IMPACT OF GREEN WALLS ON INDOOR AIR HUMIDITY

A case study of a medium-sized office building in Malmö, Sweden

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Master thesis in Energy-efficient and Environmental Buildings,
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Lund University

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The degree project is the final part of the master's program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

This thesis presents a case study of an indoor Green Wall (GW) installed in an office building in Malmö, Sweden. The study analyzed the effect of the GW on air humidity during low temperature and dry moisture outdoor conditions. The objective was to determine the green wall's indoor humidity contribution while enabling an adequate comparison *before* and *after* the GW installation, which requires defining an appropriate space to evaluate. Regarding temperature, humidity, and airflow variations, the office performs as a controlled system that employs an air handling unit (AHU) with an efficiency of up to 90% of humidity recovery (HR). The measurements began in September 2021 and ended 27 weeks later, in April 2022. The data was collected and recorded using sensors previously installed at different points of the office, which were also helpful in identifying the humidity variations according to the proximity of the measuring devices to the GW installation. Subsequently, an analysis was carried out in different phases using Excel. One week of data-record represents the case conditions *before*, while three weeks represent the conditions *after* the installation. By establishing a similar scenario to compare, the measurements *before* and *after* GW installation were compared with each other, conducting a further discussion. In addition, a brief assessment focused on Carbon Dioxide (CO_2) emissions was carried out to suggest a potential environmental reduction in a real-life building. The accuracy of the measurements was assessed by installing additional sensors in the office and AHU to compare the data collected from the ventilation sensors already found in the site study. Even though a few limitations were identified and described in this thesis, the results suggested that the GW installation positively impacts indoor humidity. The conclusions from this study are expected to lead us beyond further analysis in favor of indoor moisture content and building occupants' well-being.

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Abbreviations and symbols commonly found

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers

BBR - Boverket's Building Regulations

A_{temp} - Heated floor area

AHU - Air Handling Unit

GW - Green wall

HRE - Humidify recovery efficiency

U-value - Heat transfer coefficient

OA - Outdoor air (fresh air)

xOutdoor - Vapor ratio measured in the air that is collected from the outdoor

xRoom - Vapor ratio measured in the indoor air

xSupply - Vapor ratio measured in the fresh air after the AHU's action

xExtract - Vapor ratio measured in the air that is removed from the room

xExhaust - Vapor ratio measured in the air that is released into the outdoor

(xRoom – xSupply) - Vapor ratio difference between the room(indoors) and supplied air

A= area

T = temperature

AH= Absolute humidity / (g_{water} / kg_{air})

RH= Relative humidity / (%)

Definitions

Office building – A building for no residential purposes but for executive/business purposes.

Heated floor area –The building floor area where the temperature is controlled and heated to more than 10 °C, according to BBR.

Service area – Area in the building represented by corridors, toilet areas, service rooms, elevators, and staircases, etc.

Table of content

1 Introduction

This chapter presents background information, which shortly describes the necessity for this study. A detailed literature review, which hints at what has been done on the subject and prospects, is also included. Subsequently, the general objectives are presented. In addition, specific limitations that serve as the basis for this thesis are stated since they must be considered throughout the case study performed in an office building. The study described in this thesis has been conducted to analyze the hygrothermal effect of a Green Wall. In a similar vein, this study evaluates the green installation's contribution to indoor humidity. The research aims to contribute to environmental building design and indoor air quality field. The expected outcomes from this thesis are to provide evidence of the GW's humidity contribution while setting reasonable boundaries to compare more accurately the performance *before* and *after* the green installation. This thesis strives to go further in knowledge about humidity and initiate discussion about green walls, leading to more investigation into indoor humidity and occupants' well-being.

1.1 Background

In the last few years, changing lifestyles have increased energy consumption (European Commission, 2019). Building energy-efficient design started to become a significant trend ongoing for over three decades among governments, architects, and engineers worldwide, perhaps, only recently strengthened by a more profound awareness of climate change and environmental challenges (Shi et al., 2016). According to the French High Council on Climate report, the building sector accounts for more than a third of the carbon dioxide emissions in the European Union (IDDRI, 2020). While the objective of achieving carbon neutrality and a highly efficient housing stock by 2050 is clear (Rüdinger, 2022), the pathway to achieve it remains uncertain. For this reason, energy-efficient measures are being increasingly implemented in all sectors (Pacheco et al., 2012) concerning more about greenhouse gas emissions and air pollutants (European Environment Agency, 2019) and becoming a mandatory requirement for green and sustainable buildings (Shi et al., 2016).

The building sector, responsible for a significant portion of the energy consumption in the world (Pacheco et al., 2012) and carbon emissions (Takano et al., 2015), claims to explore different approaches to reduce the energy demand and environmental impact. The European Union has solidified several goals to increase energy efficiency and reduce greenhouse gas emissions in the upcoming years (European Commission, 2019). Evidence among many is the variety of building standards adopted by many countries, including energy-efficient design as an integral part of a heavyweight. Sweden is the EU country with the highest amount of renewable energy, reaching the goal of 50% renewable energy eight years in advance and achieving 60% of renewable energy by 2020 (CLEANTECH, n.d.). Then, it is essential to continue exploring new paths and spread a trustworthy direction to improve buildings' energy efficiency while also aiming to reduce the environmental impact.

Building stock plays a significant role in energy demand (Baniassadi et al., 2022). However, while evaluating the energy demand and carbon emissions of a building, it is essential to consider energy efficiency and environmental performance (Escandón et al., 2018). The indoor environment highly influences energy demand (Ghazalli et al., 2018) because most of the building's energy is used in heating, cooling, and artificial ventilation systems (Pacheco et al., 2012). Thus, a typical way to optimize the building's performance is through passive or active measures; for instance, it is decreasing the building's energy demand and use (Pacheco et al., 2012) or reducing the environmental impact by applying more environmentally friendly materials to the building's structure (Asdrubali et al., 2015).

Lowering ventilation rates as an energy-efficient measure challenges achieving acceptable RH levels and hygienic conditions (Psomas et al., n.d.). Also, it can be difficult to achieve the right balance between air quality factors that can endanger the well-being and health of the users and future generation citizens (European Commission, 2019). Humidity is essential in determining indoor air quality (Wolkoff et al., 2022), occupants' thermal comfort (Reinikainen & Jaakkola, 2003), and building energy consumption (Qin et al., 2020). Although the range for a healthy and comfortable indoor environment recommended by ASHRAE is between 40% and 65% RH (ASHRAE Handbook—Fundamentals, 2021), studies among others have shown that a RH between 40% and 60% appears optimal for work performance (Wolkoff et al., 2022), and for lowering the risk of infection (Wolkoff et al., 2021). However, there is no efficient way to control such indoor air condition, except perhaps, ventilation (Lim et al., 2009).

In addition, low indoor relative humidity is a real issue in Swedish dwellings that drastically affects the building users, especially in those with higher indoor temperatures, small volumes, and high ventilation rates (Psomas et al., n.d.). It has become mandatory to explore solutions in order to attenuate these air quality issues (Manso et al., 2020), especially since the most common method usually involves mechanical dehumidification/ humidification while using electricity (Qin et al., 2020). However, studies suggested that the correct employment of indoor plants with species consideration would help to reduce the energy consumption of HVAC systems (Gubb et al., 2020) while minimizing the risk of infection (Wolkoff et al., 2021). In real-life settings, plants' total capacity will need to be clarified (Moya et al., 2019). Ventilation is a modifying factor that should be integrated with these green systems while considering indoor air humidity and room temperature in a joint strategic control (Wolkoff et al., 2021). Therefore, the effects of green systems combined with mechanical elements such as conventional heating, ventilation, and air conditioning must be explored while considering indoor air quality, health, and functional performance.

