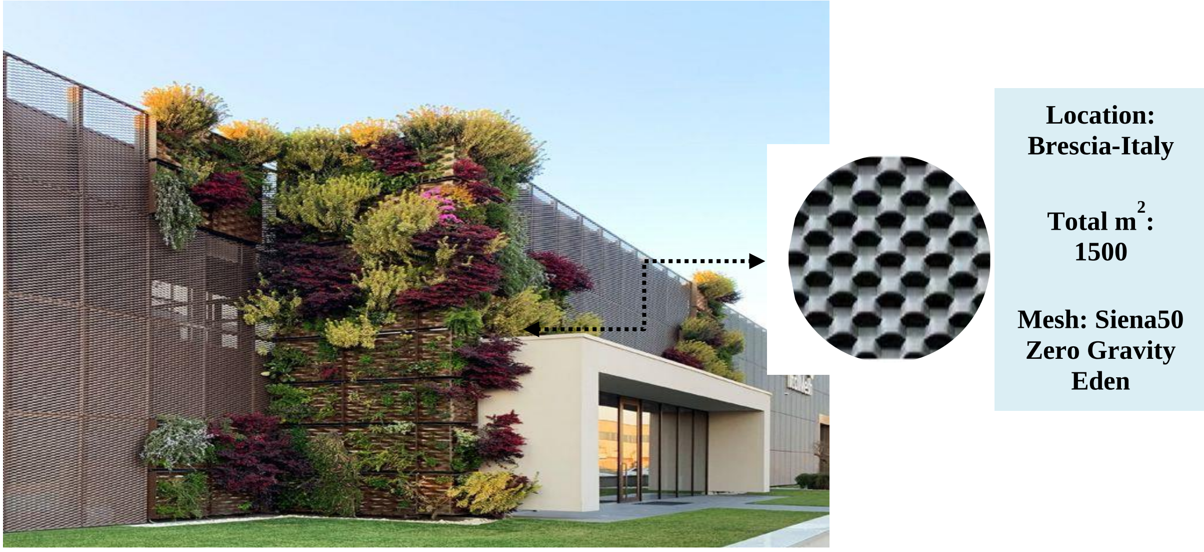


Figure 22: ItalMesh Headquarter- Siena 50/Zero Gravity Eden

5.1.3 The Case of Nicosia, Cyprus:

Cyprus is in the eastern Mediterranean, where its location plays an important role in shaping its 10,000-year history. It has become an important commercial center over the past decades. Cyprus is one of the most important tourist destinations in Europe. It has 340 days of sunshine throughout the year. It also has a beautiful coastline with sandy and other rocky areas with clean beaches and its water is also considered the cleanest water in the Mediterranean Sea. Cyprus has magnificent landscapes, a country of work and entertainment, and life in the East and West (Figure 23).

Figure 23: Cyprus *(Google Earth)*

Cyprus as a country has an ancient historical charm with many ancient monuments and historical rural and urban sites. It also has a beautiful landscape characterized by its mountainous ranges, beautiful beaches, attractive gardens, farms, and orchards full of citrus and olive trees, clean green spaces, and unique historical monuments such as castles, walled cities, churches, and temples (Cyprus Profile, 2018). North Cyprus has five main provinces as Nicosia, Famagusta, Kyrenia, Güzel yurt and Iskele. North Nicosia is capital city of north Cyprus.

Figure 24: Increase of built environment in North Nicosia ***(Wander Globe, 2017)***

North Cyprus has faced a rapid urbanization in the last twenty years. North Nicosia is among these cities that had a fast urban development (Figure 24Figure 24). As a result, with the lack of green areas, buildings increased leading to the construction materials such as concrete and asphalt in the city. This process is causing temperature rise in the atmosphere of urban environment of the city, noise, and dust in addition; it also decreases human wellbeing and quality of life. Therefore, it seems that, to solve problems in the city, sustainable urban planning solutions are crucial. Vertical greenings as living walls and green facades are among these sustainable solutions to mitigate the ecological problems also in north Nicosia.

According to the macro climate classification of North Cyprus, it is among the climate zone called semi-arid. It is hot and dry in the summer due to its location on a Mediterranean island; Mediterranean climate is seen where the winter is warm and less rainy. The average annual temperature in north Cyprus is 19.0 °C. The hottest month throughout the year is usually July. During this month, the air temperature is between 37.0 °C and 40.0 °C during the day. The coldest month of the year is usually January, and the temperature is between 9.0 °C - 12.0 °C during the day and the coldest nights of the year are mostly experienced in this month. On such nights, the temperature of the soil with the decrease of the air temperature drops below 0.0 °C, especially in the inner parts, causing frost events in places (KKTC Meteor, 2019).

Nicosia 35.18N, 33.36E

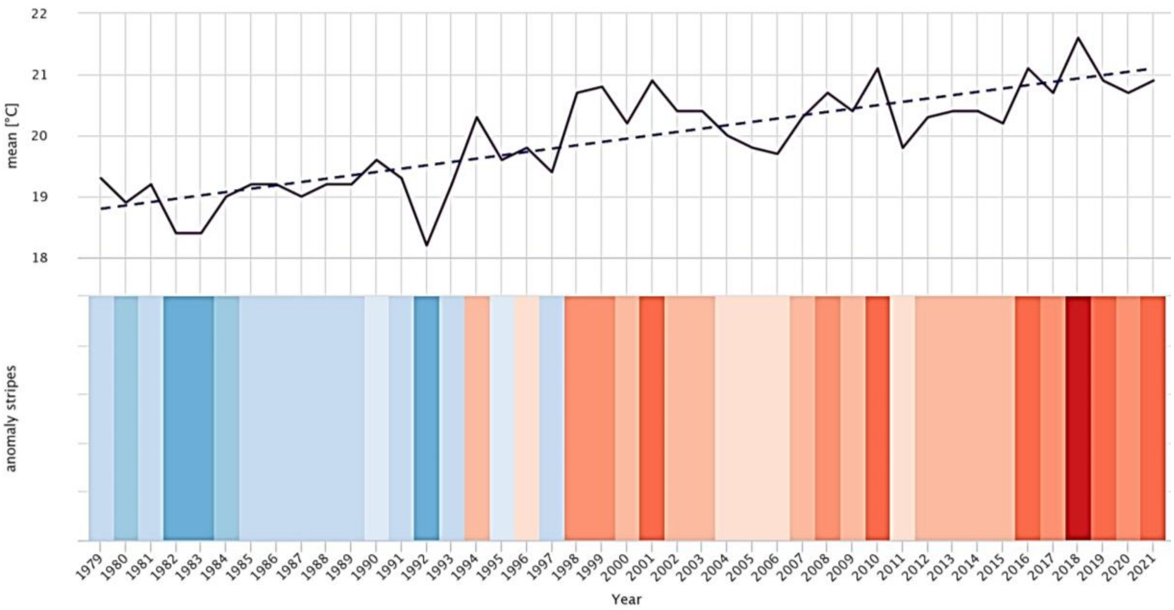


Figure 25: Mean Yearly Temperature, trend, and anomaly, 1979-2022 ***(Meteoblue.com)***

Cyprus is the third largest island in the Mediterranean, dominated by two mountain ranges: the Troodos, which covers much of the southern and western parts of the island, and the Girne Mountains that extend along the north coast of Cyprus, where Girne's city is located. The Troodos Mountains occupy an area and a higher altitude than the Kyrenia Mountains. The island of Cyprus is generally characterized by mild weather and hot summers, but its climate is affected by fluctuations, sea impacts and storms (Figure 25). The temperature of the island varies between night and day. This difference is more pronounced in the summer, with winter variations between 8 °C and 10 °C in low areas and between 5 °C and 6 °C in high areas, while the summer weather variations reach 16 °C in the low areas and from 9 °C to 12 °C in high areas (Republic of Cyprus, 2019).

5.2 Data Collection and Monitoring:

The monitoring and collection of the health related, and the meteorological data is collected with the help of sensors and manual tools.

5.2.1 ARPA Lombardia

Agenzia Regionale per la Protezione dell'Ambiente / Regional Environmental Protection Agency): The Regional Meteorological Service, active in ARPA Lombardia since 1st January 2004, has a meteorological monitoring network consisting of around 250 automatic stations.

It lets users view the meteorological forecasts of Lombardy and perform a meteorological monitoring thanks to a network of automatic measurement stations operating in real time and remote sensing tools.

Features of ARPA:

- Measure weather data in real time.
- The weather forecasts for the Lombardy provinces are represented by time slots, ensuring greater precision.
- The Lombardy weather report is produced daily by ARPA meteorologists, from Monday to Saturday.
- The bulletin of the ultraviolet radiation index is prepared daily, while the heat discomfort, called Humidex, is prepared daily from June 1 to September 15.

It deals with prevention and protection of the environment, supporting regional and local institutions in multiple activities. From the fight against atmospheric and acoustic pollution to interventions for water protection surface and underground, from monitoring electromagnetic fields to investigations on soil contamination and remediation processes.

This meteorological data is useful to compare the effect of the living wall on the weather in the real time.

5.2.2 AIRCARE

AirCare® is an Italian project that redesigns the indoor wellbeing paradigm, its direct focus on air quality and comfort control is exclusively dedicated to people's wellbeing. In addition to the HW components, AirCare offers a platform dedicated to the control and management of your devices, which analyses the data collected and allows access to information of interest. Finally, AirCare supports you in obtaining more credits related to indoor air quality requirements with the aim of obtaining environmental certifications.

AirCare is a small smart device, with a smooth and white surface, with reduced dimensions and a simple and linear design. The small slits on all sides allow continuous ventilation for effective air quality measurement. Given the cubic shape, it can be positioned without the need for supports, for example on shelves and tables. If necessary, wall mounting is made available from the appropriate slot or from the display that can be branded with your company logo. The AirCare device can connect to the collection server (in the cloud or on an intranet) via Wi-Fi or NB-IoT connectivity. On request it can support LTE-4G, LTE-M, LoRa, LoRa-WAN wireless connectivity. Finally, AirCare has indicator lights on the top of the case. Based on the frequency of illumination and colour, they allow you to understand the activity in progress and the general health of the device. Acoustic indicators signal the switching on and off the device.

What does it measure?

AIRCARE tracks and manages indoor air quality by monitoring 3 internal parameters: air quality, environmental comfort, and electro smog.

Air quality:

- *Volatile Organic Compounds (VOCs):* They are carbon compounds that participate in photochemical reactions in the atmosphere. VOCs are numerous, varied, and ubiquitous. In indoor environment we can find VOC in new furnishings, paints, coatings, and office equipment such as printers, stoves combustion and tobacco smoke. VOC levels can be 5 times higher indoors than outdoors. Health effects may include eye, nose, and throat irritation. Headaches, loss of coordination and nausea. Damage to liver, kidney, and central nervous system. Some organics can cause cancer in animals, some are suspected or known to cause cancer in humans.

- *Particulate Matter (PM 10 - PM 2.5)*: Particulate matter, categorized in PM10 (diameter less than 10 µm) and PM 2,5 (diameter less than 2.5 µm), is a complex mixture of polluting particles present in the air we breathe, and they can penetrate the pulmonary alveoli. In the air quality directive (2008/EC/50), the EU has set two limit values for particulate matter (PM10) for the protection of human health: the PM10 daily mean value may not exceed 50 micrograms per cubic metre (µg/m3) more than 35 times in a year and the PM10 annual mean value may not exceed 40 micrograms per cubic metre ($\mu g/m^3$). In the air quality directive (2008/EC/50), the EU has set a target value for fine particulate matter (PM2.5) for the protection of human health: the PM2.5 annual mean value may not exceed 25 micrograms per cubic metre (µg/m3).

- *Air Quality Index*: Based on a smart algorithm the sensor gives ad indoor air quality (IAQ) output. This output indicates the quality of air available according to other sensors parameters correlated (VOC, temperature, humidity, pressure). It causes similar discomforts indicated in the VOC, where the threshold is exceeded, the environment is considered unhealthy.

- *CO_2*: Carbon dioxide (CO_2) is a colourless and odourless gas and is the main product of the combustion of coal, hydrocarbons and in general organic substances. In indoor environments is anthropogenic and is easily found in poorly ventilated work environments. Generally, it is related to the number of occupants. Exposure to high concentrations of CO_2 was a risk factor for irritative symptoms of the upper respiratory tract and for sick building syndrome, irritation to eyes, nose, throat, neurological problems, allergic reactions in general (source GARD Group – IT Ministry of Health).

- *CO_2 Equivalent:* Carbon dioxide (CO_2) is the most known and common greenhouse gas, but it’s not the most dangerous. CO_2 equivalent is a measure used to compare the emissions of various greenhouse gases according to VOC measured.

Environmental comfort:

- *Sound pressure*
- *Air Temperature*
- *Relative Humidity*

- *Ambient light*
- *Atmospheric pressure*

5.3 Manual Devices for Data Collection:

There are numerous portable instruments available to measure environmental variables including air quality. To confirm the validation of vertical garden model, measurements of the panels covered in vegetation were made. The procedure involved measuring the façade and the environmental impact of the Living Wall System's installation. At 1.5 and 3 meters from the panels, respectively, measurements are taken using manual techniques. By aiming the tools at the panels and taking the recordings, the measurements are made. Ten to fifteen minutes are given for the tools to calibrate before the readings are recorded.

1. **Temptop**: Temptop LKC-1000S Indoor Air Quality Monitor is a professional indoor air quality monitor with high accuracy electrochemical formaldehyde sensor and laser particle sensor provides the most reliable readings for PM2.5, PM 10 & HCHO (Table 4 and Table 5). This advanced third-generation laser particle sensor has a lifetime of up to 20,000 hours. It makes particle measurement more accurate and stable when combined with the unique particle swarm optimization algorithm. It also provides the readings for Air Quality, Number of Particles, Temperature and Humidity (Figure 26).

Figure 26:Temptop LKC-1000S

Table 4: Specifications- Temptop

Specification	**Measurement Range**	**Resolution**
PM 2.5	0-999ug/m^3	0.1ug/m^3
PM 10	0-999ug/m^3	0.1ugm^3
HCHO (Formaldehyde)	0-5mg/m^3	0.01mg/m^3
TVOC	0-5mg/m^3	0.01mg/m^3

Table 5: Product details- Temptop

Product Details	
Type of Product	Air Quality Monitor
Temperature Range	0-50°
Operating Humidity Range	0-90°
Display	TFT colour LCD screen
Battery Voltage	3.7VDC
Model Number	LKC-1000S

2. **Peak-Tech**: This meter is designed to combine the functions of Sound Level, Light meter, humidity meter, and Temperature meter (Table 6). It is an ideal multi-Function environment meter instrument with scores of practical applications for professional use. The sound level functions can be used to measure noise in factories, schools, offices, airports, home, etc. checking acoustics of studios, auditoriums, and hi-fi installations. The light functions are used to measure illuminance in the field. It is fully cosine corrected for the angular incidence of light. The light sensitive component used in the meter is a very stable, long life silicon diode. The Humidity / Temperature use a humidity / semiconductor sensor and K type thermocouple The Light functions is used to measure illuminance in the field (Figure 27).

Table 6: Specifications – Peak Tech

Specifications	
Light	0 – 2000 Lux
Sound Level	-200C – 7500C
Humidity	25% - 95% RH
Temperature	Lo 35 – 100Db / Hi 65-130 Db
Operating Voltage	9V Battery

Figure 27: Peak-Tech 5035

3. **Solar Power Meter**: Meter portable digital solar (model SM206), a precision instrument for measurement of the radiation solar and other applications where solar energy is important. It takes the measurements directly, no need for adjustments. This meter is a precision instrument measuring the intensity of sunlight. There are two units that can be selected: W/m^2 and Btu. It supports maximum value hold function and data hold function. It measures directly without adjustment, steadily measure for a long period. It is widely used for solar radiation measurement, solar energy research, meteorology, agriculture, physical and optical experiments (Figure 28).

Table 7: Specifications – Solar Power Meter

Solar Power Meter Specifications	
Model	SM206
Resolution	0.1W/m^2, 0.1Btu/(ft^2-h)
Range Error	±10W/m^2 (±3Btu/(ft^2-h) or ±5% of measured value
Temperature Error	±0.38W/m^2/ ±0.12Btu/(ft^2-h)/ deviation at 25°C
Display	3-3/4 LCD display, maximum 3999
Sampling Time	0.25 seconds/time
Operating Temperature & Humidity	0~50, <80%RH
Storage Temperature and Humidity	-10~60, <70%RH
Measurement Range	0.1-399.9W/m^2, 1-3999W/m^2, 0.1-399.9Btu/(ft^2-h), 1-3999Btu/(ft^2-h)

Figure 28: Solar Power Meter SM 206- SOLAR

4. **Infrared Thermometer**: Infrared thermometers are great for checking surface temperature; however, they do not measure the internal temperature of an object It is useful for trending the temperature of an object or comparing a measurement to a specification. This thermometer has a continuously illuminated, vivid LCD screen, to see the parameters clearly. Apart from the measurement of surface temperature, it also measures air temperature and humidity (Figure 29).

Table 8: Specifications – Infrared Thermometer

Specifications	
Brand	MESTEK
Model	IR01D
Temperature measurement range	-50~800℃
Ambient temperature	-10 ~ 60 °C
Ambient Humidity	0%~100%RH
Emission level	0.1~1 adjustable
Response spectrum	8~14um
Laser	<1mW/630-670nm
Response time	<0.5 s
Operating temperature	0~40℃
Storage temperature	-10 ~ 60 °C
Power supply	1.5V * 2 AAA battery (not included)

Figure 29 : MESTEK- Infrared Thermometer

6 RESULTS AND DISCUSSION

The data collected by the four AIRCARE PRO equipment housed in the green facades of the two buildings (9 and 10) inside the Politecnico di Milano campus is shown in the report that follows. The average value per hour was calculated to produce the graphs.

6.1 Case study 1 – Building 9, Politecnico di Milano, Italy

The Politecnico di Milano's building 9 faces south and is next to a parking area on campus. It has a study hall and various classrooms. There are four panels of the green wall built on building 9. The bottom two panels measure 0.9 m × 1.4 m and the top two measure 1.04 m x 1.4 m. On the entire panel, two air quality monitors have been mounted, one on the external side and the other toward the internal side. The sensors' data is based entirely on hourly values calculated on monthly basis.

The sensor placed towards the external side is represented as ‘External’ and the one towards internal side is represented as ‘Internal’ in the graphs.

Position of Sensor (AIRCARE PRO)	Percentage of working hours during March	Percentage of working hours during April	Percentage of working hours during May	Percentage of working hours during June	Percentage of working hours during July	Percentage of working hours during August
External	29%	72%	98%	98%	97%	30%
Internal	93%	40%	100%	100%	94%	64%

The External and Internal sensors measure the following parameters:

- Air Temperature
- Relative Humidity
- Particulate Matter 2.5 (PM2.5)
- Particulate Matter 10 (PM10)

- Sound
- Volatile Organic Compounds (VOC)

Figure 30: Case study 1 Building 9- Green panel

Figure 31: Externally positioned sensor of Green panel installed on Building 9

6.1.1 Air Temperature

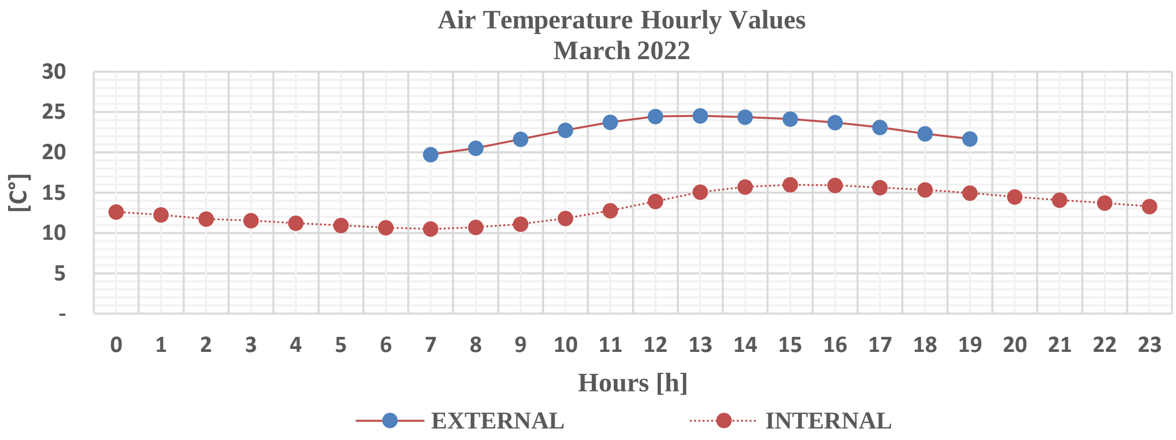


Figure 32: Air Temperature hourly values measured by AIRCARE PRO during March

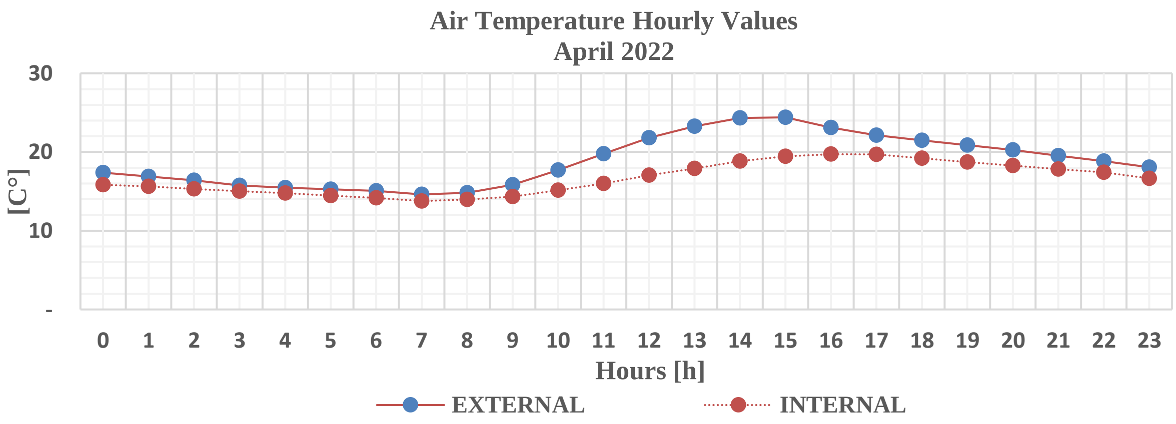


Figure 33: Air Temperature hourly values measured by AIRCARE PRO during April

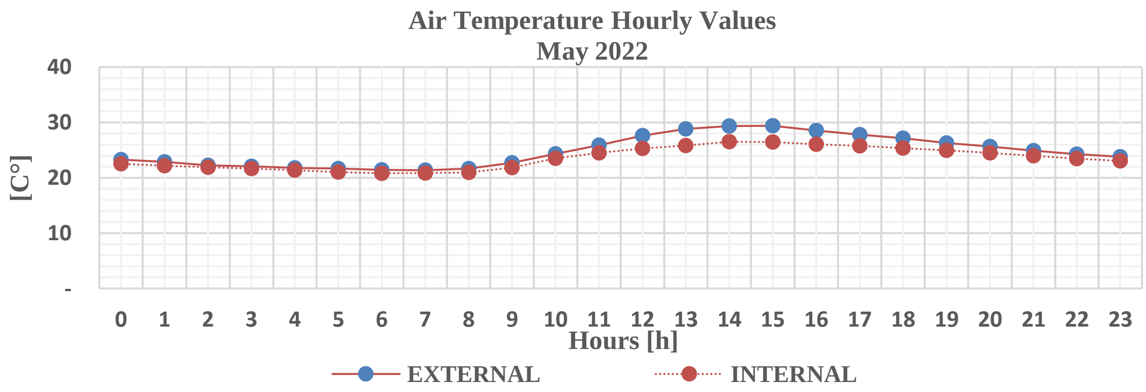


Figure 34: Air Temperature hourly values measured by AIRCARE PRO during May

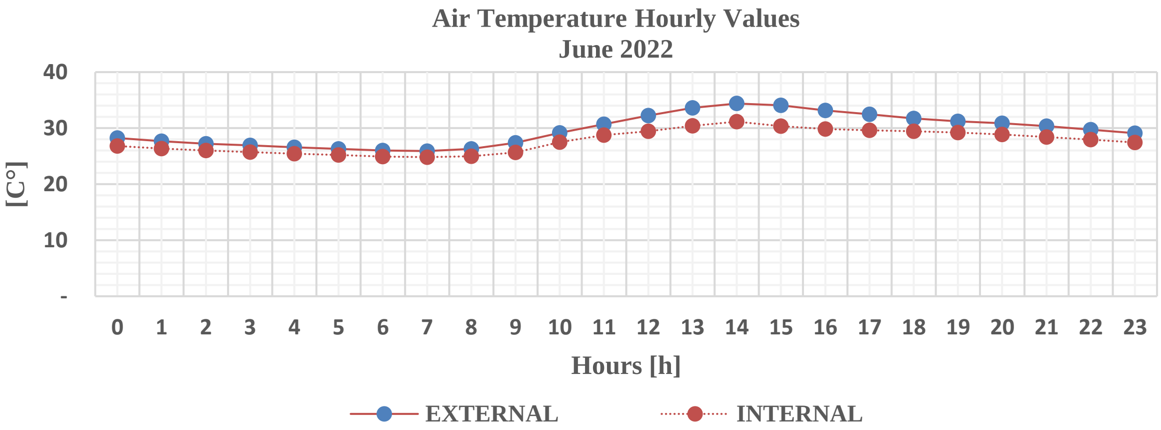


Figure 35: Air Temperature hourly values measured by AIRCARE PRO during June

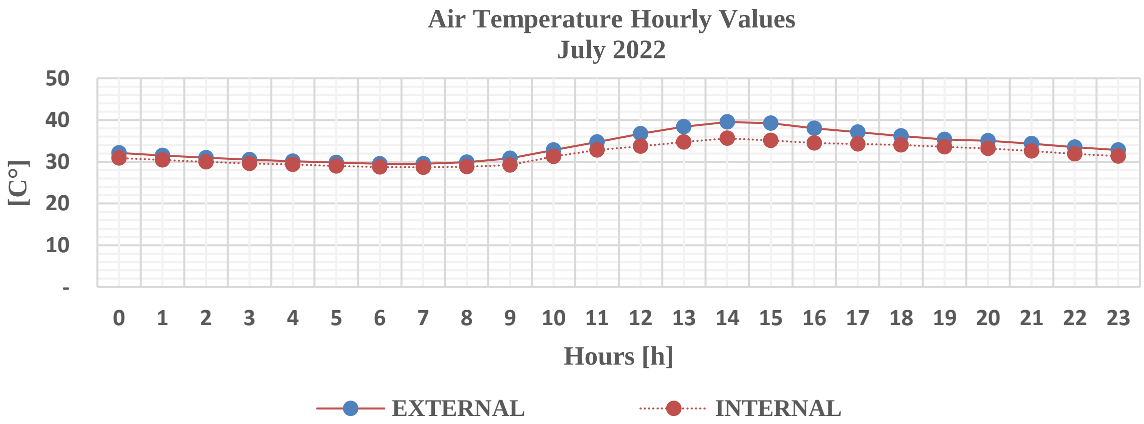


Figure 36: Air Temperature hourly values measured by AIRCARE PRO during July

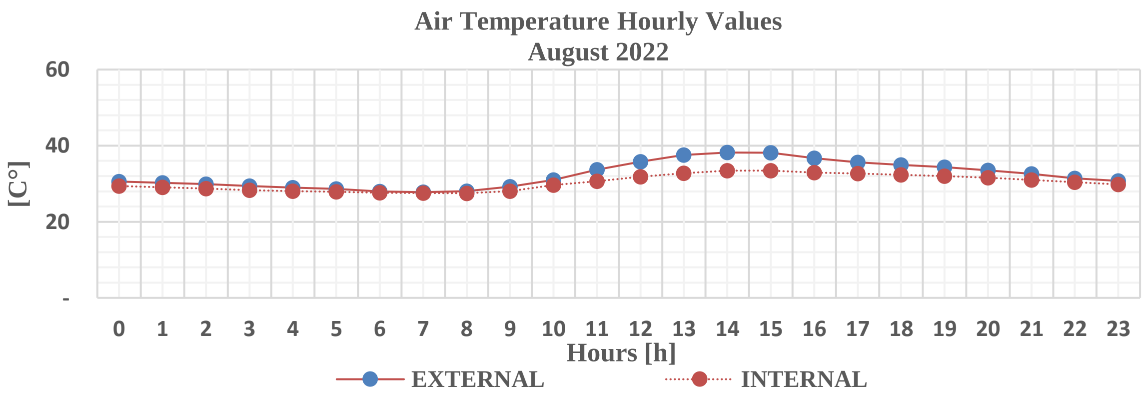


Figure 37: Air Temperature hourly values measured by AIRCARE PRO during August

- The values of air temperature were recorded by the AIRCARE sensors placed with respect to the panel. The sensors are located externally and internally. The values are measured based on data from March to August 2022.
- The sensors' plots show that the sensor positioned externally was able to measure the temperatures at their highest hourly values. For the summer months of July and August, respectively, the peak hourly values of 39.5˚C and 38.2˚C were recorded.
- In comparison to the externally mounted sensor, the results obtained by the inside sensor showed low temperatures. This is because of the ability of the panel to obstruct the incoming solar radiation which provides cooling.
- The maximum and minimum temperatures varied more during March and April than they did during the other months, reaching levels of about 14˚C and 10˚C.

6.1.2 Relative Humidity

The American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc (ASHRAE) guidelines recommend a relative humidity (RH) of 30 to 60 percent.

Level	Relative humidity (%)
comfortable	30-60
Recommended	45-55
High	55-80

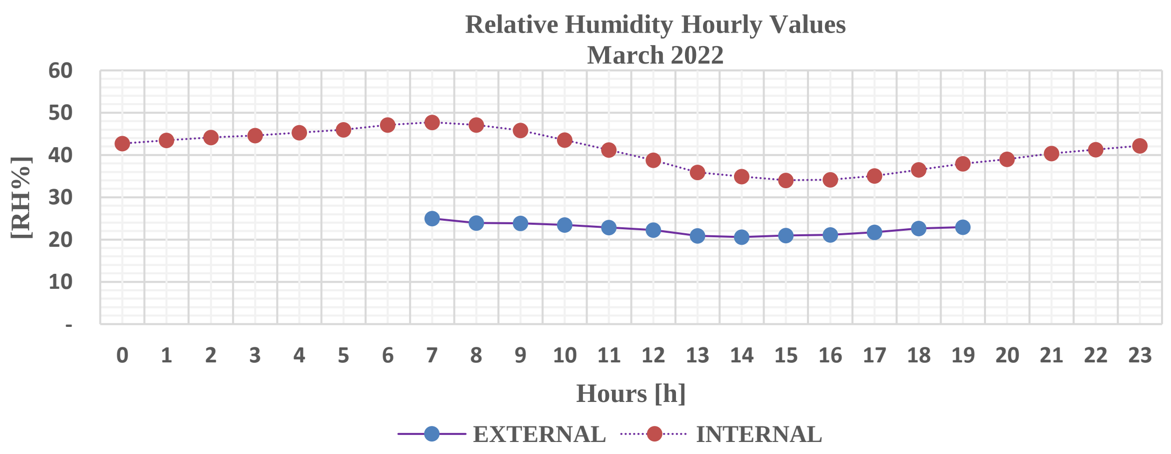


Figure 38: Relative Humidity hourly values measured by AIRCARE PRO during March

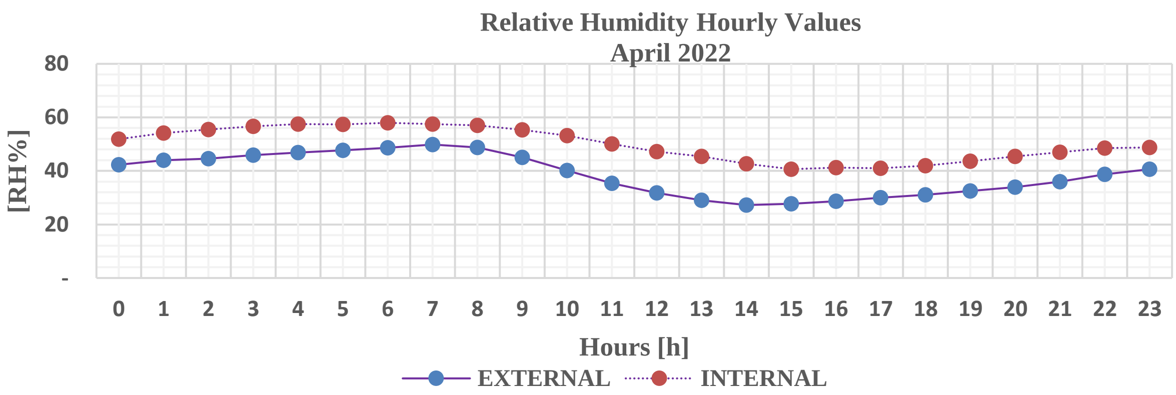


Figure 39: Relative Humidity hourly values measured by AIRCARE PRO during April

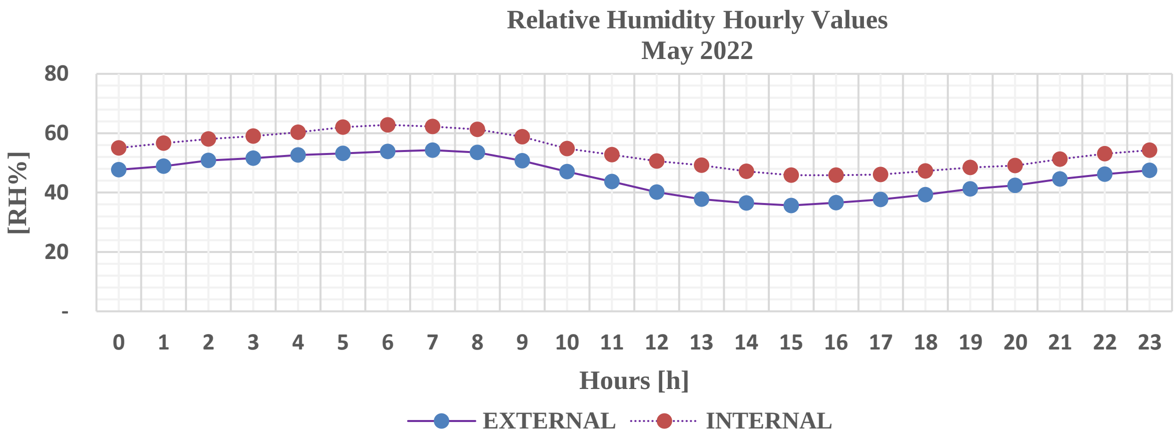


Figure 40: Relative Humidity hourly values measured by AIRCARE PRO during May

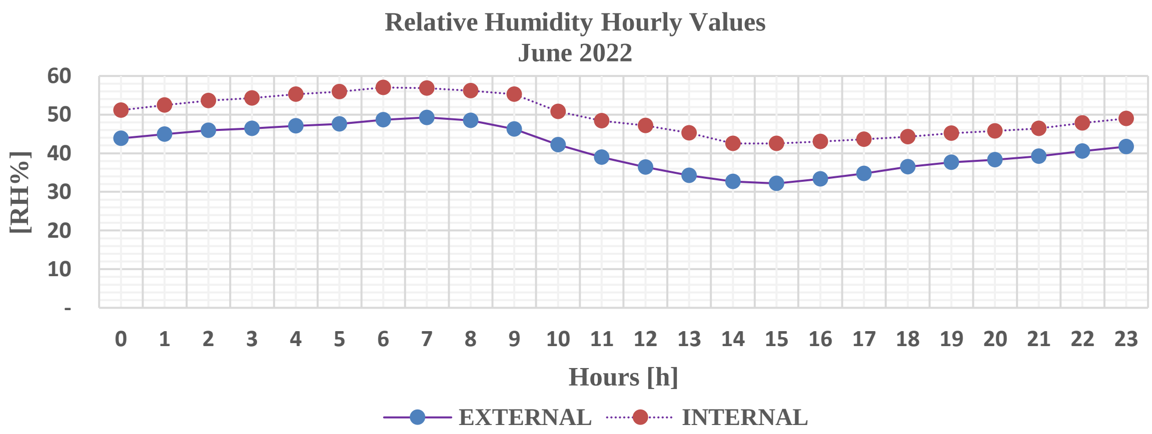


Figure 41: Relative Humidity hourly values measured by AIRCARE PRO during June

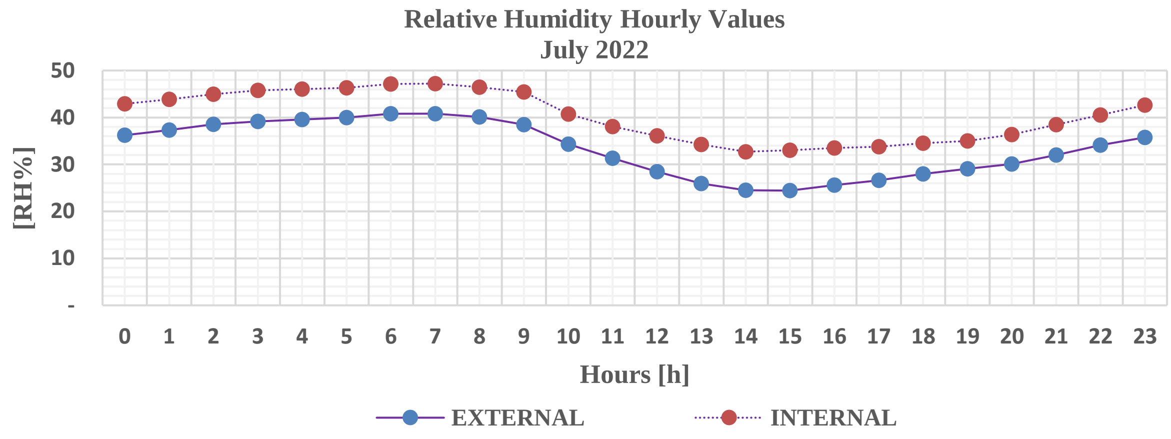


Figure 42: Relative Humidity hourly values measured by AIRCARE PRO during July

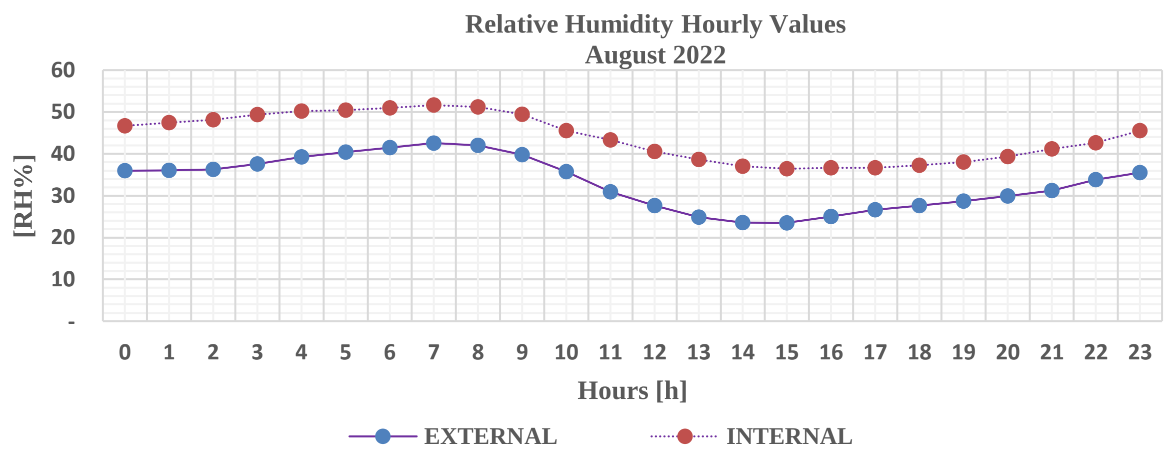


Figure 43: Relative Humidity hourly values measured by AIRCARE PRO during August

- The sensor that is internal to the panel measures humidity levels that are higher than the sensor that is placed externally. During the transition from spring to summer, the month of May saw the greatest value of 62.82%.
- A general pattern was seen for humidity, with greater values being recorded in the morning and evening and a little decline in the middle of the day. The Relative humidity is highest around sunrise when the overnight low temperature is close to the dew point. Low humidity levels are caused by sunlight during the day, which lowers the amount of water in the air.

- The highest humidity differential, which was almost 27%, was recorded in March. Similar trends are shown during the peak spring (April, May) and peak summer (June, July) months, with peaks of roughly (31%, 27%) in spring and (25%, 23%) in summer. Again, a modest rise in the difference in humidity is observed in August.

6.1.3 Particulate Matter2.5

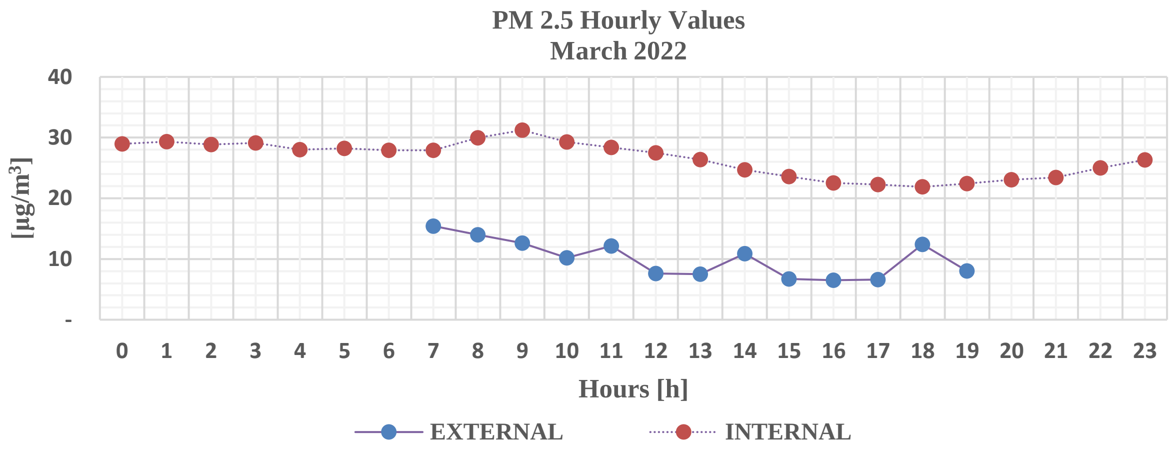


Figure 44: PM 2.5 hourly values measured by AIRCARE PRO during March

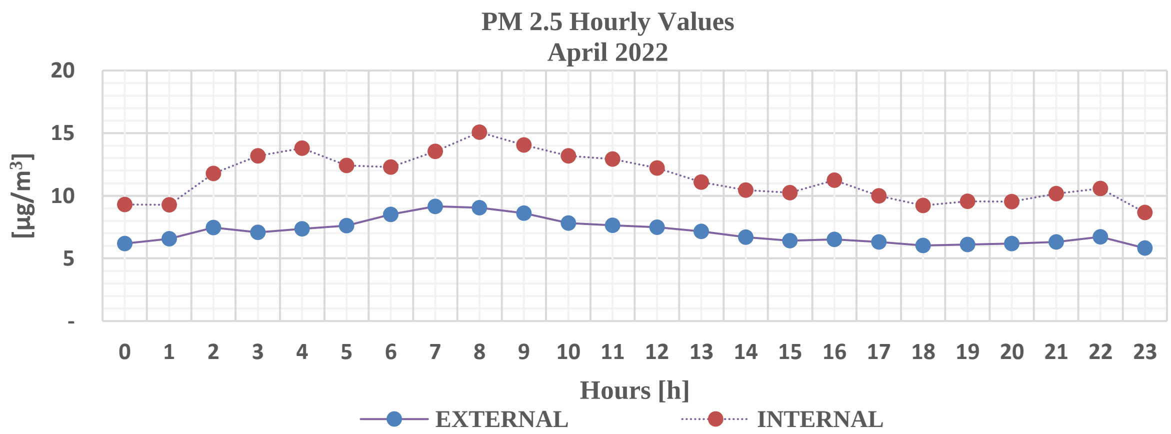


Figure 45: PM 2.5 hourly values measured by AIRCARE PRO during April

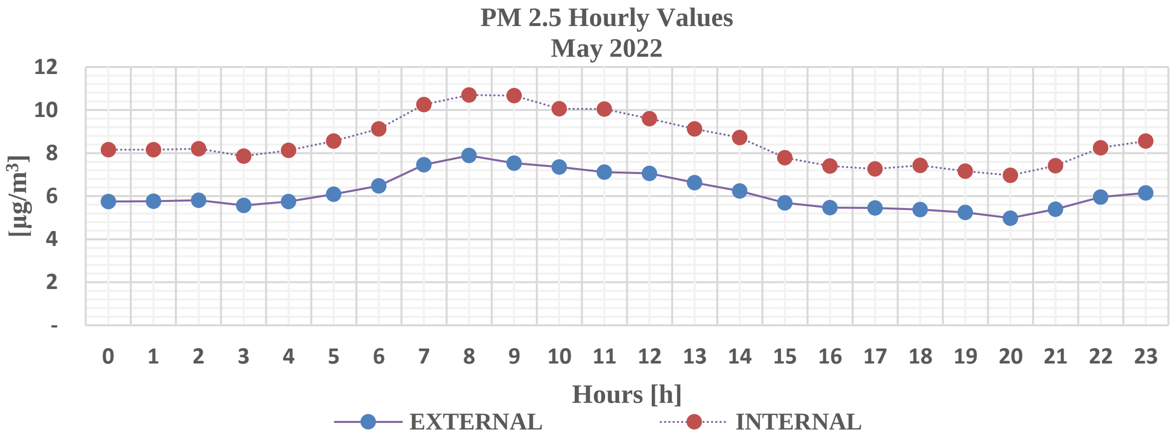


Figure 46: PM 2.5 hourly values measured by AIRCARE PRO during May

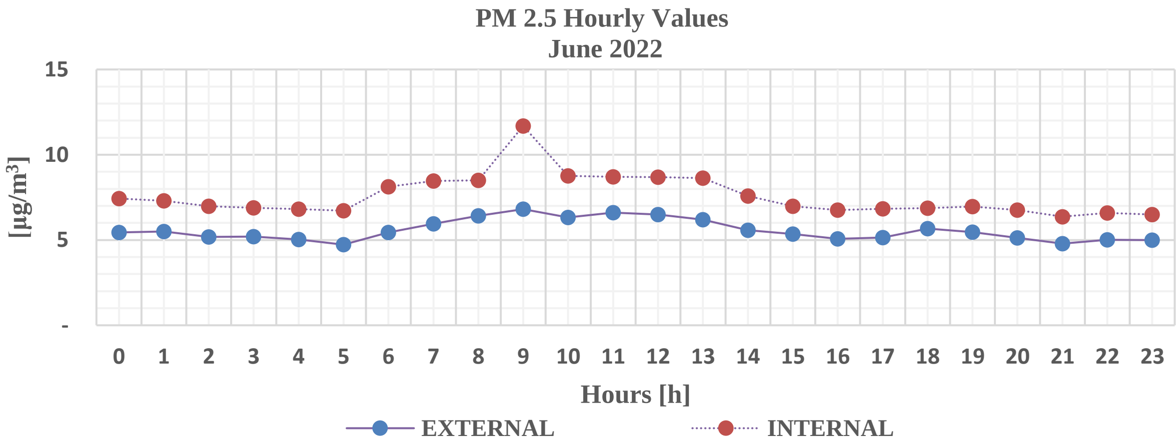


Figure 47: PM 2.5 hourly values measured by AIRCARE PRO during June

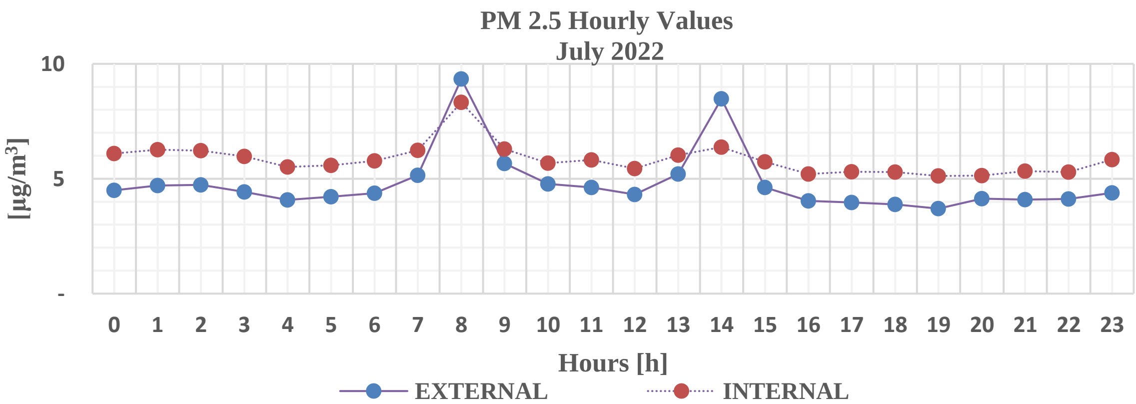


Figure 48: PM 2.5 hourly values measured by AIRCARE PRO during July

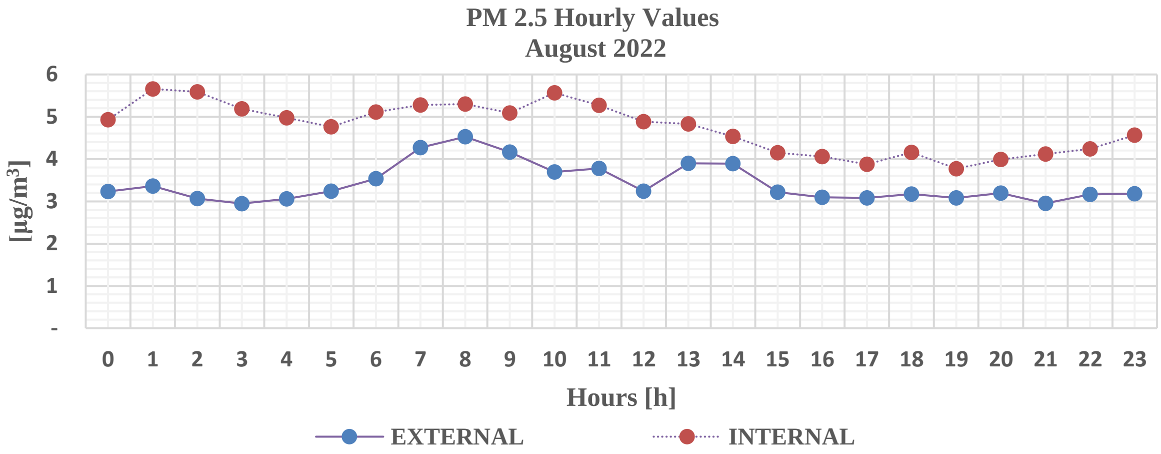


Figure 49: PM 2.5 hourly values measured by AIRCARE PRO during August

- Higher values of PM2.5 was obtained in the morning with the sensors located internally. In March, peak PM2.5 value of 31.23 µg/m^3 was achieved. Spring to summer transition causes a decrease in PM2.5 levels.
- For the month of July, there are two anomalies at 8 a.m. and 2 p.m. where the higher PM2.5 values of 9.34 µg/m^3 and 8.48 µg/m^3 were obtained with externally positioned sensors as opposed to internal ones.