Green walls (GW) allow vegetation development on a vertical surface generally attached to building facades or indoor walls (Pérez-Urrestarazu et al., 2016). Among numerous benefits, GWs represent a powerful technology of passive building design, allowing vegetation to cover facades, as illustrated in ***Fig.1,*** and creating a second skin that can improve building thermal performance (Widiastuti et al., 2020). Lim et al. conducted a study that showed houseplants made little difference to indoor air temperature but significant differences in other factors under airtight conditions (Lim et al., 2009). Literature suggests that due to the transpiration process, adding plants into an indoor environment would modify the humidity levels in the air (Ghazalli et al., 2018) and help lower the temperature around the plant's environment (Widiastuti et al., 2020). The water vapor released by the plant into an indoor environment is expected to increase RH indoors (Gubb et al., 2020) and cause a higher comfort level (Tudiwer & Korjenic, 2017). In other words, GW can be utilized for air cooling and humidity control (Moya et al., 2019).

Fig.1: *Example of an outdoor green wall in Malmö, Sweden; 2022. Photography by Sahit TM*

However, research on their indoor comfort effect remains scarce, green wall implementation is often limited due to additional costs compared to other conventional solutions (Manso et al., 2020), and their benefits can change in different contexts and climates (Pirouz et al., 2020). In the case of indoor GW technologies, studies suggested that the air is cooled (Widiastuti et al., 2020), bio-filtered (Lim et al., 2009), which potentially would reduce the ventilation requirements (Pérez-Urrestarazu et al., 2016), and might improve indoor comfort level (Tudiwer & Korjenic, 2017). Although some studies have been performed on green walls on the influence of thermal comfort, carbon emissions, or even acoustic blocking-properties, more research ought to be done analyzing their actual effect on humidity. Studies among others suggested that such green technologies humidify the air (Ghazalli et al., 2018). Nevertheless, research analysis assessing the indoor humidity environment holistically should be done while considering building-systems characteristics, behaviors, occupancy patterns, and health symptoms-complaints (Psomas et al., n.d.).

1.2 Literature Review

GREEN SYSTEMS RELEVANCE

For instance, studies have emphasized green systems' environmental benefits and energy savings (Lim et al., 2009). Although houseplants have traditionally behaved as 'passive' bio-filters, new approaches and technologies are moving towards integration within the building's air conditioning and ventilation systems (Pérez-Urrestarazu et al., 2016). The environmental-friendly air regulation can enhance energy savings while decreasing carbon -monoxide -dioxide (Lim et al., 2009). Thus, it has been suggested even that indoor greenery should be considered a building service alongside traditional ventilation systems (Gubb et al., 2020), which provide significant differences, especially under airtight conditions (Lim et al., 2009). These walls can reduce heat transfer by providing thermal insulation to the building (Blanco et al., 2018) (Baniassadi et al., 2022), while they can lower the energy demand for mechanical cooling appliances (Pirouz et al., 2020).

Historical research suggests that the first examples of green systems can be found in the Hanging Gardens of Babylon. Later, from Scandinavia to Japan, numerous civilizations used climbing plants to cover buildings making what is now called green façades (Saifi et al., 2013). Generally, green walls (GW) can be divided into two main categories, including green facades (GF) and living walls (LW) (Pirouz et al., 2020). The first ones support the natural growth of climbing plants that can cover a wall surface over a few years (Saifi et al., 2013), while the living walls provide visual aesthetics as a design feature, apart from the natural insulation provided to the wall surface (Pirouz et al., 2020). Even though, from a functional perspective, most of these LW systems might demand a more complex design and maintenance (Perini et al., 2011). In other words, living wall systems, mostly known as GW, are planting structures attached to the walls that are usually carefully designed with their soil or other growing medium based (Perini et al., 2011). These technologies usually use balanced nutrient solutions to provide the plant's food and water requirements (Pirouz et al., 2020).

Different technologies have been used to design green systems (Daemei et al., 2021).In addition to the relatively new urban design trend (de Lucia et al., 2021), these innovative green solutions suggest psychophysical well-being (Moya et al., 2019). Green walls can allow plants to grow in places that do not typically support vegetation (Manso et al., 2020), creating a microclimate valued for its aesthetic value (Ghazalli et al., 2018) and all the overall health benefits that follow. A study by Moya et al. suggested that plants may change human attitudes and behaviors; even biophilic workspaces interaction has suggested improving productivity (Moya et al., 2019).

The additional thermal mass provided to the wall by the greenery layer contributes to limiting the thermal losses toward the outdoor environment (Bevilacqua et al., 2020). The thermal losses represent a critical element that contributes significantly to energy consumption (Ghazalli et al., 2018). GW benefit thermal comfort by acting as an insulation layer that contributes to preventing the loss of heat (Perini et al., 2011), especially in colder climates. The effect brought by the plant foliage propitiates environmental benefits (Pirouz et al., 2020) that include reducing heat flows through the wall of buildings (de Lucia et al., 2021) and lowering energy consumption for heating or cooling applications (Saifi et al., 2013).

In addition to the thermal comfort effects of these systems (Widiastuti et al., 2020), they have shown positive effects on indoor air quality (Tudiwer & Korjenic, 2017), as well as improving the acoustic insulation (Pirouz et al., 2020). Remarkably, recent studies and experimental measurements suggest the potential effect that green walls can propitiate on humidity (Ghazalli et al., 2018), (Moya et al., 2019), (Daemei et al., 2021). Moreover, to improve indoor building comfort level, the effects of green systems, combined with elements such as mechanical ventilation, should be deeply explored, considering indoor air quality, user health, and working performance (Wolkoff et al., 2021).

IAQ (Indoor Air Quality)

During the last years, indoor quality for different types, including houses, apartments, and office buildings premises, has shown growing importance from the perspective of health, environment, sustainability, and economy (Welat Han, 2021). The modern working environment has been a paramount health concern for people who stay in buildings at least eight hours a day (Chou et al., 2007).

The indoor environmental quality (IEQ), dependent on many parameters, represents the physical and psychological conditions experienced by the building occupants due to the surrounding environment in which are exposed (Omer, 2008). In other words, it could be defined as the perceived condition of comfort in the room experienced by the user. In addition to lighting and noise, the main physical parameters affecting IEQ are air quality, speed, temperature, and relative humidity (Omer, 2008). Humidity has shown an influence on factors related to indoor quality (Wolkoff et al., 2022), some of them, immediately perceived such as the odour (Welat Han, 2021), which potentially could reduce complaint rates and favor work performance (Wolkoff, 2018a).

DRYAIR PERCEPTION

Although air conditioners are top-rated in modern life, low humidity occurs in these air-conditioned buildings, frequently providing a humidity range below 40% RH (Chou et al., 2007). Low humidity exposure, which is usually associated with increased infections (Gavhed & Klasson, 2005), could cause progressive pathological skin changes (Sunwoo et al., 2006) and increase urine concentration (Chou et al., 2007). Therefore, particular attention is necessary to low-humidity environments. If the indoor environment is equipped with a ventilation system, the building occupants should be cautious about health manifestations, and continuous humidity monitoring is recommended (Chou et al., 2007). Also, a proper humidifier should be incorporated with the air-conditioner if necessary (Ikäheimo et al., 2016).

Dry air is a common complaint about the perceived indoor quality that seems to be a puzzle (Nielsen & Wolkoff, 2017). When using air-conditioning, temperature and humidity become essential physical elements affecting human comfort inside a building (Reinikainen & Jaakkola, 2003). Unfortunately, the humidity was dismissed more than four decades ago as the cause of dryness complaints (Wolkoff, 2018b). Thus its perception appeared confusing to human beings reporting, especially without an associated humidity receptor (Nielsen & Wolkoff, 2017). Instead, indoor pollutants are usually proposed as possible exacerbating causative agents (Wolkoff, 2018b). However, the possible association between perceived dry air and poor IAQ caused by indoor pollutants rather than low RH should be re-considered (Wolkoff & Kjærgaard, 2007). Moreover, the relationship between humidity should be addressed thoroughly in the entire spectrum of indoor quality (Baughman & Arens, 1996).

Is therefore, that medical and questionnaire surveys are usually conducted on earlier studies evaluating user complaints. However, it is essential to distinguish between these investigations. Although studies have shown the adverse effects of low but beneficial elevated humidity, more information is needed to understand how symptom reporting usually influences the results (Wolkoff, 2018b). Of course, people's experience is valuable; however, since they are generally not sufficiently familiar with determining humidity variations (Wolkoff, 2018b), it becomes essential not to rely solely on questionnaire surveys. Studies of the perception of temperature and air dryness may give a partial picture of the comfort experienced (Gavhed & Klasson, 2005). People consider discomfort problems due to indoor air climate factors, such as temperature and drought (Lukcso et al., 2016); therefore, someone might feel 'slightly warm, but still report feeling comfortable.

HUMIDITY AND HEALTH

Whether the dryness can be due to low humidity levels, humidity does not solely cause the experience of dry air (Wolkoff, 2018a); people could report dry air even if it is not physically dry. According to Wolkoff's work "Indoor air humidity, air quality, and health - An overview" (2018), the experience of dry air is a common problem in office environments and a recurring complaint in health surveys where indoor air quality is studied. The author suggested that the perceived reactions associated with different humidity levels may vary and depend on personal factors such as age, gender, weight, physical activity, and chronic diseases. Moreover, when investigating people's experience of indoor humidity, it is pertinent to include health and psychological factors, such as mood and stress (Wolkoff, 2018a).

Moreover, according to Wolkoff, women, older adults, and people with allergic diseases reported more respiratory symptoms under low indoor humidity conditions, between 20-30% RH (Wolkoff, 2018b). However, as indicated in the study by the author, there could be various reasons. For instance, dry air may also be confused with stuffy air, another common indoor air quality complaint that may cause nasal congestion due to no fresh air (Wolkoff, 2018b). Likewise, the dryness reported might be influenced by hormonal factors (Apotea, 2022), or the person might misunderstand it with any other aging or allergic symptom. Tear production might decrease as people age, in parallel to the respiratory sensibility of people with allergic diseases, becoming more perceptible in low-humidity environments (Wolkoff, 2018b). Occupants with a high prevalence of asthma and allergic diseases might report discomfort disproportionately and loss of productivity (Lukcso et al., 2016). Thus, the experience of physically dry air, while related to humidity, can easily be confused with a physical condition or irritating substances in the air, complicating the sensation description by the user.

On the other hand, epidemiological, clinical, and human exposure studies have similarly evaluated humidity levels to predict human reactions. Animals, like mice, are frequently studied in laboratories (Wolkoff & Kjærgaard, 2007). They are used in, for example, the Alarie test, which investigates the lungs' irritation and airflow limitation (Nielsen & Wolkoff, 2017). Then, fluorescein is a substance commonly used in eye examinations that drops into the eye and gives color to damaged areas of the cornea; the more the eye has been damaged, the more prominent rashes will be (Nielsen & Wolkoff, 2017). According to the experiment, the mice in a room with a low humidity level (15% RH) caused decreased tear production and increased fluorescein staining in the cornea (Wolkoff, 2018a). The experiment also compared other environmental conditions and concluded that the effects on dry conditions were similar to those reported by humans (Wolkoff, 2018a); low RH (between 5-30%) increased complaints. In comparison, positive effects were observed by increasing the RH to 50%, showing a significant improvement in the eyes' tear film and alleviating the symptoms of dryness in the office workers after exposure to these conditions for just one hour (Wolkoff, 2018a).

MEASUREMENTS OF HUMIDITY

Humidity, expressed in grams per kilogram (g/kg), represents the mass of water vapor to the mass of dry air with which the water vapor is associated. However, it is essential to understand absolute humidity and relative humidity. Absolute humidity (AH) represents the content of water vapor in the air (expressed, e.g., in vapor pressure, hPa, g water/kg air), while relative humidity (RH), the ratio of the actual and saturation vapor pressure in function of air temperature (Reinikainen & Jaakkola, 2003). In other words, AH shows how much water vapor the air can contain at different temperatures: the warmer the air, the more water vapor it can contain. Thus, as air can hold a fixed amount of water vapor, the relative humidity (RH), usually expressed in percentage (%), represents the water vapor ratio while considering the whole content the air could contain at a given temperature.

There is an increasing trend to apply AH as a parameter for comparison and a better correlation between outdoor and indoor than RH (Wolkoff, 2018b). However, the indication sensors usually utilized on the instruments respond to different moisture property contents such as wet-bulb temperature, relative humidity, humidity (mixing) ratio, dew point, and frost point. In addition, complete calibration usually requires observation of a series of temperatures and humidity, relying on precise regime methods in a controlled environment to generate known humidity and achieve an accurate measurement (ASHRAE Handbook—Fundamentals, 2021). Therefore, this study refers to humidity as vapor ratio, expressed in grams per kilogram(g/kg).

However, humidity might be complex. Standards include upper limits for relative humidity (RH) that typically range from 60% to 80% (Baughman & Arens, 1996). Although the reasons for the limits are not often explicitly stated, it might be assumed to be out of concern for the health effects that might occur if humidity becomes too high. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends the RH to be 30 to 60%. In addition, scientific evidence suggests that humidity may cause pathophysiological responses at higher levels that increase the host's susceptibility to viral infections (Ikäheimo et al., 2016). The primary effects of high humidity are caused by the growth and spread of biotic agents, such as bacteria, viruses, and air pollutants, that may cause adverse health effects (Baughman & Arens, 1996). The evidence suggests that inhaling cold and dry air can lower the upper airway temperature and dry the mucous membrane, which might cause respiratory tracts and mucosal irritation (Wolkoff, 2018b).

Perhaps adverse health effects, such as skin symptoms and nasal dryness, are also related to behavioral, socioeconomic, and housing factors (Reinikainen & Jaakkola, 2003); temperature and humidity do affect the thermal balance of the human body (Wolkoff, 2018a). Moreover, both conditions have shown their effect on human health. It can be directly via respiratory organs and skin while regulating human comfort through thermal sensations; or indirectly by changing the perceived indoor air quality parameter such as stuffiness (Reinikainen & Jaakkola, 2003). Substantial evidence exists on the seasonal variation of respiratory morbidity and mortality with the increased use of health services and hospital admissions during the winter (Ikäheimo et al., 2016). Thus, an adequate adjustment of such conditions appears to be the way toward a comfortable indoor environment.

Considering humidity is essential to satisfy the requirements for optimal perceived indoor air quality (Wolkoff et al., 2021). Research about air humidity at different levels has become a growing area, suggesting several health-related agents affected by indoor humidity (Omer, 2008) and providing evidence about the impact on virus survival and spread (Wolkoff et al., 2021). For instance, a study conducted by Sunwoo, Chou, Takeshita, Murakami, and Tochihara, tested people in different environments and observed their responses at different RH. According to their conclusions, above 30% RH seems suitable for avoiding dry eyes, while 10% RH is appropriate for avoiding nasal dryness complaints (Sunwoo et al., 2006). Even though humidity affects air sensation, individuals' performance, and reporting symptoms (Wolkoff, 2018a) is something scientists still investigate today, aiming to find a more acceptable answer.