6.1.4 Particulate Matter 10

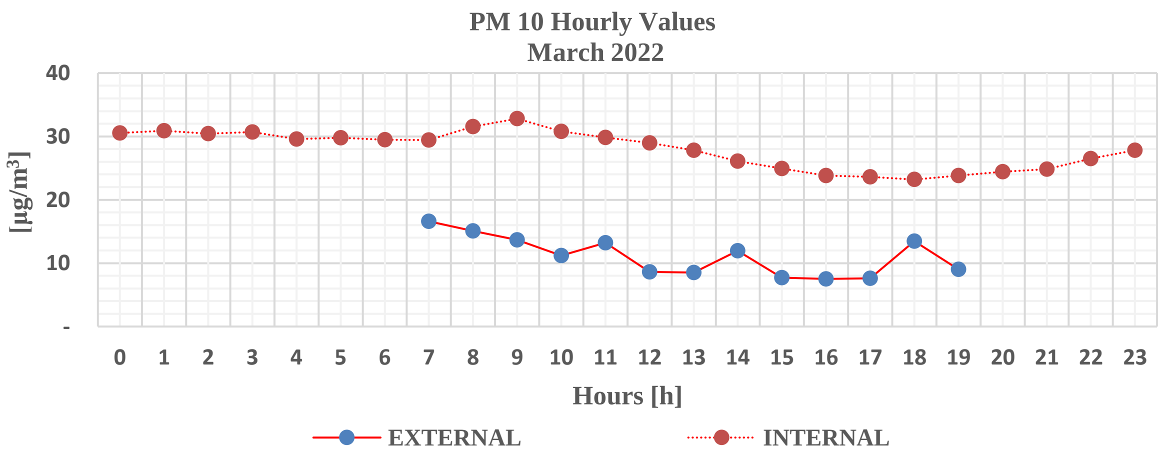


Figure 50: PM 10 hourly values measured by AIRCARE PRO during March

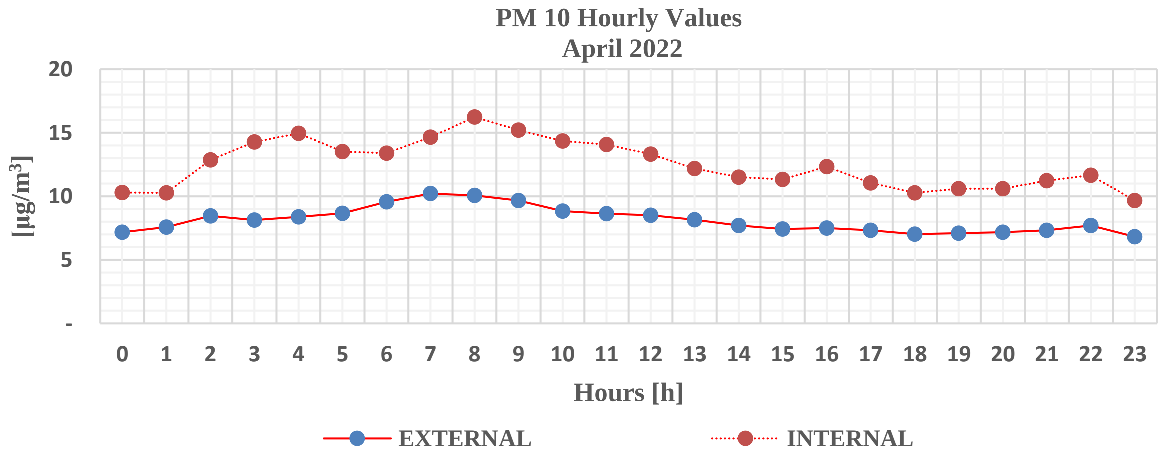


Figure 51: PM 10 hourly values measured by AIRCARE PRO during April

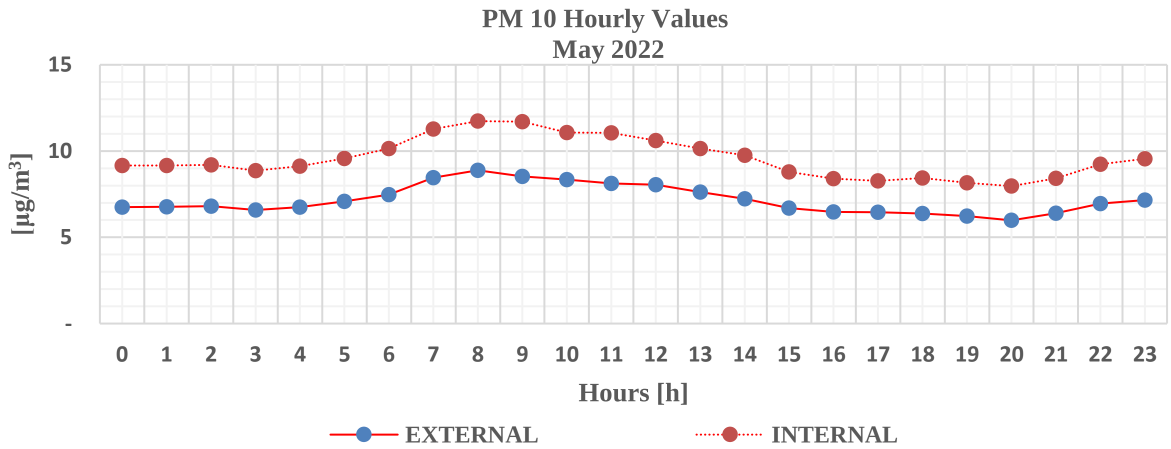


Figure 52: PM 10 hourly values measured by AIRCARE PRO during May

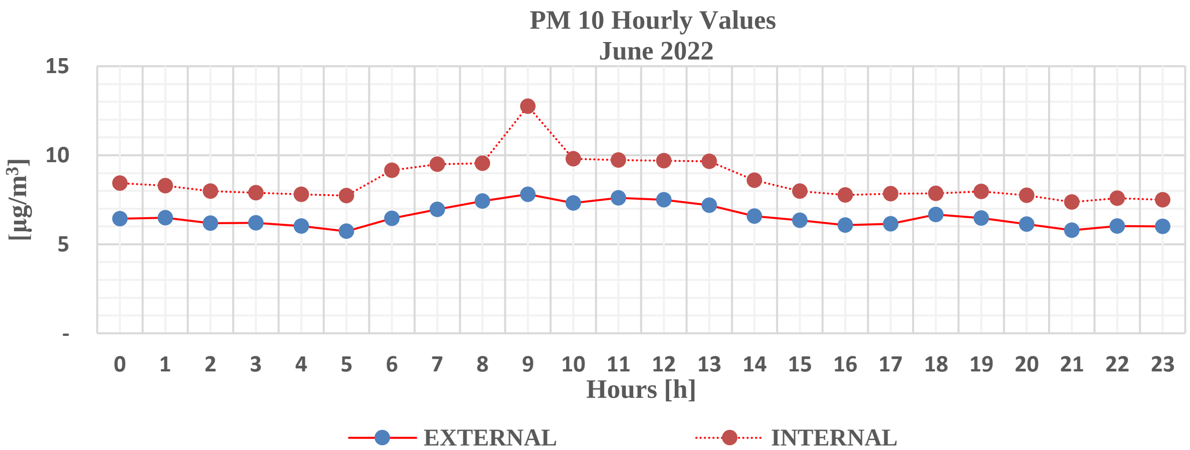


Figure 53: PM 10 hourly values measured by AIRCARE PRO during June

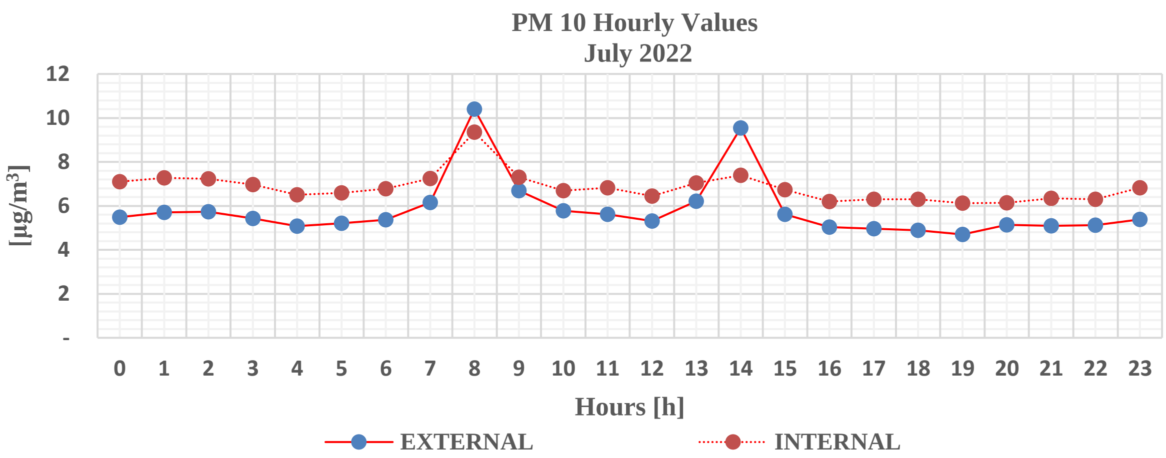


Figure 54: PM 10 hourly values measured by AIRCARE PRO during July

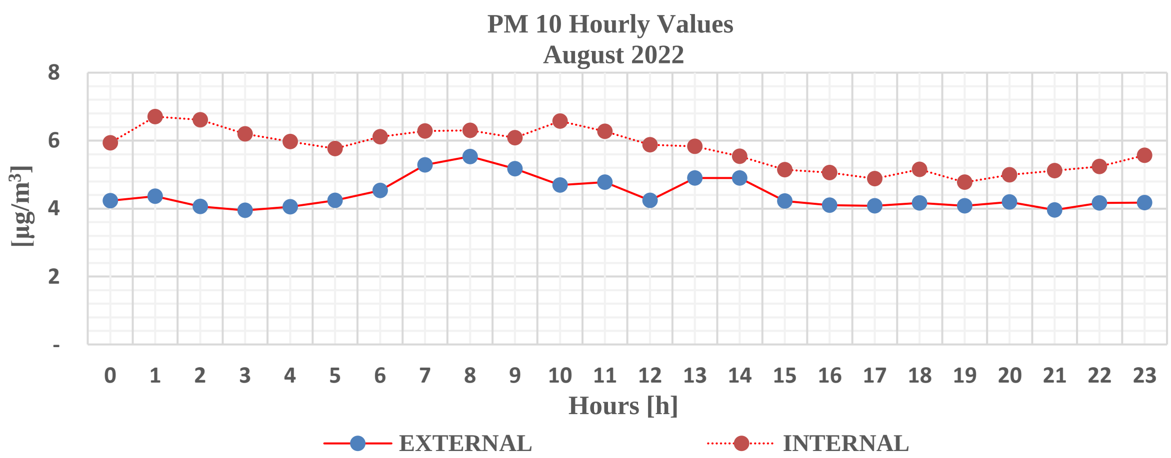


Figure 55: PM 10 hourly values measured by AIRCARE PRO during August

- The internally positioned sensor consistently recorded elevated PM10 readings from March through August. The highest values, which peaked at 32.80 µg/m^3, were noted in the month of March.
- The months of March, April, May, June, and August show a typical pattern of higher PM10 levels in the morning and a minor decline towards the evening.
- When compared to an internally positioned sensor, an externally located sensor specifically for the month of July at 8 AM and 2 PM displays higher values with a peak of 10.40 µg/m^3 and 9.4 µg/m^3 respectively.

6.1.5 Sound

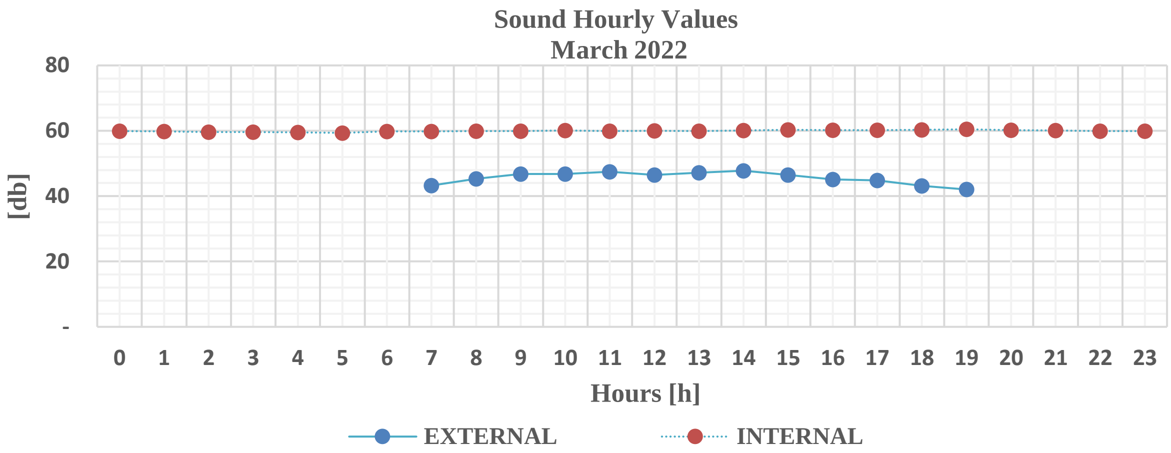


Figure 56: Sound hourly values measured by AIRCARE PRO during March

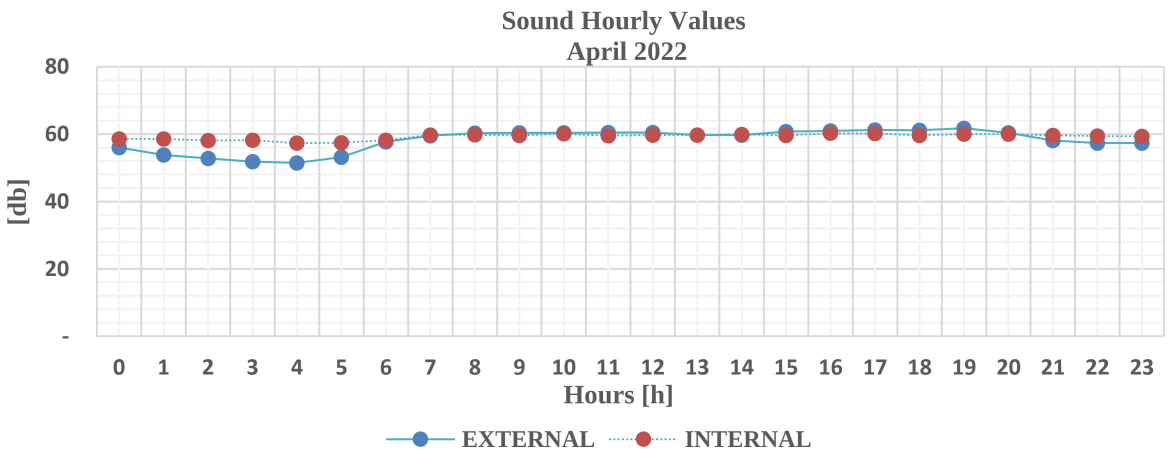


Figure 57: Sound hourly values measured by AIRCARE PRO during April

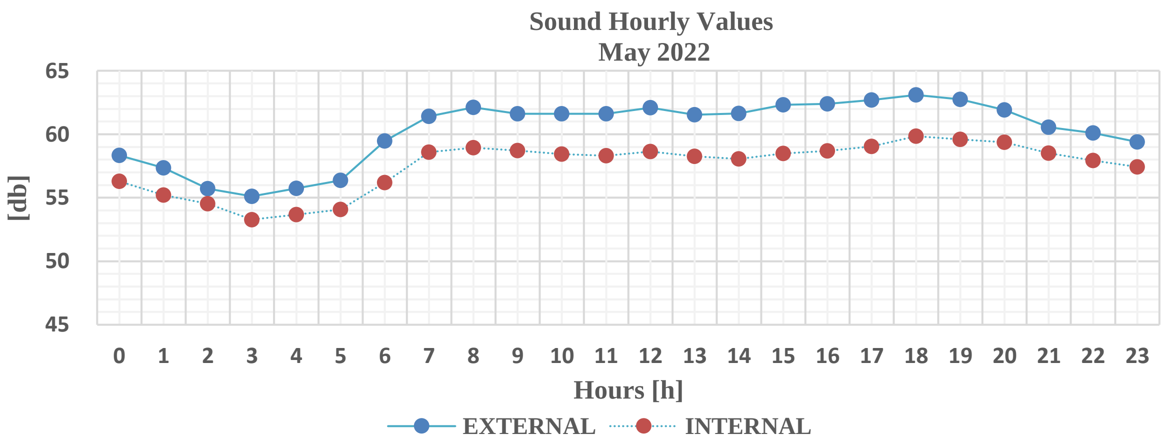


Figure 58: Sound hourly values measured by AIRCARE PRO during May

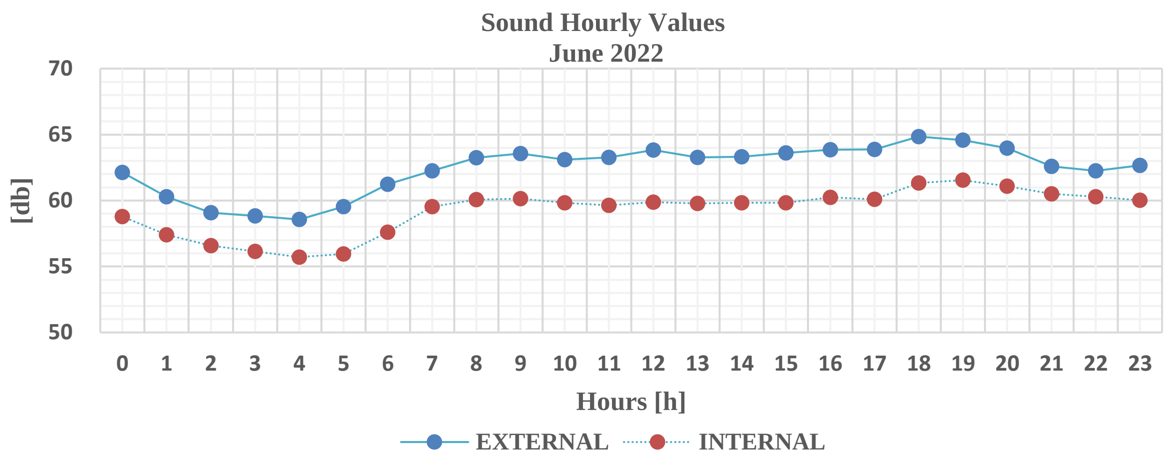


Figure 59: Sound hourly values measured by AIRCARE PRO during June

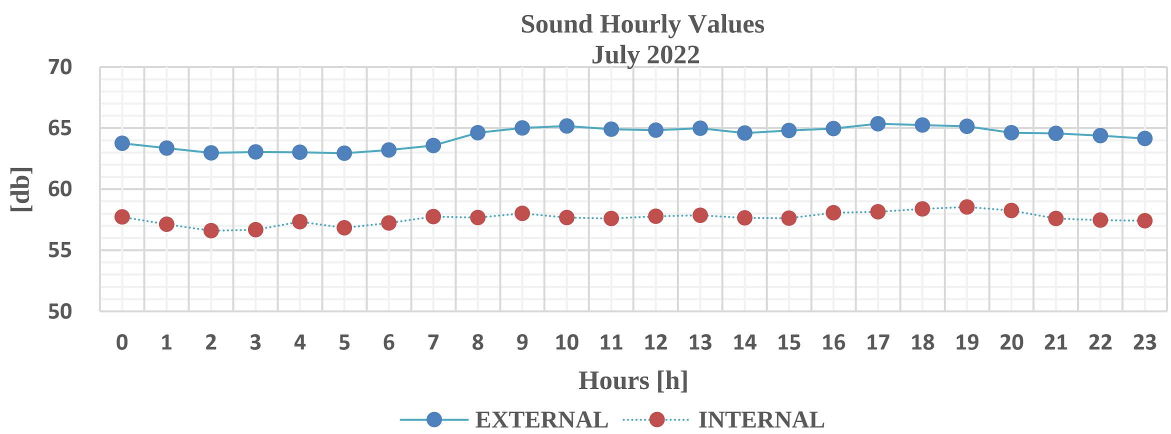


Figure 60: Sound hourly values measured by AIRCARE PRO during July

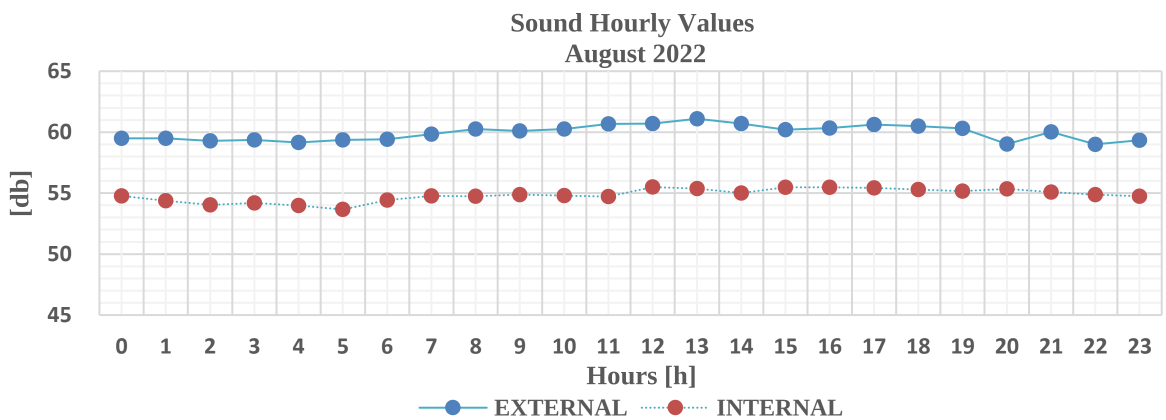


Figure 61: Sound hourly values measured by AIRCARE PRO during August

- The hourly measurements recorded by the internal sensor for the month of March looked to be higher than those recorded by the externally placed sensor. This is explained by the panel's direct installation on the building's exterior face of the classroom.
- The hourly measurements taken by the internal sensor are lower than those taken by the external sensor when spring gives way to summer. This phenomenon can be explained by the panel's increased plant density throughout the summer, which causes more noise from the classroom to be absorbed.
- The sound is captured at its highest levels between the hours of 8 in the morning and 7 in the evening during the day. The summer months of June and July have the highest sound values.

6.1.6 Volatile organic compound (VOC)

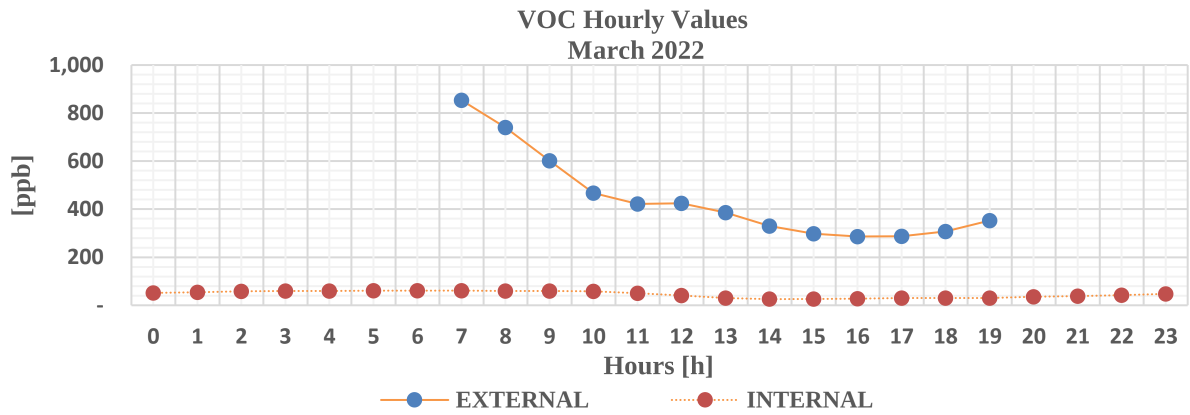


Figure 62: VOC hourly values measured by AIRCARE PRO during March

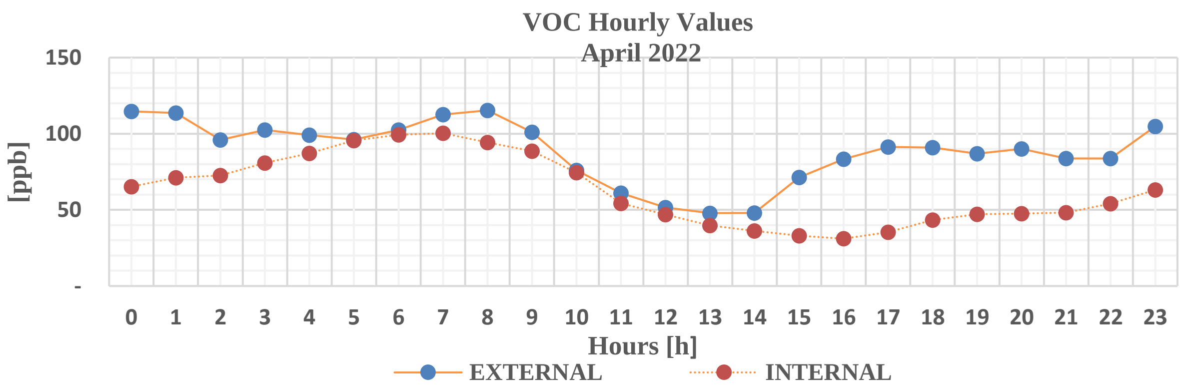


Figure 63: VOC hourly values measured by AIRCARE PRO during April

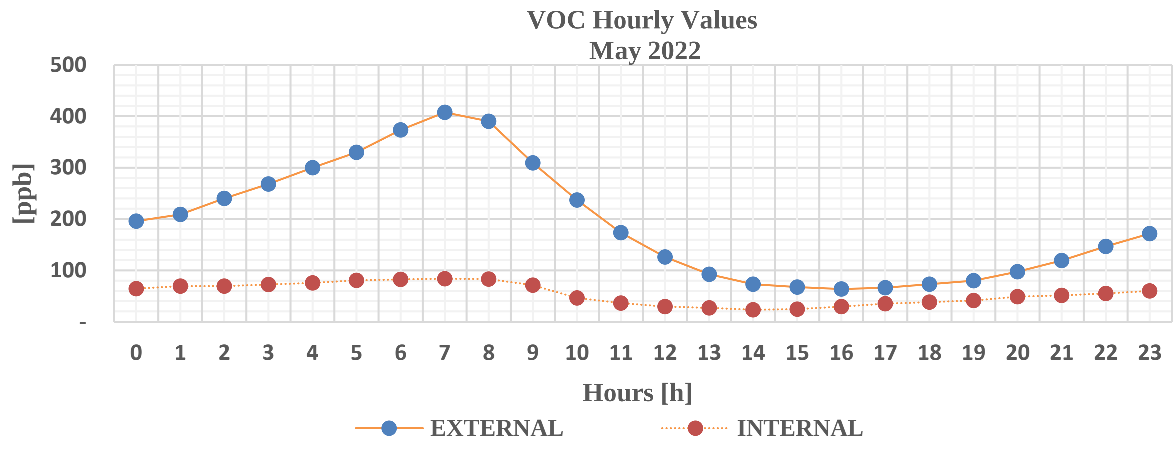


Figure 64: VOC hourly values measured by AIRCARE PRO during May

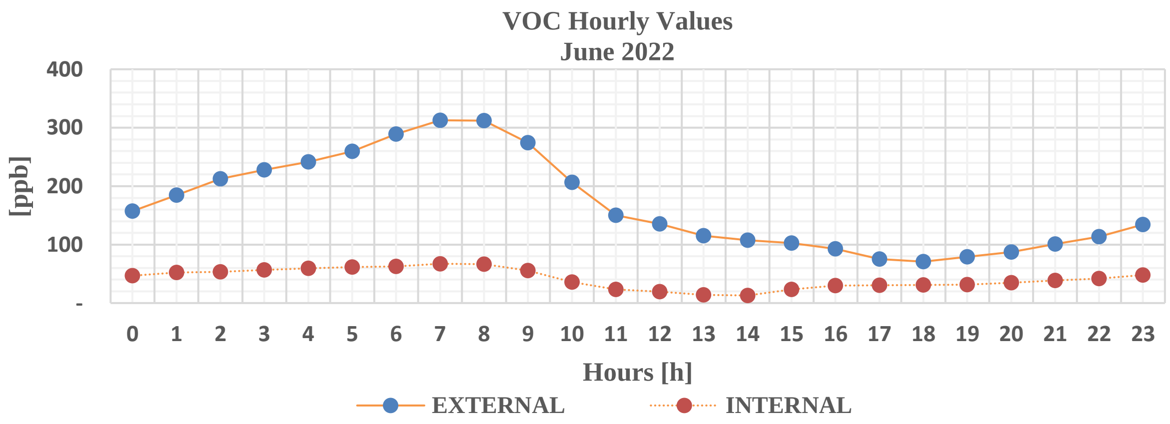


Figure 65: VOC hourly values measured by AIRCARE PRO during June

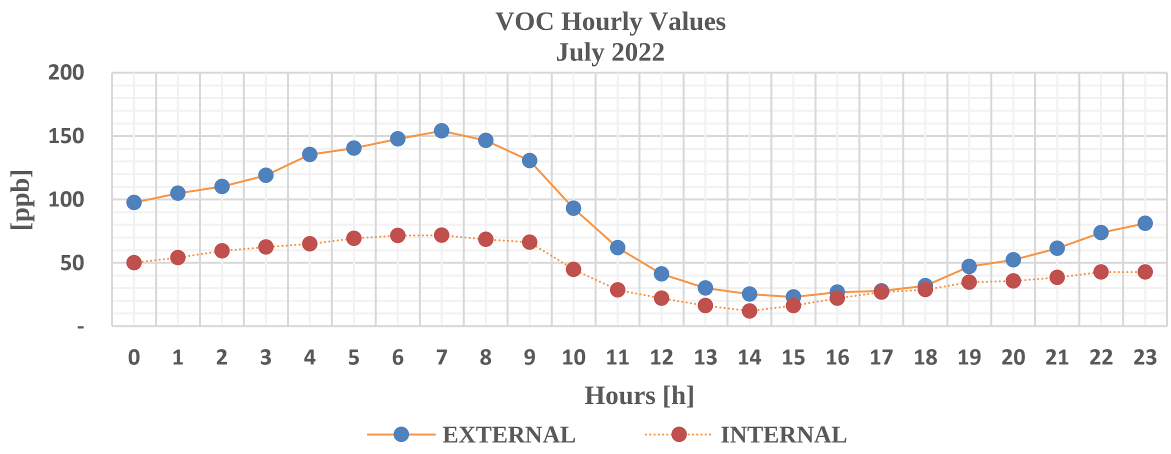


Figure 66: VOC hourly values measured by AIRCARE PRO during July

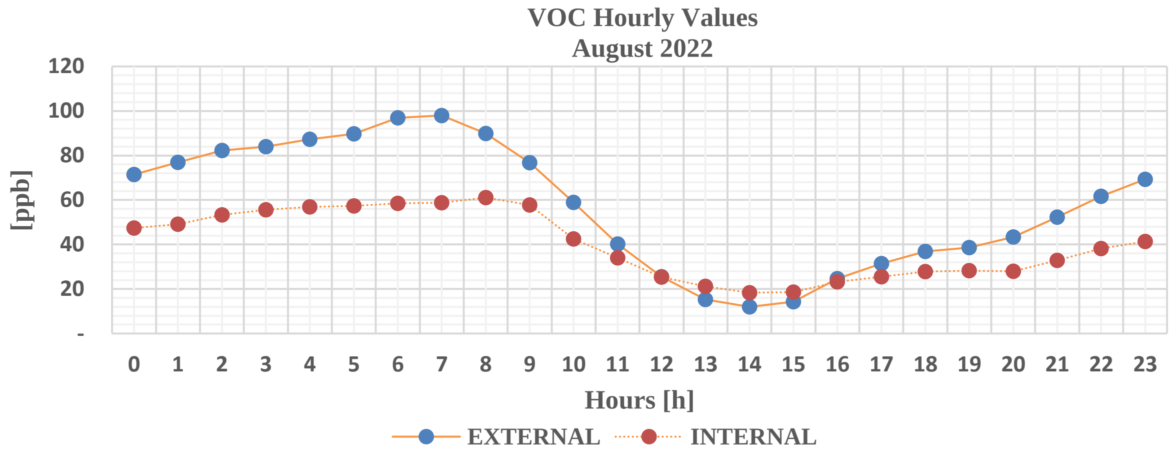


Figure 67: VOC hourly values measured by AIRCARE PRO during August

- The hourly readings for volatile organic compounds as shown by the external sensors are greater from March to August. There is a significant difference in the data supplied by the external and internal sensors for each month.
- The graphs trend indicate that the amount of VOC is higher in the morning, dips little at noon, and then climbs once more toward the end of the data.

6.2 Case Study 2 - Building 10, Politecnico di Milano, Italy

Building 10 (Figure 68) at the Politecnico di Milano faces south and is situated on Via Bonardi, which frequently sees traffic from bicycles, vehicles, buses, trams, and pedestrians.

Figure 68: Case study 2 building 10- Green panel mounted on the wall

On building 10, there are four green wall panels. Each panel is 0.95 × 1.3 meters long. The panel is mounted on the wall. Two air quality monitors have been put on the complete panel, one facing the outside and the other the inside. Data from the sensors is based solely on hourly numbers that are monthly averaged. The analysis was performed from the month of January to September 2022 based on the data provided by the sensors. In the graphs, the sensor positioned on the external side is labeled "External," while the sensor positioned on the inside side is labeled "Internal."

Position of Sensor (AIRCARE PRO)	% working hours (January)	% working hours (February)	% working hours (March)	% working hours (April)	% working hours (May)	% working hours (June)
External	0	42%	29%	25%	81%	
Internal	95%	78%	0	0	100%	

Position of Sensor (AIRCARE PRO)	% working hours (July)	% working hours (August)	% working hours (September)
External	29%	52%	20%
Internal	80%	87%	62%

The External and Internal sensors measure the following parameters:

- Air Temperature
- Relative Humidity
- Particulate Matter 2.5 (PM2.5)
- Particulate Matter 10 (PM10)
- Sound
- Volatile Organic Compounds (VOC)

6.2.1 Air Temperature

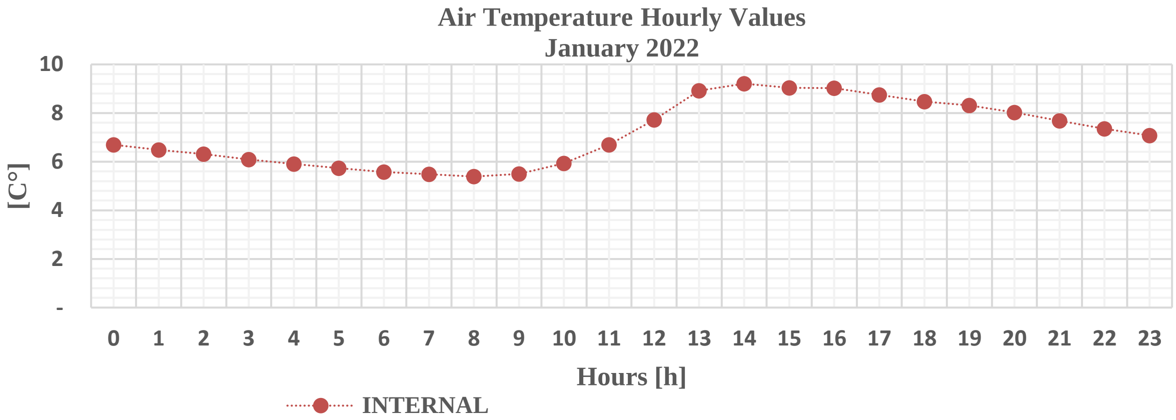


Figure 69: Air Temperature hourly values measured by AIRCARE PRO during January

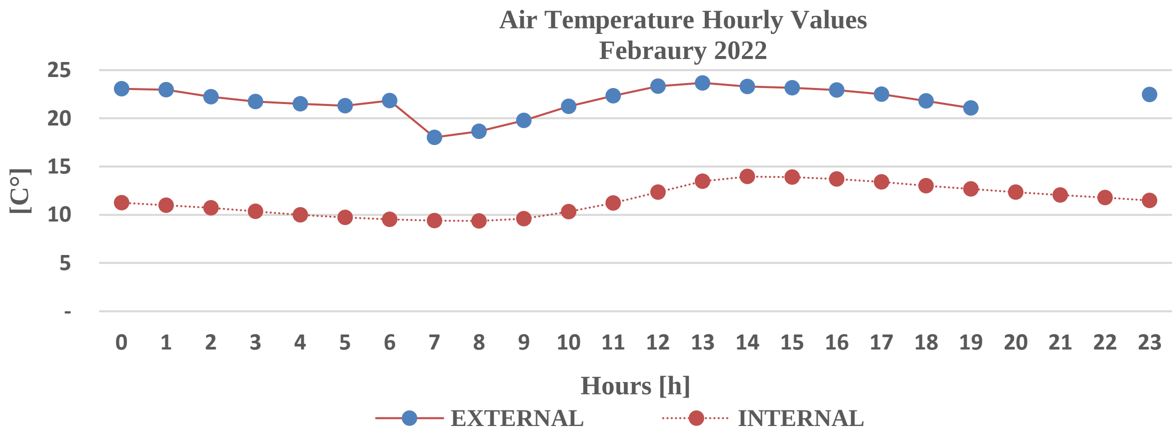


Figure 70: Air Temperature hourly values measured by AIRCARE PRO during February

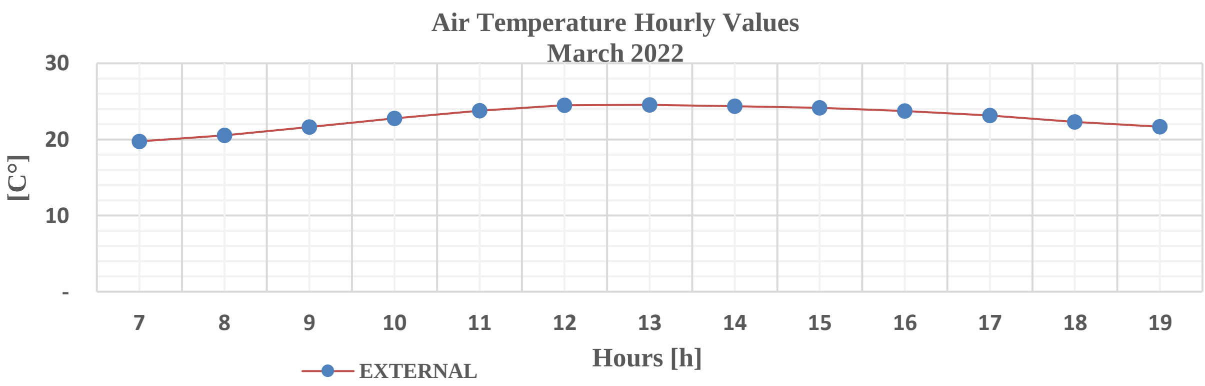


Figure 71: Air Temperature hourly values measured by AIRCARE PRO during March

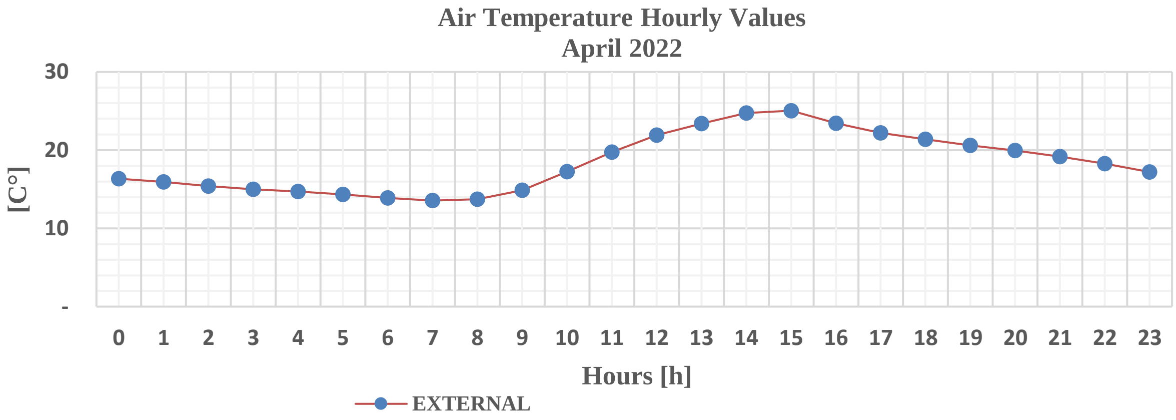


Figure 72: Air Temperature hourly values measured by AIRCARE PRO during April

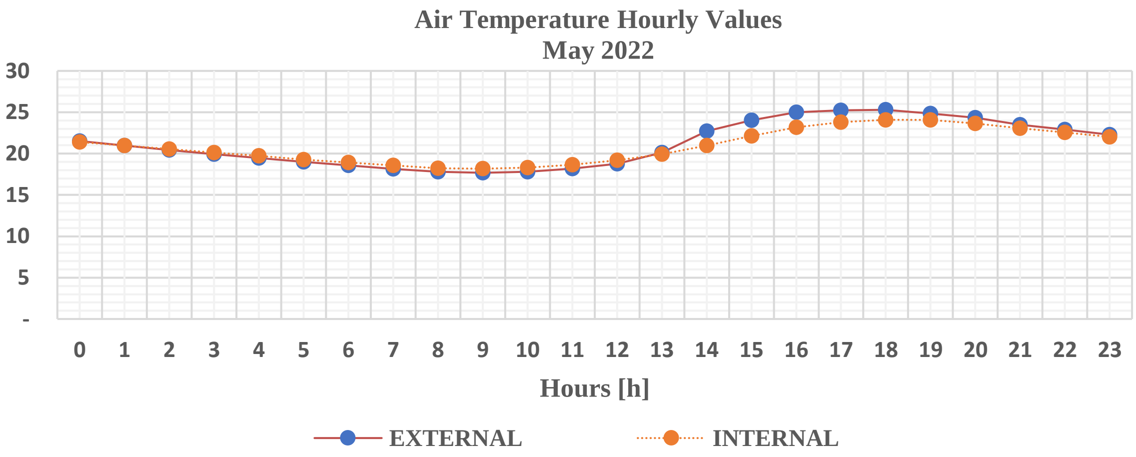


Figure 73: Air Temperature hourly values measured by AIRCARE PRO during May

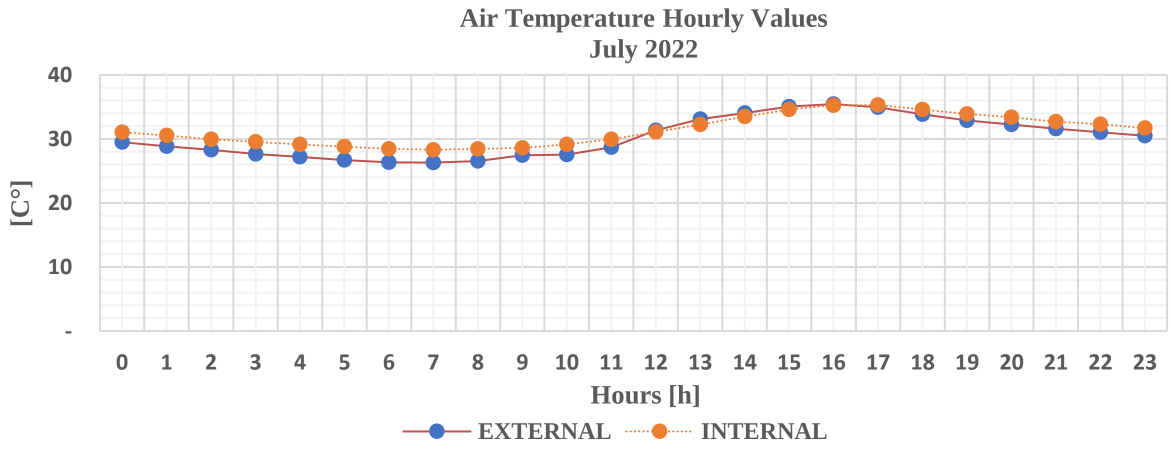


Figure 74: Air Temperature hourly values measured by AIRCARE PRO during July

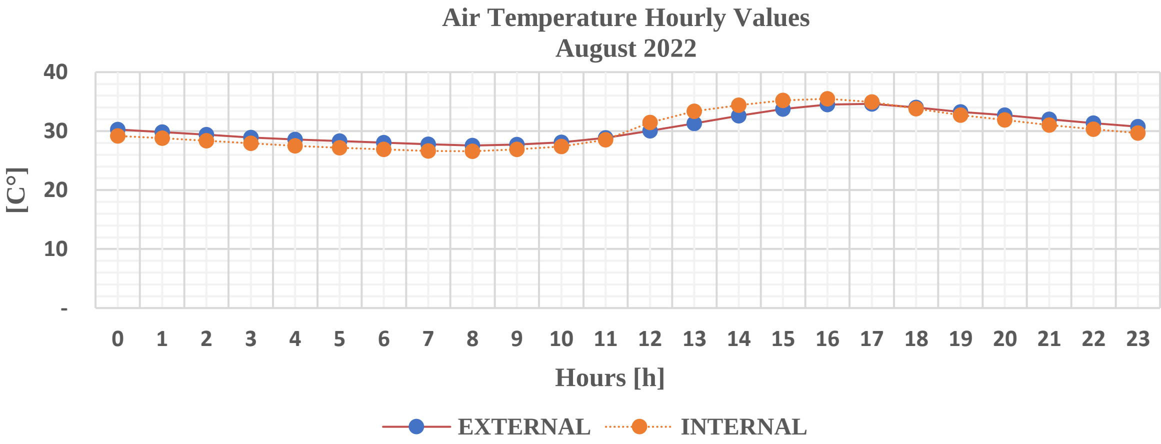


Figure 75: Air Temperature hourly values measured by AIRCARE PRO during August

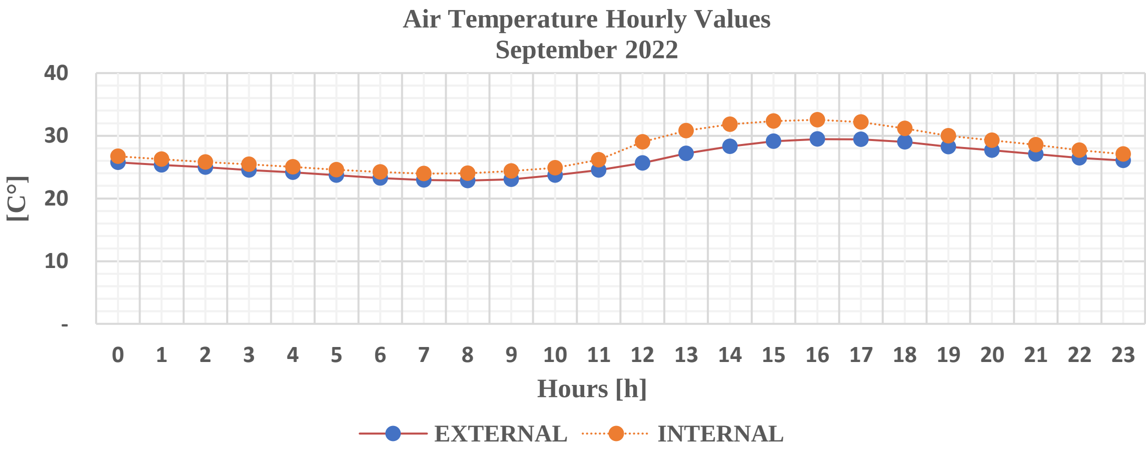


Figure 76: Air Temperature hourly values measured by AIRCARE PRO during September

- The values are based on data from January through September 2022.
- The external sensor records higher temperature values for the month of February while the internal and external sensors' hourly temperature readings for the months of May, July, and August are quite close.
- For the month of September, the trend is a little different, with greater midday temperatures recorded by the inside sensor than by the external sensor.
- The maximum temperature variation of approximately 14˚C was recorded during February compared to other months.