Likewise, the high moisture levels in building materials have a detrimental effect that may also harm the building envelope's thermal performance (ASHRAE Handbook—Fundamentals, 2021). Transport phenomena are difficult to predict, especially regarding airflow, because mainly occur through accidental gaps, cracks, or imperfect joints (ASHRAE Handbook—Fundamentals, 2021). Therefore, analyzing the combined heat, air, and moisture transfer through building assemblies is advisable, especially air movement and liquid flow, which have a high priority in moisture control (ASHRAE Handbook—Fundamentals, 2021). While maintaining relative humidity between 40 and 60 percent showed to be more healthful than between 20 and 30 percent, it is practically impossible to maintain this high range in cold weather (Wolkoff, 2018a) due to excessive condensation, freezing on the windows, or even, inside the walls. Although an adequate RH level can reduce complaints and benefit comfort (Wolkoff, 2018a), research into these effects is ongoing, practitioners can only use simplified tools or hydrothermal models that still need to cover all airflow, gravity, and pressure gradient-induced moisture flows aspects (ASHRAE Handbook).

1.3 Aim and objectives

This thesis aims to study the impact of a Green Wall (GW) on indoor air humidity through field measurements in an office building, a case study. The main objective was to isolate the impact of the GW and avoid the influence of other external agents in the office or the surrounding environment during the study period. The perspective of the health and well-being of the user provided by suitable indoor humidity conditions is considered a fundamental component of this thesis. This study, which considers indoor moisture risk, has hypothesized a positive indoor humidity contribution due to the GW installation and aims to gather knowledge to be applied to improve other conditions/scenarios.

1.4 General limitations

It is worth mentioning that this study solely tested and analyzed the green wall's humidity contribution. There was no participation throughout the GW design process involving the proposed structure size, design, layers, or plant selection. The wall was installed by a third company named Green Works. The conclusions are limited to the site study in which the wall is installed, an office building in Malmö, Sweden.

2 Materials and Method

The materials, equipment, and method are described in this chapter. For simplicity, it has been split into three sub-sections. The first subsection provides information about the study site. The second describes design details regarding the green wall (GW) installation. The last sub-section provides information about the data collection process and further analysis later performed.

2.1 Building site

The study was carried out in an office located in Kabingatan 9, Malmö, Sweden. Some pictures of the building under study are included in ***Fig.2***. The picture on the left side shows an aerial view of the entire building. However, the study site was limited to the second floor, where the office is located. A picture of the entrance in more detail can be found on the right picture of ***Fig.2***.

Fig.2: *Aerial view of the building in study (left); Kabingatan 9, Malmö, Sweden. Photography by Sahit TM*

The rooms and areas in the office have different sizes, purpose(s), and expected occupancy. However, the number of occupants, around 12 people per week, remained constant throughout the study. A representation of the office building plan is illustrated in ***Fig.3***.

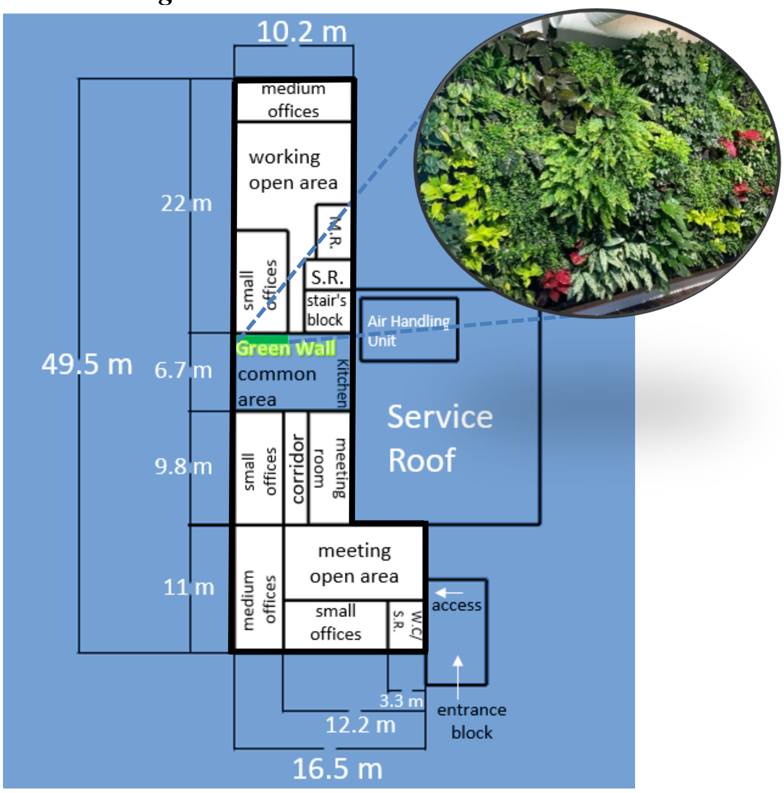

Fig.3: *Office-building plan*

In the northern part of the building, there is a shared working open area and three medium-size offices, a medium size meeting room, designed for eight to ten people, and three small offices, designed for one to two people each. A service room, and a stair-block are in front of those offices. The small, medium-sized offices, and the meeting rooms have glass divisions and doorways connected by the main corridor. The division doors inside the office remain rarely closed, which may help improve indoor air circulation during the working day.
At the center of the office, there is an open-common area, where the green wall was installed. An important room to consider in this study. There is also a tiny kitchen in that shared space, designed for up to 15 people but utilized for minimum purposes, such as preparing coffee, suggesting that no meaningful heat and moisture loads could be expected with usual occupancy/usage.

The southern part of the building has a shared area designed for up to eight people. The shared space, featured with a projection screen, is surrounded by small and medium-size offices along the south-east direction corner. Also connected by the corridor is the main meeting room of the office, up to 14 people. In addition, a service room and toilet area are found in the south-east corner of the study site, close to the office's main entrance.

Thus, the office was divided into three zones, as illustrated in ***Fig.4,*** for its analysis. The first one represents the open-office block in the north. The second zone is the meeting room in which the GW was installed. The third represents the south area of the office, close to the main entrance on the second floor. Some details of the office are attached to ***Table 1***.

Fig.4*: Detail of the office zone-division for its analysis.*

Table 1*. Proposed zones inside the office.*

Zone	Area/m^2	Volume/m^3	People occupancy	Occupancy density	Zone occupancy density
1	225	560			18.75
2	70	170	12 people	41.67	5.83
3	280	700			23.33
Total	575	1430		m^2/person	m^2/person
If considering a heated area of 550m^2		1400			

Through measurements the office space was determined to be represented by a heated floor area of 550 m^2, excluding the service room, and the stair-block in *zone 1*. Considering the distance from the floor to the room's ceiling, 2.51 m, a total indoor air volume of 1400 m^3 is assumed for this second-floor premise.

2.2 Green Wall (GW)

Regarding humidity, the difference experienced in the office is expected to be influenced by the characteristics of the installed green structure. The GW installation, completely installed within one week, measures 2.1m x 3.8 m, roughly representing an area of 8 m^2. The structure holds small pockets or compartments that conform to a grid connection. A set of 11 lines of 19 small horizontal compartments integrate the entire grid of the green structure. The GW structure is a set of small compartments, each measuring no more than 20 × 20 cm, with enough soil to place the small plants. The plants were selected based on the accessibility to natural sunlight of the space, as it receives low-medium natural light. The species selected are habitually applied for indoor landscaping. The office users would be allowed to allocate new plants or green components on the wall, following the previous criteria for selection. Some details of the GW installation, which concluded on November the 30th, 2021; are included in ***Fig.5***.