6.2.2 Relative Humidity

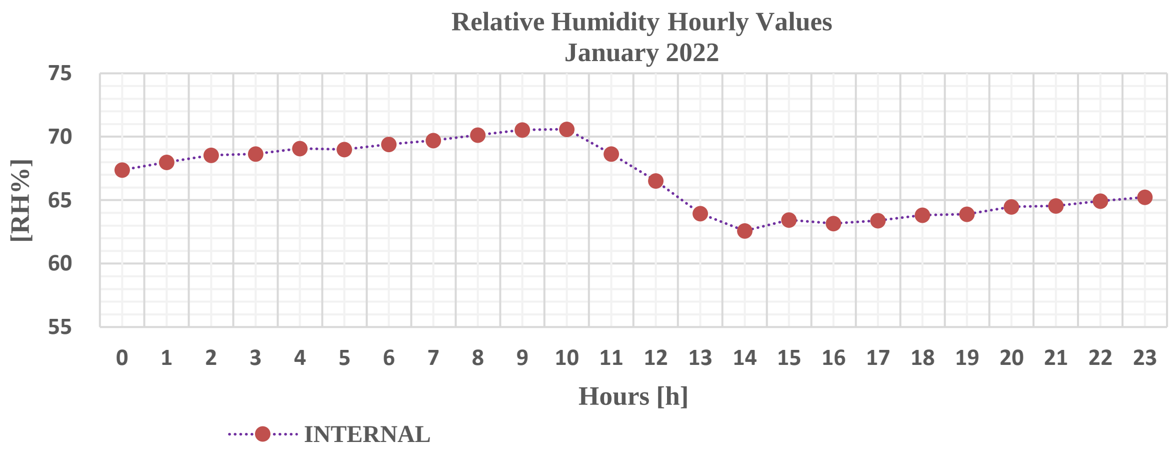


Figure 77: Relative Humidity hourly values measured by AIRCARE PRO during January

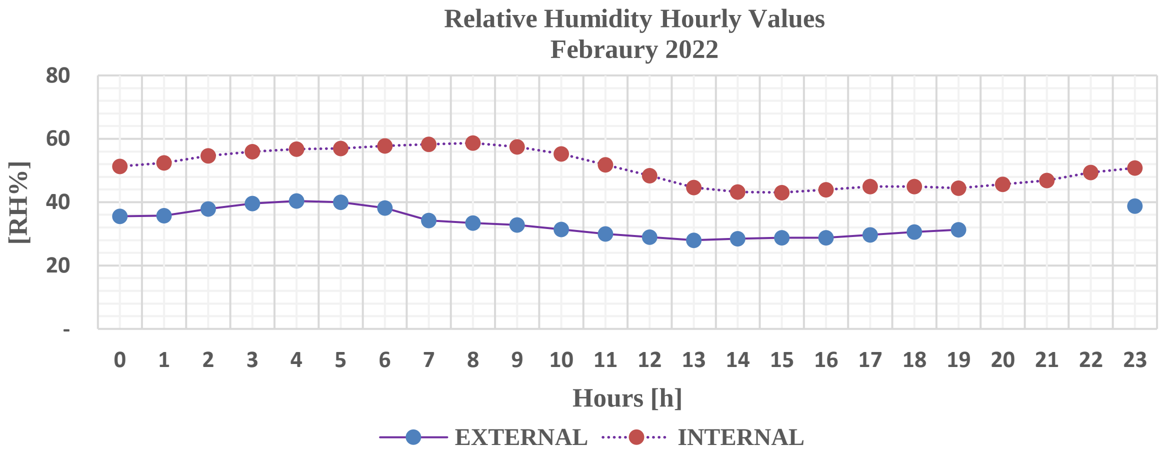


Figure 78: Relative Humidity hourly values measured by AIRCARE PRO during February

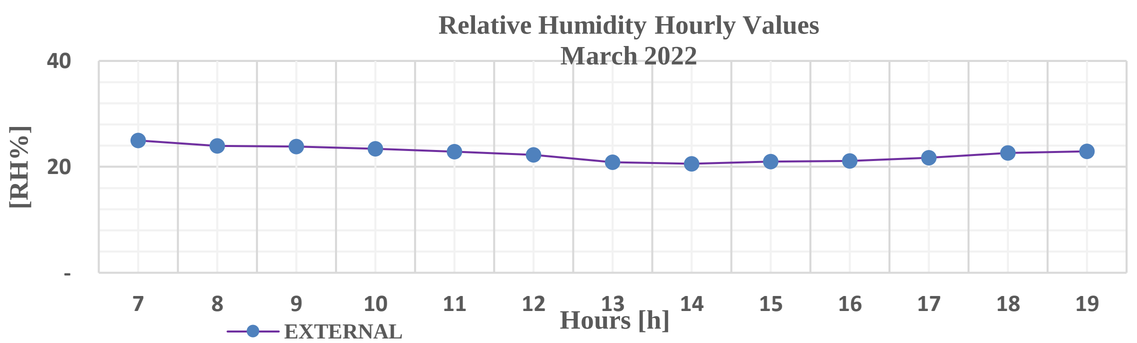


Figure 79: Relative Humidity hourly values measured by AIRCARE PRO during March

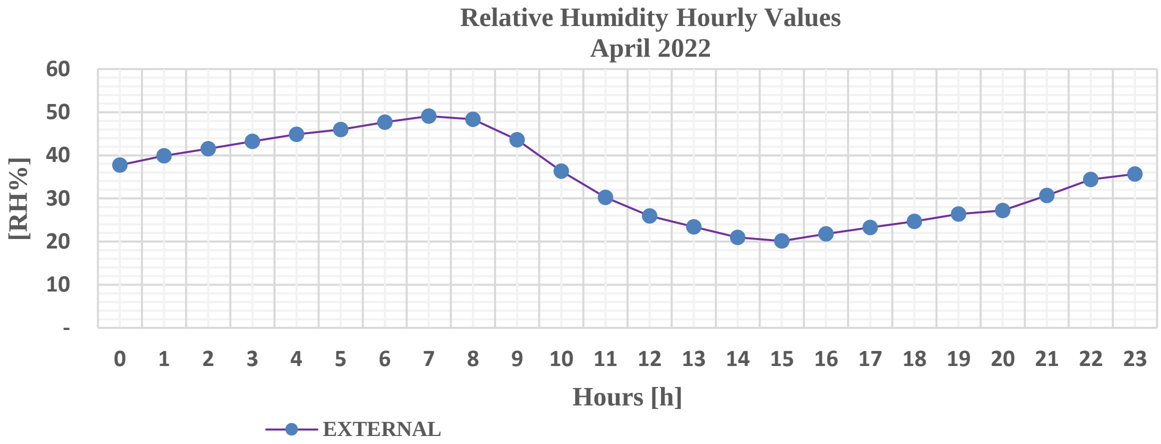


Figure 80: Relative Humidity hourly values measured by AIRCARE PRO during April

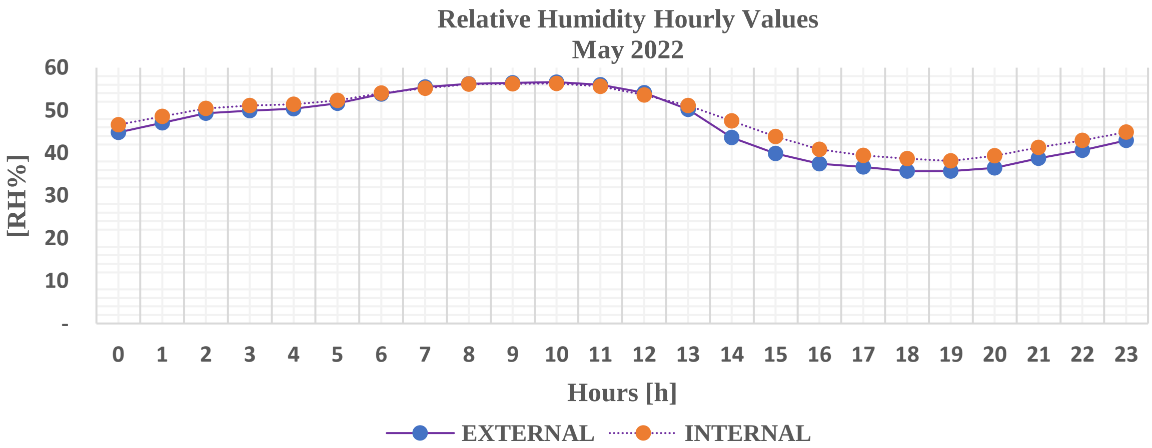


Figure 81: Relative Humidity hourly values measured by AIRCARE PRO during May

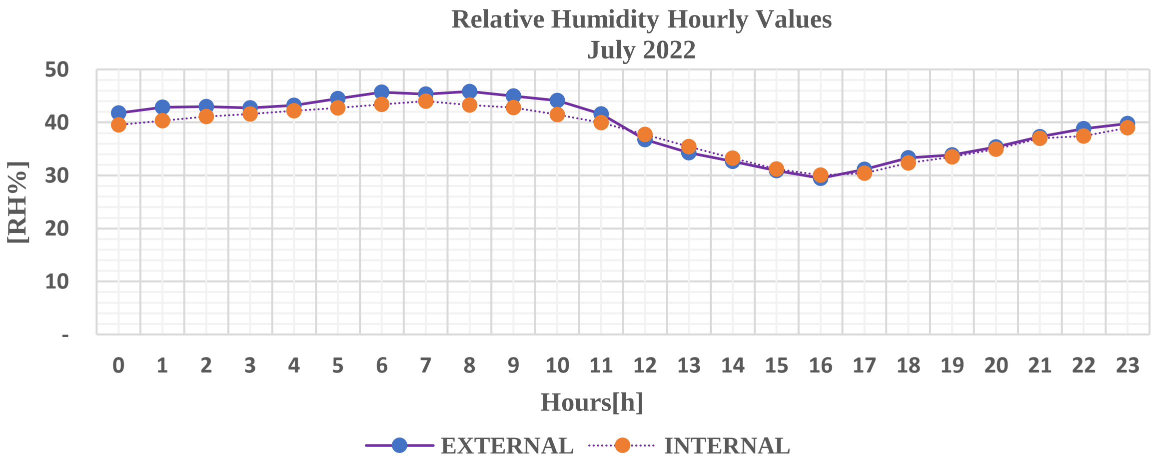


Figure 82: Relative Humidity hourly values measured by AIRCARE PRO during July

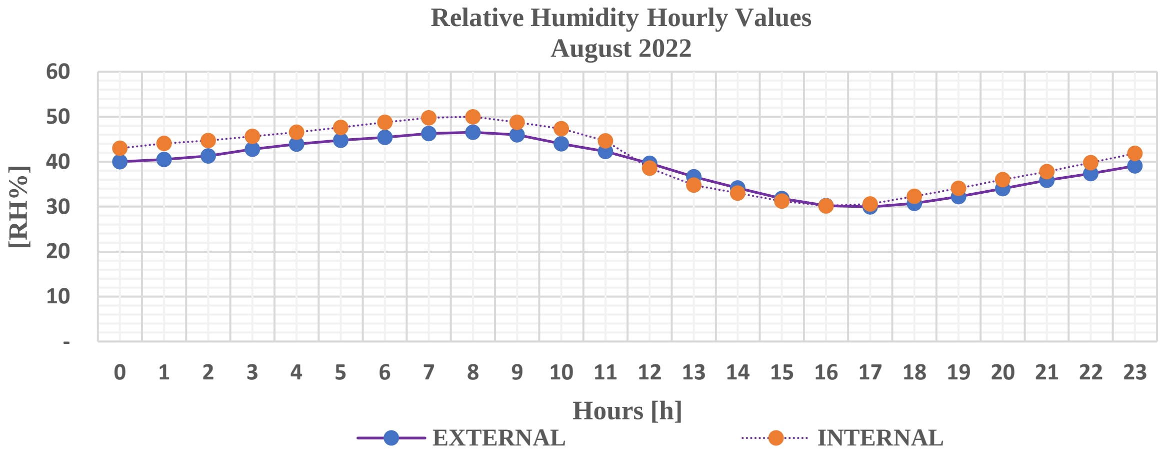


Figure 83: Relative Humidity hourly values measured by AIRCARE PRO during August

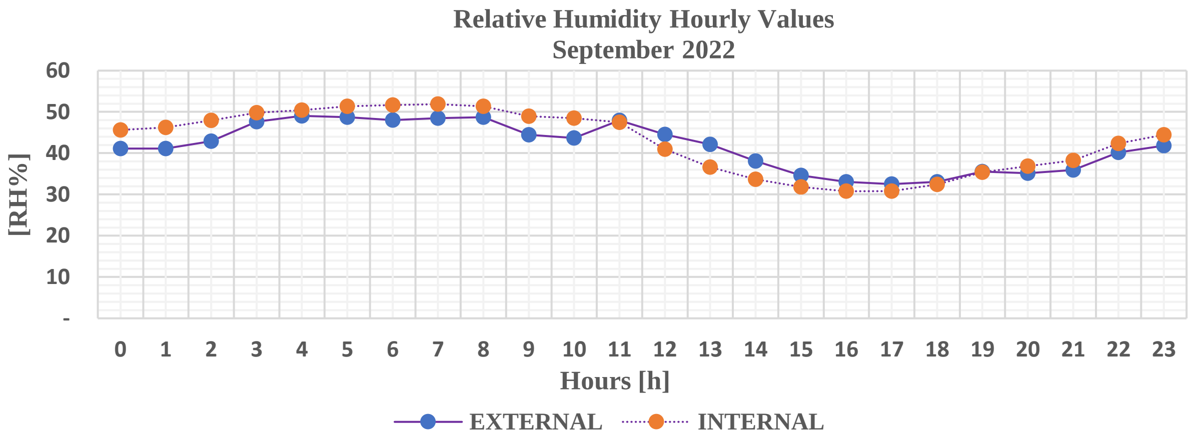


Figure 84: Relative Humidity hourly values measured by AIRCARE PRO during September

- The inside sensor's readings of relative humidity for the month of February are higher than those from the external one. The difference between the internal and exterior sensors is 30.7%.
- The readings recorded by both internal and external sensors for the months of May, July, August, and September exhibit a similar pattern. In the morning, the relative humidity rises, peaking at an average maximum of almost 49%. The value starts to rise in the late afternoon after experiencing a decrease in the morning.

6.2.3 Particulate Matter (PM) 2.5

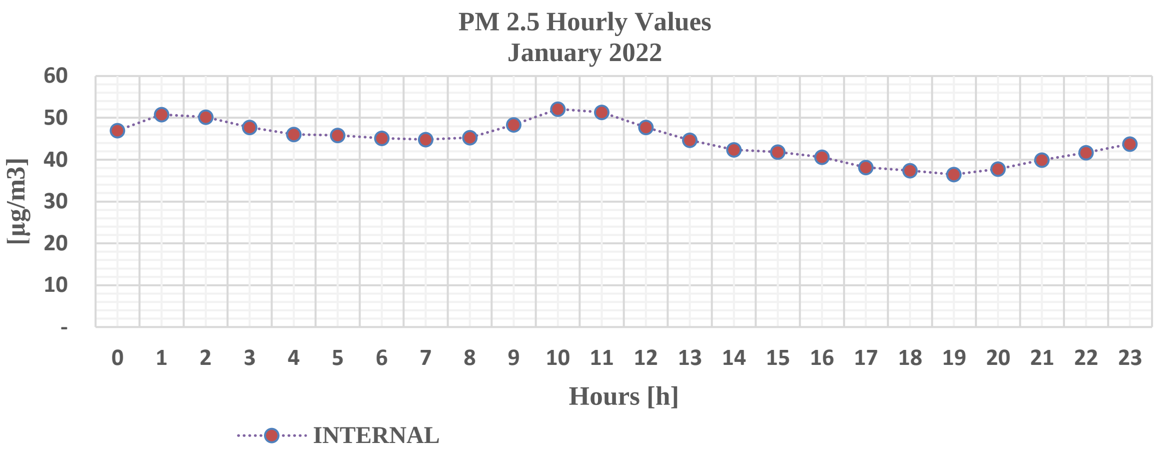


Figure 85: PM 2.5 hourly values measured by AIRCARE PRO during January

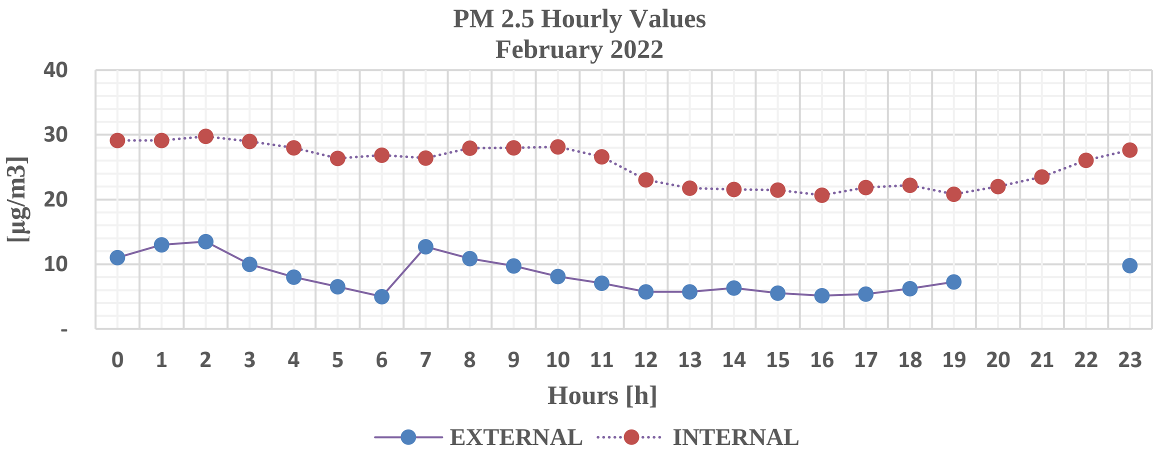


Figure 86: PM 2.5 hourly values measured by AIRCARE PRO during February

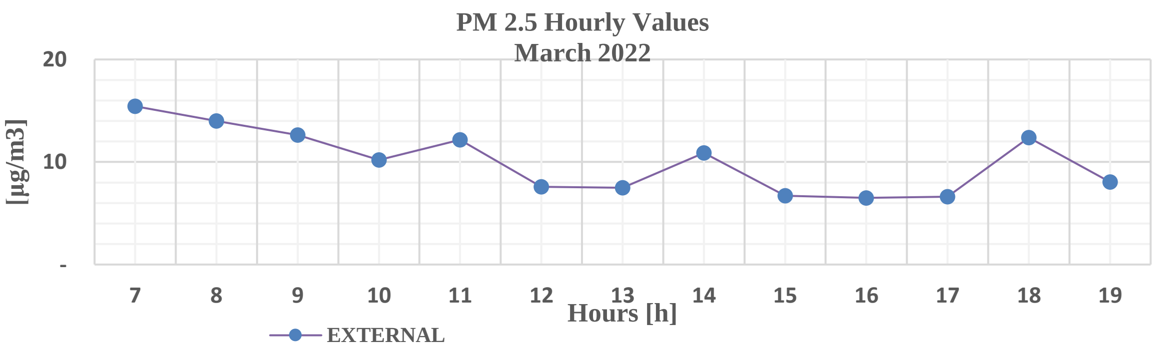


Figure 87: PM 2.5 hourly values measured by AIRCARE PRO during March

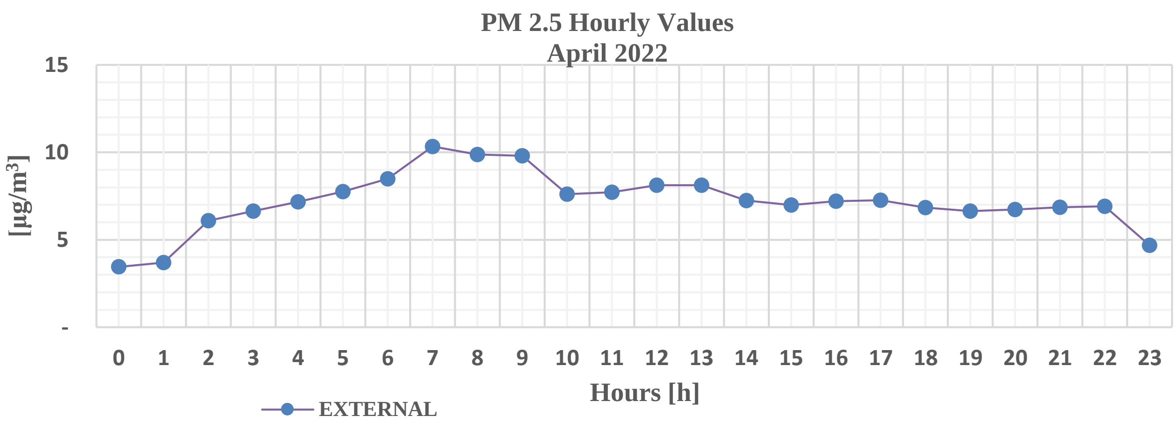


Figure 88: PM 2.5 hourly values measured by AIRCARE PRO during April

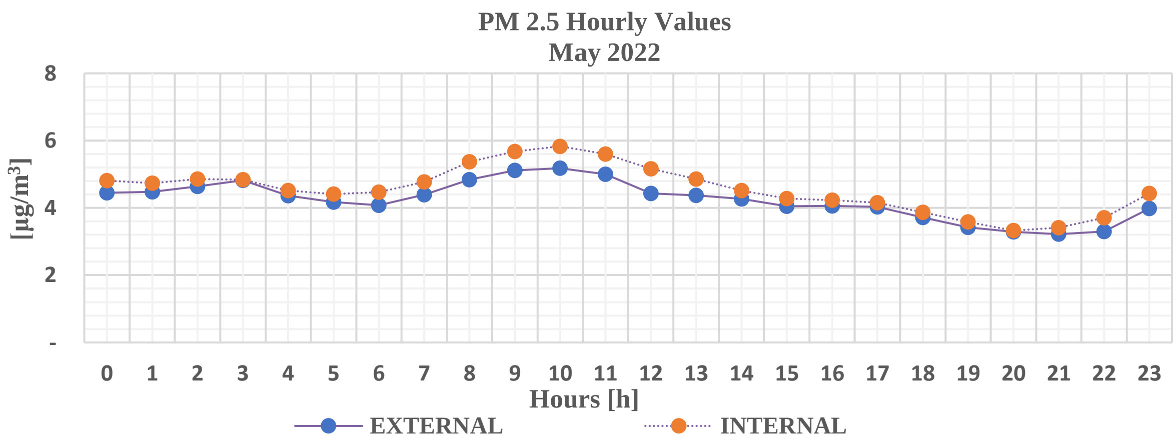


Figure 89: PM 2.5 hourly values measured by AIRCARE PRO during May

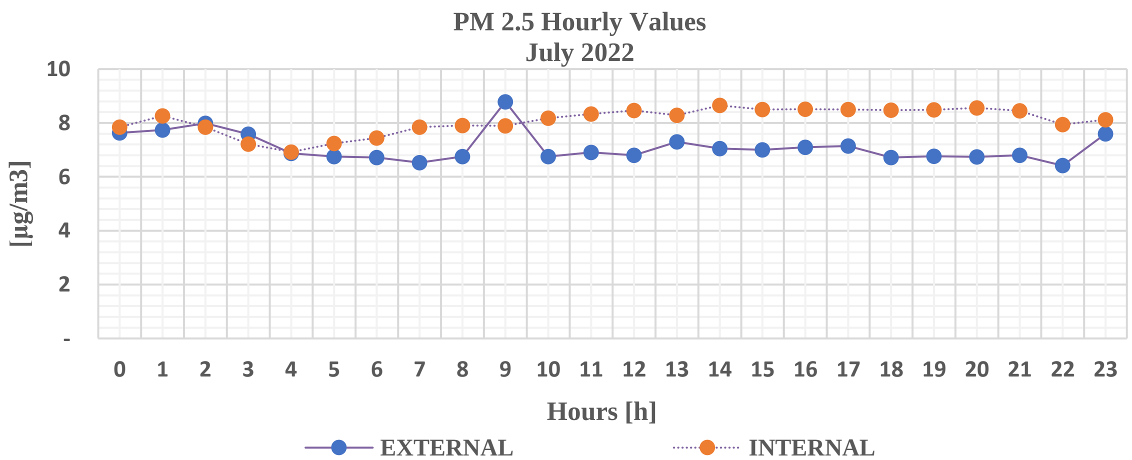


Figure 90: PM 2.5 hourly values measured by AIRCARE PRO during July

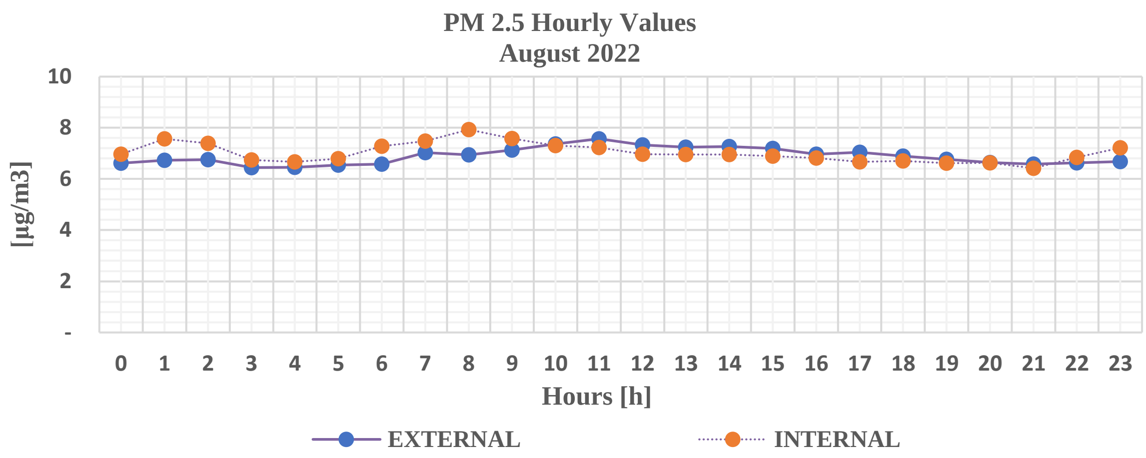


Figure 91: PM 2.5 hourly values measured by AIRCARE PRO during August

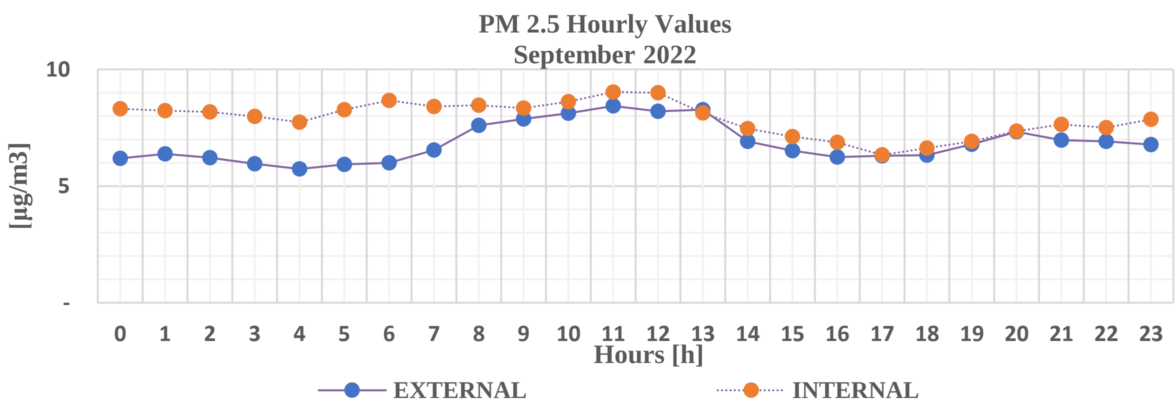


Figure 92: PM 2.5 hourly values measured by AIRCARE PRO during September

- With the internally located sensor, the maximum PM2.5 readings were achieved in the wintertime in the month of February. A peak value of about 28 µg/m^3 on average was reached during morning hours.
- An anomaly is discovered for the month of July at 9am, when the peak value of 8.79 µg/m^3 was recorded using an outside placed sensor as opposed to an inside one. Higher readings of particle matter are recorded from the internally situated sensor in addition to reaching peak at nine in the morning.
- The curve derived from the data of both sensors for the months of May and August displays a similar pattern. However, the highest levels of PM2.5 are measured between the hours of 7 and 11 in the morning.

- The internally situated sensor records greater readings for September. The PM2.5 concentration gradually increases from 7 to 12 in the morning before rapidly declining at the end of the day.

6.2.4 Particulate Matter (PM) 10

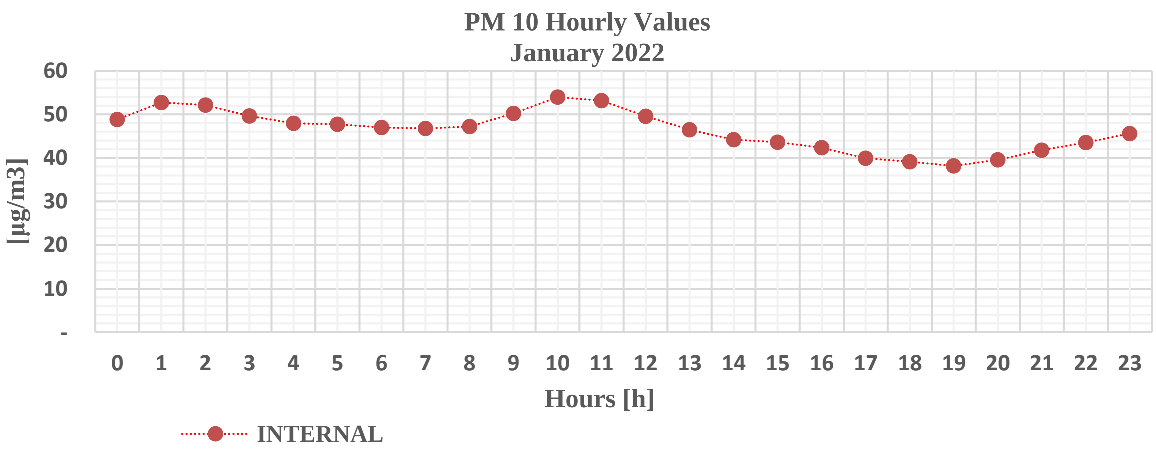


Figure 93: PM 10 hourly values measured by AIRCARE PRO during January

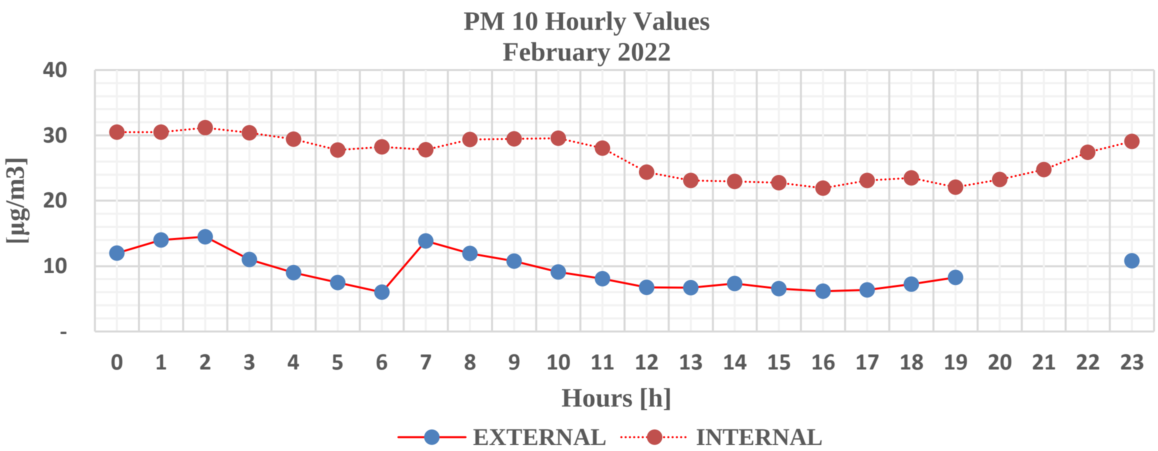


Figure 94: PM 10 hourly values measured by AIRCARE PRO during February

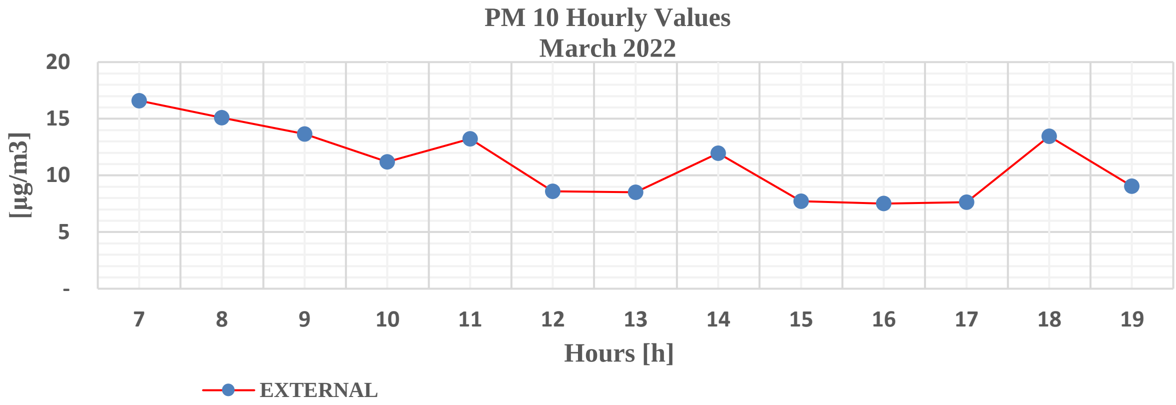


Figure 95: PM 10 hourly values measured by AIRCARE PRO during March

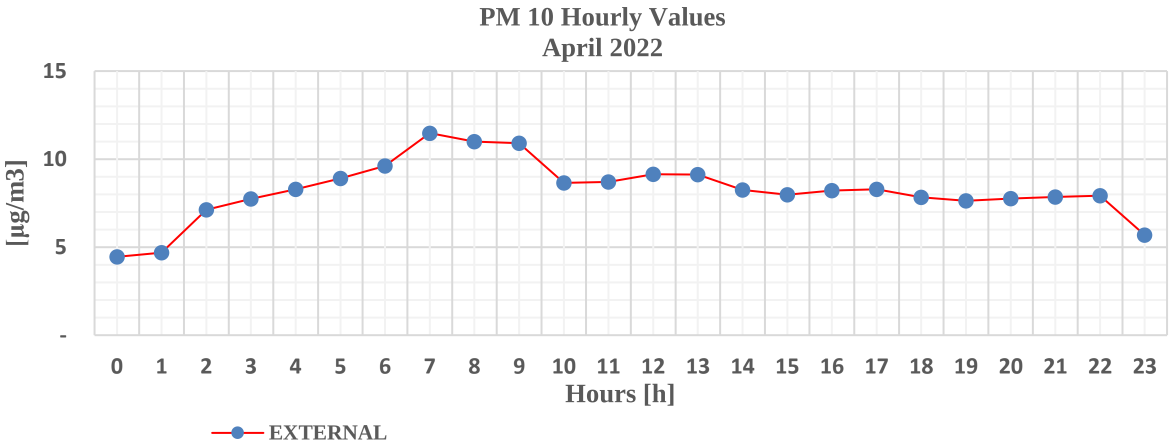


Figure 96: PM 10 hourly values measured by AIRCARE PRO during April

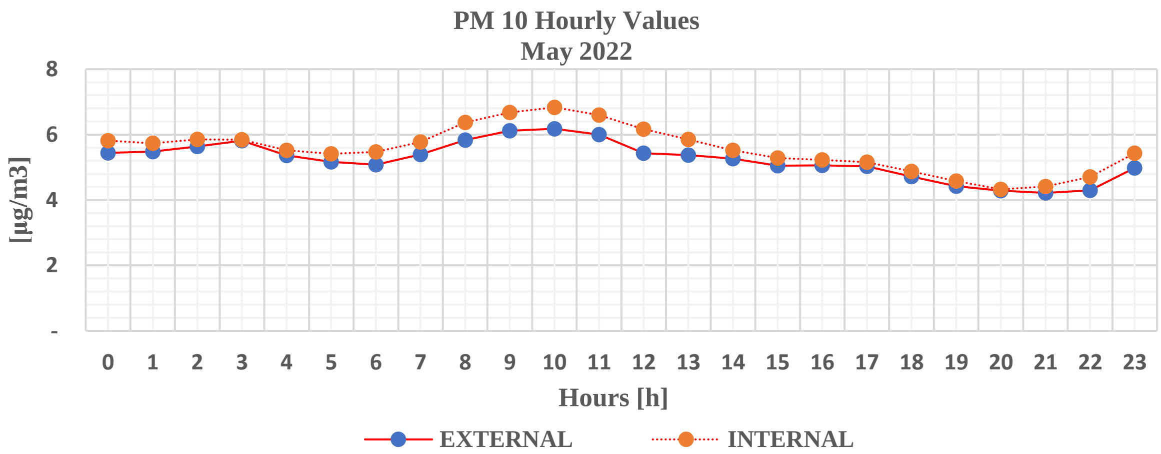


Figure 97: PM 10 hourly values measured by AIRCARE PRO during May

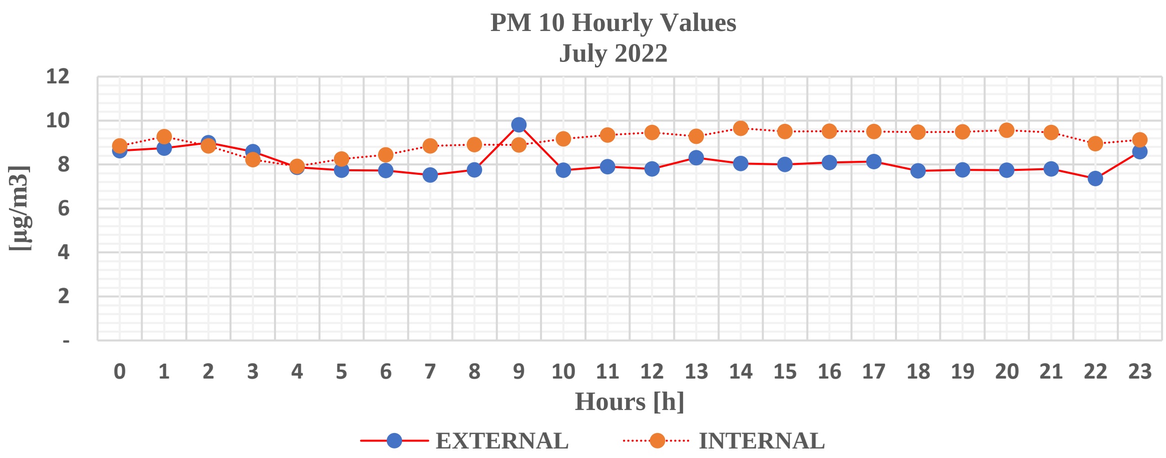


Figure 98: PM 10 hourly values measured by AIRCARE PRO during July

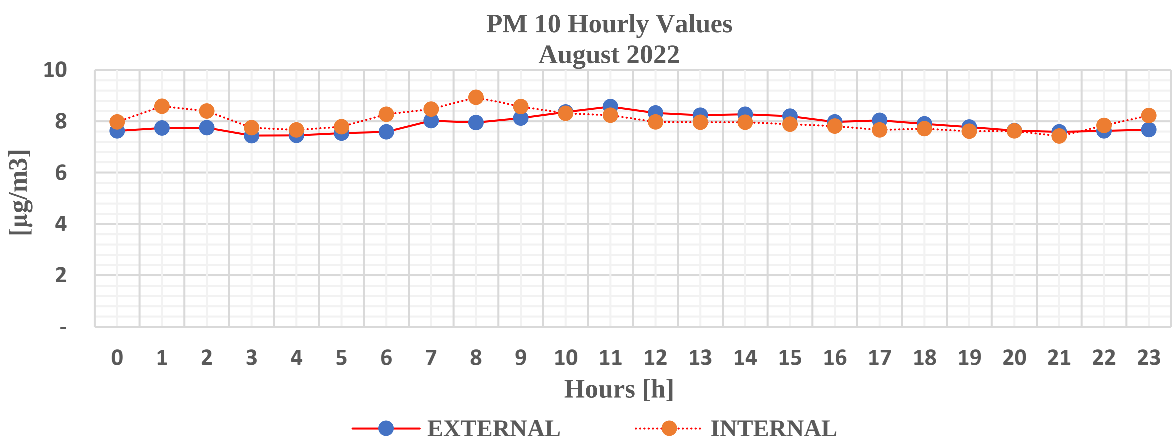


Figure 99: PM 10 hourly values measured by AIRCARE PRO during August

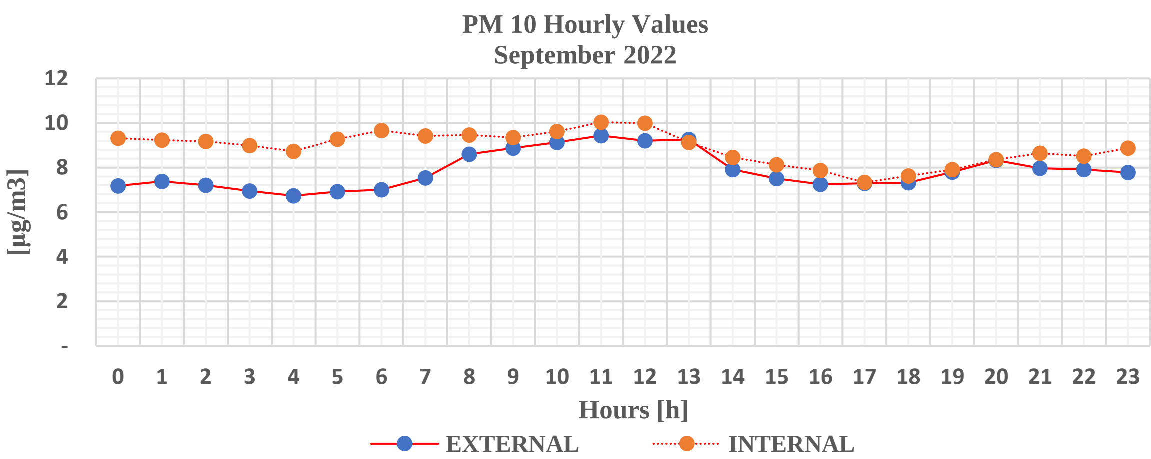


Figure 100: PM 10 hourly values measured by AIRCARE PRO during September

- The internally positioned sensor consistently recorded elevated PM10 readings from January through September 2022. From the available data, the highest value was recorded at 31.17 μg/m^3 noted in the month of February.
- The months of May, August and September show a typical pattern of higher PM10 levels in the morning and a minor decline towards the evening.
- When compared to an internally positioned sensor, an externally located sensor specifically for the month of July at 9 AM displays a higher value with a peak of 9.80 μg/m^3.