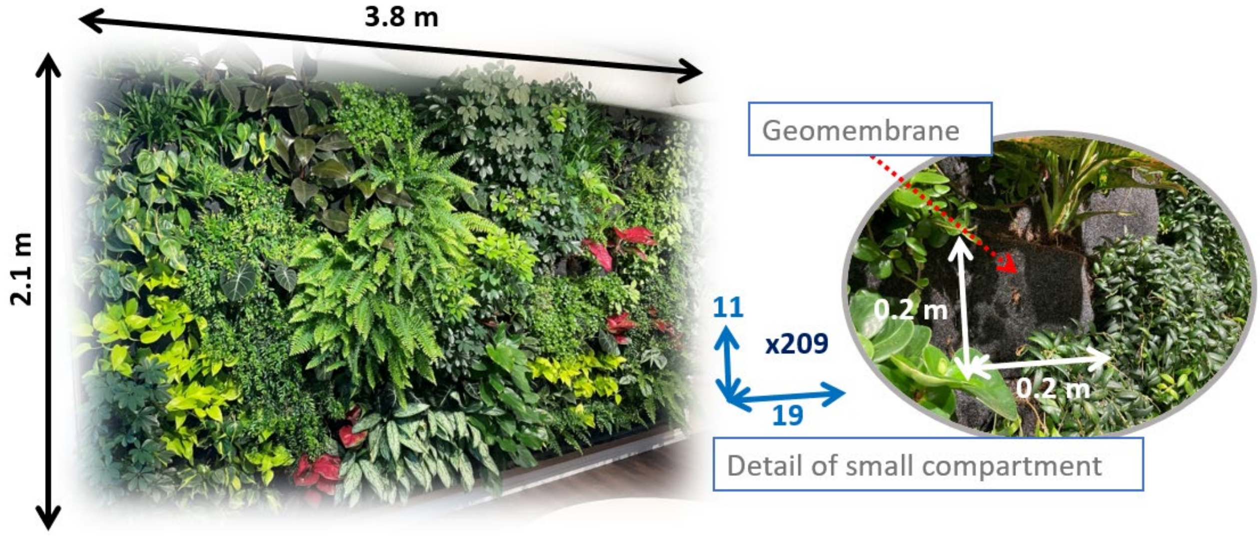

Fig.5*: Detail of small compartments technology of the green wall structure. Photography by Sahit TM.*

The green wall results from a careful design process before its installation. Besides more sophisticated details, the GW has an outer metallic framework at the back that acts as a barrier to prevent moisture transfer into the office wall. In addition, there is an air gap existing between the metallic framework and the greenery structure. In other words, the greenery structure, which holds all the small planting compartments, is not attained to the wall by itself but to this metallic layer or framework. Also, it is pertinent to mention the function of the geomembrane. This outer layer of the GW acts as a membrane that maintains the soil and small-size plant selection and improves the water inlet's distribution across the other connected compartments.

The greenery structure also encloses an irrigation system that provides water to the wall. This system also provides a commercial nutrient mix that was used in advance so that the plants are watered and fertilized as needed. The GW receives an average water flow of 12 liters daily, making the soil humid enough for the plants. The structure usually drains 1 liter daily into the metallic duct at the bottom. In addition, three soil humidity sensors are located and distributed along the GW. With these sensors, an issue with irrigation was identified in the soil in early January. The issue related to the irrigation system valves resulted in the incorrect liquid supply to some of the compartments of the GW at the beginning of the year. Nevertheless, the valve was successfully repaired on January the 31st, 2022. Pictures of the metallic framework, draining duct details at the bottom of the GW, and the humidity sensors are included in ***Fig.6*** *and* ***Fig.7.***

Fig.6*: Detail of the metallic framework- outer protection structure (left), and draining duct at the bottom of the green wall. Photography by Sahit TM*

Fig.7*: Detail of humidity sensors located in the green wall. Photography by Sahit TM*

2.3 Data Collection

An Air Handling Unit (AHU), situated on a service roof on top of the building, provides mechanical ventilation to the office. Since airflow impacts indoor air humidity, measurement data from the Air Handling Unit (AHU) were compared before and after the GW installation. A monitoring phase with a high focus on airflow (l/s), outdoor-indoor temperature (ºC), and vapor ratio (humidity/%) was necessary to provide similar conditions and, therefore, conduct a fair comparison before and after GW installation. The measurements commenced in September 2021, before the installation of the GW took place, carried out and recorded each minute from Monday to Friday, from approximately 6:20 hrs. until a couple of minutes after 19:00 hrs. In a similar vein, they represent more than 3600 measurements for each study week. When there was usually no occupancy on weekends, the ventilation remained in low mode. These ventilation sensors continuously collected data for 27 weeks until April the 1st, 2022.

The Air Handling Unit (AHU) which determines the outdoor, supply, extracted, and exhausted air conditions related to the office, has a maximum airflow capacity of 1680 l/s, according to the manufacturer's specifications. The unit has a humidity recovery system with up to 90% efficiency. Besides more sophisticated appliances, the AHU holds a pre-heater, outdoor air filter, humidification system, muffler, and fans to supply fresh air. Throughout the study, the maximum airflow usually remained below 1000 l/s.

Regarding the airflow, the process occurring in winter may be simplified as follows. The fresh air, cold and dry from the outdoors, first passes through mechanical ventilation with an air pre-heating system and filtration. Using a heat and moisture recovery wheel, as well as cooling and heating batteries, the outdoor air is humidified and heated, reaching a temperature of more than 18°C after the AHU, then the air is supplied to the office. In the room, the air is mixed, where another temperature and vapor ratio (humidity) are gathered, creating a difference between the supply and indoor conditions. Posteriorly, the indoor air is extracted from the room through ventilation devices and returned to the AHU. There, air passes through high-efficiency heat and humidity recovery exchangers in the handling unit to pre-heat and pre-humidify the air from outdoors. Afterward, the air is exhausted and released into the ambient. ***Fig.8*** illustrates a simplification of the airflow process involved.

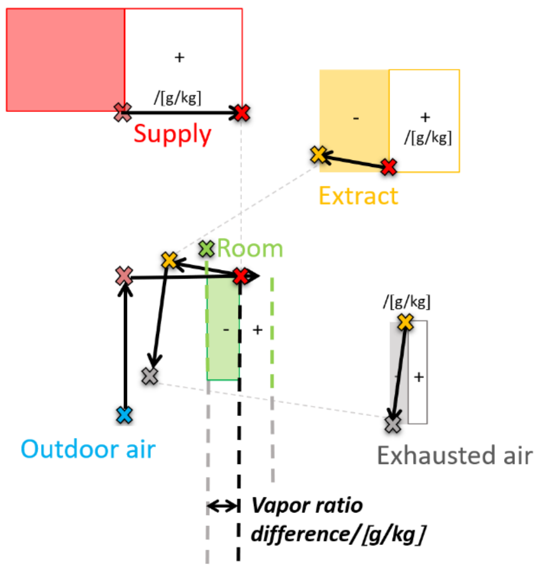

Fig.8: *Representation of the airflow process occurring on winter season.*

The airflow analysis also suggested that the room air is highly susceptible to the outdoor air conditions, which equally impacts the supply conditions, both after the action of the Air Handling Unit. As illustrated in ***Fig.9***, the outdoor air passing through the AHU is then supplied to the room where the air is mixed, acquiring another temperature and vapor ratio and creating a difference between the supply and indoor conditions. This study refers to vapor ratio difference as the variation existing between the vapor ratio content of the supply and the air room conditions as expressed in ***Eq.1***: *Vapor ratio difference.*

Eq.1: *Vapor ratio difference = (xRoom – xSupply) / (g/kg)*

where:

xRoom = vapor ratio measured in the mixed-air at the room (indoors)/(g/kg)
xSupply = vapor ratio measured in the air supplied to the room from the AHU/(g/kg)

It is worth noting that when the difference between the room and supply conditions is below zero (*xRoom – xSupply < 0*), the vapor ratio in the room is lower than the supply air, indicating that the air in the room remained dryer than the supply conditions. On the other hand, if the difference is positive *(xRoom – xSupply > 0)*, it would indicate that the vapor ratio in the room is higher or more humid than the supply air conditions, suggesting humidity contribution due to the GW installation.