6.2.5 Sound

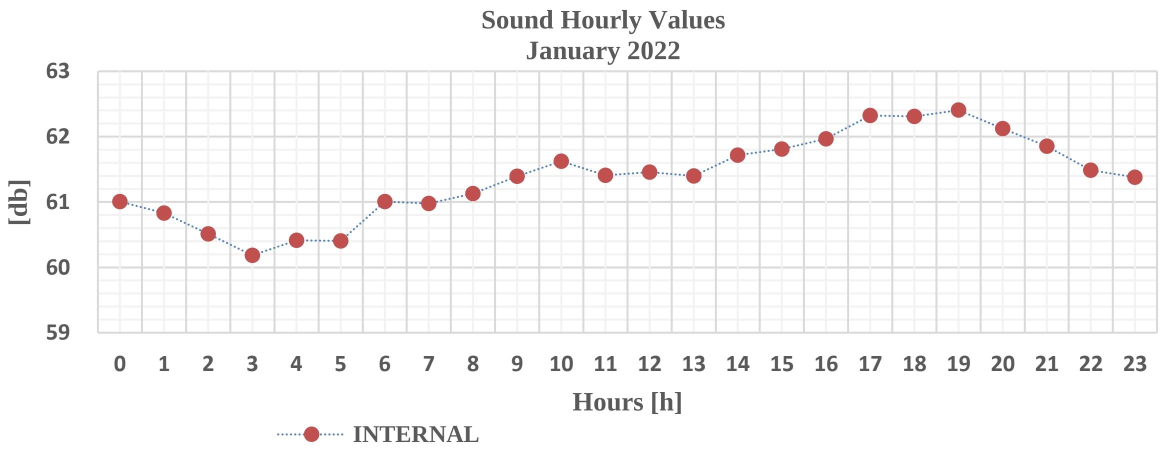


Figure 101: Sound hourly values measured by AIRCARE PRO during January

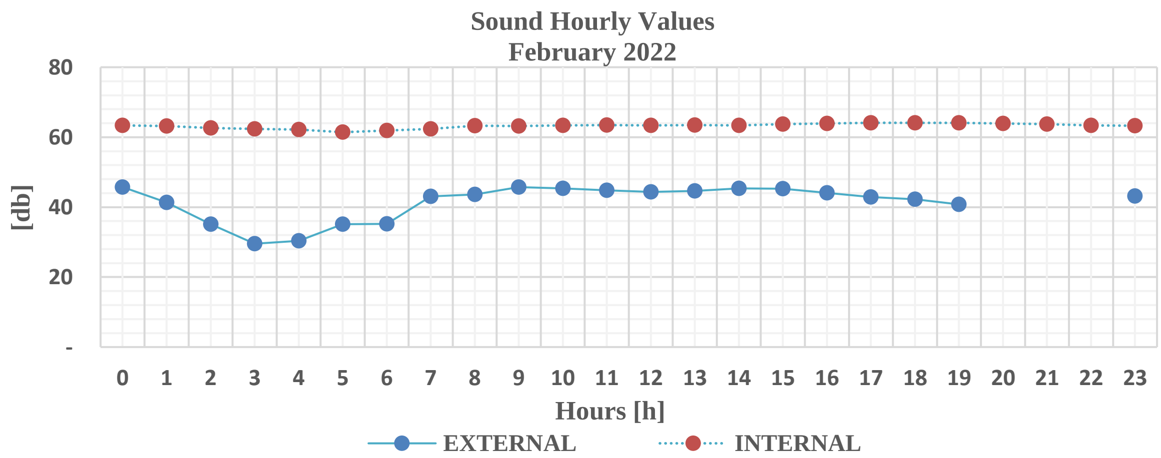


Figure 102: Sound hourly values measured by AIRCARE PRO during February

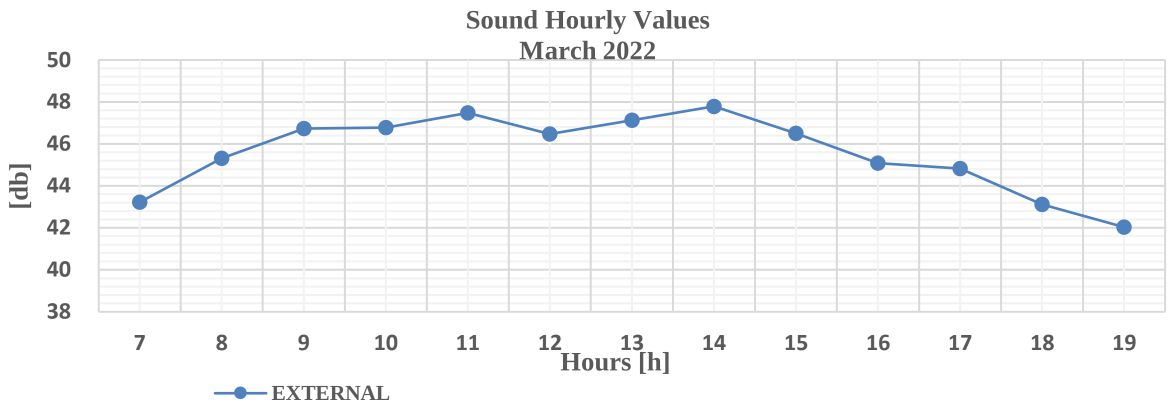


Figure 103: Sound hourly values measured by AIRCARE PRO during March

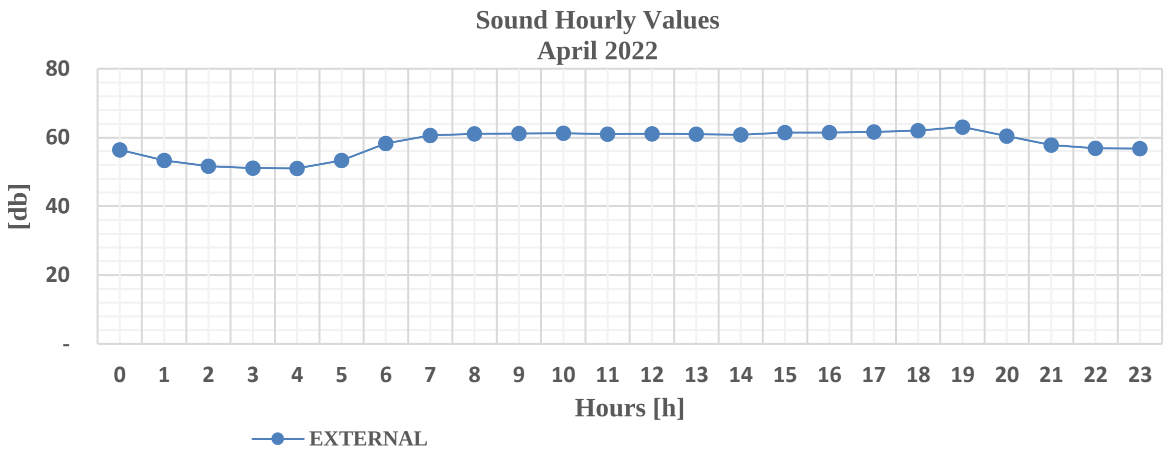


Figure 104: Sound hourly values measured by AIRCARE PRO during April

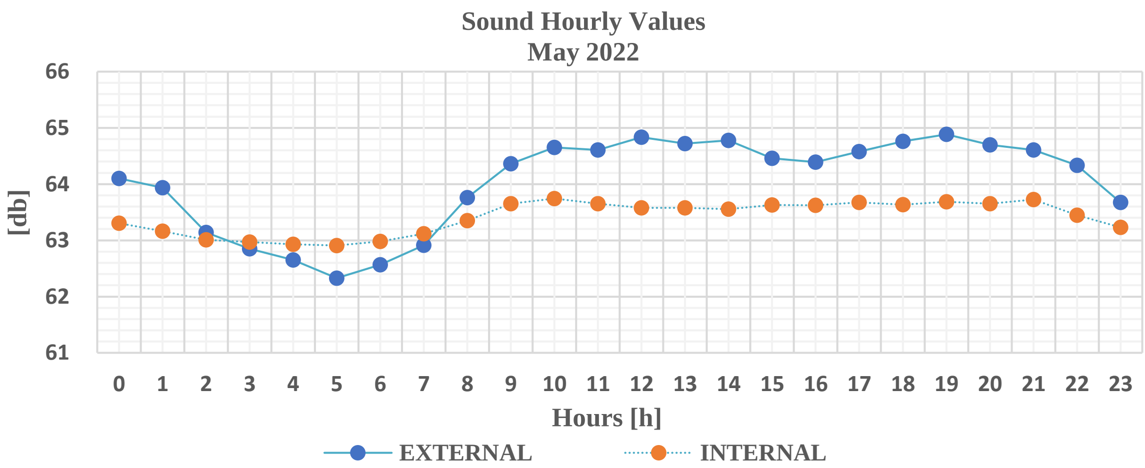


Figure 105: Sound hourly values measured by AIRCARE PRO during May

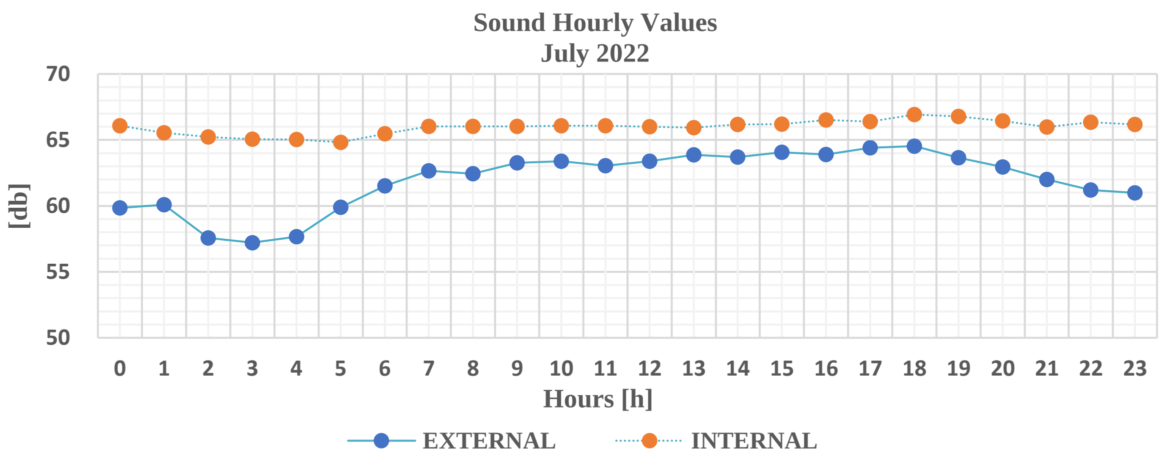


Figure 106: Sound hourly values measured by AIRCARE PRO during July

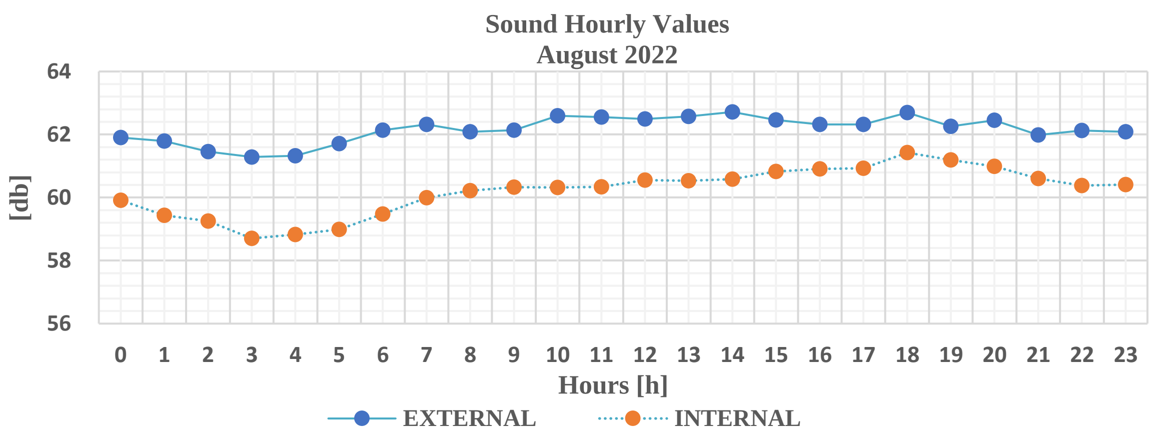


Figure 107: Sound hourly values measured by AIRCARE PRO during August

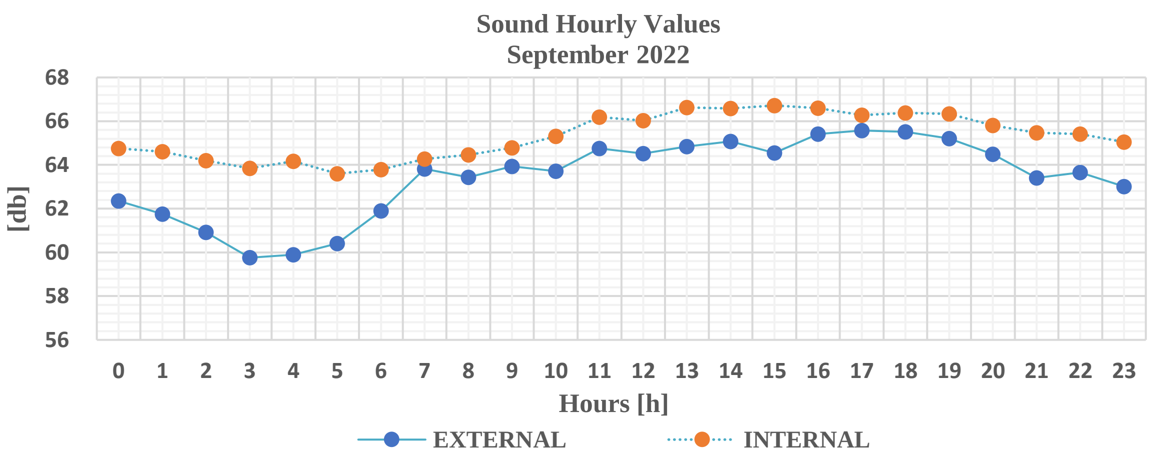


Figure 108: Sound hourly values measured by AIRCARE PRO during September

- The hourly measurements recorded by the internal sensor for the month of February looked to be higher than those recorded by the externally placed sensor.
- The hourly measurements taken by the internal sensor are lower than those taken by the external sensor during the months of May and August.
- Higher values are recorded for the outside mounted sensor for the months of July and September. The sound is captured at its highest levels between the hours of 8:00 in the morning and 19:00 in the evening.

6.2.6 Volatile organic compound (VOC)

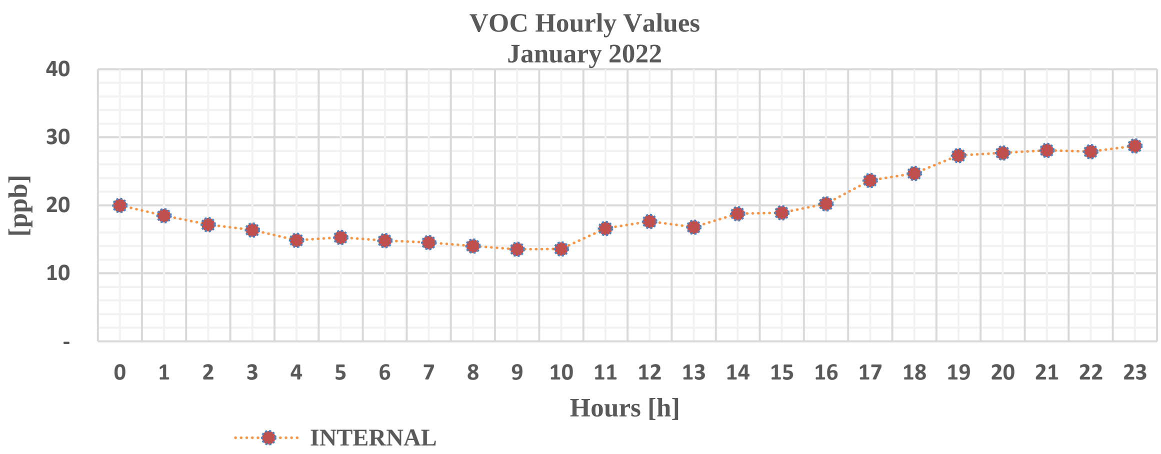


Figure 109: VOC hourly values measured by AIRCARE PRO during January

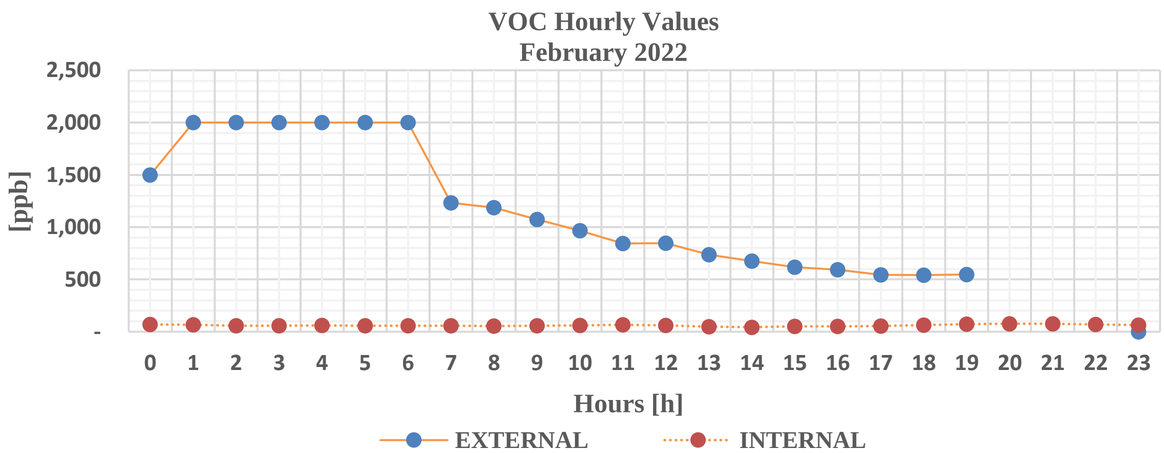


Figure 110: VOC hourly values measured by AIRCARE PRO during February

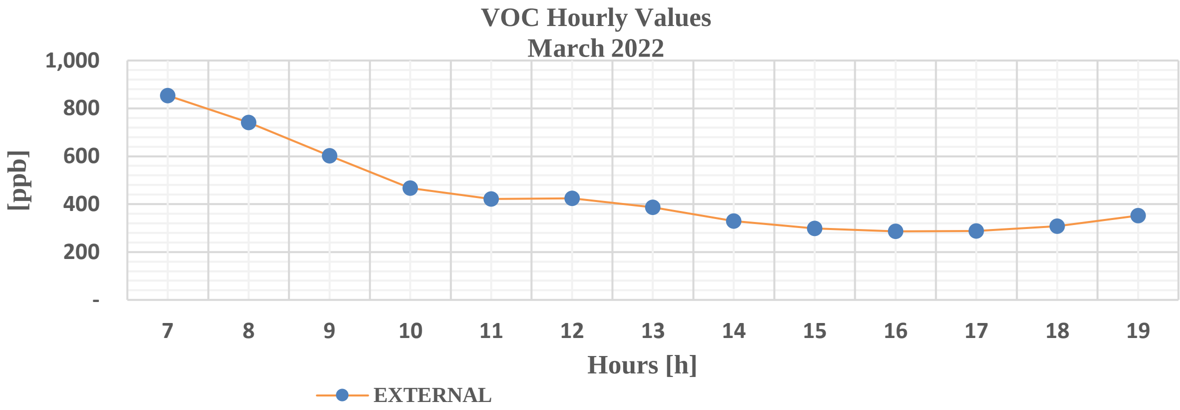


Figure 111: VOC hourly values measured by AIRCARE PRO during March

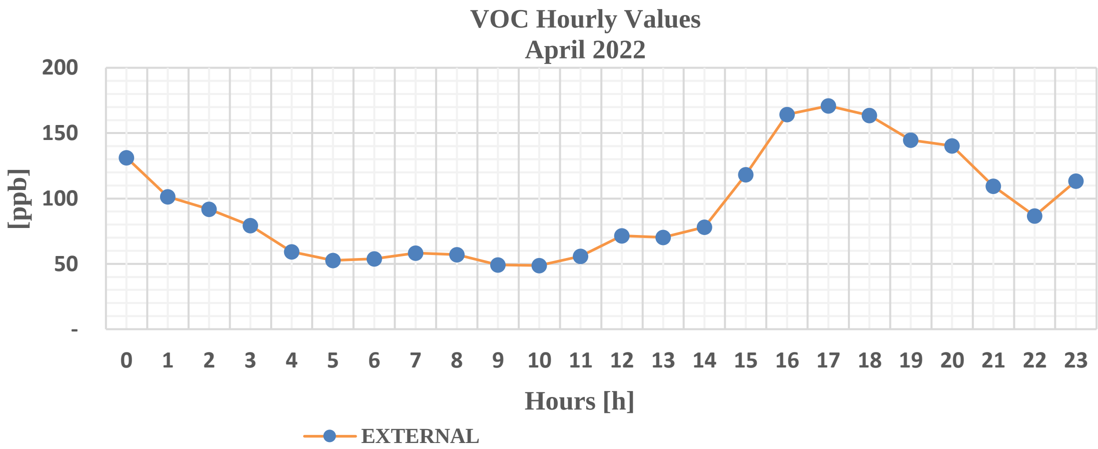


Figure 112: VOC hourly values measured by AIRCARE PRO during April

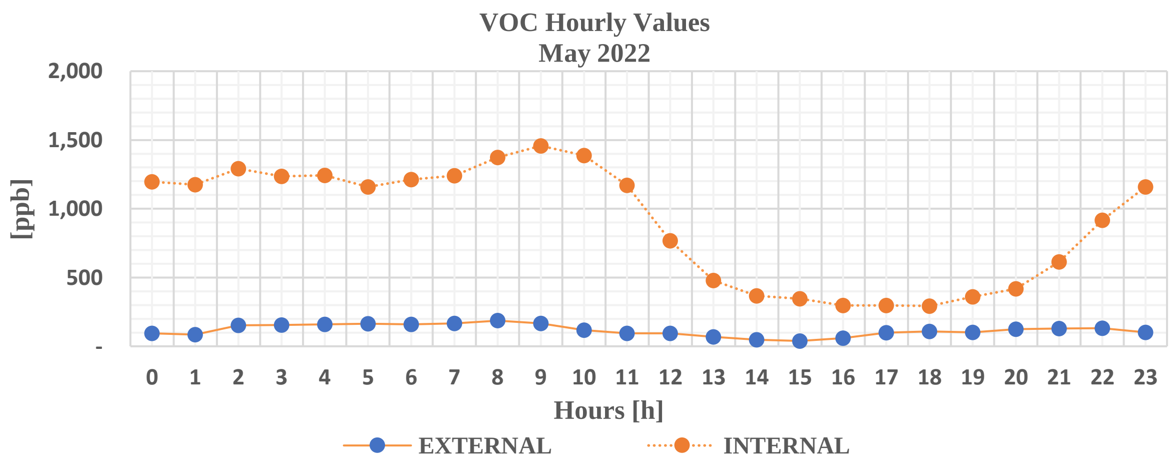


Figure 113: VOC hourly values measured by AIRCARE PRO during May

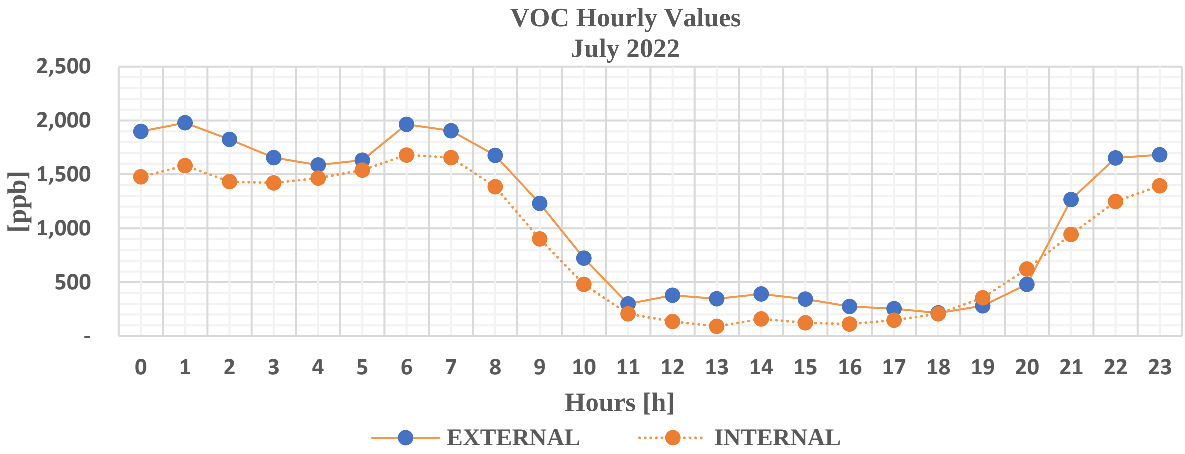


Figure 114: VOC hourly values measured by AIRCARE PRO during July

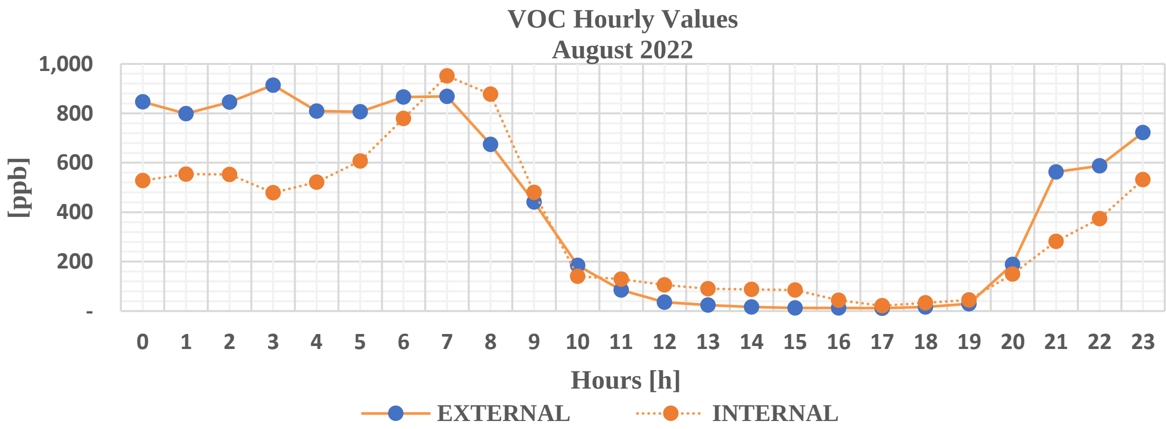


Figure 115: VOC hourly values measured by AIRCARE PRO during August

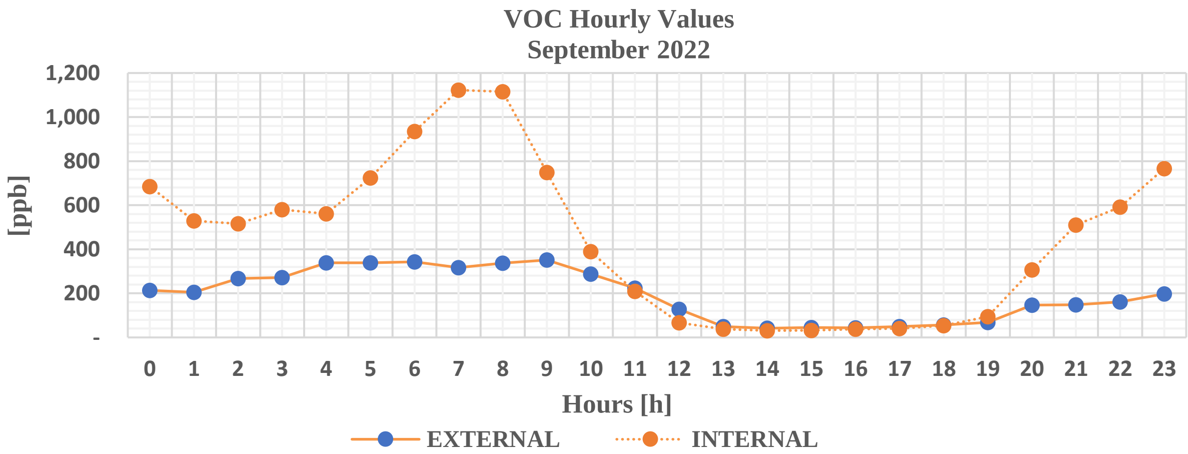


Figure 116: VOC hourly values measured by AIRCARE PRO during September

- When compared to the inside sensor, the external sensor recorded greater readings during the month of February. The external sensor's peak was captured between 1:00 and 6:00. The internal sensor's values were observed to be constant.
- Volatile organic compound measurements taken by internal sensors are greater in May than those taken by external ones. The readings quickly increase in the morning, then quickly decline as the day progresses. The external sensor's output curve exhibits a consistent trend from the beginning to the end.
- Similar patterns are observed throughout the months of July and August, with the highest values being recorded early in the day by both internal and external sensors. An exterior sensor records the peak value for July at 1964.31 ppb at 6:00 in the morning, but an internal sensor records the peak value for August at 951.31 ppb at 7:00 in the morning.
- According to data from an internal sensor for the month of September, the VOC rises from 5:00 to 9:00 in the morning before experiencing a significant decline in the middle of the day. From 12:00 p.m. to 19:00 p.m., the curve derived from the values captured by the external sensor intercepts the curve of the external sensor.

6.3 Case Study 3- Nicosia, Cyprus:

One sensor is situated at the front (Internal) of the green panel in Nicosia, Cyprus, and the second one is installed at the back (External) of the panel. The sensor, called AIRCARE PRO+, offers hourly measurements for several environmental variables. From January 2022 until June 2022, observations are made available by sensors. Environmental monitoring by sensors has generally focused on the detection and measurement of contaminant concentrations and identifying when contaminants have dissipated to levels that no longer pose a public health risk. Monitoring approaches assess the chemical, physical, radiological, and biological properties of air. More recently, the focus area of environmental monitoring has expanded beyond contamination detection to include noise pollution, solar radiation levels, and ambient urban conditions.

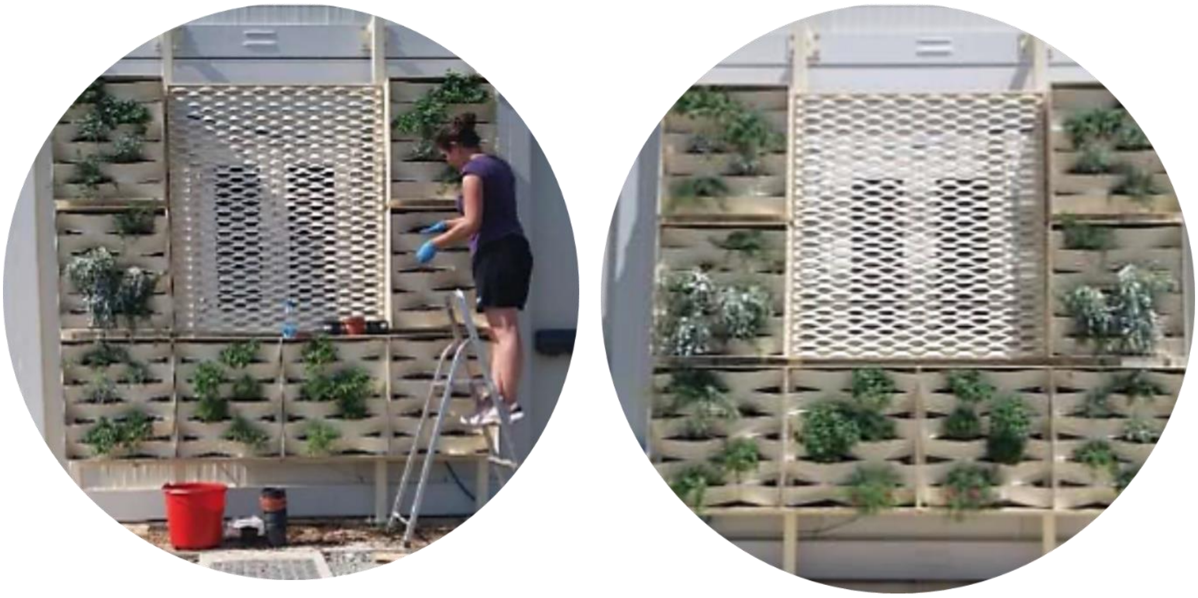


Figure 117: Installation of Green panels in Cyprus Institute

For each of the month, starting from January 1, 2022, to June 14, 2022, the sensor AIRCARE PRO+ has provided the hourly values of the following parameters:

- Air Temperature
- Relative Humidity
- PM2.5 and PM10
- Sound
- TVOC
- Air Quality
- Concentration of CO_2
- Indoor air quality

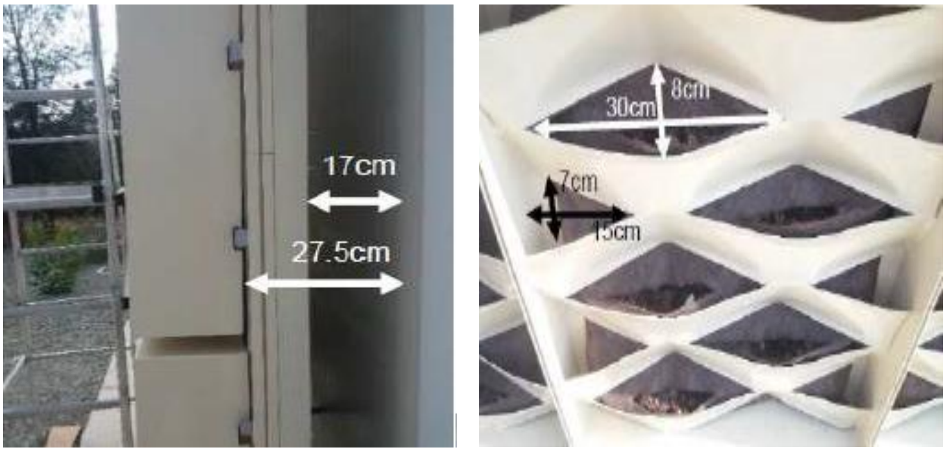


Figure 118: Spacing of the Green panel with respect to the wall and mesh

6.3.1 Air Temperature

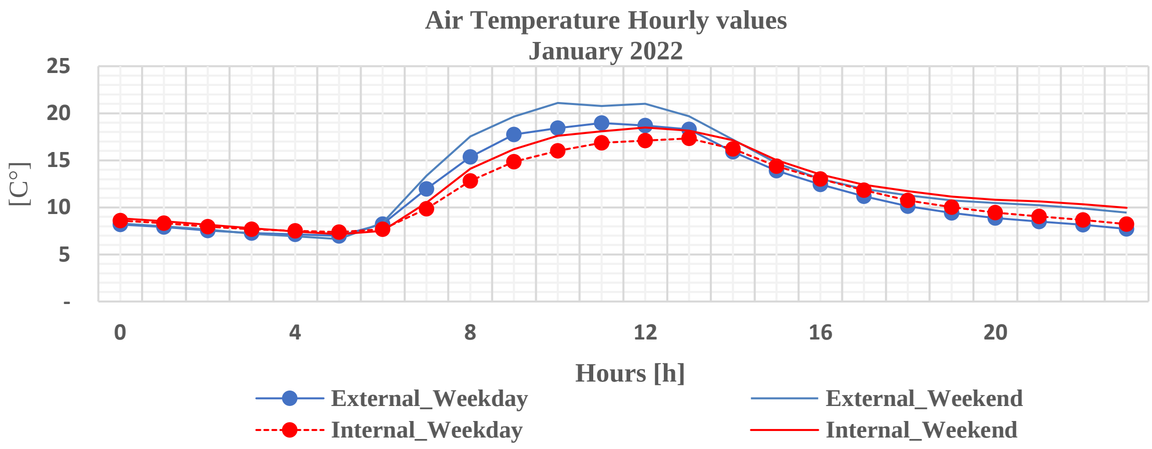


Figure 119: Air Temperature hourly values measured by AIRCARE PRO+ during January

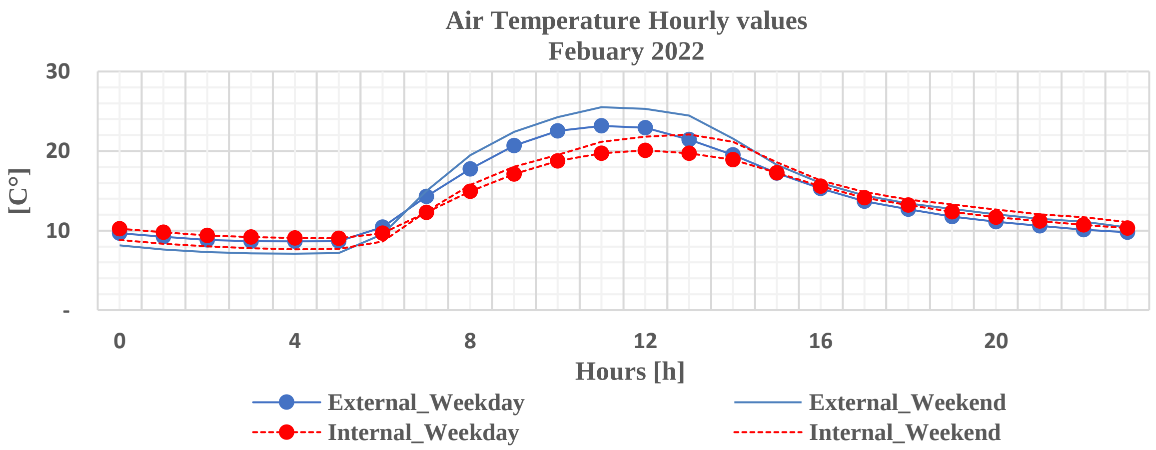


Figure 120: Air Temperature hourly values measured by AIRCARE PRO+ during February

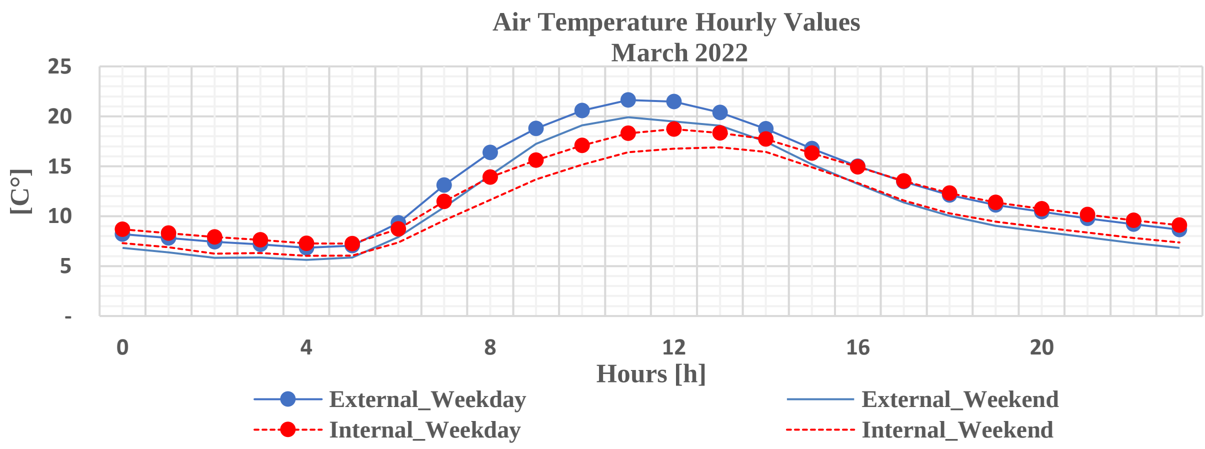


Figure 121: Air Temperature hourly values measured by AIRCARE PRO+ during March

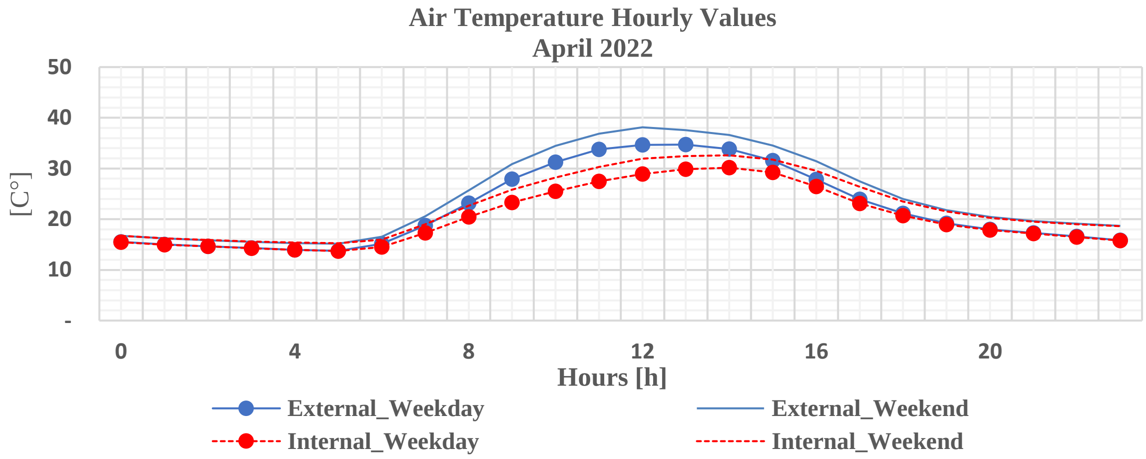


Figure 122: Air Temperature hourly values measured by AIRCARE PRO+ during April

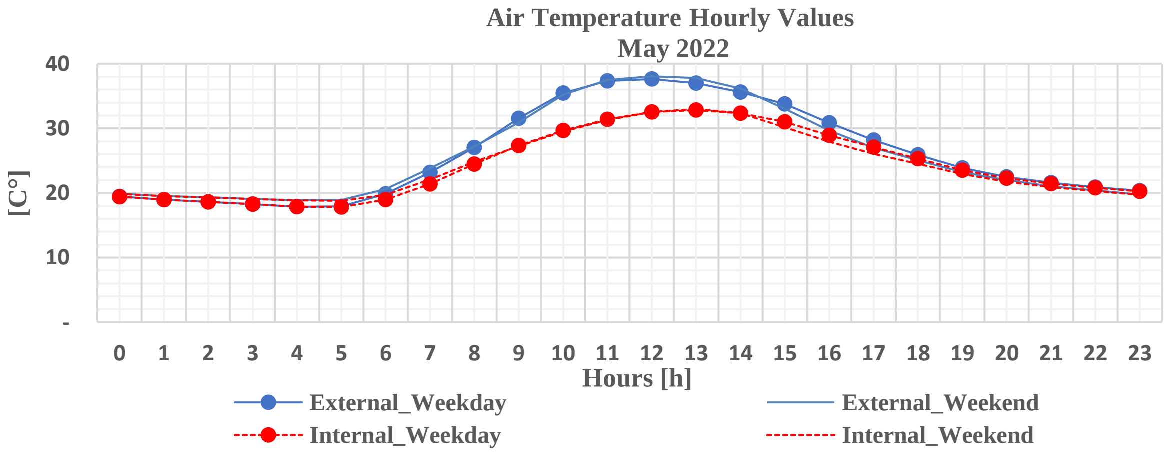


Figure 123: Air Temperature hourly values measured by AIRCARE PRO+ during May

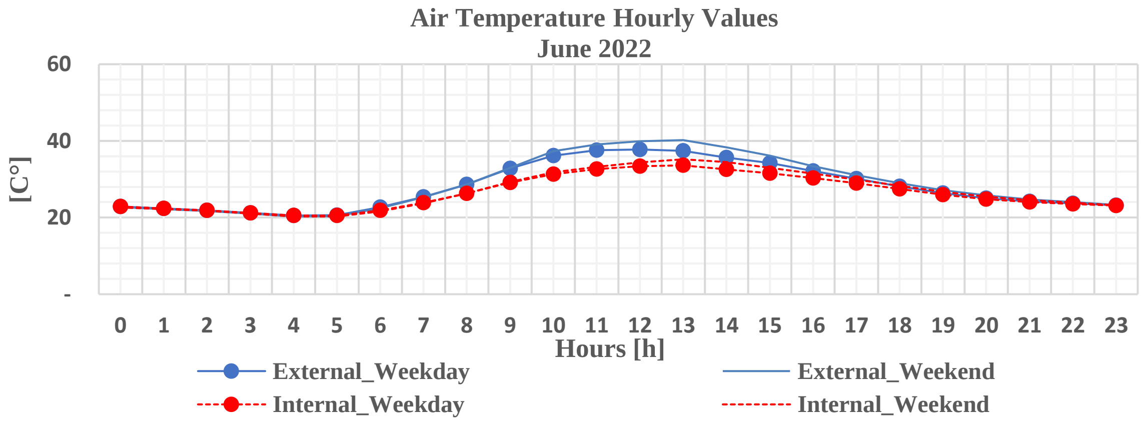


Figure 124: Air Temperature hourly values measured by AIRCARE PRO+ during June

- On both weekdays and weekends, the hourly air temperature values recorded by the external sensor are observed to be greater than those recorded by the interior sensor.
- The weekend in June saw the highest temperature ever recorded by the external sensor, which was 40.12˚C (Figure 124).
- Between the external and interior sensors, the air temperature varies by around 5°C from January to June 2022.