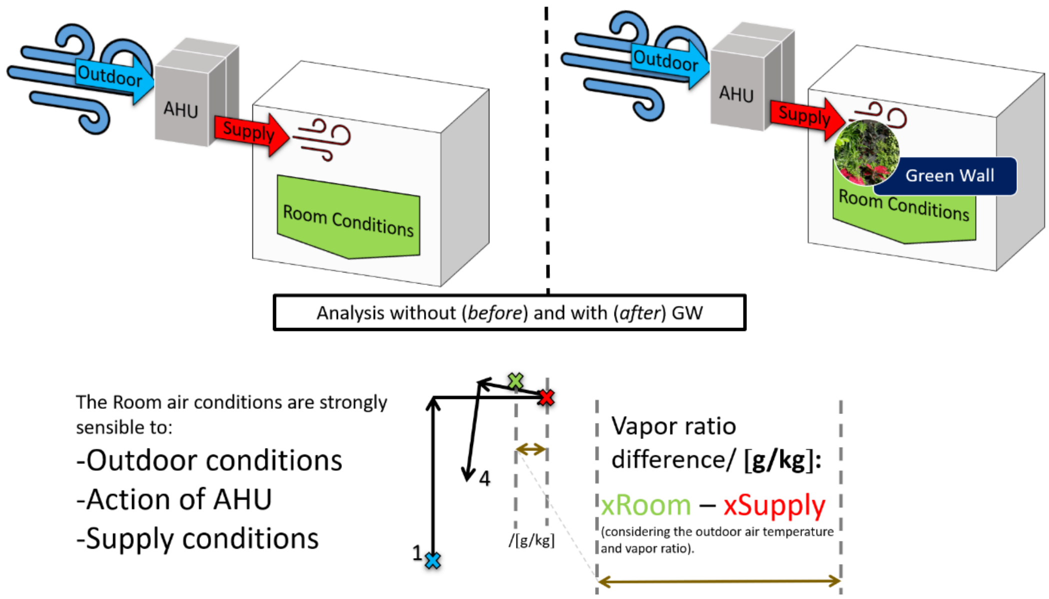

Fig.9: *Representation of the vapor ratio difference (xRoom – xSupply)*

The results provided in this thesis were obtained through measurements collected by temperature and humidity sensors devices, a feature of the ventilation system. Sensors inside the office measured the air temperature and humidity and were used to analyze the impact of proximity to the GW.

Although the selection criterion of attaining similar conditions before and after the GW installation, such as temperature(°C), vapor ratio (g/kg) and ventilation rate (l/s) to drive a proper comparison, considerably reduced the number of possible scenarios from the study period. By following the described elimination process, the data collected over some weeks were chosen corresponding to the conditions without the green wall- "*before*", and after the installation took place- "*after GW*". The further analysis consisted of evaluating the selected data and comparing similar scenarios to determine the effect of the green wall on indoor humidity.

Data Calibration

In order to determine the accuracy of the measurements, the collected data were compared with additional measurements provided by sensors later installed on site. In other words, additional measurements were conducted for a couple of days throughout this calibration to evaluate and determine the error present in the data previously collected, recorded, and used for comparing and analyzing the results. Therefore, four sensor devices measuring temperature and humidity were installed on March the 21st, 2022. Two sensors were located inside the office—the first set in the northern area (*zone 1*). The second was in the room where the GW was installed (*zone 2*). ***Fig.10*** and ***Fig.11*** show and represent the sensors allocated inside the office in more detail.

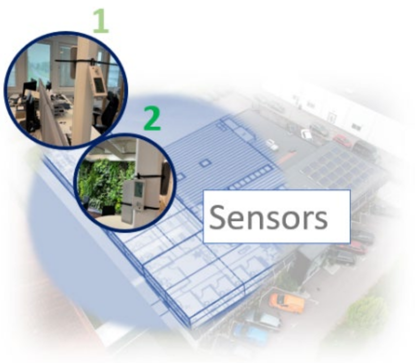

Fig.10: *Representation of the temperature and humidity sensor's allocation inside the office*

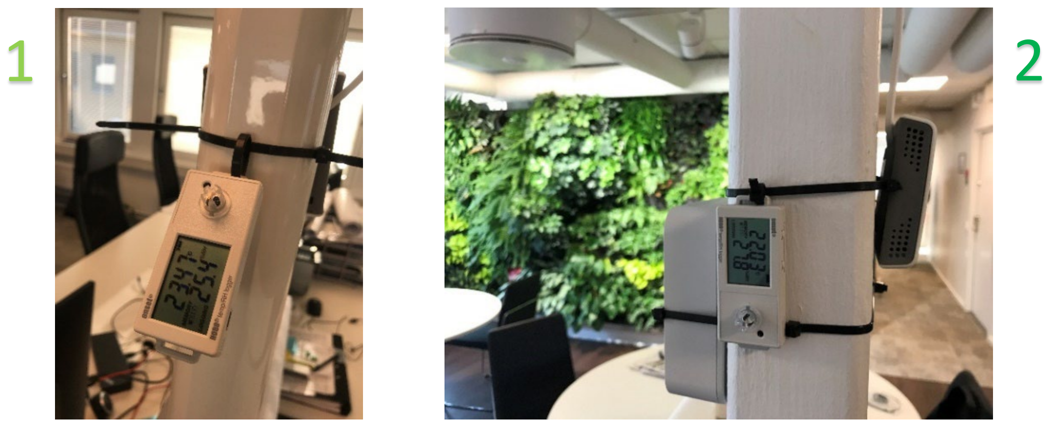

Fig.11: *Detail of sensors installed inside the office: North open office area (zone1), GW's common area (zone2). Photography by Sahit TM*

The *ONSET HOBO UX100 Humidity Data Logger* was the sensor utilized for room calibration. This logger accurately measures and records temperature and relative humidity in indoor environments according to specifications (HOBO, 2022). The UX100-003 data logger can measure temperatures from -20 to 70 degrees Celsius and from 1% to 95% RH with a measurement range of 0.21 C and 2.5% RH accuracy. The logger's display shows current measured temperature and humidity readings, recording mode, battery level, and alarm status. The humidity sensor's logger range varies from 1% to 95% RH (non-condensing). Also, the accuracy deviates by ±2.5% from 10% to 90% RH. However, below 10% and above 90%, up to ±5%. Regarding response time, it may vary from 43 seconds to 90% in airflow of 1 m/s. The UX100 Series of data loggers has a software-selectable sampling rate of 1 second to 18 hours, storing up to 84,650 measured readings before downloading the recorded data to a computer if necessary. Data can be exported by USB connection and graphed within the software for analysis. Thus, these sensors were appropriate for monitoring the office (indoors).