6.3.2 Relative Humidity

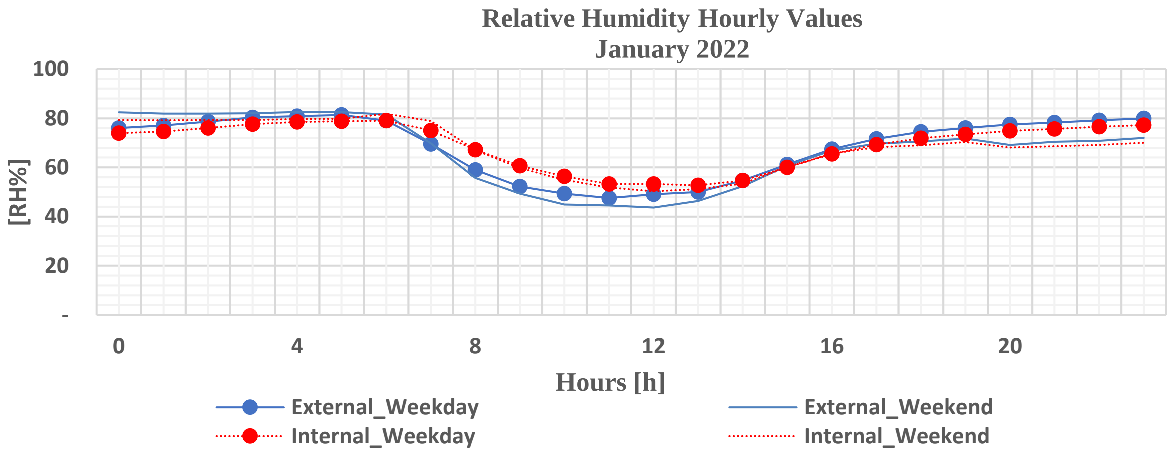


Figure 125: Relative Humidity hourly values measured by AIRCARE PRO+ during January

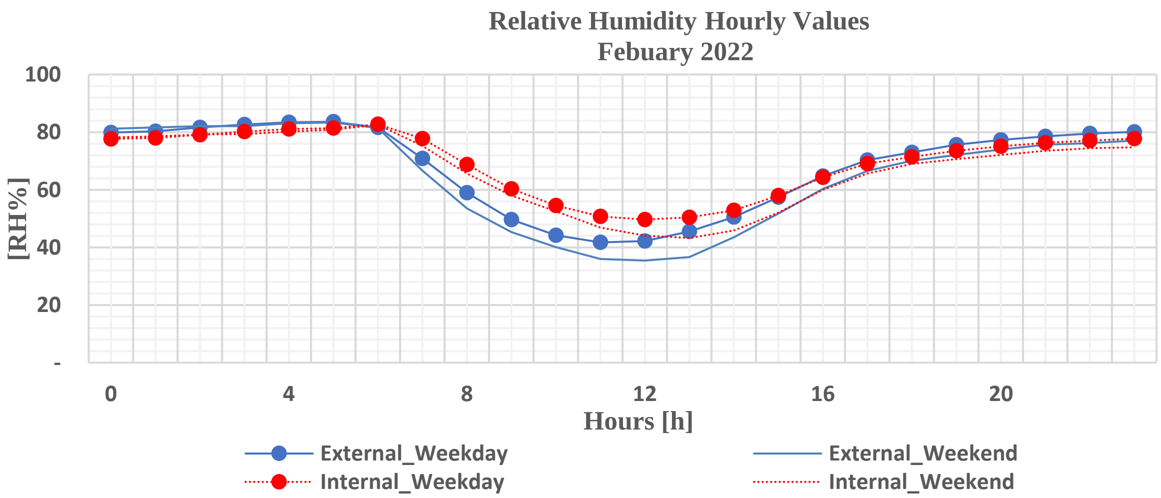


Figure 126: Relative Humidity hourly values measured by AIRCARE PRO+ during February

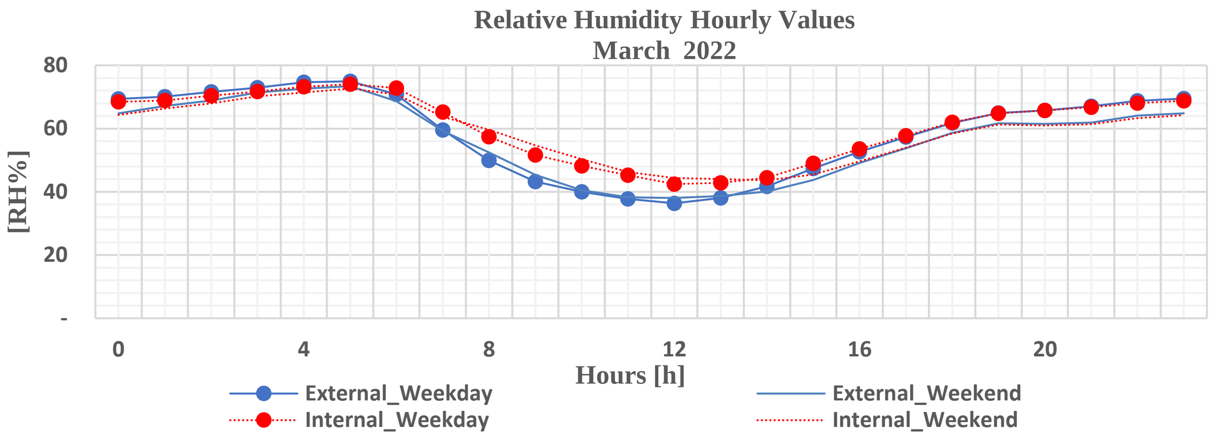


Figure 127: Relative Humidity hourly values measured by AIRCARE PRO+ during March

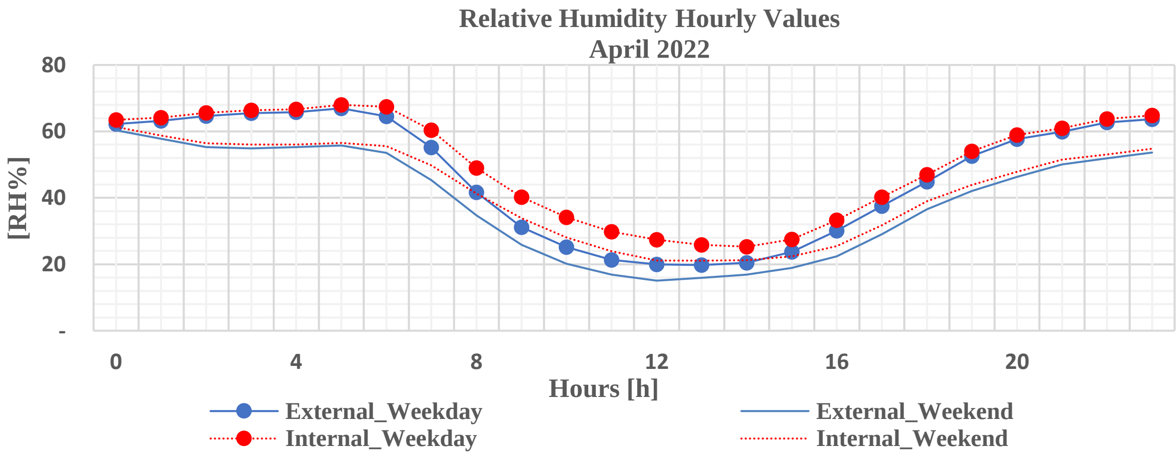


Figure 128: Relative Humidity hourly values measured by AIRCARE PRO+ during April

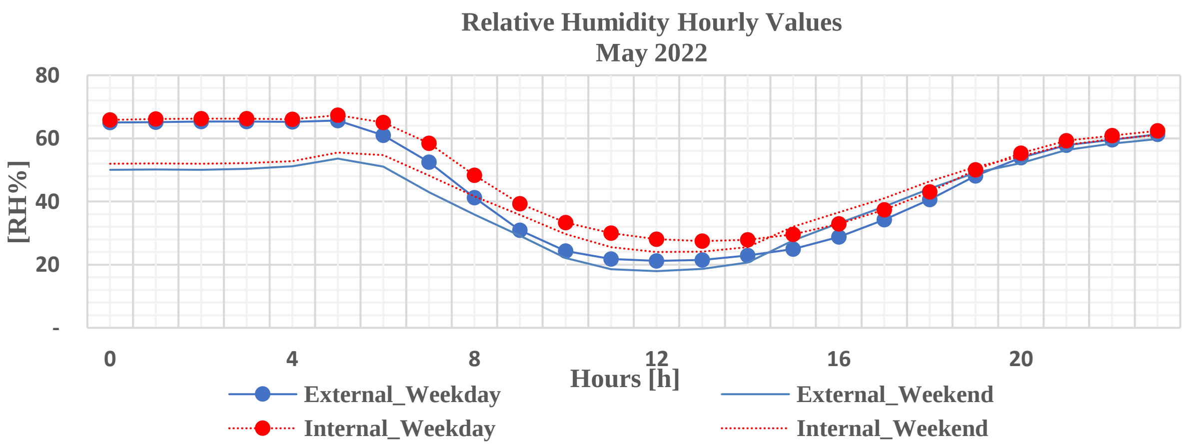


Figure 129: Relative Humidity hourly values measured by AIRCARE PRO+ during May

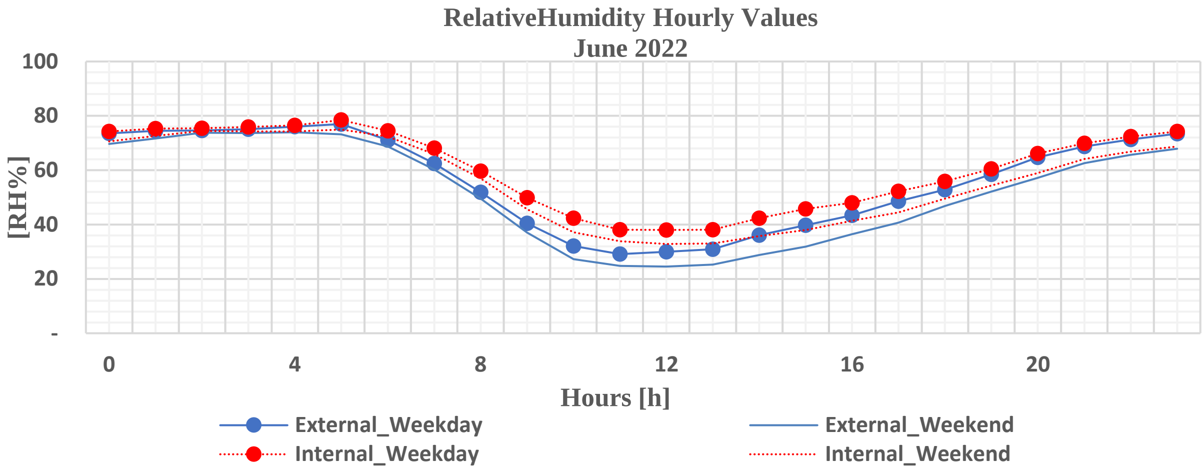


Figure 130: Relative Humidity hourly values measured by AIRCARE PRO+ during June

- The relative humidity levels during the months of January through June 2022 follow a similar pattern, with higher values in the morning, a steady decline into the day, and a minor increase once more into the evening.
- The relative humidity levels during the months of January through June follow a similar pattern, with higher values in the morning, a steady decline into the day, and a minor increase once more into the evening.

6.3.3 Particulate Matter 2.5 (PM 2.5)

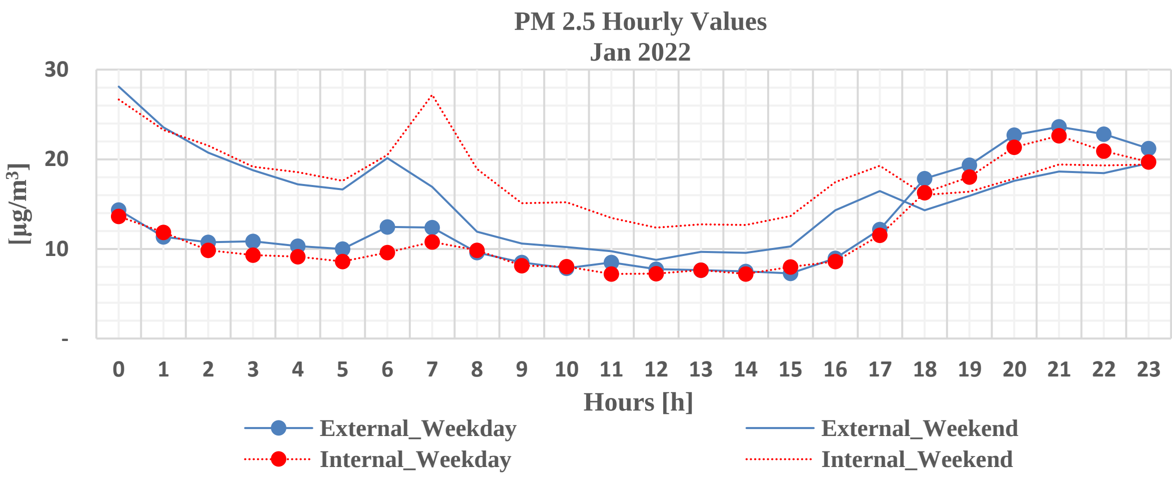


Figure 131: PM 2.5 hourly values measured by AIRCARE PRO+ during January

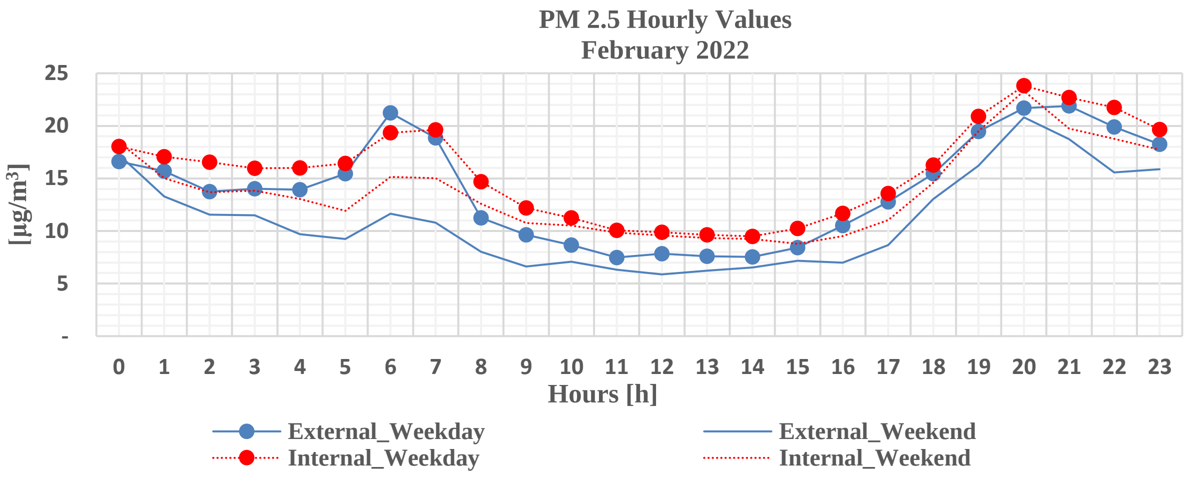


Figure 132: PM 2.5 hourly values measured by AIRCARE PRO+ during February

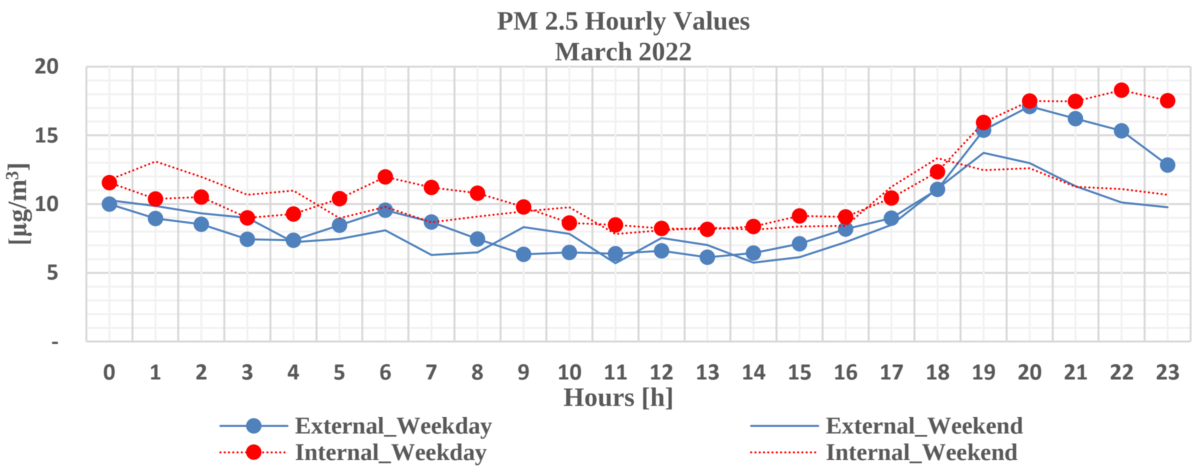


Figure 133: PM 2.5 hourly values measured by AIRCARE PRO+ during March

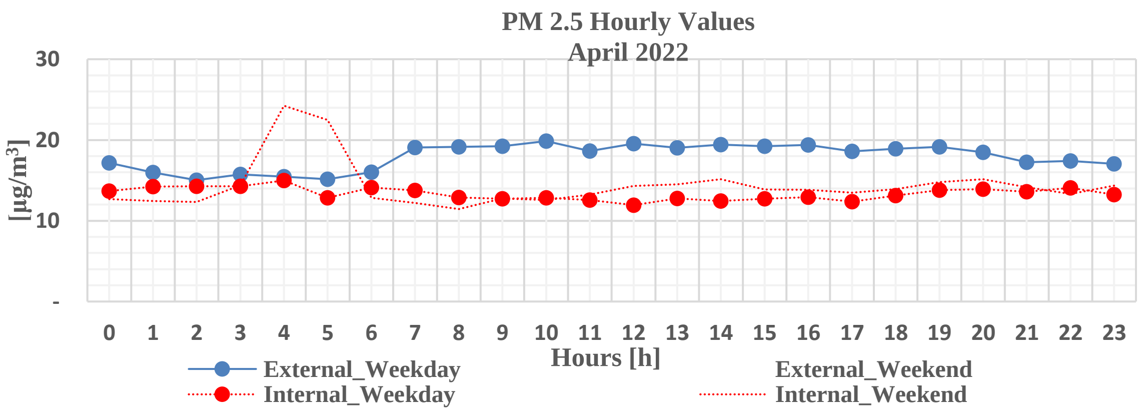


Figure 134: PM 2.5 hourly values measured by AIRCARE PRO+ during April

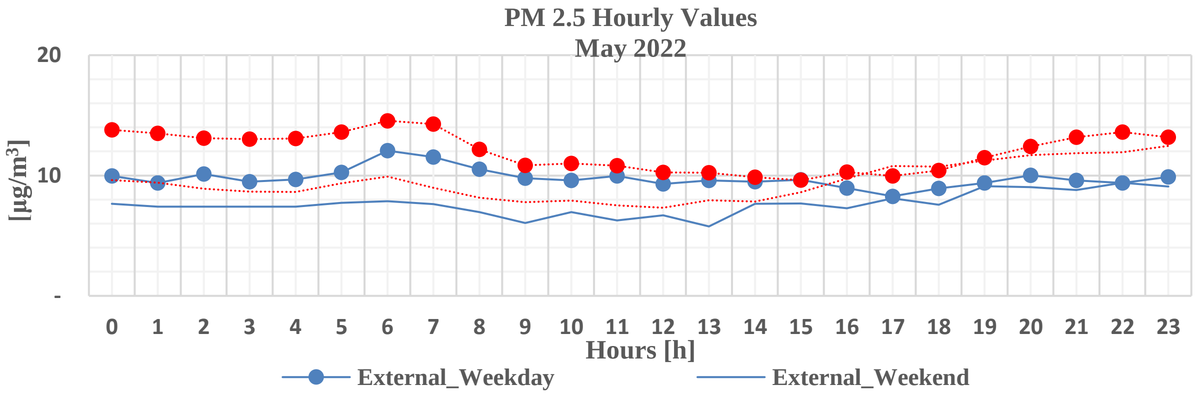


Figure 135: PM 2.5 hourly values measured by AIRCARE PRO+ during May

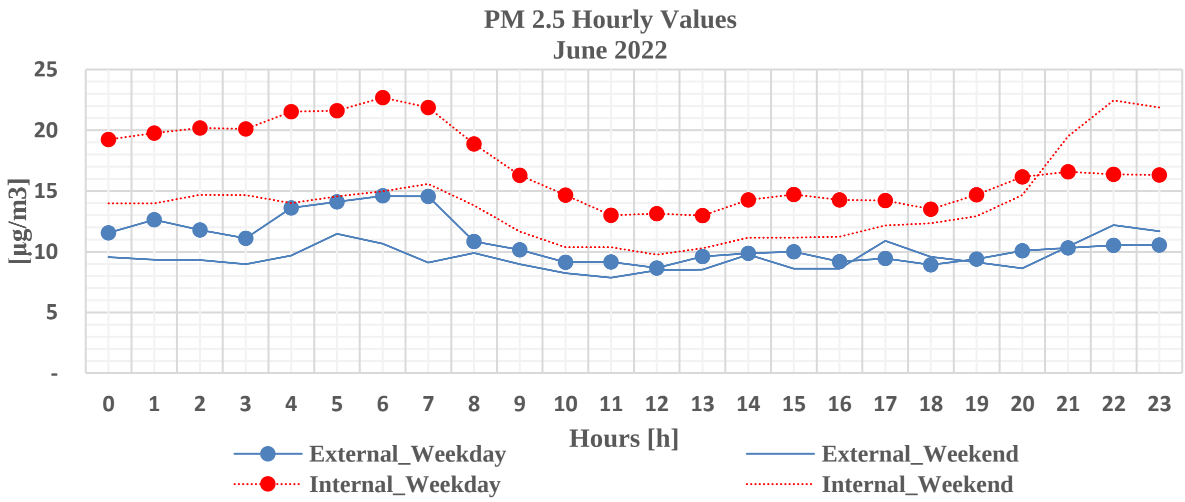


Figure 136: PM 2.5 hourly values measured by AIRCARE PRO+ during June

- During the hourly numbers gathered by the internal and external sensor for weekdays and weekends from January to June 2022, a different trend may be detected. But at the same time, the values seem to be intersecting at multiple points.
- For the month of January, the internal sensor's PM2.5 concentration levels appear to be greater on weekends than they are during the week, with weekdays recording the lowest results. The values recorded by the internal sensor are between those detected by the exterior sensor during weekends and weekdays. The internal sensor's weekend reading of 27.19µg/m^3 for the maximum PM2.5 concentration was noted. The observation was made at 7:00 in the morning (Figure 131).

- The values of the concentration levels detected by the internal sensor on weekdays were greater for the months of February, March, May, and June. Similar trends are seen, with values rising in the morning and falling in the lunchtime and evening (Figure 132,Figure 133,Figure 135 and Figure 136).
- Weekday results from the external sensor for the month of April (Figure 133) seemed to be higher than those from the interior sensor. however, the internal sensor's recorded data shows a sharp rise 24.24 µg/m^3 between 4:00 and 6:00 in the morning.

6.3.4 Particulate Matter 10 (PM 10)

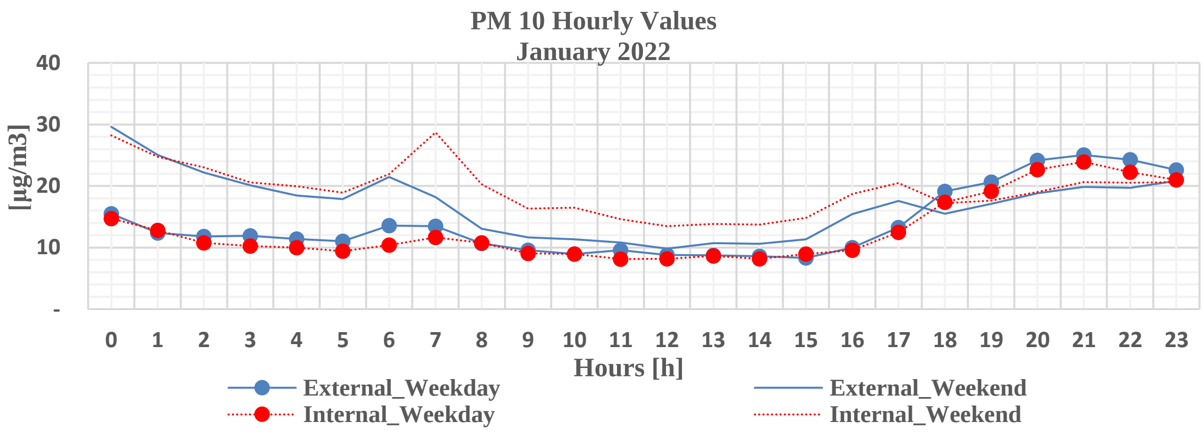


Figure 137: PM 10 hourly values measured by AIRCARE PRO+ during January

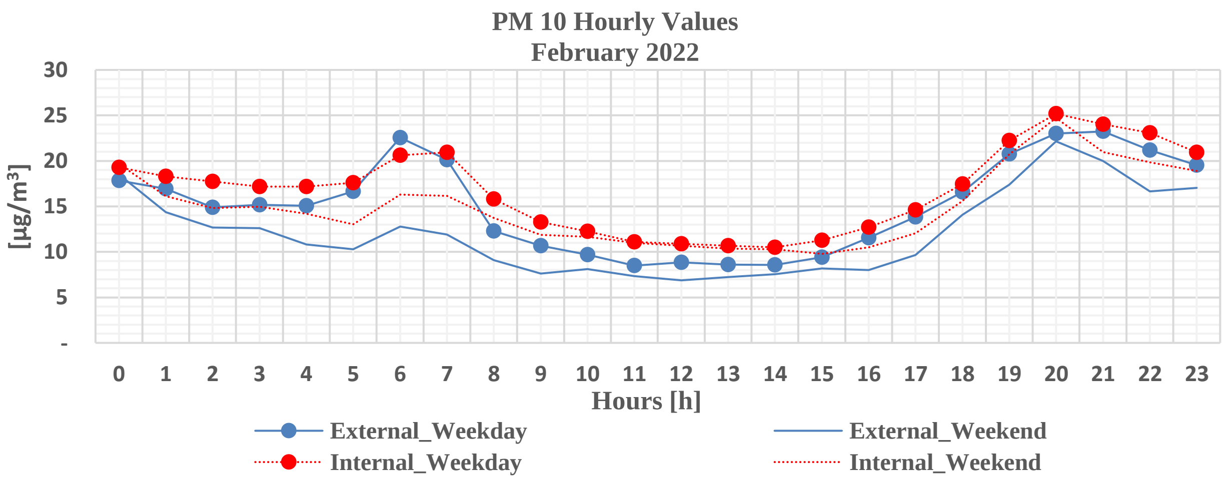


Figure 138: PM 10 hourly values measured by AIRCARE PRO+ during February

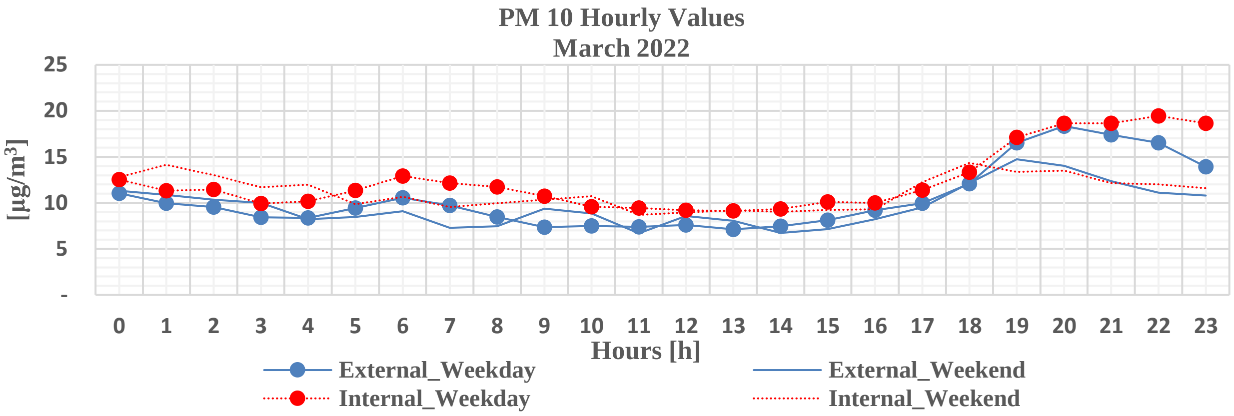


Figure 139: PM 10 hourly values measured by AIRCARE PRO+ during March

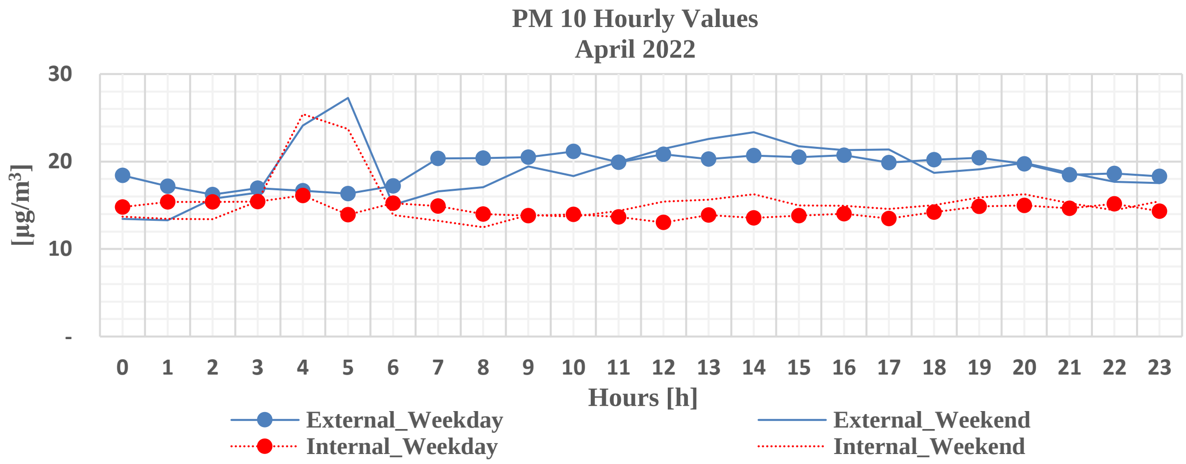


Figure 140: PM 10 hourly values measured by AIRCARE PRO+ during April

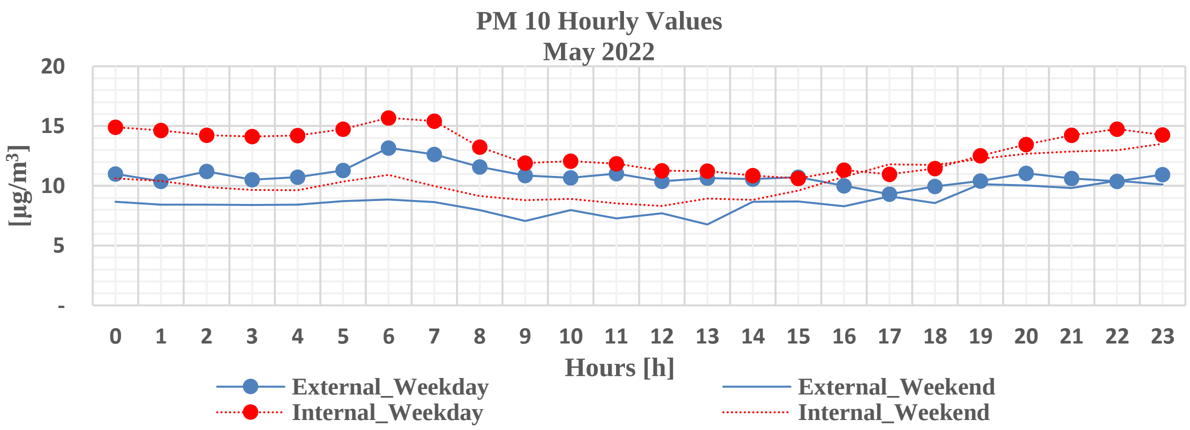


Figure 141: PM 10 hourly values measured by AIRCARE PRO+ during May

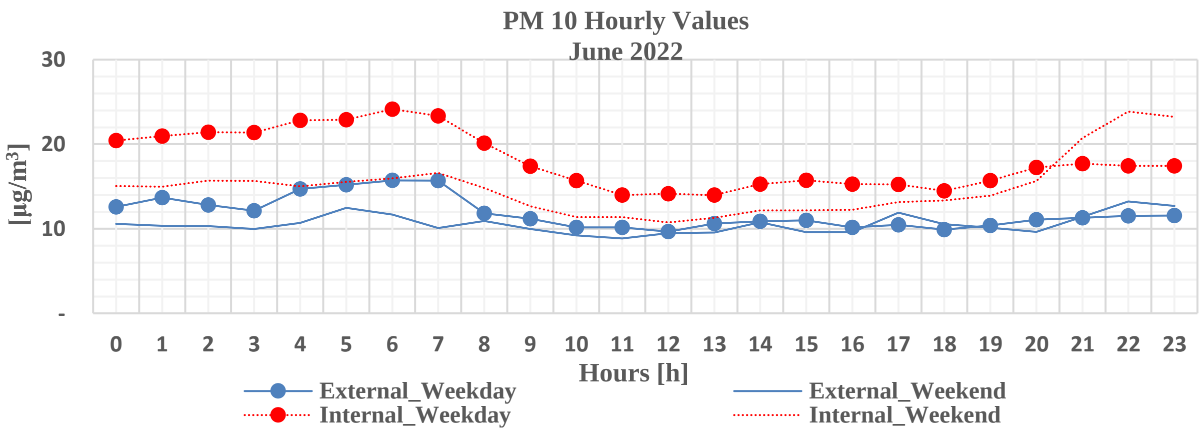


Figure 142: PM 10 hourly values measured by AIRCARE PRO+ during June

- Similar to what was reported for PM2.5, greater values for the weekends were recorded by an internal sensor for PM10 for the month of January (Figure 137). The tendency is the same for both internal and exterior sensors; values rise in the morning, fall in the middle of the day, and then rise again in the evening.
- The values recorded by the internal sensor for weekends and weekdays were found to be greater than those recorded by the external sensor for the months of February, March, May, and June (Figure 138,Figure 140,Figure 141 and Figure 142).
- Weekday and weekend data from the external sensor for the month of April (Figure 139) appear to be higher than those obtained from the interior sensor. On weekends, a sharp rise can be seen for both exterior and internal sensors between 4:00 and 6:00 a.m.

6.3.5 Luminosity

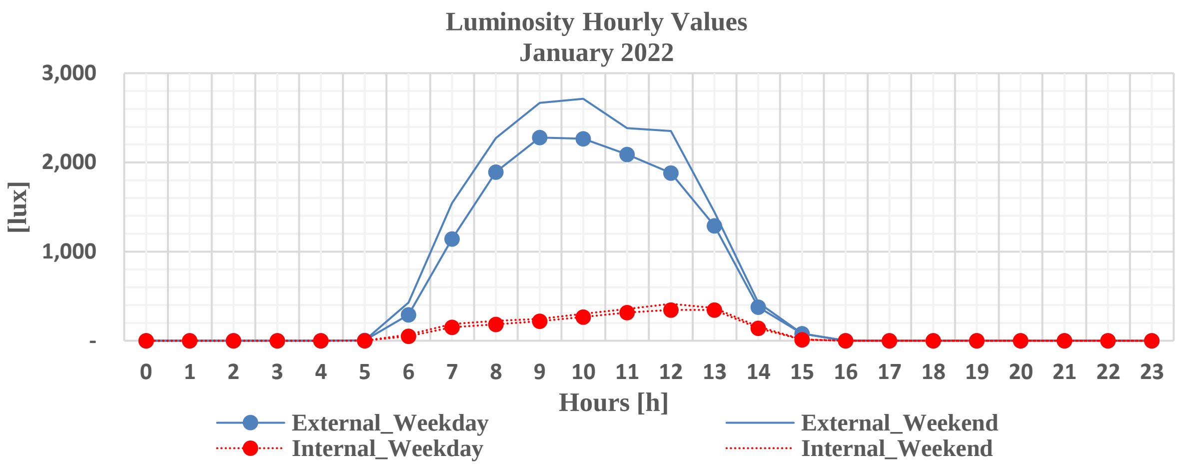


Figure 143: Luminosity hourly values measured by AIRCARE PRO+ during January

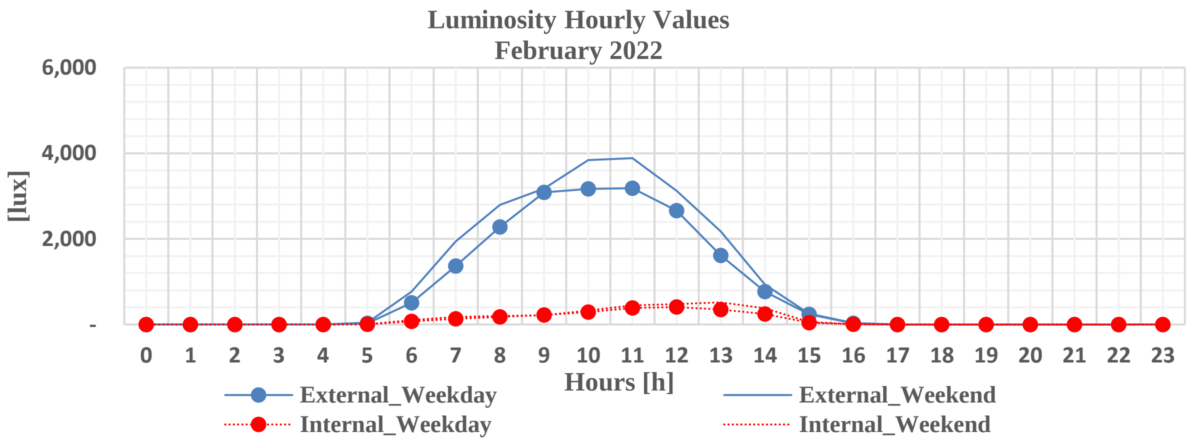


Figure 144: Luminosity hourly values measured by AIRCARE PRO+ during February

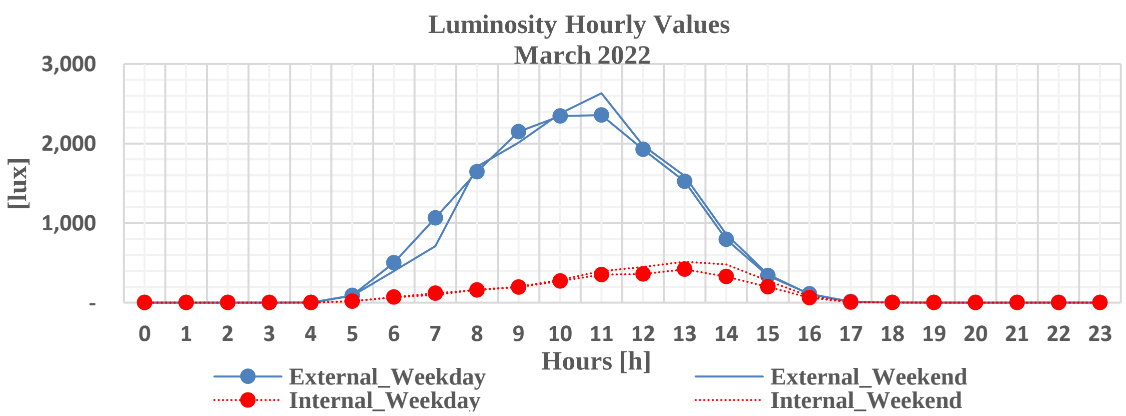


Figure 145: Luminosity hourly values measured by AIRCARE PRO+ during March

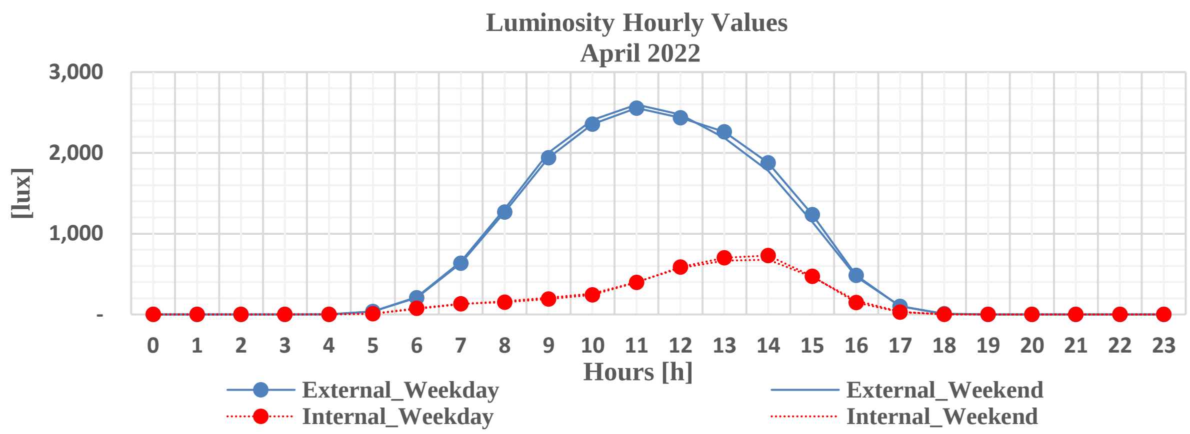


Figure 146: Luminosity hourly values measured by AIRCARE PRO+ during April

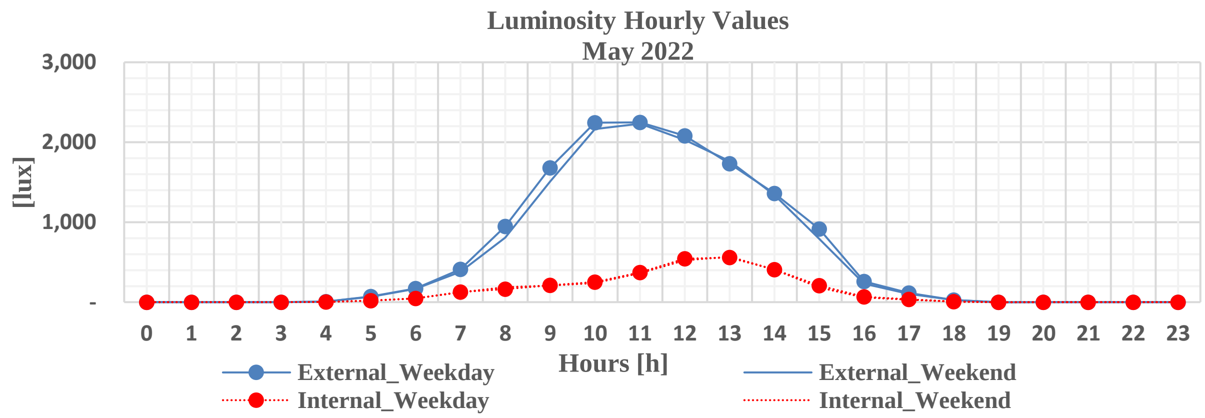


Figure 147: Luminosity hourly values measured by AIRCARE PRO+ during May

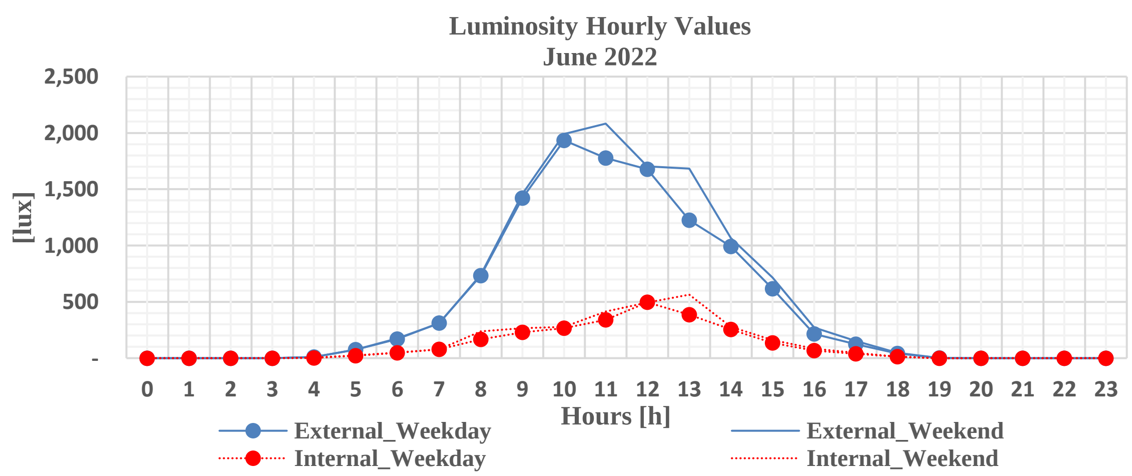


Figure 148: Luminosity hourly values measured by AIRCARE PRO+ during June

- For the winter months of January and February (Figure 143 and Figure 144), it was found that the luminosity values recorded by the exterior sensor were higher from 6:00 in the morning until 15:00 in the afternoon, both on weekends and on weekdays. The maximum luminance values during the spring and summer months of March, April, May, and June (Figure 145, Figure 146, Figure 147 and Figure 148) were recorded between 6:00 am to 17:00 pm.
- Weekday and weekend values recorded by the internal sensor seem to be less than those recorded by the external sensor. Given that the sensor is housed inside the plant-covered panel, this makes reasonable.

6.3.6 CO_2 concentration

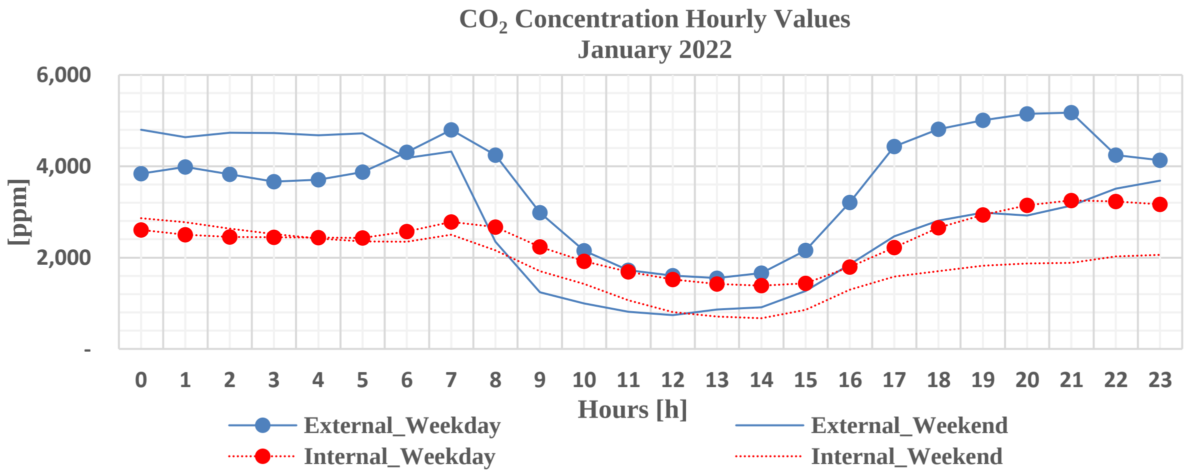


Figure 149: Concentration of CO_2 hourly values measured by AIRCARE PRO+ during January

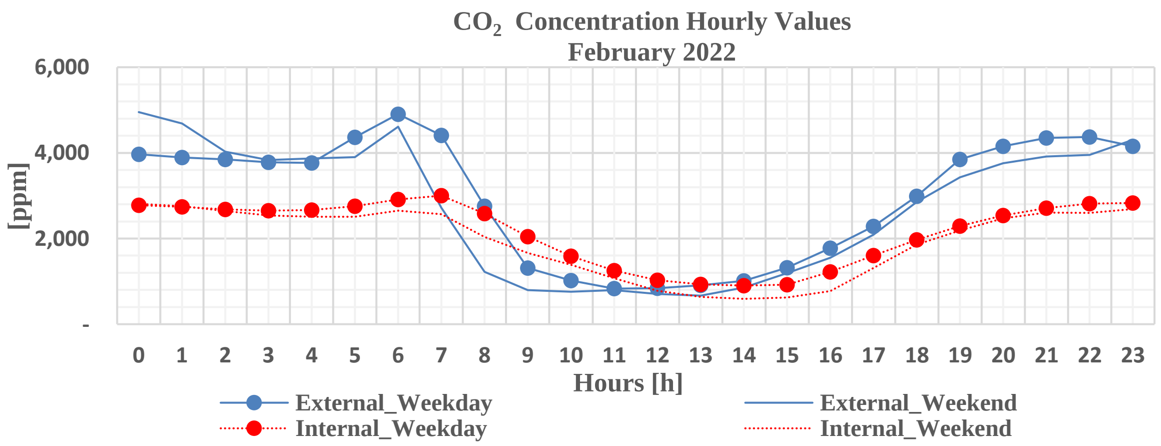


Figure 150: Concentration of CO_2 hourly values measured by AIRCARE PRO+ during February

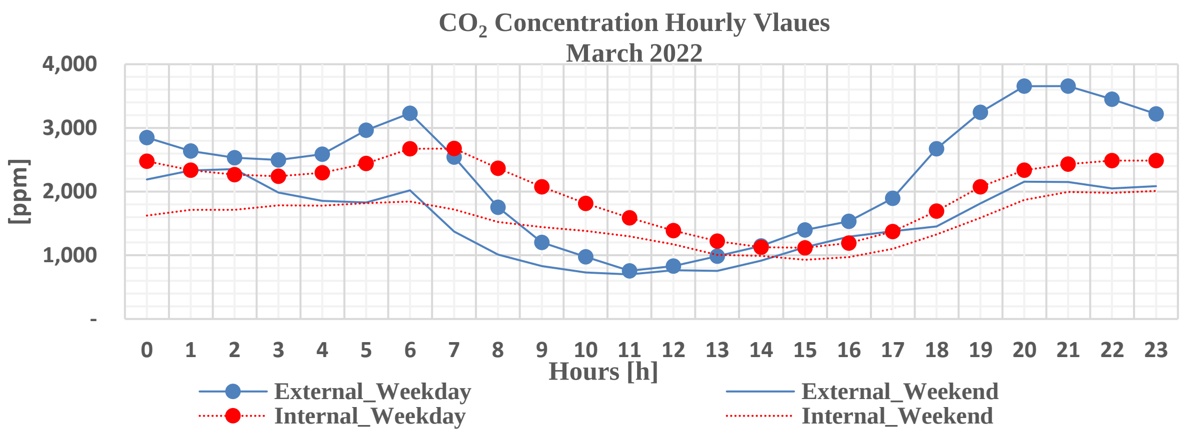


Figure 151: Concentration of CO_2 hourly values measured by AIRCARE PRO+ during March

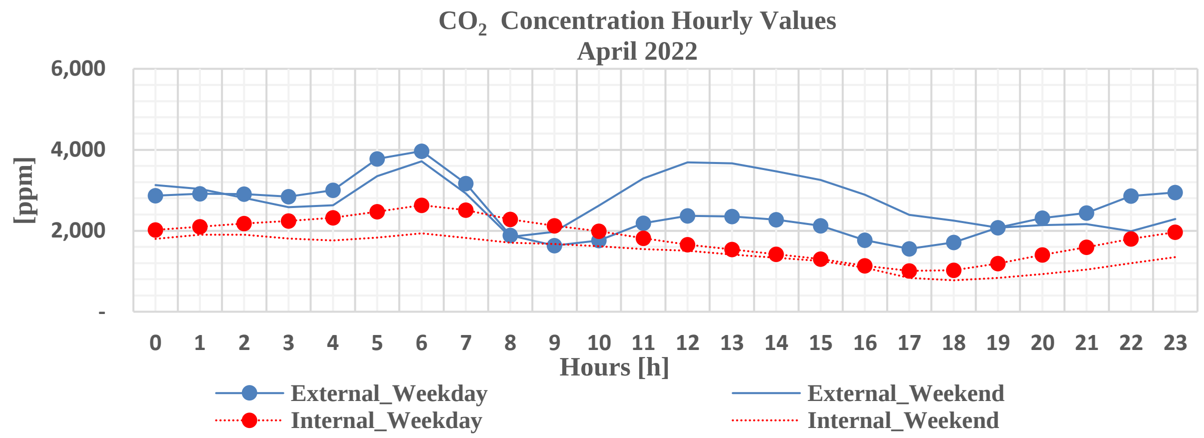


Figure 152: Concentration of CO_2 hourly values measured by AIRCARE PRO+ during April

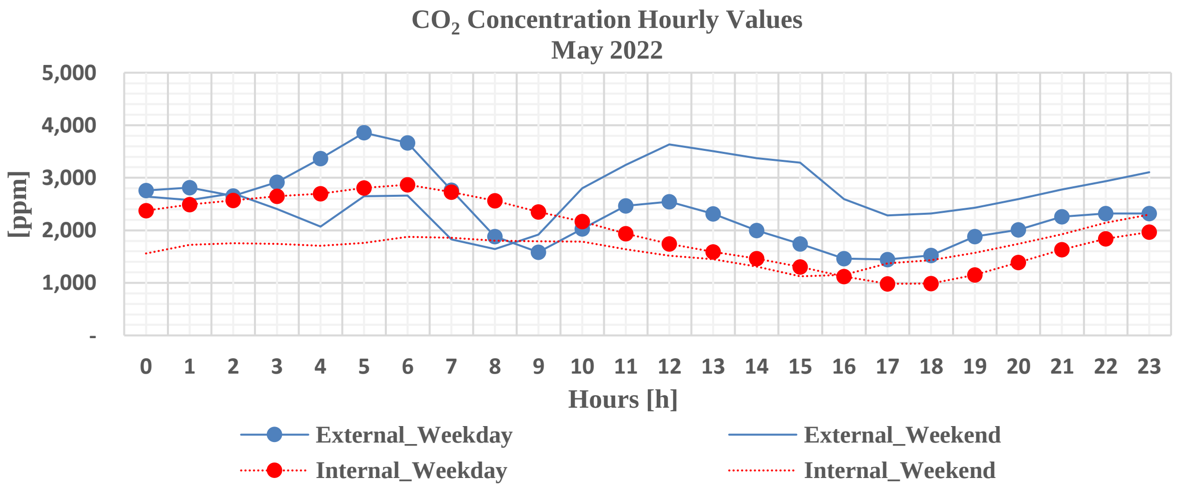


Figure 153: Concentration of CO_2 hourly values measured by AIRCARE PRO+ during May

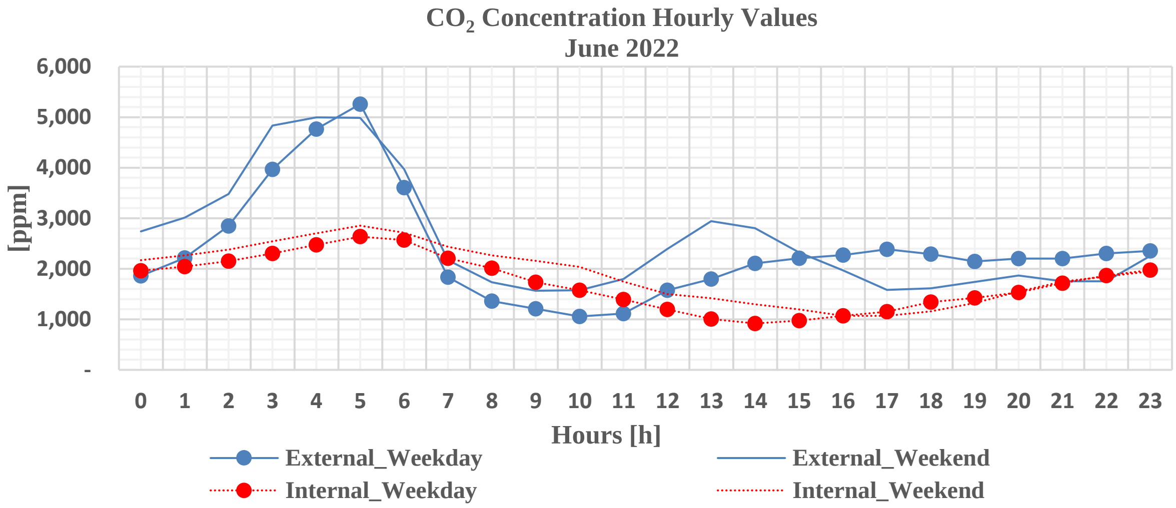


Figure 154: Concentration of CO_2 hourly values measured by AIRCARE PRO+ during June

- From January to June 2022, the carbon dioxide concentration as measured by internal and external sensors during weekends and weekdays followed a similar pattern. One tendency that can be observed is that the carbon dioxide concentration levels seemed to be higher at night than they did throughout the day. This can be explained by the obvious fact that plants only respire at night and do not engage in photosynthesis (since absence of sunlight). Therefore, the concentration of CO_2 released is higher at night.
- On average, it seemed that the values recorded by the exterior sensor were higher than those reported by the inside sensor.

6.3.7 Indoor Air Quality (IAQ)

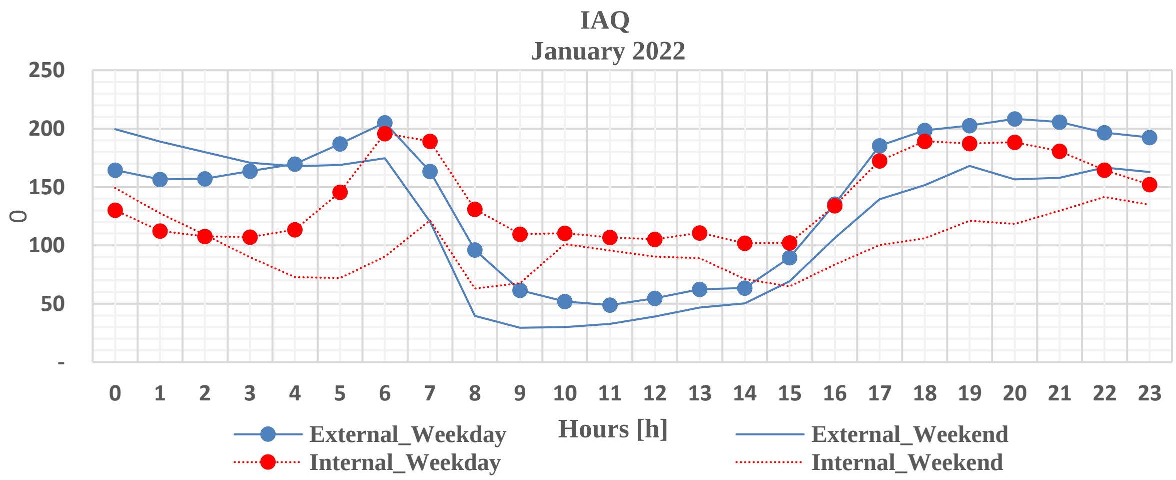


Figure 155: Indoor air quality hourly values measured by AIRCARE PRO+ during January

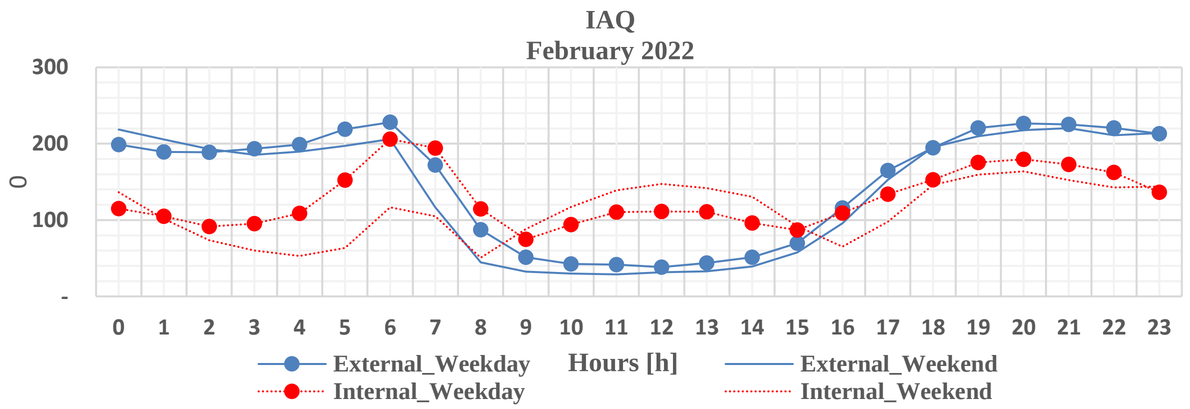


Figure 156: Indoor air quality hourly values measured by AIRCARE PRO+ during February

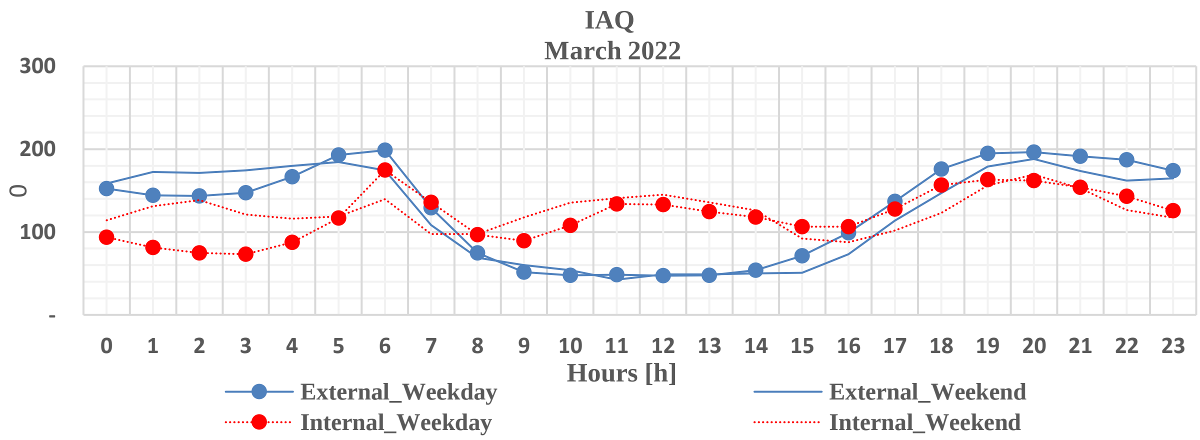


Figure 157: Indoor air quality hourly values measured by AIRCARE PRO+ during March

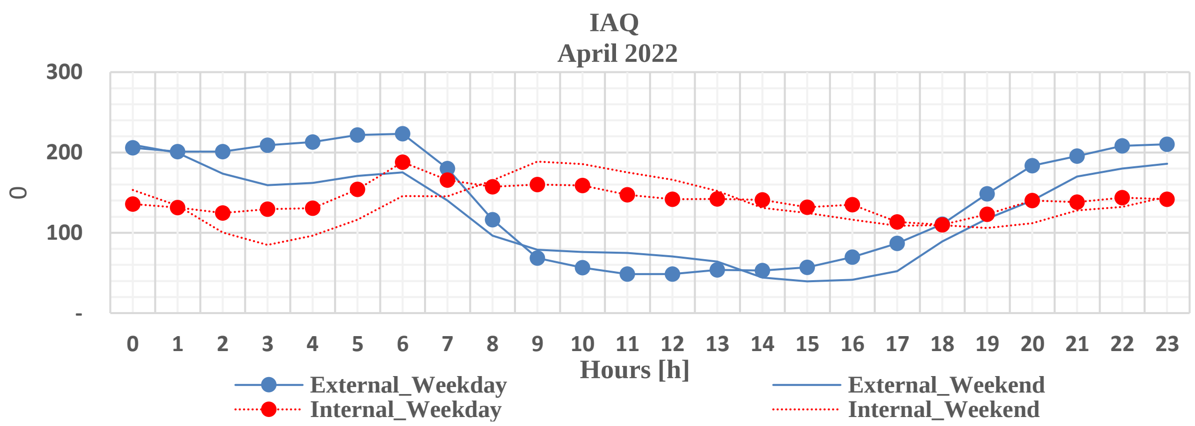


Figure 158: Indoor air quality hourly values measured by AIRCARE PRO+ during April

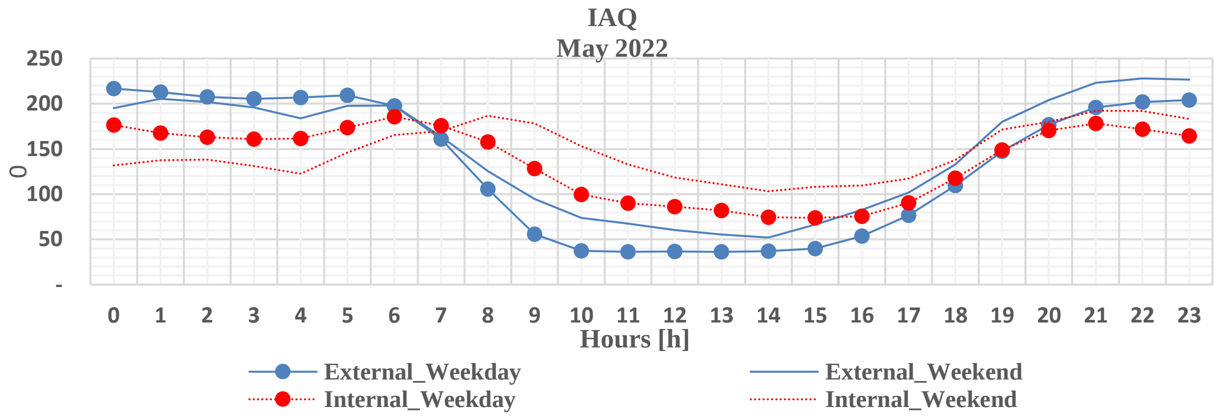


Figure 159: Indoor air quality hourly values measured by AIRCARE PRO+ during May

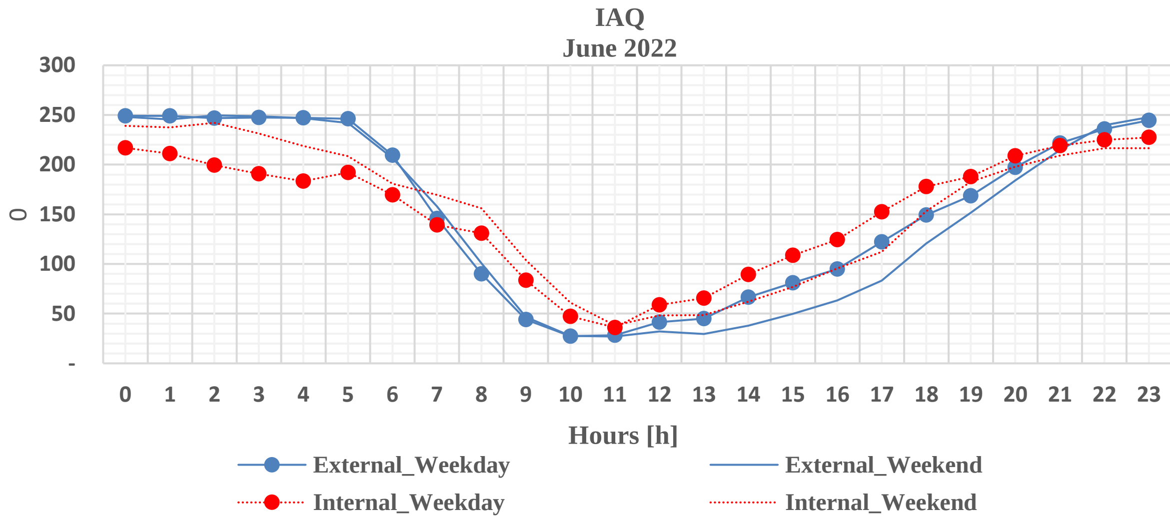


Figure 160: Indoor air quality hourly values measured by AIRCARE PRO+ during June

- According to the data gathered from both internal and external sensors, a similar trend for the Indoor Air Quality (IAQ) is observed between January and June 2022. The pattern can be explicated by the fact that Indoor Air Quality is better at night than it is during the day as air pollution can accumulate closer to the ground at night because there is typically less wind.
- Weekday and weekend values recorded by the external sensor seem to be greater at night, although daytime values recorded by the internal sensor seem to be higher. The highest value of IAQ = 248.16 was recorded in the summer month of June.

6.3.8 Sound

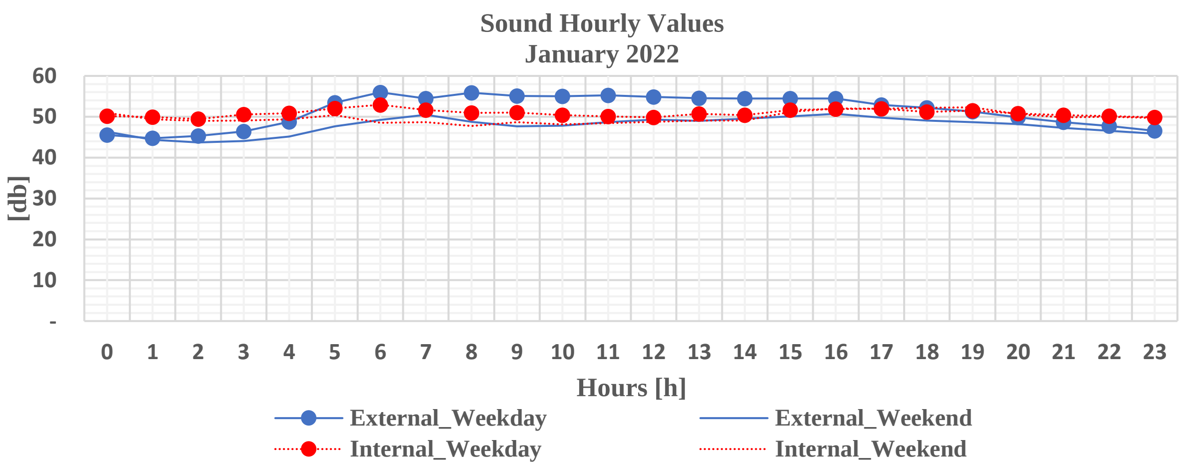


Figure 161: Sound hourly values measured by AIRCARE PRO during January

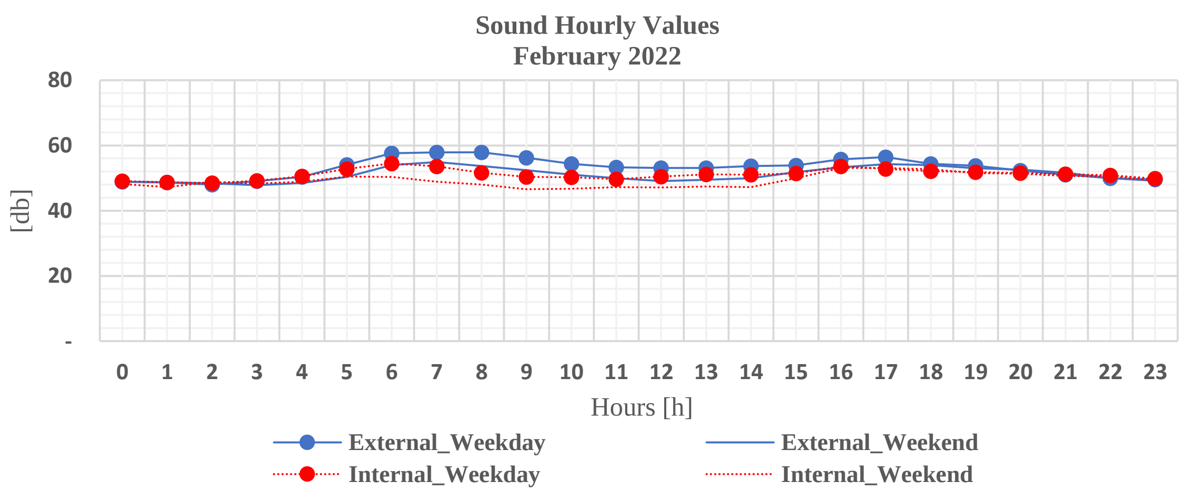


Figure 162: Sound hourly values measured by AIRCARE PRO during February

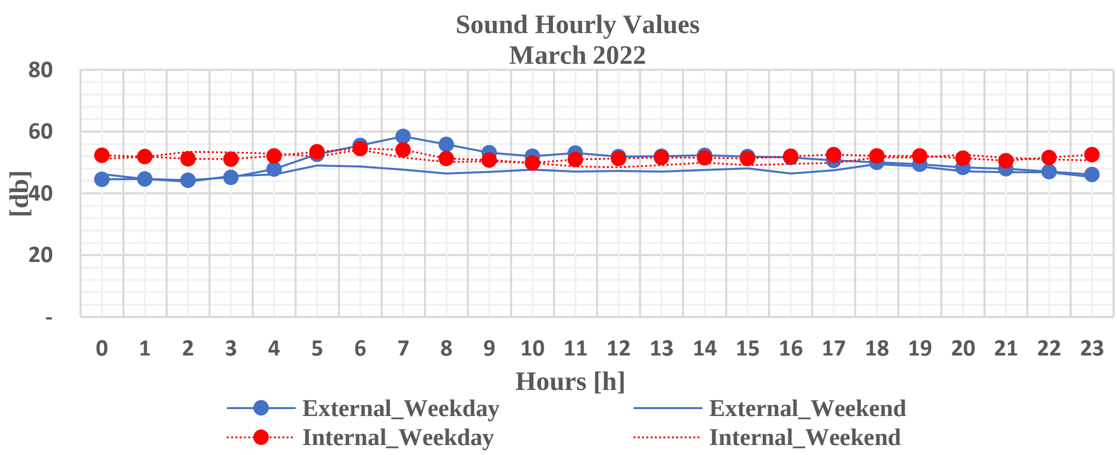


Figure 163: Sound hourly values measured by AIRCARE PRO during March

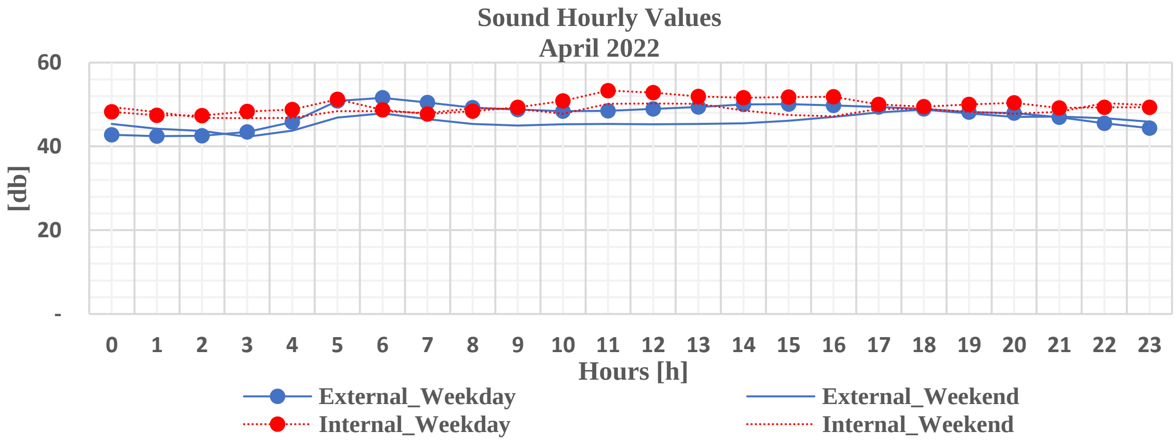


Figure 164: Sound hourly values measured by AIRCARE PRO during April

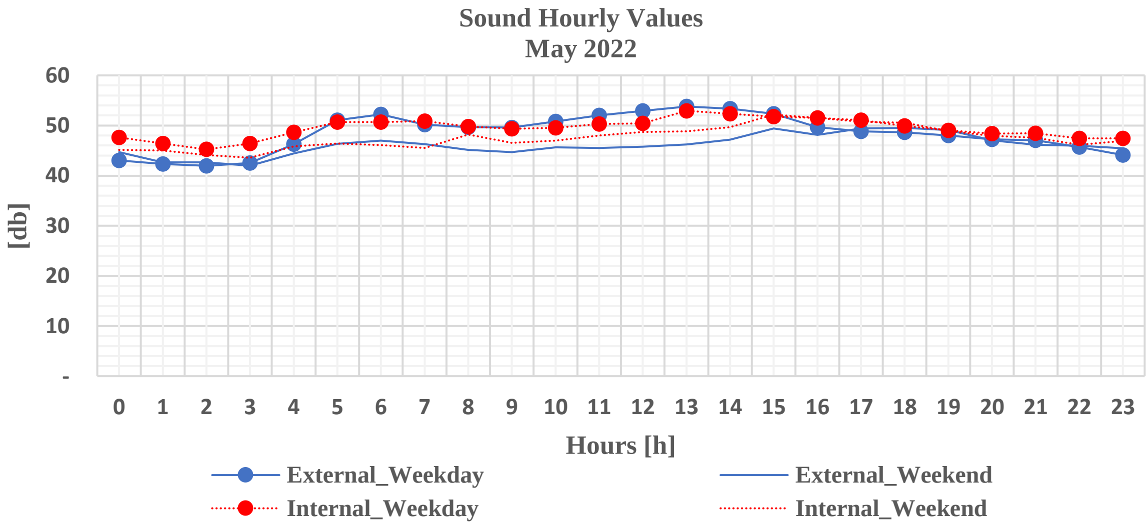


Figure 165: Sound hourly values measured by AIRCARE PRO during May

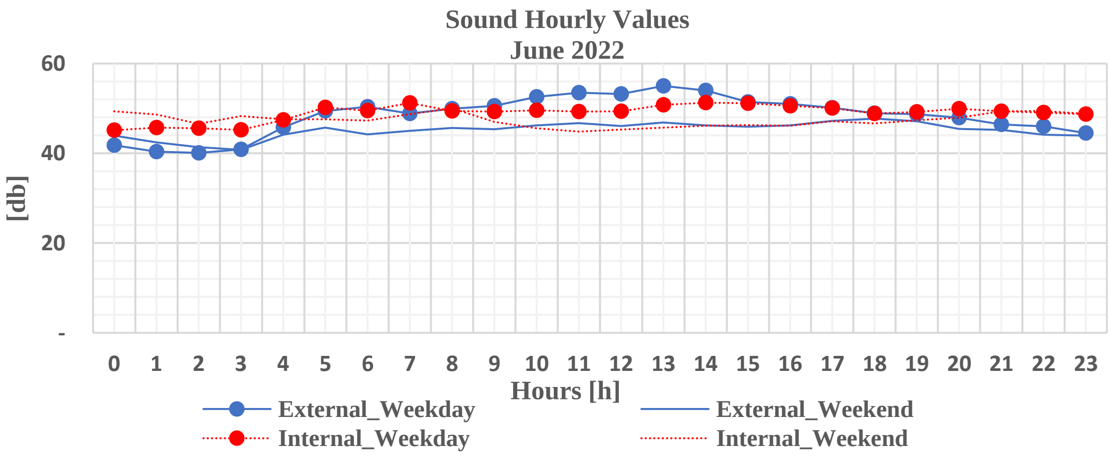


Figure 166: Sound hourly values measured by AIRCARE PRO during June

- The Sound profiles acquired by the exterior and internal sensors are quite similar from January to June (Figure 161, **Figure 162**, Figure 163, Figure 164, **Figure 165** and **Figure 166**). However, the internal sensor records higher sound values on weekdays and weekends between the hours of 12:00 and 4:00 in the night.
- The exterior sensor records a peak sound value of 58.46 dB in March (Figure 163) at 7:00 in the morning on workdays.

6.4 Case Study 4- Brescia, ItalMesh Headquarter

Using AirCare Pro sensors, Case Study 4 study was carried out from March to June 2022. According to the panel, the sensors are placed both internally and externally. The following parameters' hourly values were obtained using the sensor data that was collected.

- Air Temperature
- Relative humidity
- Particulate Matter 2.5
- Particulate Matter 10
- Luminosity
- Carbon dioxide concentration
- Indoor Air Quality
- Sound

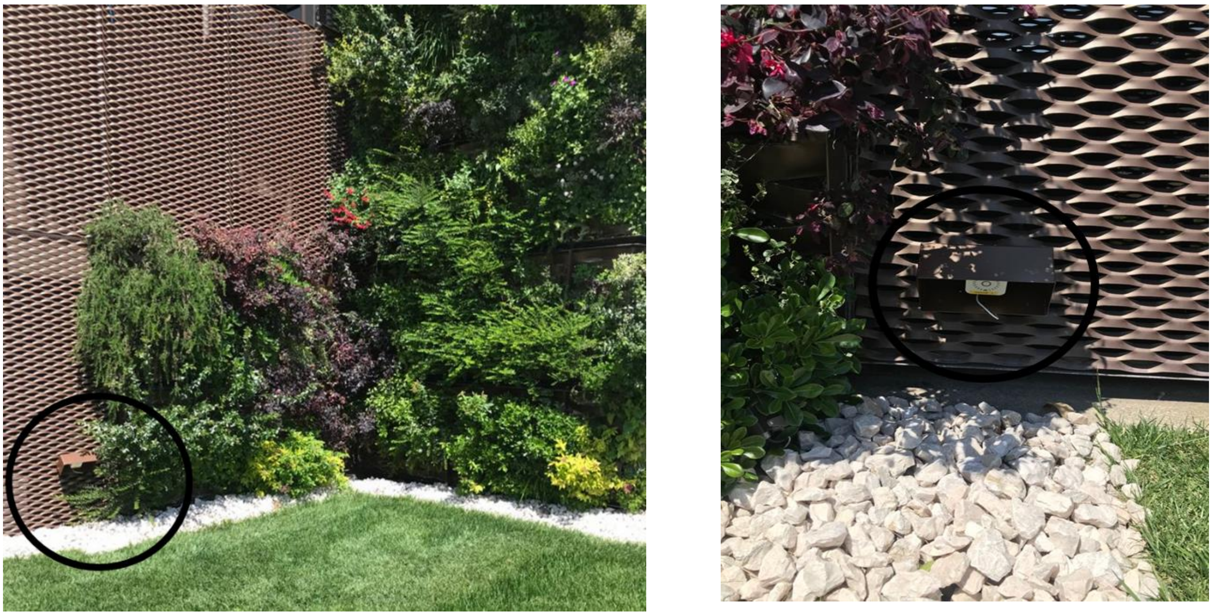


Figure 167: Sensors installed on the Green Panels in Brescia, ItalMesh Headquarter

6.4.1 Air Temperature

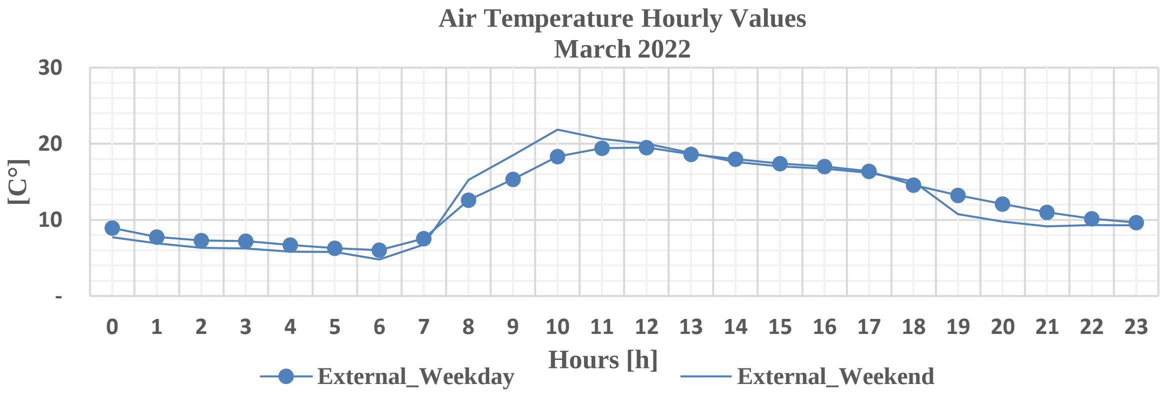


Figure 168: Air Temperature hourly values measured by AIRCARE PRO+ during March

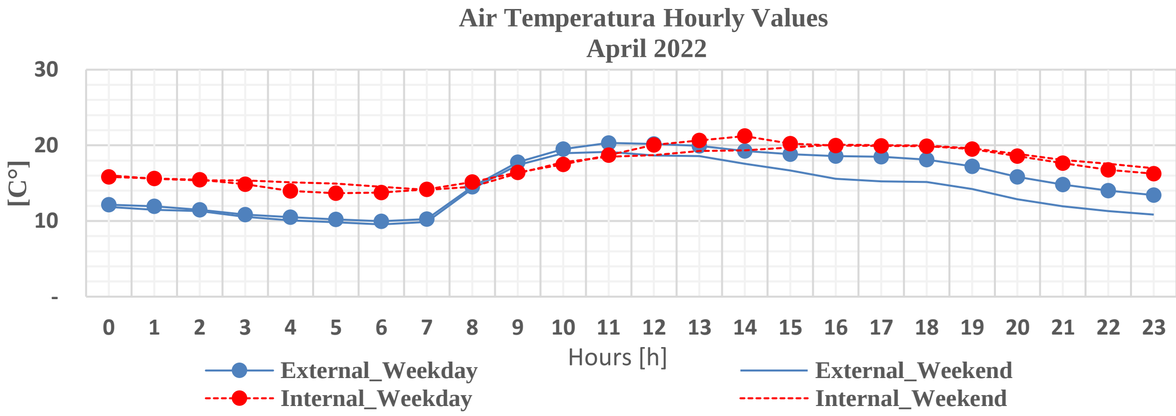


Figure 169: Air Temperature hourly values measured by AIRCARE PRO+ during April

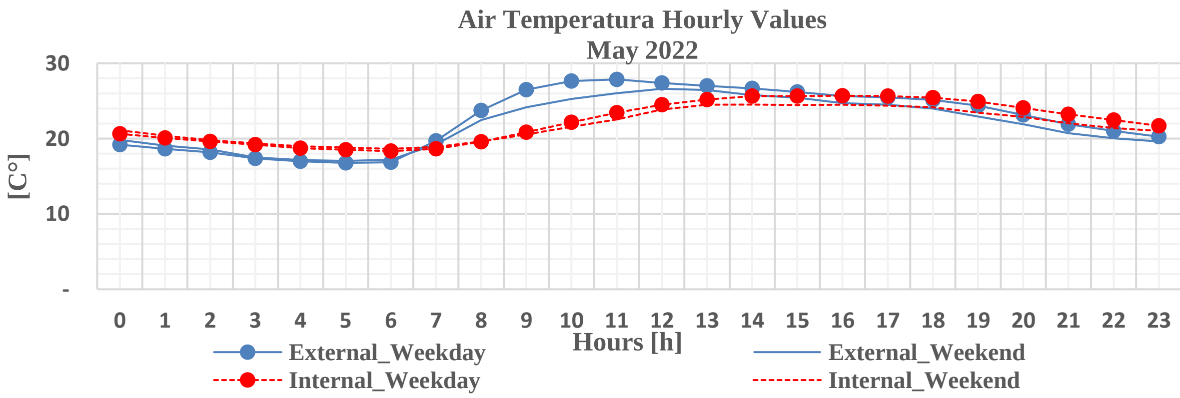


Figure 170: Air Temperature hourly values measured by AIRCARE PRO+ during May

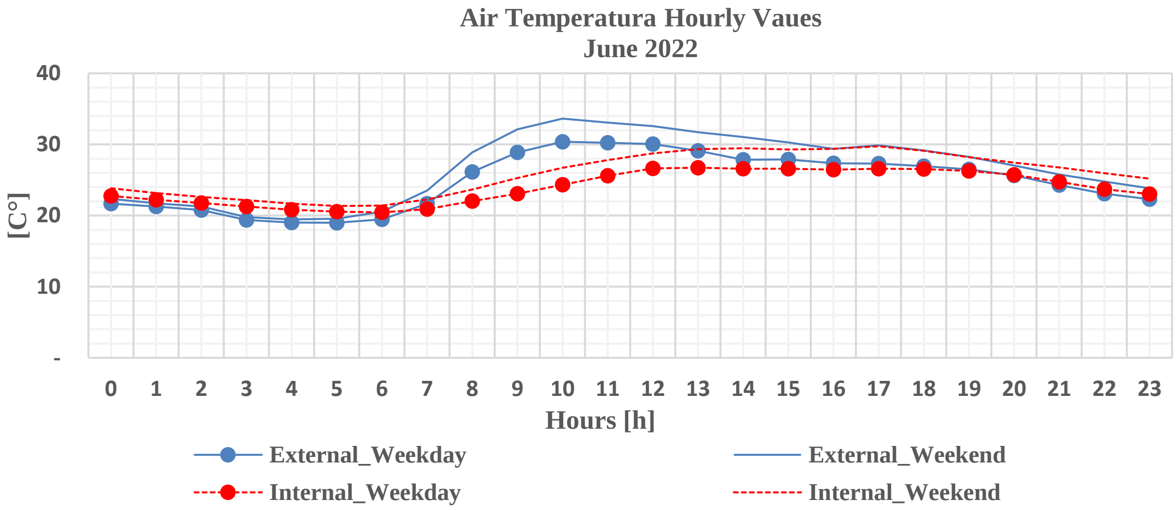


Figure 171: Air Temperature hourly values measured by AIRCARE PRO+ during June

- The hourly temperature values collected by the internal sensor are higher than those taken by the external one, according to the temperature profile that was derived from the external and internal sensors from the month of March to June 2022 (Figure 169, Figure 170 and Figure 171). However, the external sensor records greater values for weekdays and weekends between the hours of 8:00 and 12:00 in the morning.

6.4.2 Relative Humidity

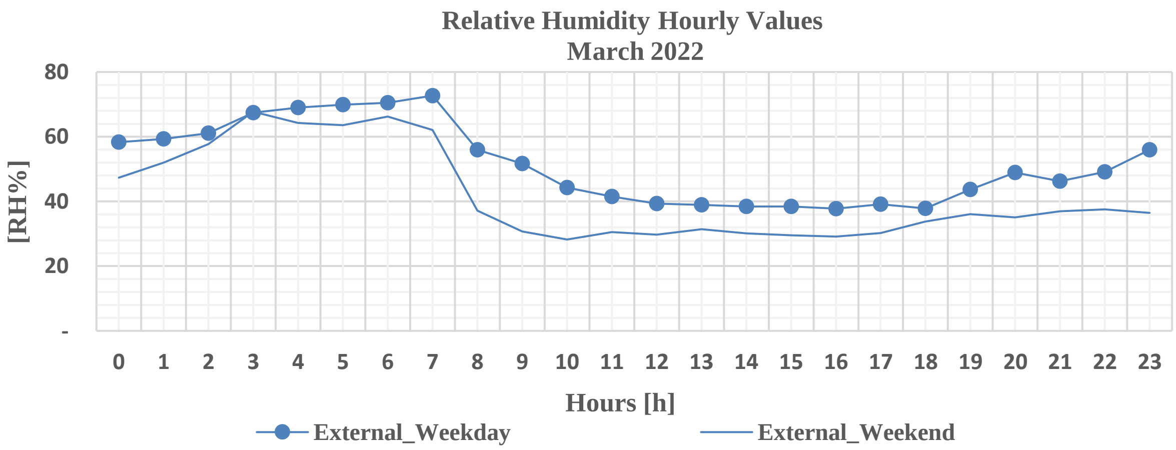


Figure 172: Relative Humidity hourly values measured by AIRCARE PRO+ during March

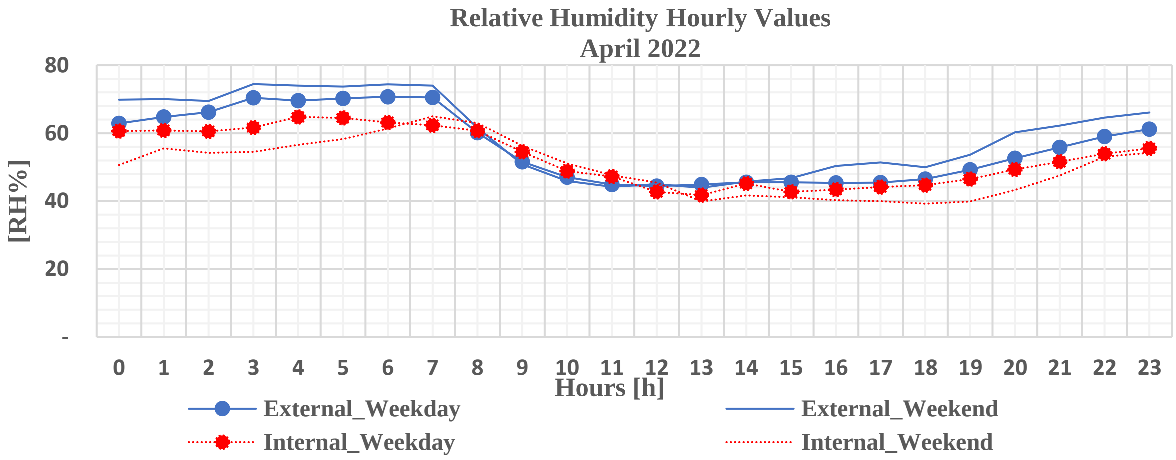


Figure 173: Relative Humidity hourly values measured by AIRCARE PRO+ during April

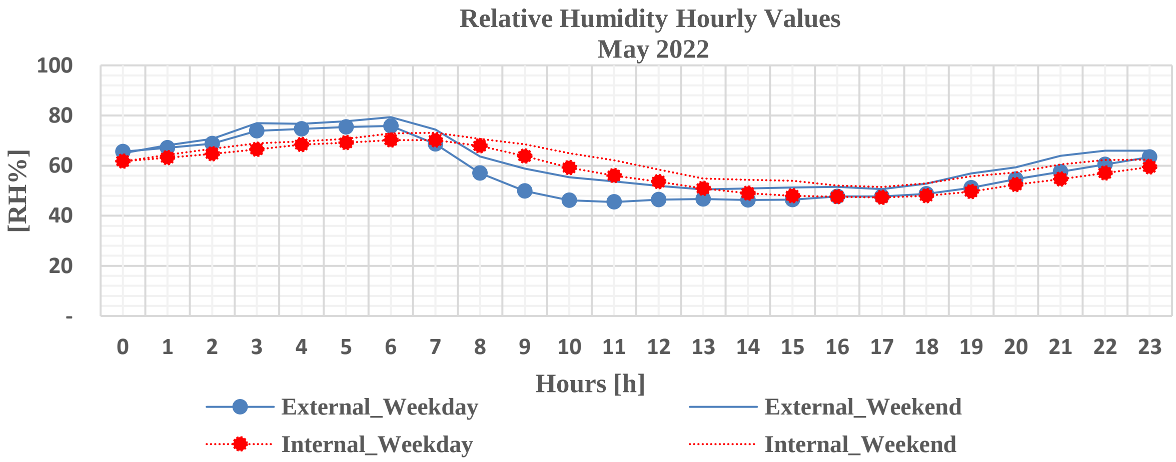


Figure 174: Relative Humidity hourly values measured by AIRCARE PRO+ during May

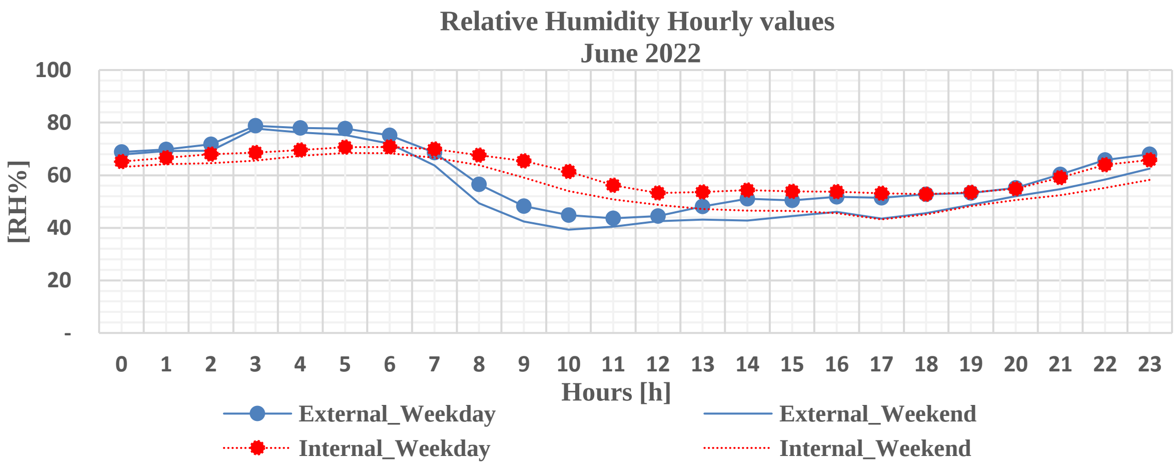


Figure 175: Relative Humidity hourly values measured by AIRCARE PRO+ during June

- The relative humidity levels during the months of March through June 2022 follow a similar pattern, with higher values in the morning, a steady decline into the day, and a minor increase once more into the evening.

- The data recorded by the internal sensor shows higher values during the daytime, extending from 7:00 in the morning to 13:00 in the afternoon, whereas the relative humidity values recorded by the external sensor indicate higher values during the night hours up until 7:00 in the morning.