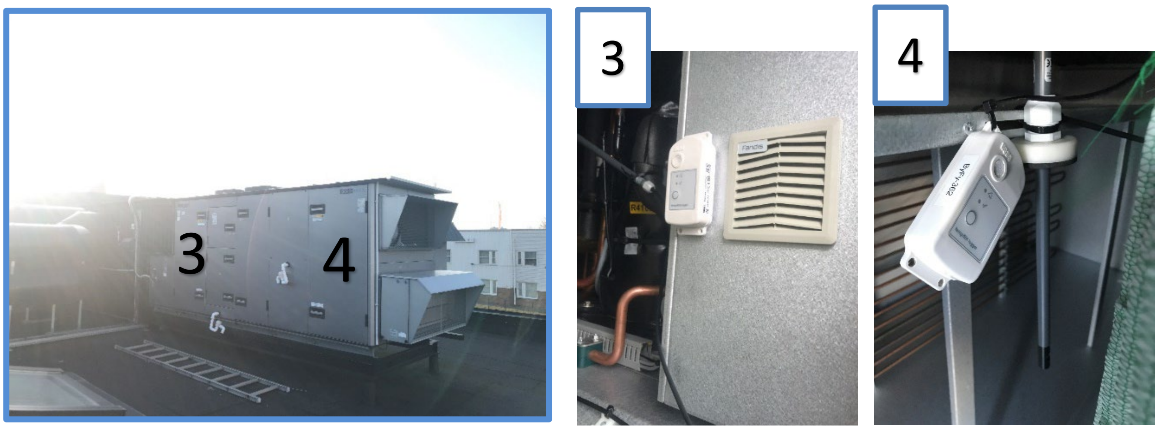

***Fig.12**: Detail of the sensors installed in the AHU. Photography by Sahit TM.*

Two more sensors were allocated in the AHU, measuring the outdoors and supplying air conditions for the office. The detail of the sensors installed in the AHU is included in ***Fig.12***. The *HOBO MX2301 Temperature/RH Data Logger* was the sensor utilized for the AHU. This sensor is a weatherproof data logger with built-in temperature and relative humidity sensors. Leveraging Bluetooth Low Energy, the logger enables easy, fast setup and data download directly from a mobile device and provides high-accuracy measurements in harsh outdoor environments with a measurement range of 0.2ºC and 2.5% RH accuracy, according to specifications. Thus, these sensors were appropriate for monitoring the Air Handling Unit.

Subsequently, the measurements obtained by these sensors were compared to the collected data from the climate chamber (*Thunder Scientific Corporation Model 2500ST*) used for the calibration. The *Humidity Generator Model 2500ST* is a self-contained system capable of producing atmospheres of known humidities using the fundamental, NIST-proven, "two-pressure" principle (Thunder Scientific Corporation, 2022). This system can continuously supply accurately known humidity values for instrument calibration, evaluation, and verification, as well as for environmental testing. Thus, humidity solely depends on the measurement of pressures and temperatures. The pressure measurements' accuracy and temperature uniformity throughout the generating system determines the humidity generation precision. In other words, the climate chamber, *Model 2500ST,* represents the actual values that were compared with the measures from the other four sensors. Therefore, the following steps were performed when analyzing the measurement data for the calibration:

- The linear function, or trend line, is a correction for the measurement data during the experiment. This function was calculated by comparing the vapor ratio between the AHU data and these four additional sensors during a given period. Thus, these results would represent the "true" or "actual" measurements for the experiment during a specific period.

- In order to determine the trend line function, a scatter plot for all four sensors was necessary. In other words, regarding the climate chamber, an average vapor ratio was initially calculated. Then, a plot was created comparing the chamber's vapor ratio (g/kg) against the measurements obtained by the additional sensors allocated in the office and AHU. However, it was essential to ensure that the correct values were compared – i.e., correct dates, same time intervals, and same time series.

- Next, the "actual" measurements were obtained by producing a scatter plot between the data sets and a trend line with a function. Although applying the correction function and considering the vapor ratio during the 27 weeks is advisable, correcting all the previously collected measurements might be optional. Thus, the trend line will show the differences between them. In other words, the linear function from the chamber will determine the source of error present in the data coming (previously collected during the 27 weeks) from the AHU devices. Therefore, the accuracy of the analysis and the measurements was assessed according to their differences.

This study refers to humidity as vapor ratio, expressed in grams per kilogram (g/kg). On the other hand, the water vapor content of air, also named humidity by volume, is denoted as v (kg/m^3). air consists of many gases, each contributing with their part to the total pressure. For water vapor, the partial pressure is denoted by p_v (Pa) and expressed in ***Eq.2***, according to the general Gas Law, which gives the relation between the vapor content and the partial pressure (Hagentoft, 2001):

Eq.2: $$p_v = 461{,}4 \cdot (T + 273{,}15) \cdot v$$

Then, according to the liquid-gas equilibrium of water, there is a maximum possible water vapor content in the air, denoted by v_s (kg/m^3), also named vapor saturation content. Thus, this *humidity by volume at saturation* is a function of temperature. The following expression in ***Eq.3*** can be used for calculating the vapor saturation content by assigning the following values according to temperature (T), which is given in degrees Celsius.

Eq.3: *Humidity by volume at saturation:* $$v_s = \frac{a \cdot \left(b + \frac{T}{100}\right)^n}{461{,}4 \cdot (T + 273{,}15)} \qquad (kg/m^3)$$

$$0 \le T \le 30 \quad a = 288{,}68\,Pa \quad b = 1{,}098 \quad n = 8{,}02$$
$$-20 \le T \le 0 \quad a = 4{,}689\,Pa \quad b = 1{,}486 \quad n = 12{,}3$$

Therefore, Relative Humidity denoted as φ, can be calculated as follows in ***Eq.4***, and expressed in percent (%):

Eq.4: *Relative Humidity:* $$\text{RH}\ (\varphi) = \frac{v}{v_s} \qquad (\%)$$

CO_2 emissions

Using measurements of the CO_2 concentration collected from the sensors in the office, the indoor air conditions *before* and *after* the GW were compared. Since these sensors were not calibrated, the results analyzed as weekly averages and expressed in particles per million (PPM) will represent more of a suggestion than a proper assessment of the GW pollutant-removal contribution.

3 Results

Data Collection

Aiming to satisfy similar conditions to make a comparison, ***Fig.13*** illustrates the outdoor temperature and vapor ratio during the 27 weeks of study. The graph on the left side shows the weekly-average temperatures expressed in degrees Celsius. In week 9 of the study, when the GW installation took place, the outdoor temperature fluctuated between 0°C to 7°C. A similar outdoor temperature is experienced between weeks nine to 25. The graph to the right in the same figure shows the vapor ratio along the weeks of study. The graph shows that the weekly average value roughly fluctuates between 3 g/kg to 6 g/kg. To minimize the impact of variations in the outdoor climate, the figure suggests a possible comparison *before* and *after GW* installation that includes week nine and, possibly, between weeks 20 to 23.

As seen in ***Fig.14***, the ventilation rate decreased after week seven due to a lower ventilation rate set up during the winter season. However, as illustrated below, no meaningful differences in the airflow rate were experienced between weeks nine and 23.