6.4.3 Particulate Matter (PM) 2.5

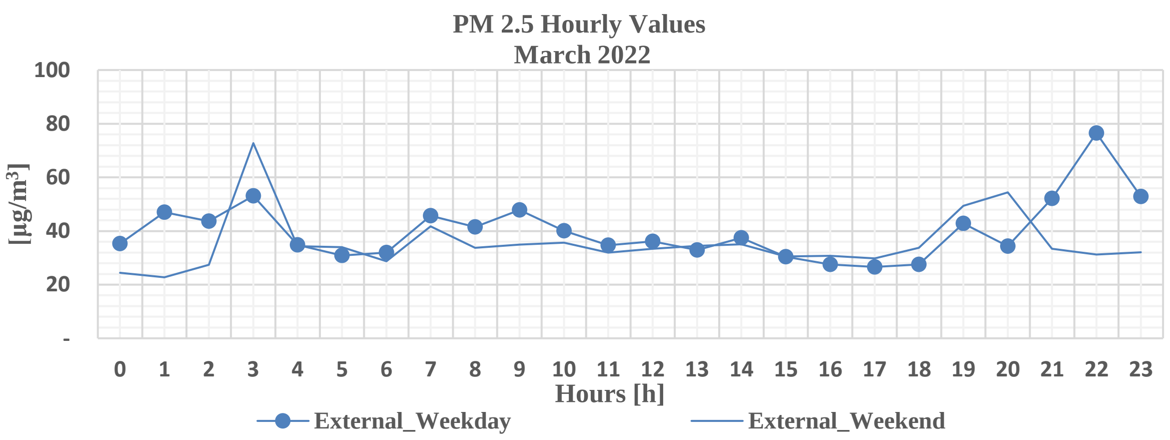


Figure 176: PM 2.5 hourly values measured by AIRCARE PRO+ during March

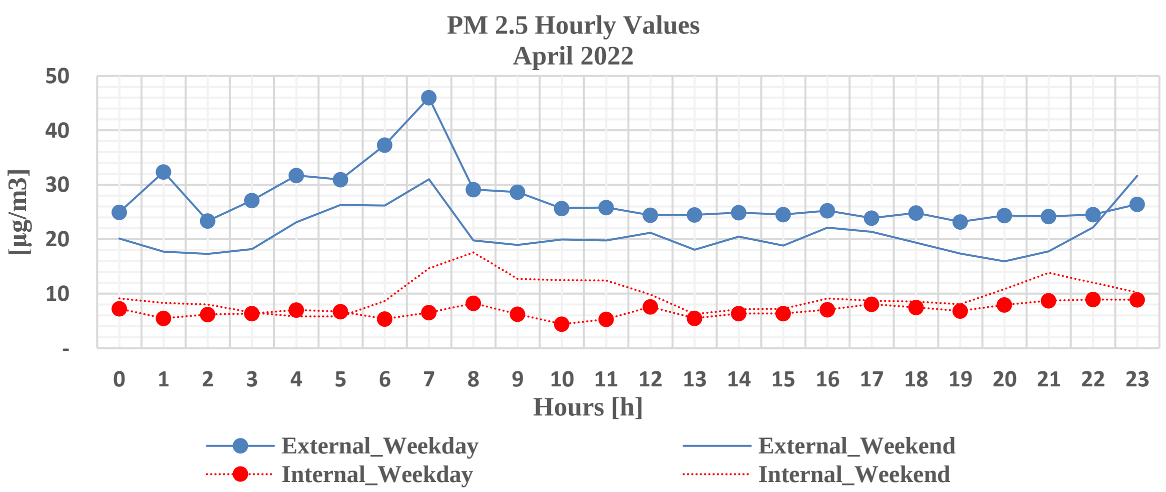


Figure 177: PM 2.5 hourly values measured by AIRCARE PRO+ during April

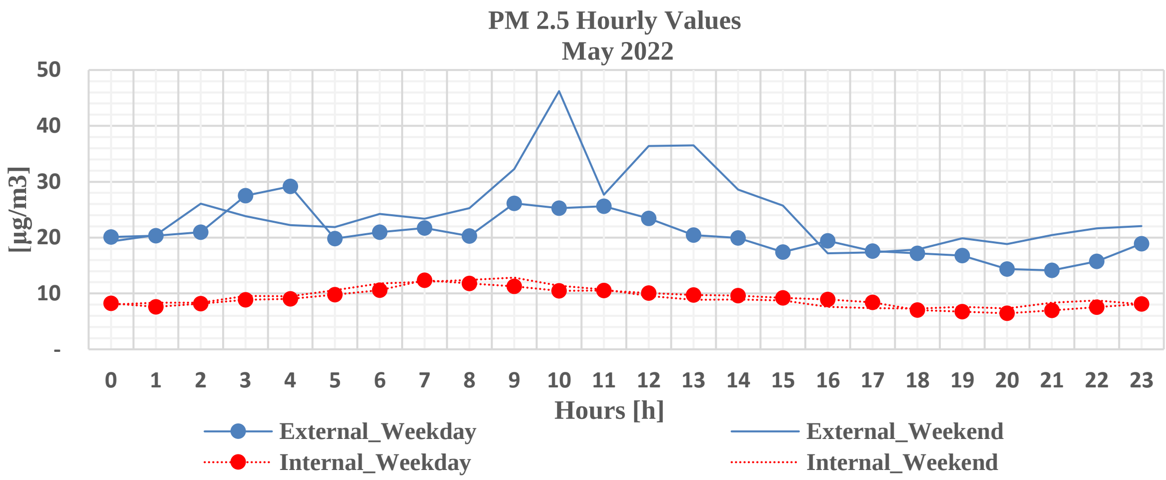


Figure 178: PM 2.5 hourly values measured by AIRCARE PRO+ during May

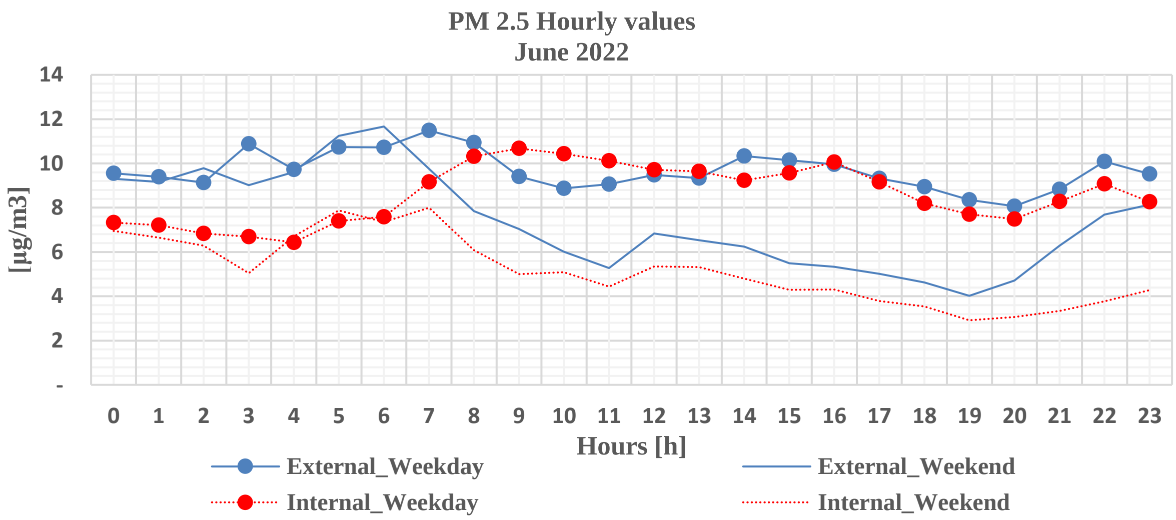


Figure 179: PM 2.5 hourly values measured by AIRCARE PRO+ during June

- The data gathered by the external sensor appeared to be higher than the internal one for the months of April and May (**Figure 177** and **Figure 178**). During the weekdays in April, there was a greater concentration of particulate matter 2.5, reaching a peak value of 46 µg/m^3 at 7:00 in the morning. In May, weekends tended to have greater PM 2.5 concentrations during the day.
- When compared to the weekend data for the month of June (Figure 179), the readings recorded during the weekdays for both the exterior and internal sensor show greater values. The external sensor's weekend peak reading of 11.67 µg/m^3 was made around 6:00 in the morning.

6.4.4 PM 10

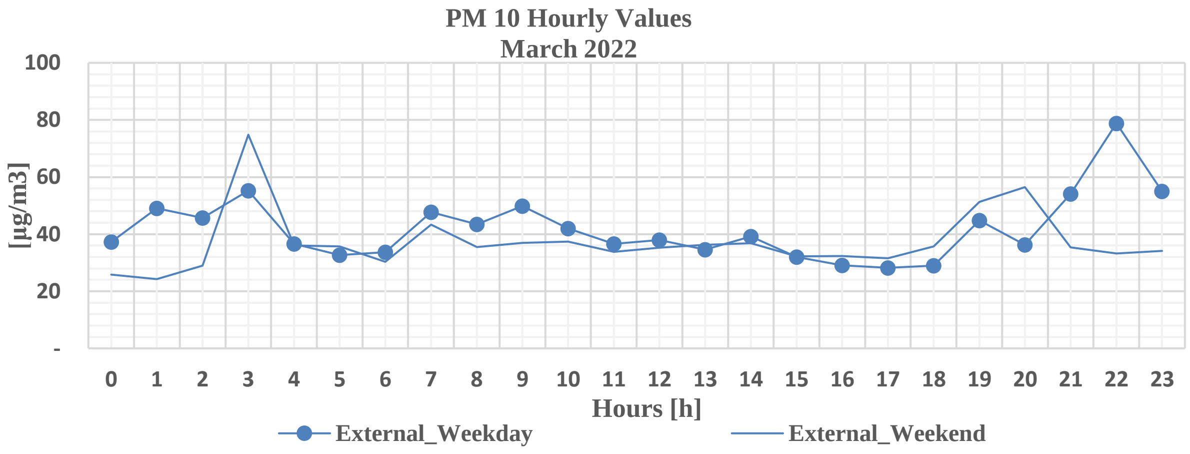


Figure 180: PM 10 hourly values measured by AIRCARE PRO+ during March

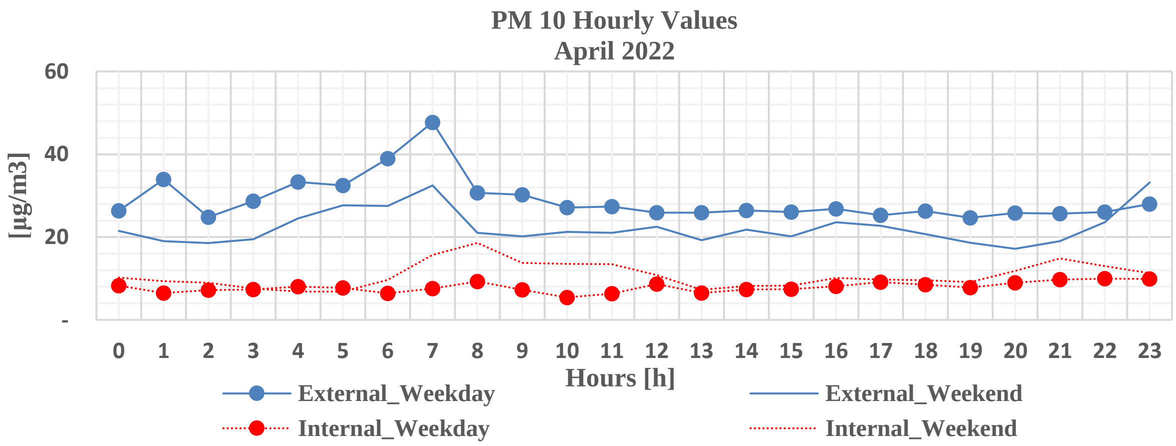


Figure 181: PM 10 hourly values measured by AIRCARE PRO+ during April

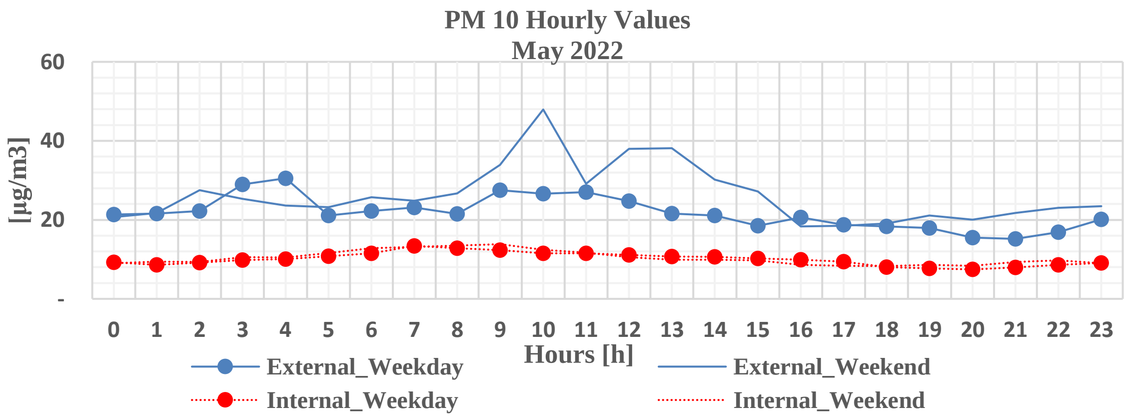


Figure 182: PM 10 hourly values measured by AIRCARE PRO+ during May

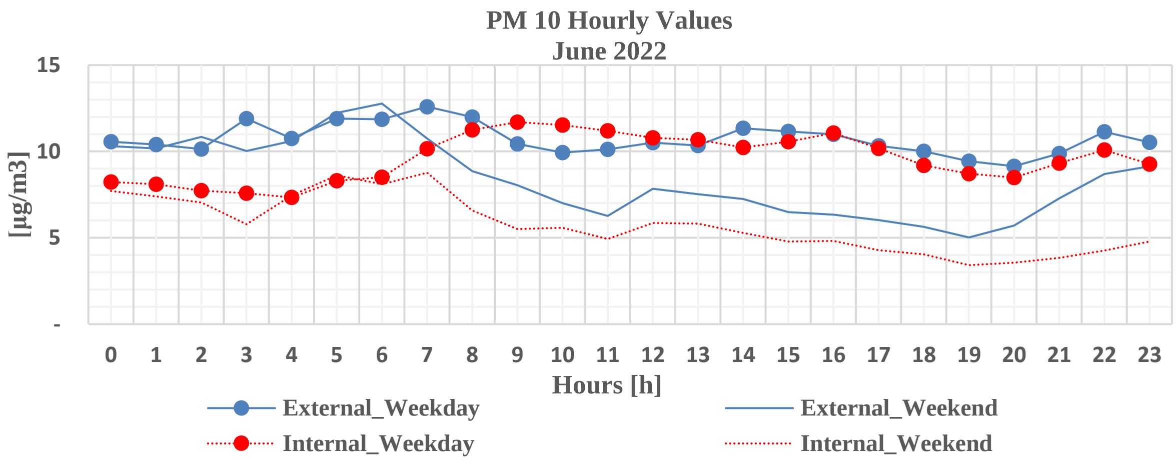


Figure 183: PM 10 hourly values measured by AIRCARE PRO+ during June

- In comparison to the inside sensor, the outdoor sensor records greater readings for weekends and weekdays in the months of April and May. For April (Figure 181), a peak value of 47.73 µg/m^3 is obtained at 7:00 in the morning for the weekdays while as a peak value of 47.94 µg/m^3 is achieved at 10:00 in the morning for the weekends for the month of May (Figure 182).
- From 12:00 p.m. until 8:00 a.m. in June (Figure 183), the PM 10 concentration appears to be greater for the external sensor. However, from 8:00 in the morning to 23:00 in the night, the weekday readings for both the external and internal sensor are higher.

6.4.5 Luminosity

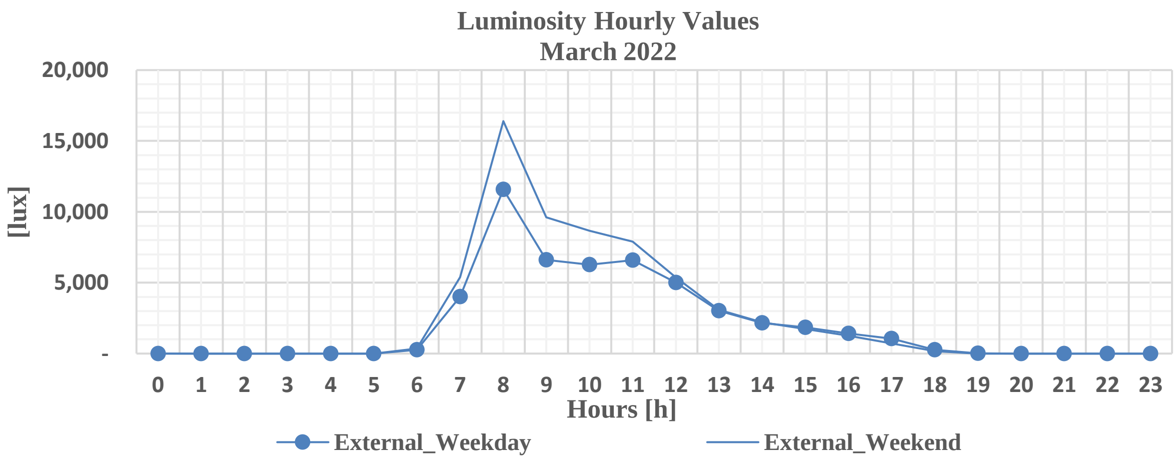


Figure 184: Luminosity hourly values measured by AIRCARE PRO+ during March

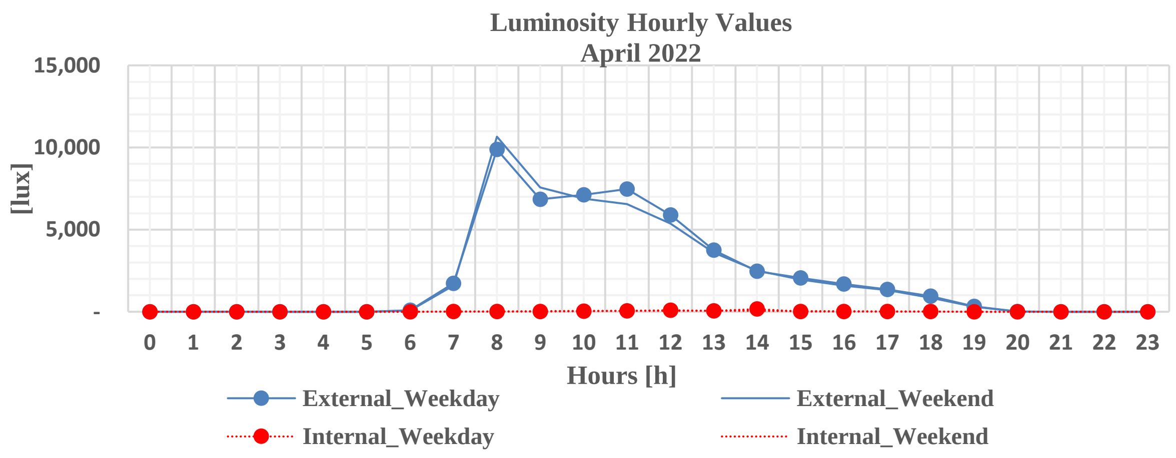


Figure 185: Luminosity hourly values measured by AIRCARE PRO+ during April

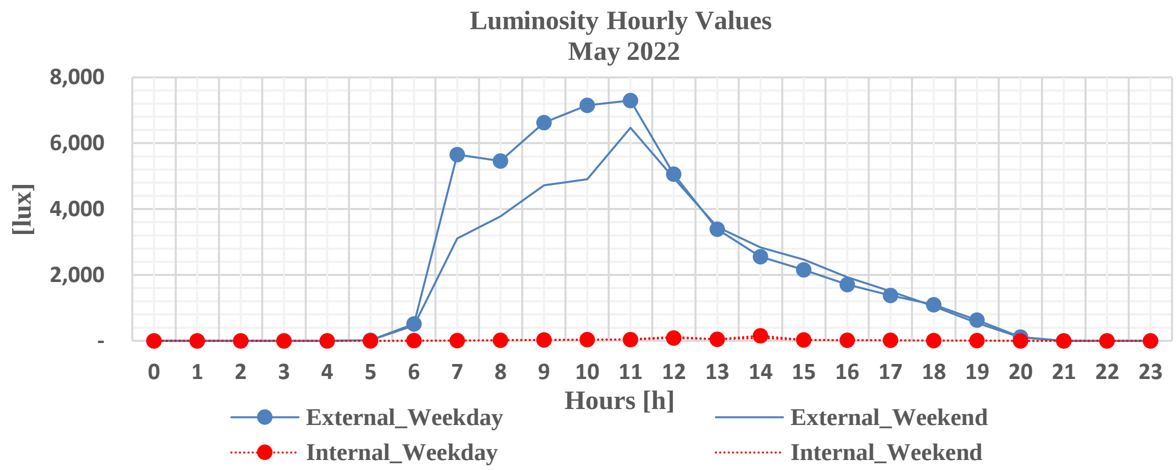


Figure 186: Luminosity hourly values measured by AIRCARE PRO+ during May

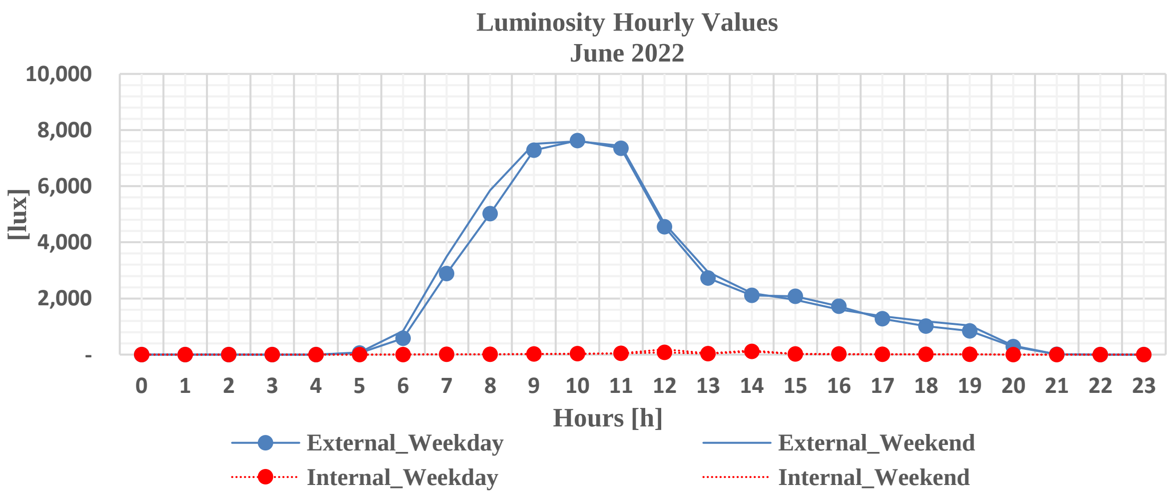


Figure 187: Luminosity hourly values measured by AIRCARE PRO+ during June

- Weekday and weekend values recorded by the internal sensor seem to be less than those recorded by the external sensor.
- For the months of March to June 2022 (Figure 184, **Figure 185**, Figure 186 and Figure 187), it was found that the luminosity values recorded by the exterior sensor were higher from 6:00 in the morning attaining a peak at 11:00 and then slow decline towards the evening 20:00, both on weekends and on weekdays.

6.4.6 CO_2 Concentration

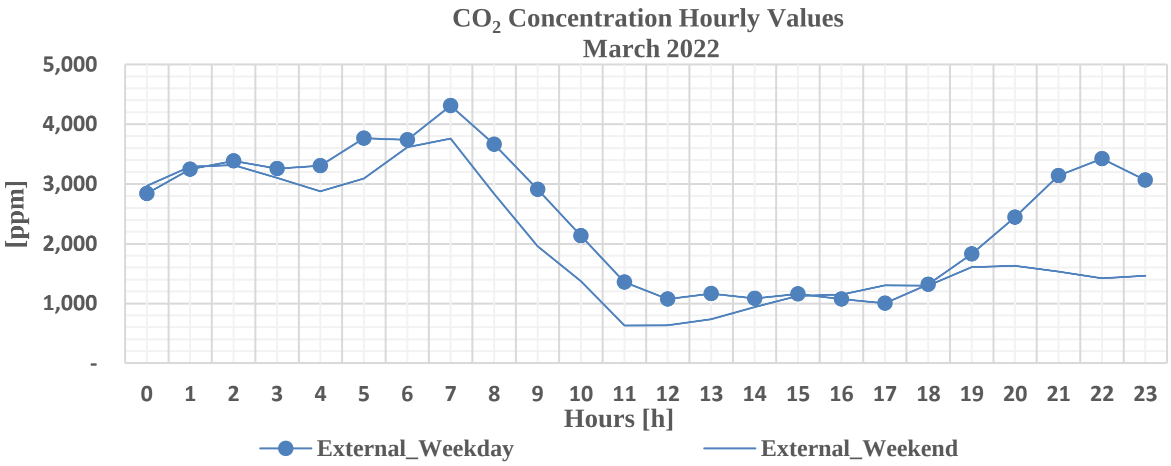


Figure 188: CO_2 concentration hourly values measured by AIRCARE PRO+ during March

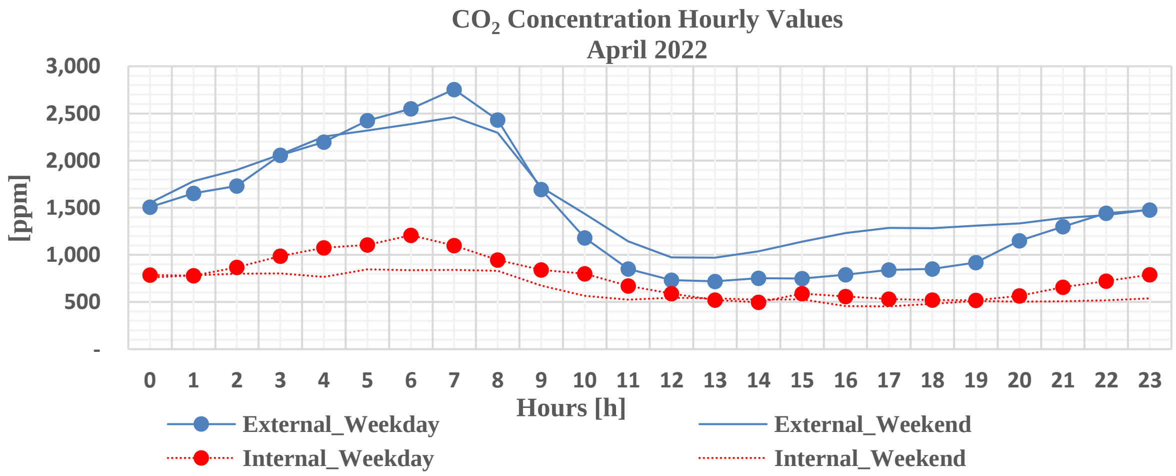


Figure 189: CO_2 concentration hourly values measured by AIRCARE PRO+ during April

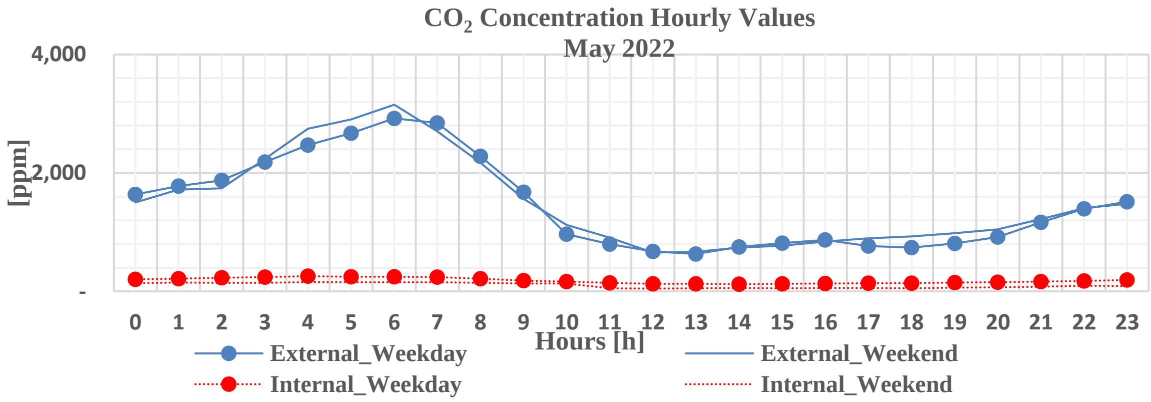


Figure 190: CO_2 concentration hourly values measured by AIRCARE PRO+ during May

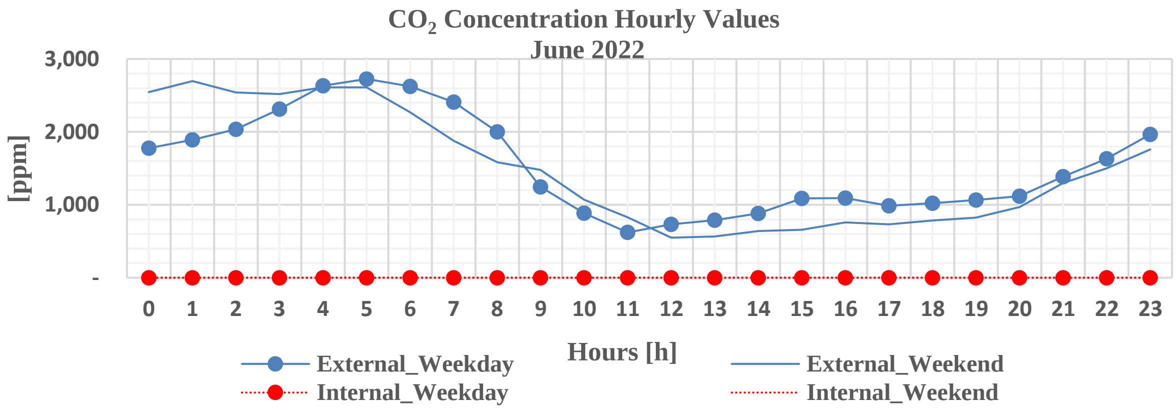


Figure 191: CO_2 concentration hourly values measured by AIRCARE PRO+ during June

- From March through June 2022 (Figure 188, **Figure 189**, Figure 190 and Figure 191), the external sensor showed that the CO_2 content was greater at night, although the inside sensor's data stayed steady during the same period.

6.4.7 Indoor air quality (IAQ)

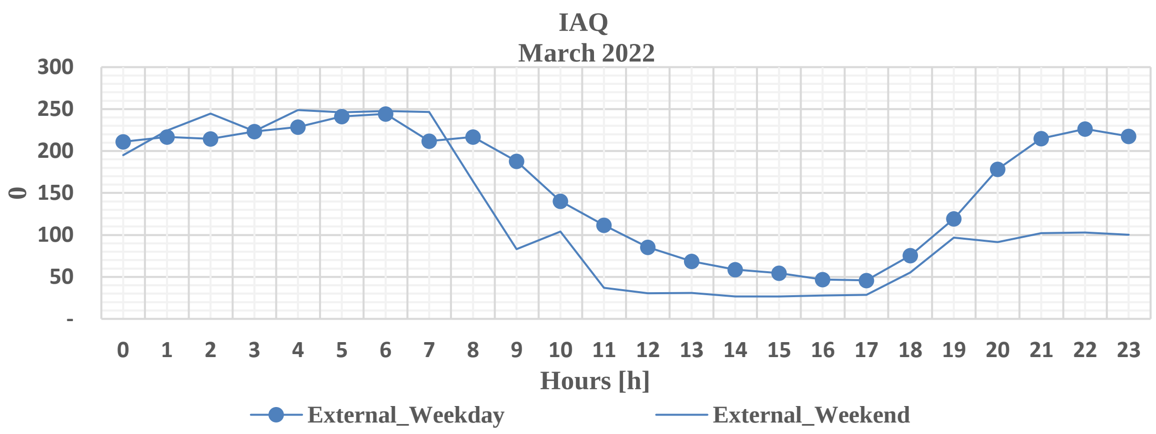


Figure 192: Indoor air quality hourly values measured by AIRCARE PRO+ during March

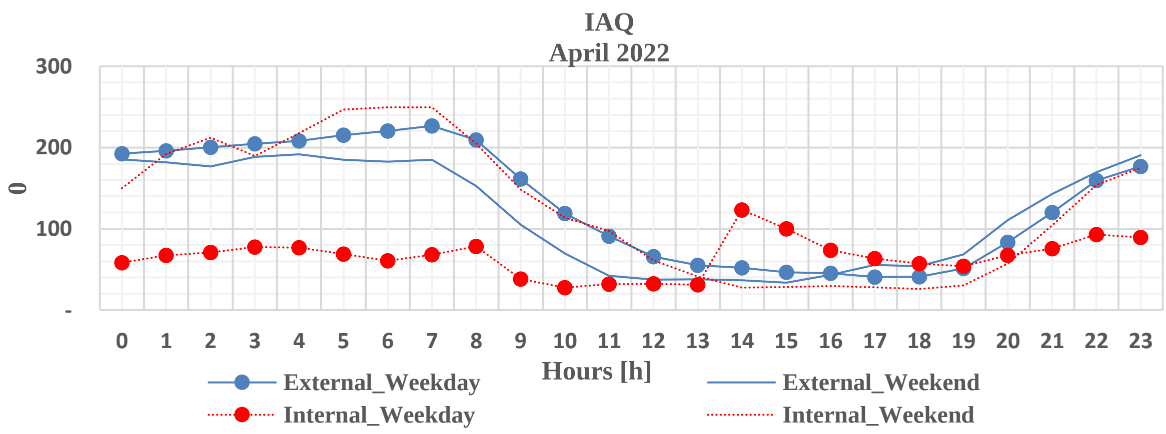


Figure 193: Indoor air quality hourly values measured by AIRCARE PRO+ during April

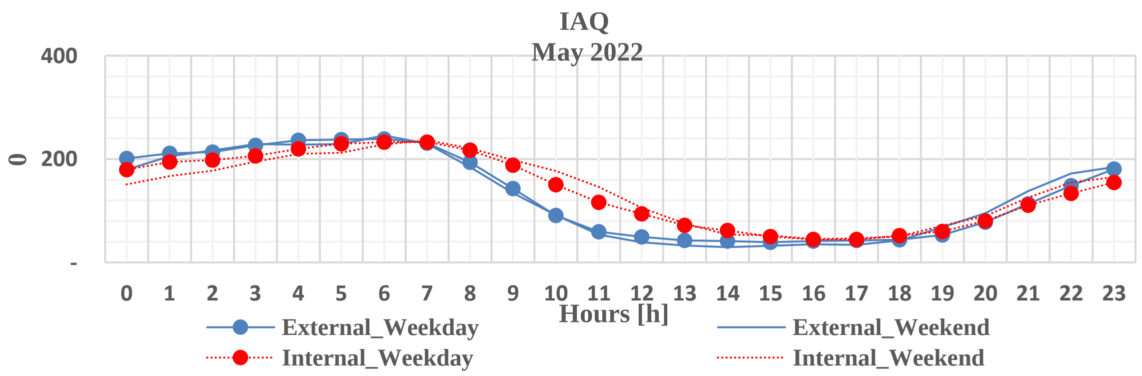


Figure 194: Indoor air quality hourly values measured by AIRCARE PRO+ during May

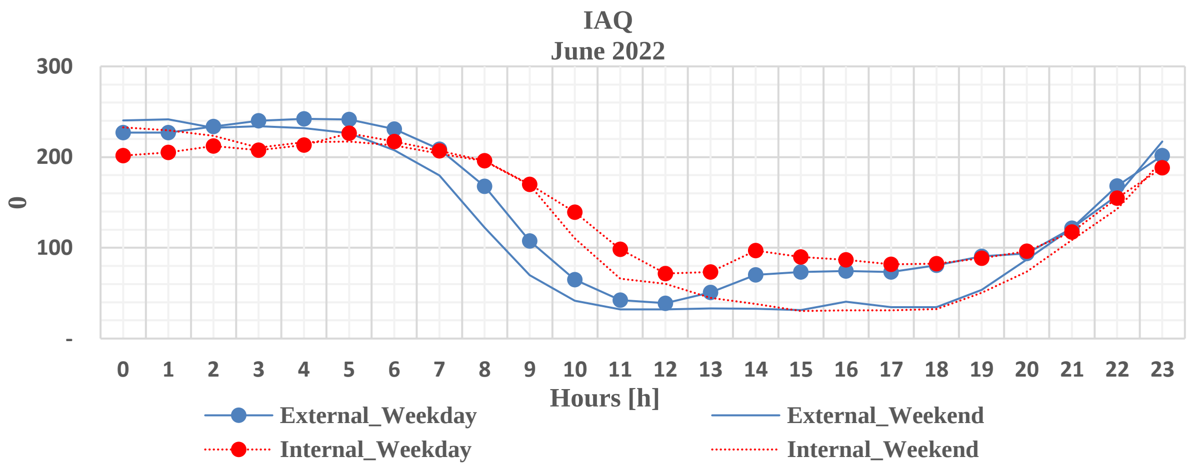


Figure 195: Indoor air quality hourly values measured by AIRCARE PRO+ during June

- The external sensor recorded better indoor air quality in April (Figure 193) than the internal one on both weekdays and weekends. However, on weekends, the internal sensor records higher IAQ readings from 14:00 to 17:00 in the afternoon.
- IAQ profiles acquired by the exterior and internal sensors show a similar pattern for the months of May and June (Figure 194 and Figure 195). IAQ measurements are taken at their highest during the night, then start to decline as daytime approaches.

6.4.8 Sound

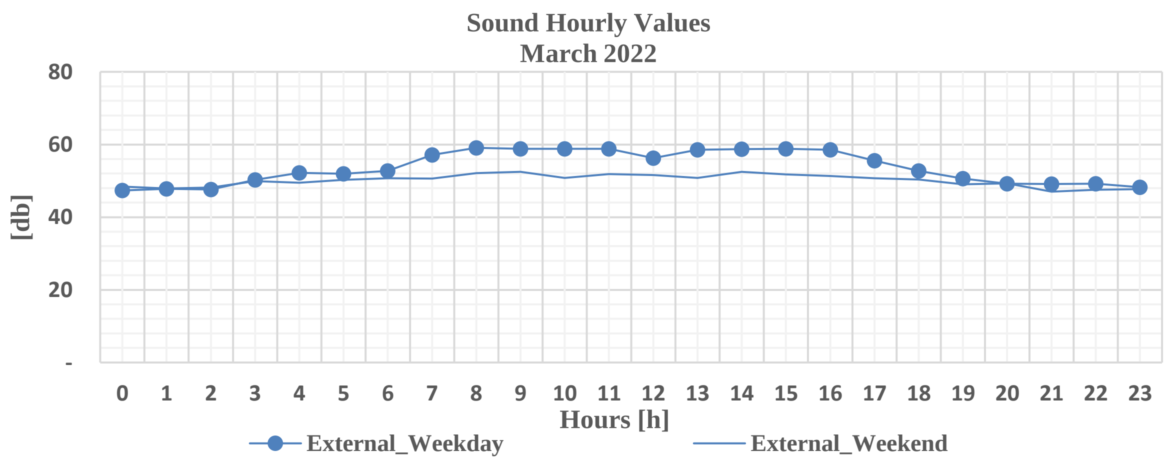


Figure 196: Sound hourly values measured by AIRCARE PRO+ during March

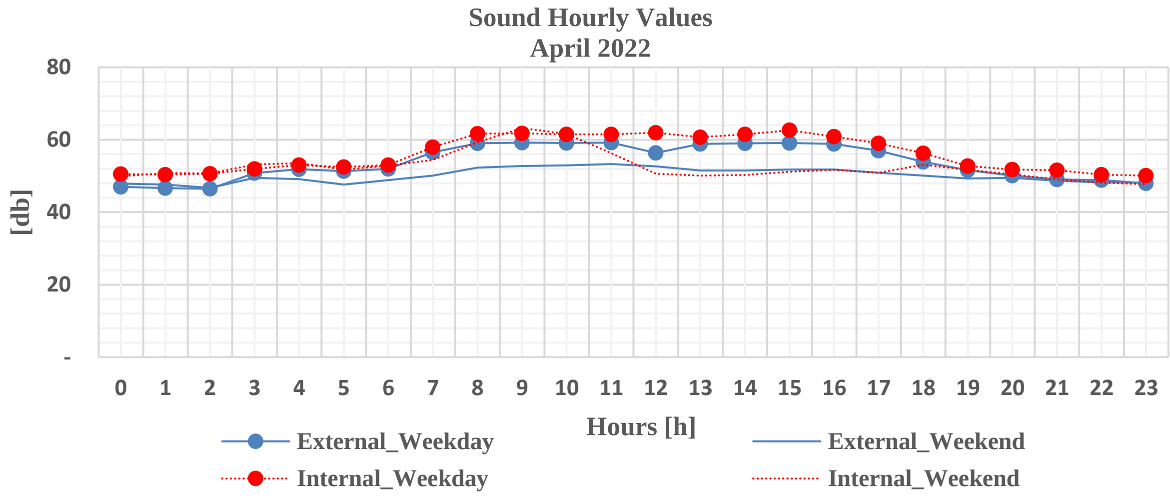


Figure 197: Sound hourly values measured by AIRCARE PRO+ during April

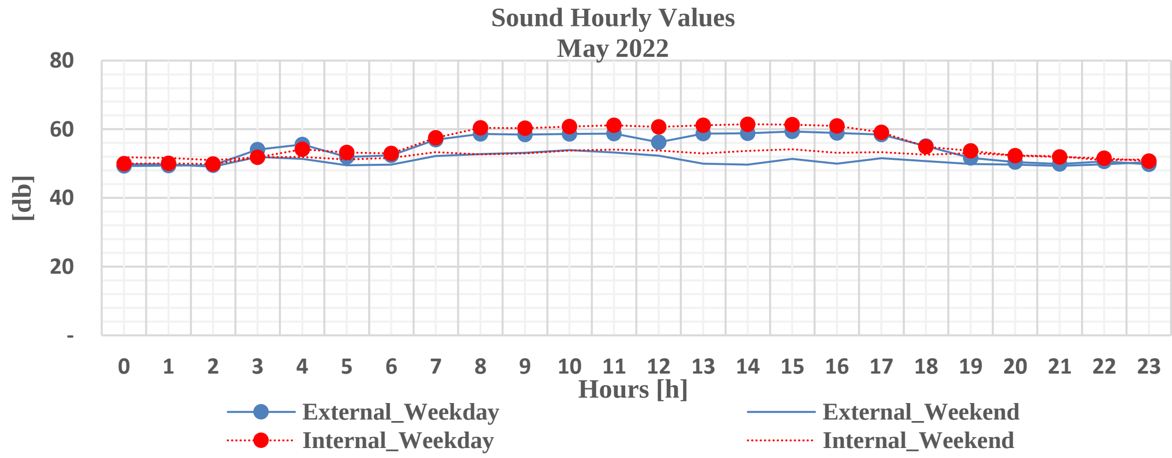


Figure 198: Sound hourly values measured by AIRCARE PRO+ during May

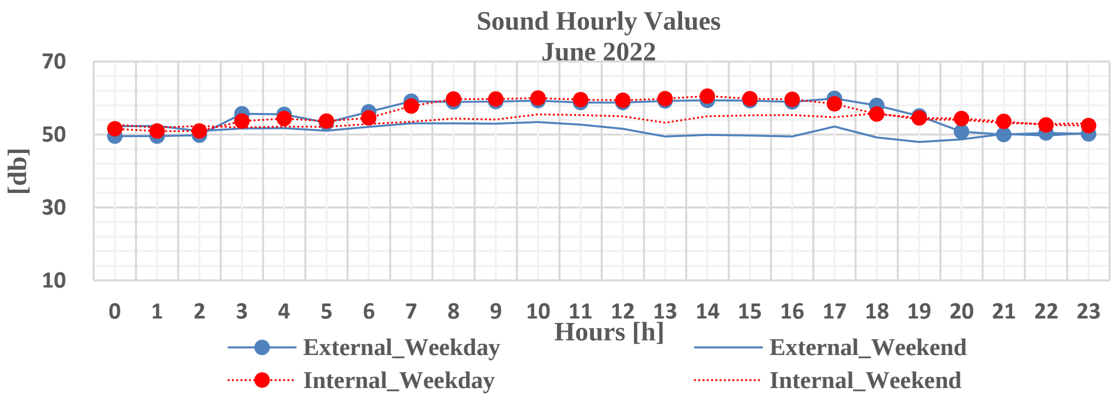


Figure 199: Sound hourly values measured by AIRCARE PRO+ during June

- The Sound profiles acquired by the exterior and internal sensors are quite similar from April to June (Figure 197, Figure 198 and Figure 199).
- The internal sensor records a peak sound value of 62.63 dB in April (Figure 197) at 15:00 in the afternoon on weekdays.

6.5 Manual devices for Living Wall System monitoring: Case Study 1 and Case Study 2

The living wall system's key performance indicators, including temperature, humidity, and air pollutants, were measured using AirCare sensors that were mounted both outside and internally to the panel. Additionally, manual devices, usually referred to as low-cost sensors, are used to capture these parameters. These devices are now widely available to the general population due to their affordable price, making them important in the field of air quality monitoring. They are increasingly being used to gather localized, real-time information of our surroundings. There are several low-cost sensors available on the market today, ranging in quality, measuring various contaminants, having various mechanisms and designs, and presenting measurements collected using a variety of metrics through various interfaces.

The records for the Air temperature and Relative humidity were taken manually with PeakTech. The Particulate matter measurements were taken manually with the help of Temptop, an air quality monitor device which measures PM2.5, PM10 and TVOC. In reference to the panel, measurements are collected from points A and B.

Point A: A distance of 1.5m with respect to the panel

Point B: A distance of 3m with respect to the panel

Figure 200: Measurement scale used to set the reference (point A and point B) with respect to the panel

6.5.1 Building 9: Temperature and Relative humidity- Comparisons for manual recordings and AirCare sensors:

The air temperature and the relative humidity measurements are taken by the AirCare sensors located externally ad internally to the panel in building 9 and 10 of Politecnico di Milano. The same measurements are taken with the potable senor or manual device PeakTech, which measure the values of air temperature and relative humidity at proper intervals of Point A (1.5m) and Point B (3m).

A cavity was made between a vertical green panel and the wall surface by installing the panel in front of the wall. A miniature microclimate with the particular thermal conditions was formed by the cavity. Based on the performance of the green panel and variations in the outside weather, the cavity's air temperature and humidity were adjusted. The indoor environment was directly impacted by these microclimatic conditions because solar radiation is absorbed by the outside surface of the building and transferred to its inside surfaces.

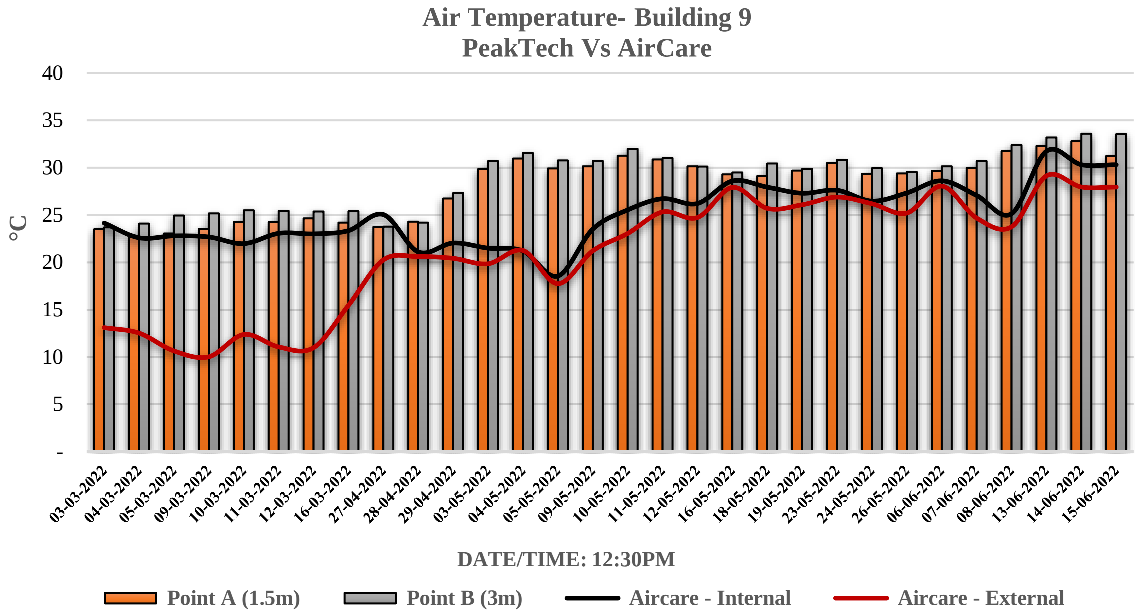


Figure 201: Comparison of Air temperature recorded manually and by AirCare Sensor of Building 9

The findings of comparing the data collected manually by the portable sensor (PeakTech) and the data collected by the AirCare sensors reveal that the manual air temperature readings made by PeakTech are greater than the readings made by AirCare sensors. As AirCare sensors are mounted on the panel, the shading and cooling effect by the plants result in the absorption of incoming solar radiation. The temperature readings at 1.5 meters from the panel are somewhat lower than the reference set at 3 meters. Due to the plants' inability to absorb solar energy, temperature rises when the measurement point is moved farther from the panel. This demonstrates a relationship between the panel size and the air temperature measurement point.

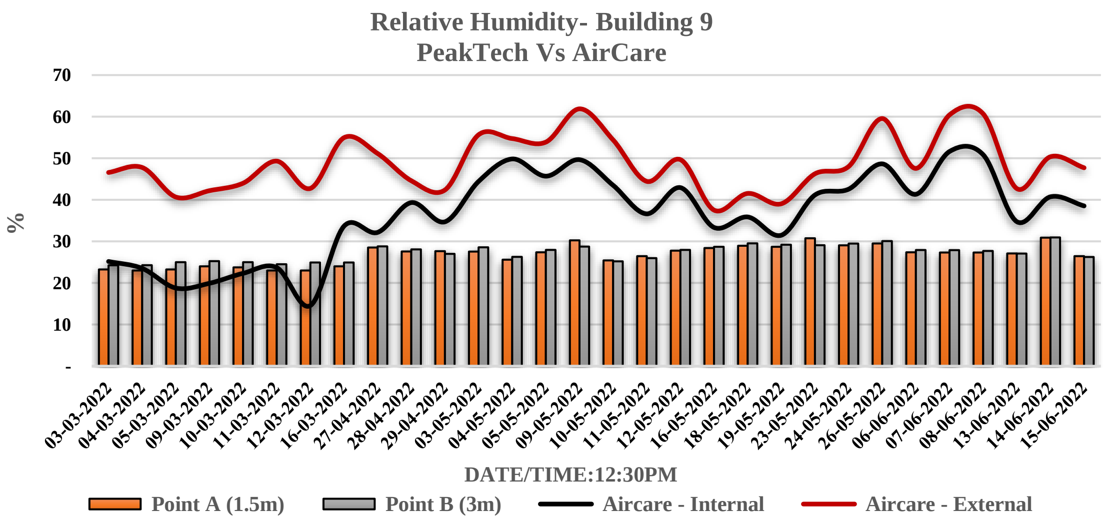


Figure 202: Comparison of Relative humidity recorded manually and by AirCare Sensor of Building 9

Humidity is one of the most important parameters in thermal comfort. The measurements of humidity gathered with the AirCare sensor and PeakTech differed significantly from spring to summer. The density of the foliage increases throughout the spring months, leading to considerable evapotranspiration and an increase in the humidity level. In summers, it gets reduced due to less foliage density and absorption of the moisture by solar radiation compared to the spring, Although there is high difference between the humidity values provided by the AirCare and PeakTech which is due to the heavy raining days in the month of June.

6.5.2 Building 10: Temperature and Relative humidity- Comparisons for manual recordings and AirCare sensors:

For building 10 the months of February and may are taken into consideration due to malfunctioning of AirCare sensors for the months of March, April, and June.

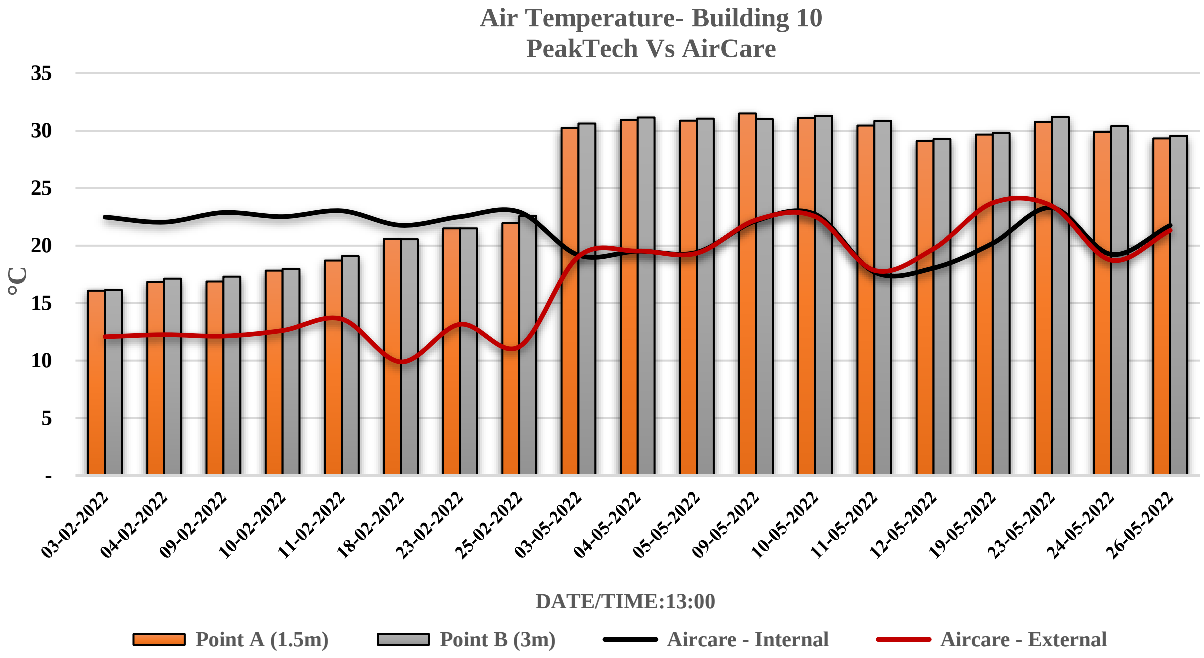


Figure 203: Comparison of Air temperature recorded manually and by AirCare Sensor of Building 10

In case of Building 10 also, air temperature values obtained from the PeakTech shows higher values compared to the AirCare sensor. Peak value of 31.3°C was obtained with PeakTech in May when the point of observation was set at 3m from the panel. In the month of May, temperature values obtained from AirCare sensor placed internal and external to the panel were approximately similar whereas in the winter month of February there is a considerable difference between the two temperature values.

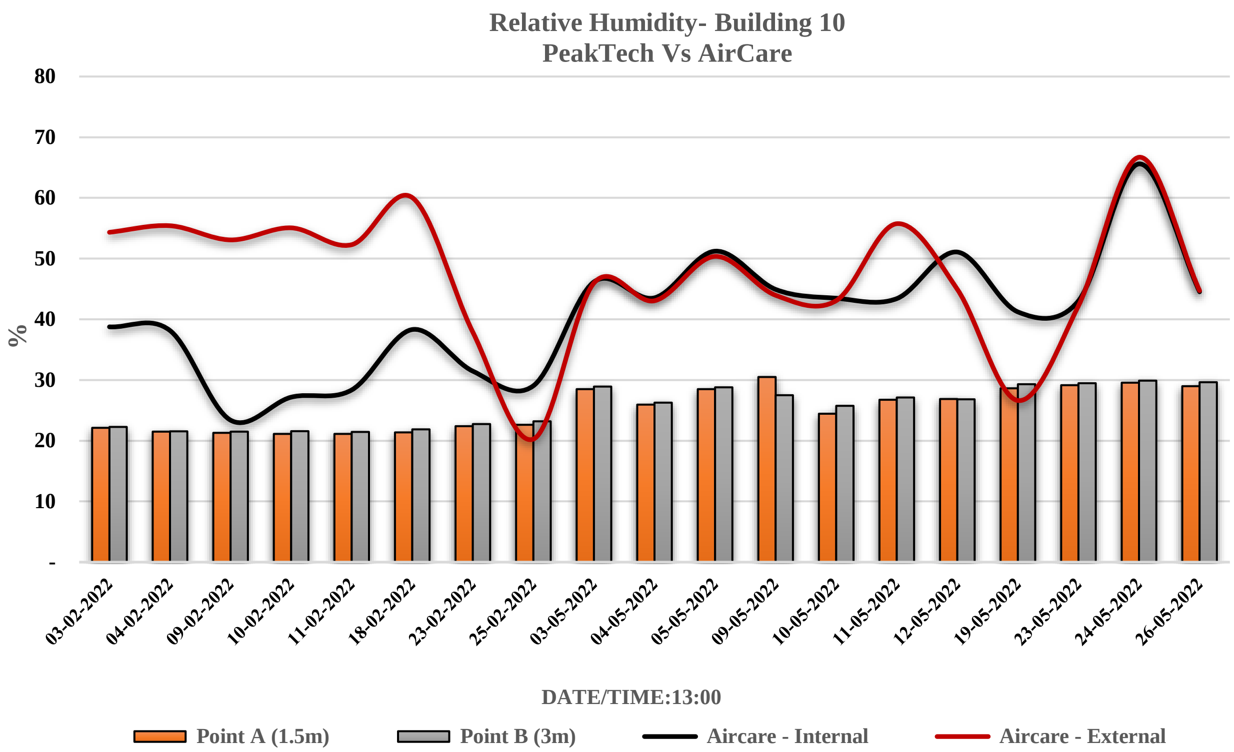


Figure 204: Comparison of Relative humidity recorded manually and by AirCare Sensor of Building 10

The data gathered manually and via sensors showed a sizable disparity in the month of February. the sensors mounted internally and externally to the panel show high values of relative humidity because of the presence of a shading from the building 10 resulting in the obstruction of incoming solar radiation. The foliage density increases as the seasons change from winter to spring, which causes the panel to begin the evapotranspiration process. The humidity inside the cavity formed between the wall and the panel also increases, which explains the behaviour of higher values of humidity recorded by sensors mounted on the panel. As the manual readings are taken away from the panel at specific reference points (1.5m and 3m), the humidity values at 1.5 values are affected by the green panel as the decrease is seen as the distance gets increased with respect to the panel.

6.5.3 Building 9 – Manual Device Temptop in contrast with AirCare sensor for PM2.5

For the months of March and April, the recordings were taken with the help of a portable sensor, Temptop for PM2.5. The data obtained was compared with the data recorded by AirCare sensors for the same months. The data taken by the manual device was recorded at 12:30 in the afternoon at points A and Point B. before taking the reading, the instrument was allowed to calibrate first.

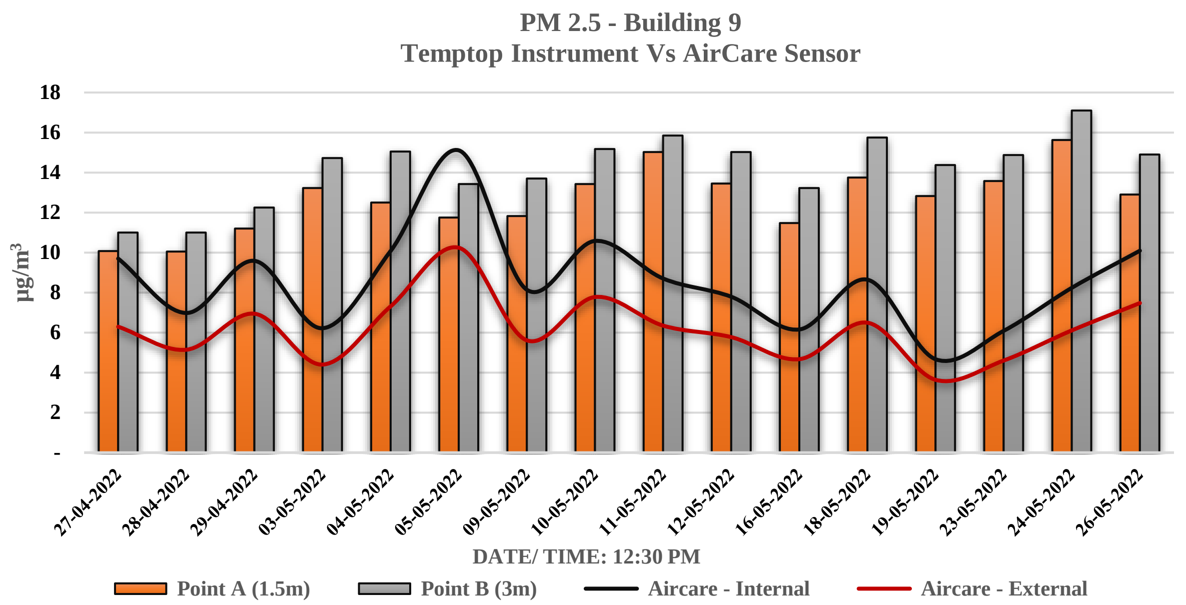


Figure 205: Comparison of PM 2.5 recorded manually and by AirCare Sensor of Building 9

From the plot, the point B, which is farthest most point from the panel, seem to have recorded the highest values of PM2.5. The highest point has been recorded on May 24, 2022, which is about 17.1 μg/m^3. The point A which is closer to panel as compared to Point B has recorded lower values of PM2.5. Therefore, the findings present in figure 1 show the effect of green wall on the surrounding air. The AirCare sensor located external to the panel also contributes towards lowering down the values. The AirCare sensor located internally, which is closest to the panel show an increased activity in the PM2.5. This can be attributed to the fact, during the spring month of April there is an increased foliage. The particulate matter present in the air get deposited and absorbed by the leaves of the plants. So, inside the panel there is an increased density of particle concentration due to which the PM levels rise.

Therefore, it can be inferred that a significant factor impacting the particulate matter concentration is the distance between the panel and the surrounding air as well as the increased foliage density in the green panel. Overall, from the plot, it can be clearly depicted that the presence of a Green Panel contributes to lowering the levels of particulate matter in the surrounding air.

6.5.4 Building 9 – Manual Device Temptop in contrast with AirCare sensor for PM10

The recordings for the Particulate Matter 10 were taken both by the manual device, Temptop and the AirCare sensors. For the manual recordings, point A and B are chosen. The data from the AirCare sensors are compared with manual recordings and the results are concluded.

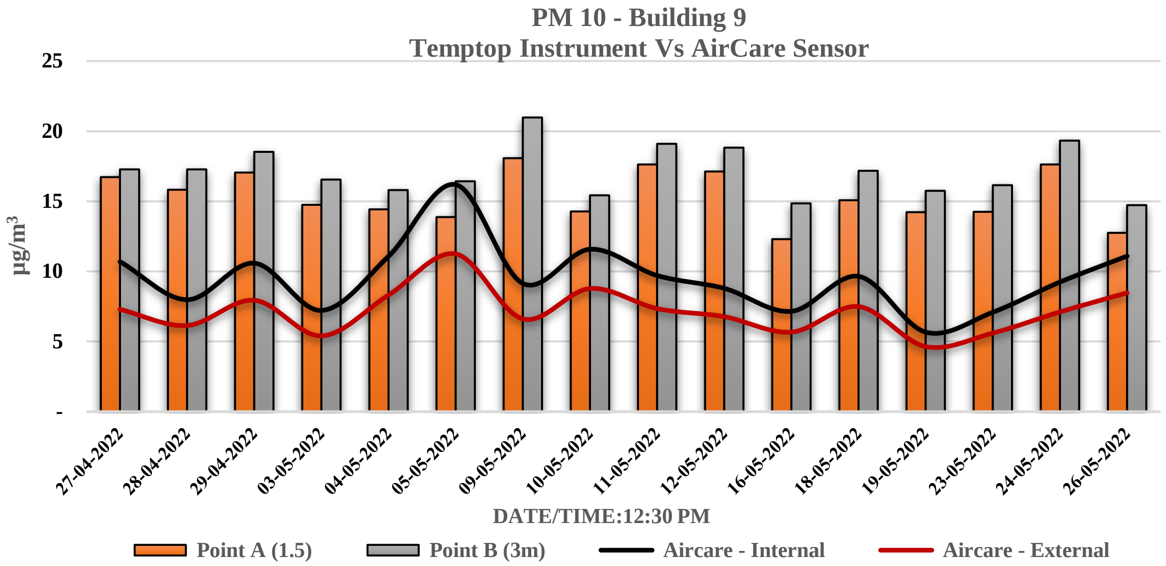


Figure 206: Comparison of PM 10 recorded manually and by AirCare Sensor of Building 9

PM10 is particulate matter in air which usually comprises of dust, smoke, particles formed indirectly from gases emitted from motor vehicles. The highest value of PM10 was obtained at point B, farthest point from the panel, closer to the street. A value of 21 µg/m^3 was recorded manually at 12:30 in the afternoon. The AirCare sensor located internally to the panel also records higher values due to agglomeration of airborne particles between the wall and the panel. The increase also results due to growth of leafage in Spring months, trap the particulate matter form the surrounding air. The point B at 1.5m from the panel show reduction in the concentration of PM10. Moreover, the externally located sensor also records lower values of particulate matter. It is observed how much the green Panel, manual devices, and measuring sensor's relative position affect PM concentrations. The results of the investigations show that green walls have a significant impact on lowering PM levels in their vicinity. Therefore, for any air quality monitoring system, the measurement location should be closely examined.

6.5.5 Building 10 – Manual Device Temptop in contrast with AirCare sensor for PM2.5

The analysis is conducted for the green panel located at Building 10 using the months of February and May. The identical process is used for Building 10 as it was for Building 9, where Point A is taken at 1.5 m from the panel and Point B is obtained at 3 m from the panel. Data from the AirCare sensors and manually collected PM2.5 data from the portable sensor Temptop are compared.

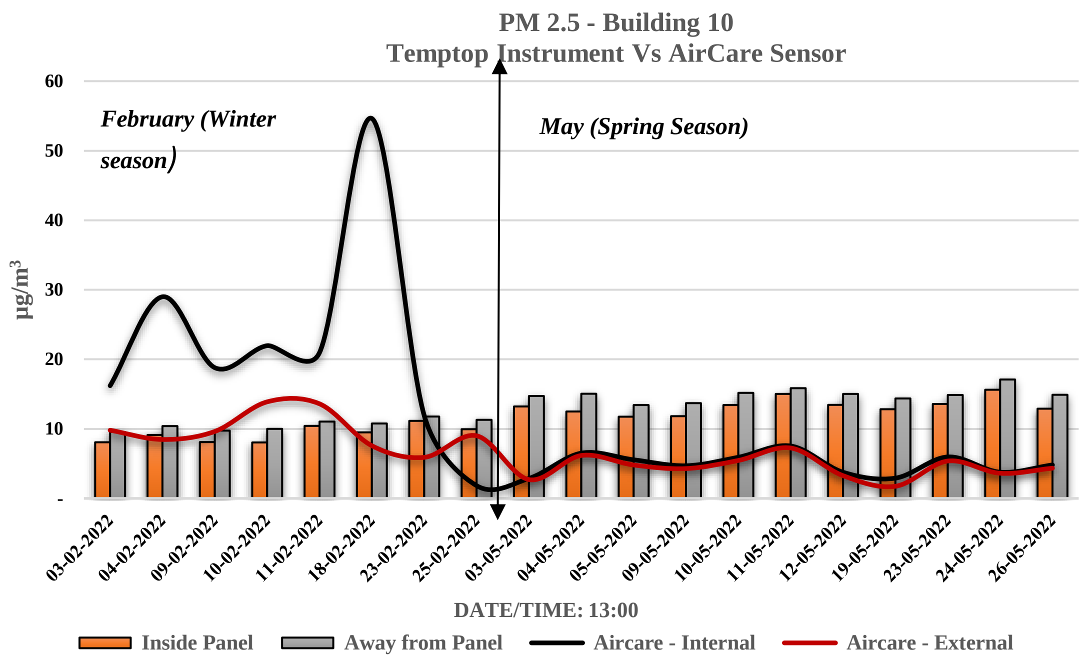


Figure 207: Comparison of PM 2.5 recorded manually and by AirCare Sensor of Building 10

It is evident from the plot that the seasonal variation has a greater impact on particulate matter concentration. The maximum peak in particulate matter concentration over the winter is 55 g/m^3, and the inside AirCare sensor recorded that value. The reason for this phenomenon is the fact that the internal sensor is located closest to the panel, which causes the air borne particles to get trapped in between the panel and the wall.

On looking at a broader perspective, the temperature also seems to affect the particulate matter concentrations. As we move from winter (February) to spring (May), the overall value of PM2.5 seems to decrease. The main reason for higher PM2.5 concentration can be attributed because of the reason of temperature inversion phenomena that happens in the winter, which induces slower pollutant diffusion. In addition to this, the smoke from chimneys and the pollutants obtained from the traffic, as the panel is closer to the street can also be the cause of higher pollutant levels during winter. The air in spring is dry and windy in Milan along with lower humidity levels during daytime. Due to winds the convective activity is increased in the surrounding air, due to which there is no inversion layer and the particles in the air are more diffused.

The reasons for the lower PM2.5 concentration at 1.5m distance from the panel is again because of the fact that there exists a corelation between the point of observation (Temptop) and the location of the panel. Depending upon the size of Green panel, it is effective only upto a specific distance, it can absorb the particulate matter in the atmosphere.

6.5.6 Building 10 – Manual Device Temptop in contrast with AirCare sensor for PM10

For the green panel situated at Building 10, the months of February and may are taken for the analysis. For Building 10 also same procedure is followed as in building 9 where point A is taken at 1.5 m with respect to the panel and point B is taken at 3m with respect to the panel. The PM10 data taken manually by the portable sensor Temptop is compared with data obtained from the AirCare sensors.

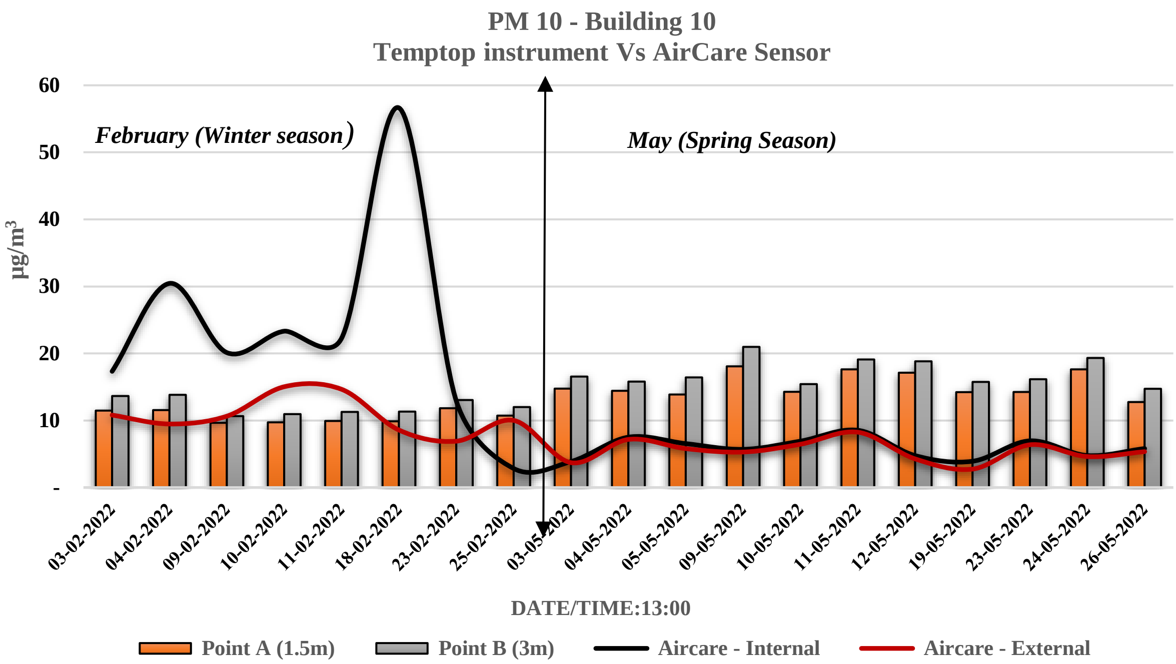


Figure 208: Comparison of PM 10 recorded manually and by AirCare Sensor of Building 10

From the plot it is clearly visible that the seasonal variation has higher effect on the particulate matter concentration. During winter a highest peak is obtained with particulate matter concentration of 56.6μg/m^3 and that too recorded by the internal AirCare sensor. The reason for this phenomenon maybe the fact that the internal sensor is located closest to the panel, which causes the air borne particles to get trapped in between the panel and the wall.

The reasons of varying particulate matter concentrations which the seasons shifts from winter to spring can be explained same as earlier, the phenomenon of temperature inversion. The same reason as mentioned earlier. Again, there is a correlation between the point of observation (Temptop) and the location of the panel, which accounts for the lower PM2.5 concentration at 1.5 m from the panel. It can absorb airborne particulate matter, but only up to a certain distance, depending on the size of the green panel.

6.6 AirCare Vs ARPA - Comparison for Particulate Matter

Particulate Matter 2.5 (PM2.5) and Particulate Matter 10 (PM10) statistics for Building 9 and Building 10 of the Politecnico di Milano were gathered from the Regional Environmental Protection Agency (ARPA). Further, comparisons were made between the data records from the ARPA and the data already acquired from AirCare pro sensors that were placed both within and externally to the panel.

6.6.1 Building 9

For comparison with the data obtained from the AirCare pro sensors, the PM2.5 data from Building 9 for the two summer months of May and June from ARPA was chosen for analysis. First, the comparison was done for the sensor that was placed internally, and then for the sensor that was placed externally. The comparison was done to determine how the living wall systems (LWS) will affect the surrounding environment.

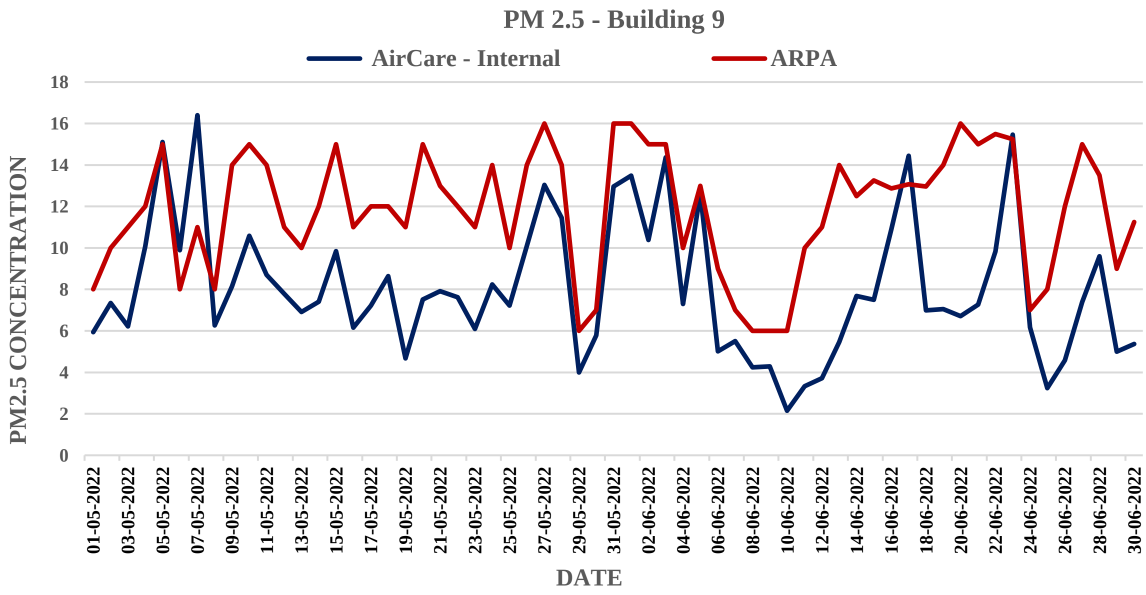


Figure 209:A study of PM2.5 Daily Average Values (AirCare Internal Vs ARPA)

The comparison above Figure 209, demonstrates that the internal AirCare sensor's average daily measurements of particulate matter 2.5 (PM2.5) are lower than the information gathered by the ARPA (Milano Pascal Citta' Studi). The AirCare sensor does, however, capture peaks at a few days. The AirCare sensor reported a maximum value of 16.4 µg/m^3 on May 7, 2022, but the ARPA sensor recorded a maximum value of 16 µg/m^3 over several days.

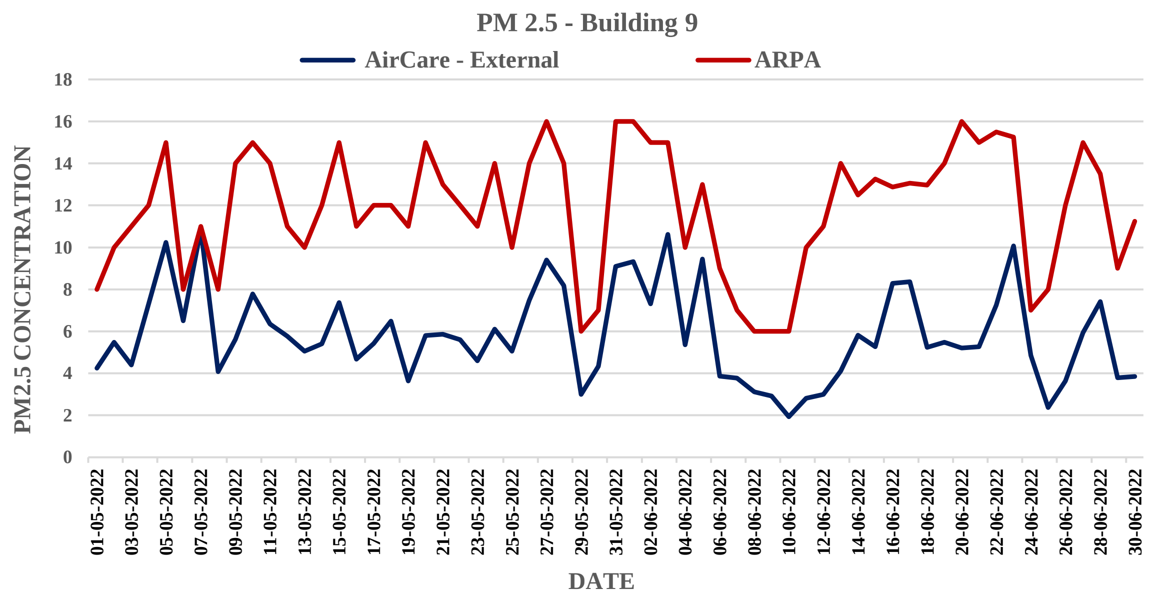


Figure 210: A study of PM2.5 Daily Average Values (AirCare External Vs ARPA)

The identical response is recoded for Figure 210, where it can be observed that the average daily values for the AirCare sensor that is mounted externally are lower. No peaks are recorded here by the sensor, as can be seen in the AirCare Internal vs. ARPA plot. The data that the ARPA (Milano Pascal Citta' Studi) recoded looks to be significantly higher, indicating that there are more Particulate Matter Concentrations in the surrounding area. The AirCare sensor reported a maximum value of 11 $\mu g/m^3$ on May 7, 2022.

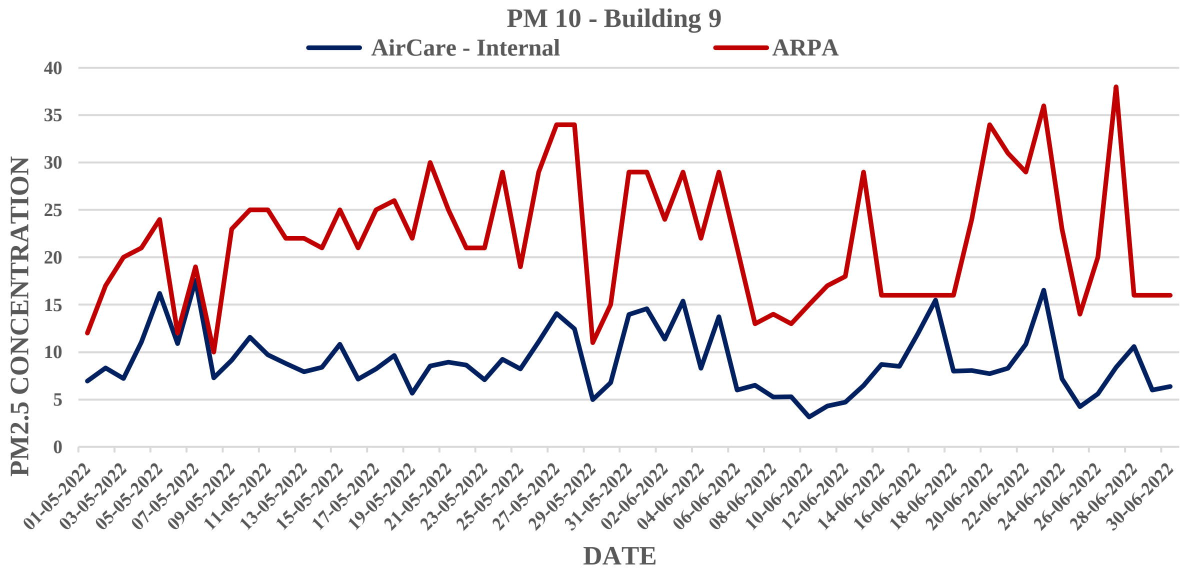


Figure 211: A study of PM10 Daily Average Values (AirCare Internal Vs ARPA)

The same response has been observed for PM 10 (Figure 211), where the average daily readings acquired from the internal AirCare sensor are lower than the values recoded by the ARPA

(Milano Pascal Citta' Studi). While the AirCare sensor recorded a peak value of 19 μg/m^3 on May 7, 2022, ARPA reported a peak value of 38 μg/m^3 on June 27, 2022.

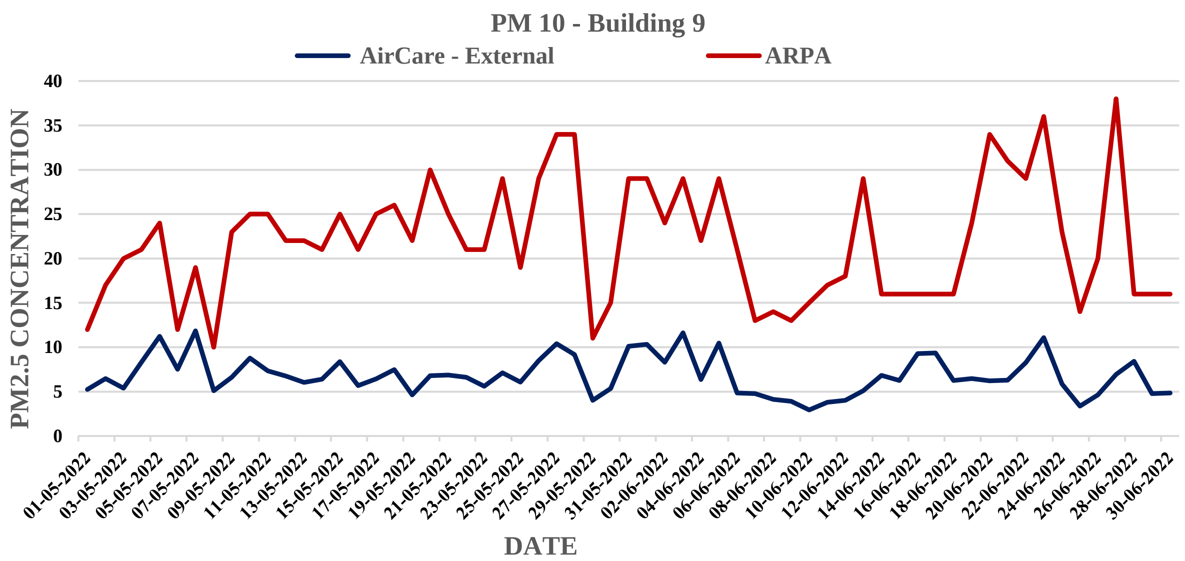


Figure 212: A study of PM10 Daily Average Values (AirCare External Vs ARPA)

We draw the conclusion that the overall average daily values of PM 2.5 and PM10 were recorded lower by the AirCare sensors based on the plots of AirCare (internal and exterior) vs. ARPA (Milano Pascal Citta' Studi). The ARPA's real-time data collection reveals increased concentrations of PM 2.5 and PM10 in the area where it is situated. The two summer months of May and June where the data is adequate and when the plants growing in the panel are in full bloom, were chosen for the analysis. This study, conducted with the use of installed AirCare sensors and ARPA, demonstrates that plants can reduce the amount of particulate matter in the environment, which can be seen in all the graphs. The placement of the AirCare sensors both internally and externally to the panel accounts for the lower PM concentration in the area around the panel's perimeter.

6.6.2 Building 10

A comparative analysis between the data obtained from the ARPA (Milano Pascal Citta' Studi) and the AirCare sensors (Internal and External) was performed for building 10. The internal AirCare sensor is considered when making a comparison with ARPA for the months of January and February. The months of February and March have been considered, along with the externally located AirCare sensor for the comparison with ARPA. Due to enough and full data being recorded for these specific months, without any sensor malfunction, these months have been chosen.

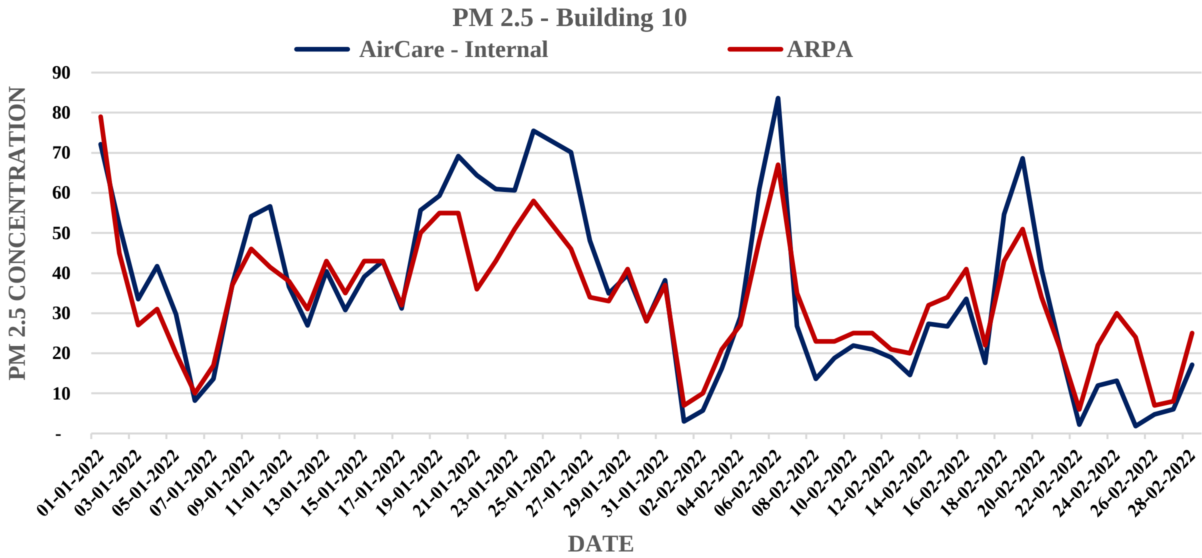


Figure 213: A study of PM2.5 Daily Average Values (AirCare Internal Vs ARPA)

Since the panel on Building 10 is located closer to the main road, higher PM10 and PM 2.5 concentrations were anticipated. The readings of the internally situated AirCare sensor for the months of January and February appeared to be nearly comparable to the values taken by ARPA (Citta Studi), according to a comparison plot of PM 2.5 measurements (Figure 213). However, some peaks were recorded for the AirCare sensor's daily average values. The inside AirCare sensor's reading of 84 µg/m^3 PM2.5 on February 7, 2022, was the highest ever recorded. On January 1, 2022, ARPA measured the PM2.5 concentration at a reading of 79 µg/m^3 that was closer to the AirCare sensor.

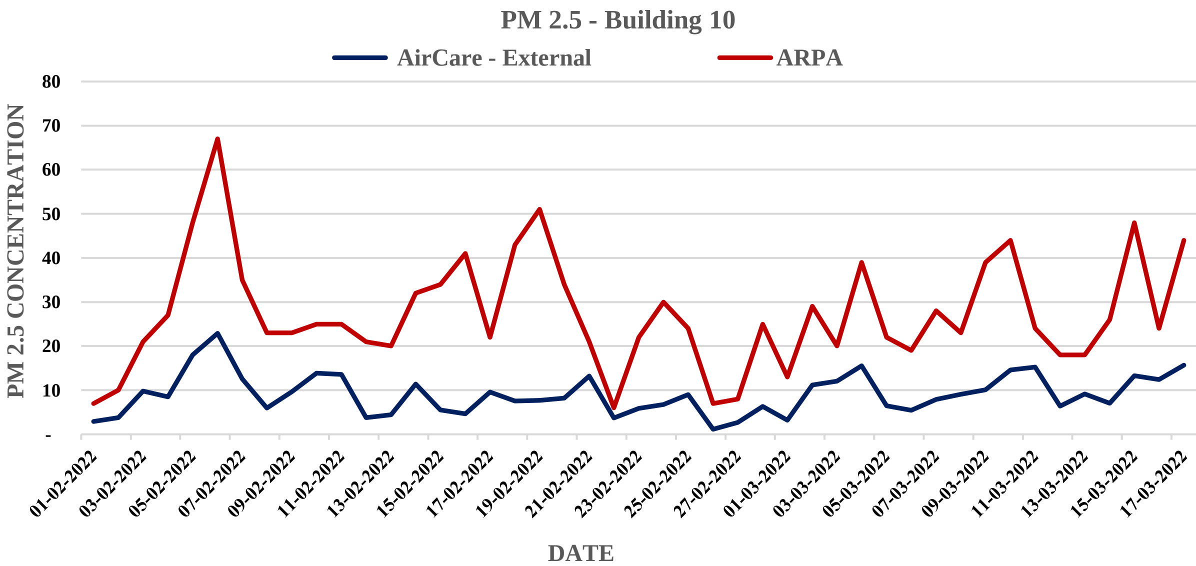


Figure 214: A study of PM2.5 Daily Average Values (AirCare External Vs ARPA)

The daily average values recorded by the externally situated AirCare sensor appeared to be lower than the values of ARPA (Figure 214) for the months of February and March, according to a trend that was noticed. On February 6, 2022, a peak value of 67 µg/m^3 was collected from the ARPA.

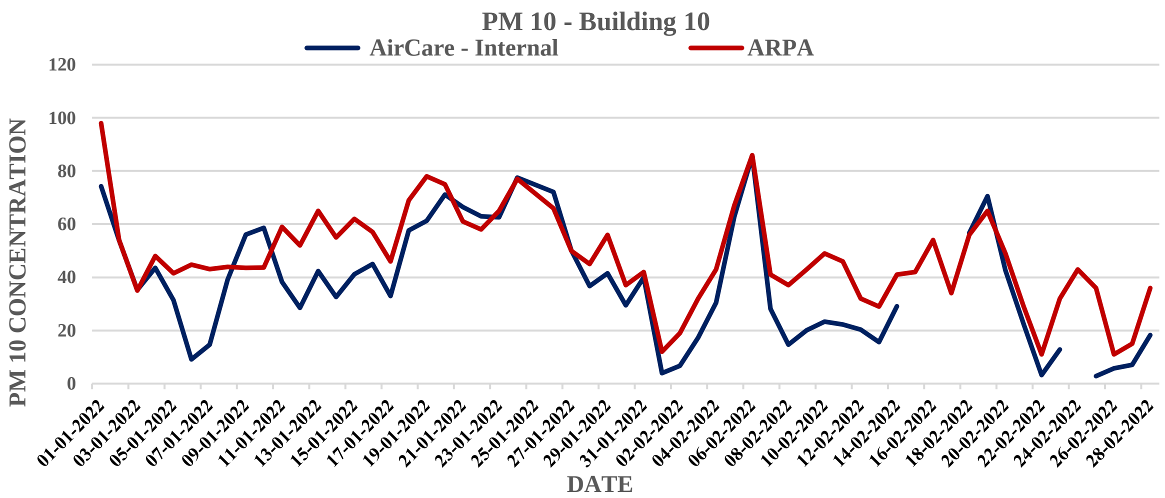


Figure 215: A study of PM10 Daily Average Values (AirCare External Vs ARPA)

When compared to the measurements made by ARPA, the internal AirCare sensor displays reduced PM10 readings. However, there are several locations where the values displayed by ARPA and AirCare are fairly comparable. This might be explained by the fact that plants don't bloom as much in January and February as they do in spring and summer. The plants are typically dormant in the winter, which reduces their ability to absorb airborne particulate particles (Figure 215).

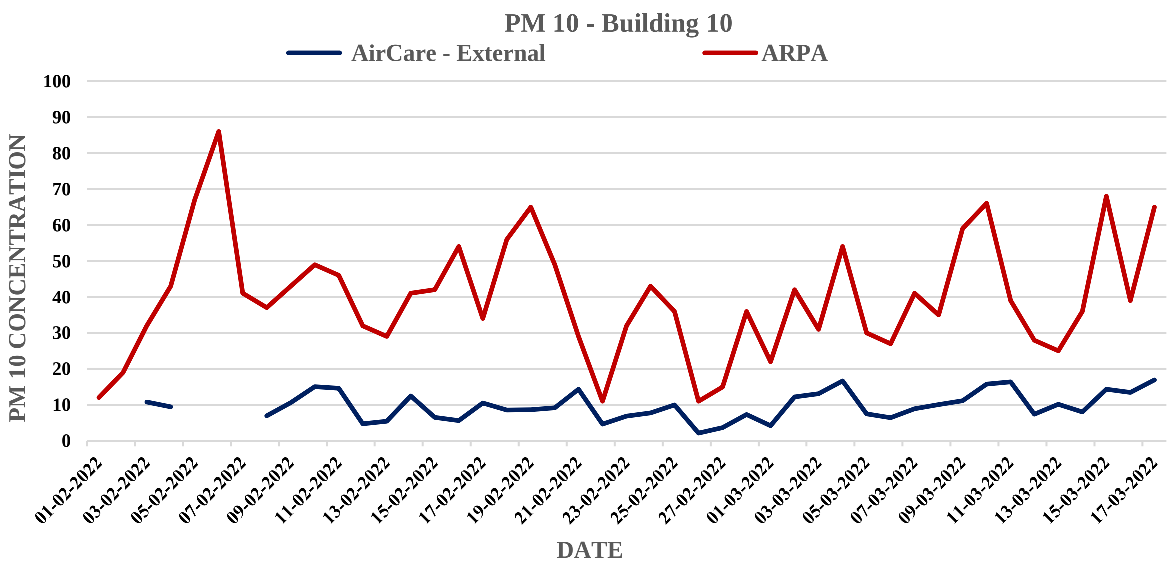


Figure 216: A study of PM10 Daily Average Values (AirCare External Vs ARPA)

For PM10 (Figure 216), the values recorded by the ARPA appeared to be higher than the values measured by the externally located AirCare sensor. this can be explained by the behaviour that that the plants installed on the panel of Building 10 absorbs the particulate matter present around the panel. The records taken by the ARPA were higher as the sensor is placed in the busy area of Citta Studi.

7 CONCLUSION AND RECOMMENDATIONS

The EU's biodiversity policy for 2030 is a thorough, ambitious, and long-term strategy to preserve the environment and stop ecological degradation. The strategy includes concrete promises and activities that are meant to put Europe's biodiversity on a path to recovery by 2030. The installation of green walls is one of the key elements of biodiversity project .It is alluring to picture the green metropolis of the future, where tall human structures seamlessly incorporate a diverse flora. In this scenario, the city is home to native wildlife species; the air is clean, and the scenery calms the mind with characteristics that are now only found in natural reserves. This report discusses some of the initiatives leading this shift, which is necessary for this utopian portrayal to become reality. The purpose of this thesis was to gather data about Living Wall System (LWS) using a range of methods and equipment, as well as information about their use and support systems, as well as information about how they are used in various climate areas of Milan, Italy: Politecnico di Milano and Brescia and Nicosia, Cyprus. The following conclusions were drawn about the behaviour of environmental characteristics (temperature, humidity, and sound) and Air Quality (PM 2.5, PM 10, and Volatile Organic Compound)

- One of the factors in lowering the air temperature is the Living Wall System. The plots produced demonstrate that the ability of the plants to offer cooling causes the internally mounted sensor to record lower values when compared to the exterior one. Thus, planting is an effective strategy to lessen urban heat islands because plants help cool the surroundings.
- One of the key environmental factors affecting human comfort is humidity. For all of the case studies from 1 to 4, the internal sensor's readings of humidity reveal a similar pattern of greater humidity levels inside the panel and decreasing humidity toward the external environment. The evapotranspiration process inside the panel increases the amount of moisture, which results in high humidity levels. However, this amount must be kept within a specified range, or it could have negative effects.
- The assessment revealed that the building would benefit acoustically from the Living Wall technology. The sound absorption was higher in the spring and summer when plants possess their full foliage. Due to inadequate foliage density in the plants, the

sound absorption during the winter months were lower than summer. To benefit from the living wall system during winter season, proper consideration needs to be taken, the specific type of plants (that gives a good bloom) to be planted in winter.

- The study suggests, in terms of particulate matter, the Living Wall System performed better. Since the case studies were situated nearer to the roadways, higher particulate matter concentrations were anticipated. A significant decrease in the amount of particulate matter surrounding the panel was seen by maintaining the reference as ARPA (Milano Pascal Citta' Studi. When the particle matter accumulates on the surface of the leaf, wind or rain will eliminate it. The impact was more pronounced in the summer since there were more leaves and more PM accumulated on them.

The sensors and manual instruments need to operate correctly in order to monitor environmental and air quality indicators with great efficiency. In every case study, the sensors failed to record 100% of the data, and blank values were discovered at several times. This happens as a result of instruments failing due to exposure to diverse environmental changes. This has a stronger impact on the outcomes. Therefore, appropriate measures should be adopted going forward to ensure constant and accurate data monitoring by sensors and devices.

8 LIMITATIONS

Although green facades offer a lot of potential, it is unclear that they will be able to control interior building temperatures across all cities, climates, building types, and heights above ground. Better experimental replication and the validation of modelling studies are required to enhance research design. We still need to learn a lot more about how different climbing support arrangements affect plant growth, how substrate, container, and irrigation system designs affect the effectiveness of green facades, and how varied air cavity widths affect how well double-skin green facades insulate. Researchers should make sure that complete descriptions of key elements of green facade design are reported as a first step. By doing this, it will be possible to arrange studies according to these design characteristics as well as climatic region. It is critical that we standardize our methodology for measuring the microclimatic characteristics of green facades and develop a deeper understanding of the climbing plant layer in order to identify the plant morphological and physiological features relevant to green facade thermal performance. Green facade energy-saving benefits may be quantified, and efforts should focus on heating and cooling in mild and temperate areas (Europe), suffering from energy crises. Already, green facades are being included for aesthetic purposes into new building designs. When their efficiency in controlling internal building temperatures has been quantified for particular climatic regions and building aspects, when the best designs for green facade elements have been developed, and when the essential plant characteristics influencing thermal performance have been identified, there will be an increase in adoption.

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