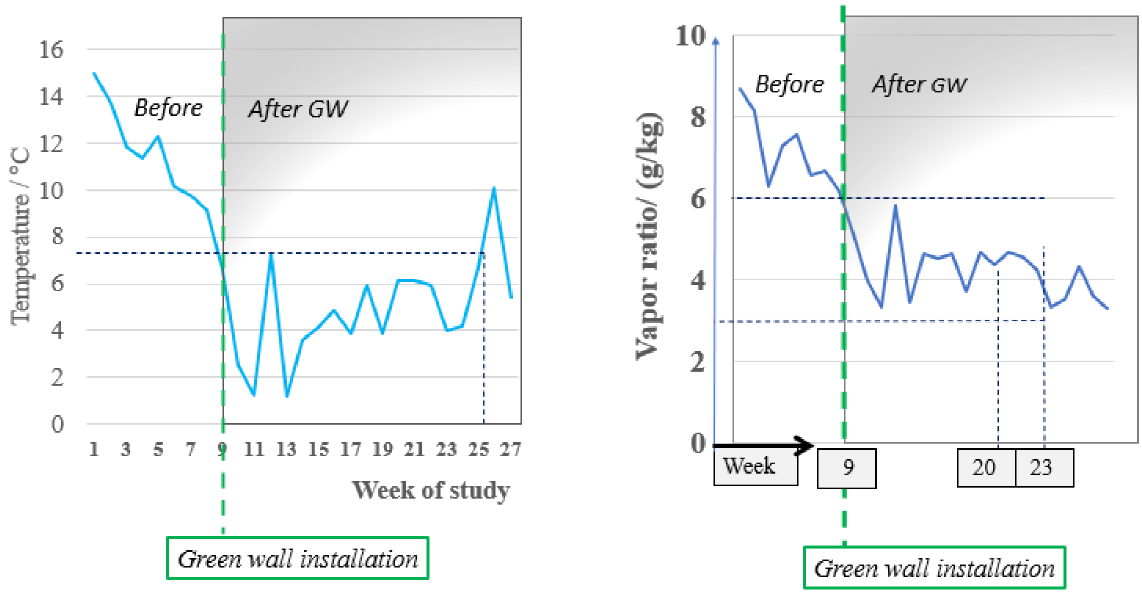

Fig.13: *Outdoor temperature (left) and vapor ratio before installation and after GW.*

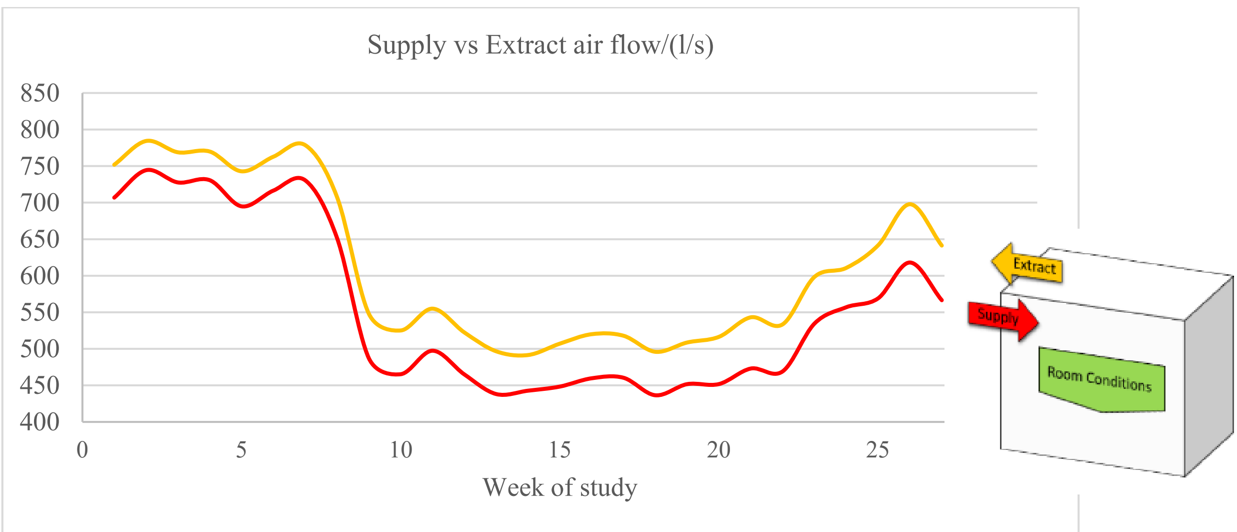

Fig.14: *Airflow rate average along the 27 weeks of study*

The graph in ***Fig.15*** is obtained when evaluating the vapor ratio in the room's air and comparing it to the outdoor and supply air conditions during the weeks of study. It is worth noting how the outdoor vapor ratio highly influenced the supplied air, and thus the room's conditions. Before the GW installation, the vapor ratio difference between the room and supply, always remained negative. By the time the GW installation took place in week 10, although some fluctuations were identified during the following nine weeks, the difference between the room and supply conditions had decreased. Along week 19, the vapor ratio in the room turns higher than the supply conditions so that the difference is not in the negative anymore. Even a lower vapor ratio is experienced during week 23 and 27, the conditions in the room remained with a higher ratio in such scenarios. After this first part of the analysis, some differences experienced after the GW installation can be noted.

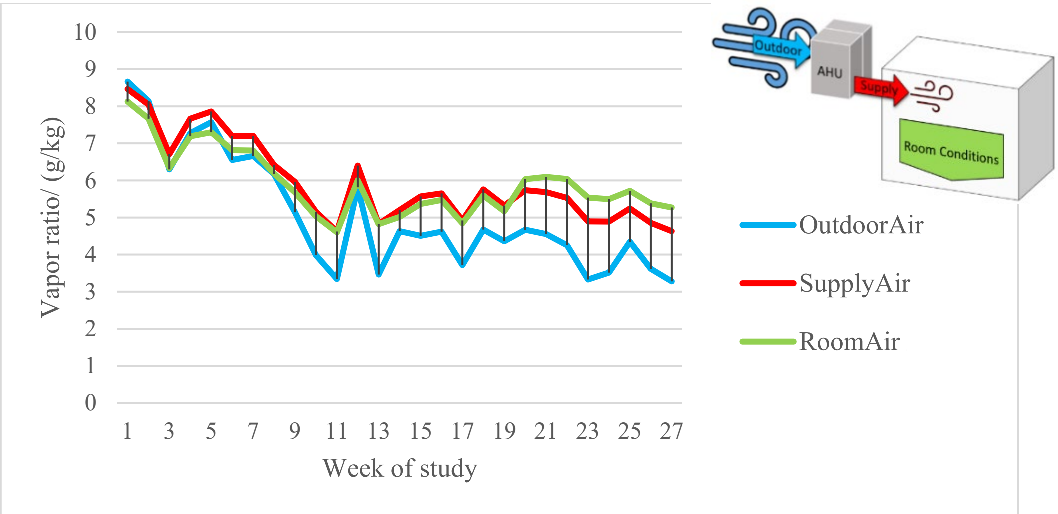

***Fig.15**: Vapor ratio along the 27 weeks of study, outdoor, supply and room air*

The vapor ratio difference in the room according to the supply and outdoor air conditions is evaluated and represented in ***Fig.16***. As illustrated, on week nine, before the GW installation, the room remained with a lower vapor ratio than the supply air conditions, or dryer, in simple words. From November the 30th, 2021, after the GW installation was completed, the indoor air's dryness seemed to decrease. However, some fluctuations can be identified for the following weeks. In that regard, the issue related to the green wall's water supply might be a possible reason for the fluctuations observed concerning the vapor ratio difference after the GW installation. Nonetheless, after week 19, the vapor ratio difference became positive.

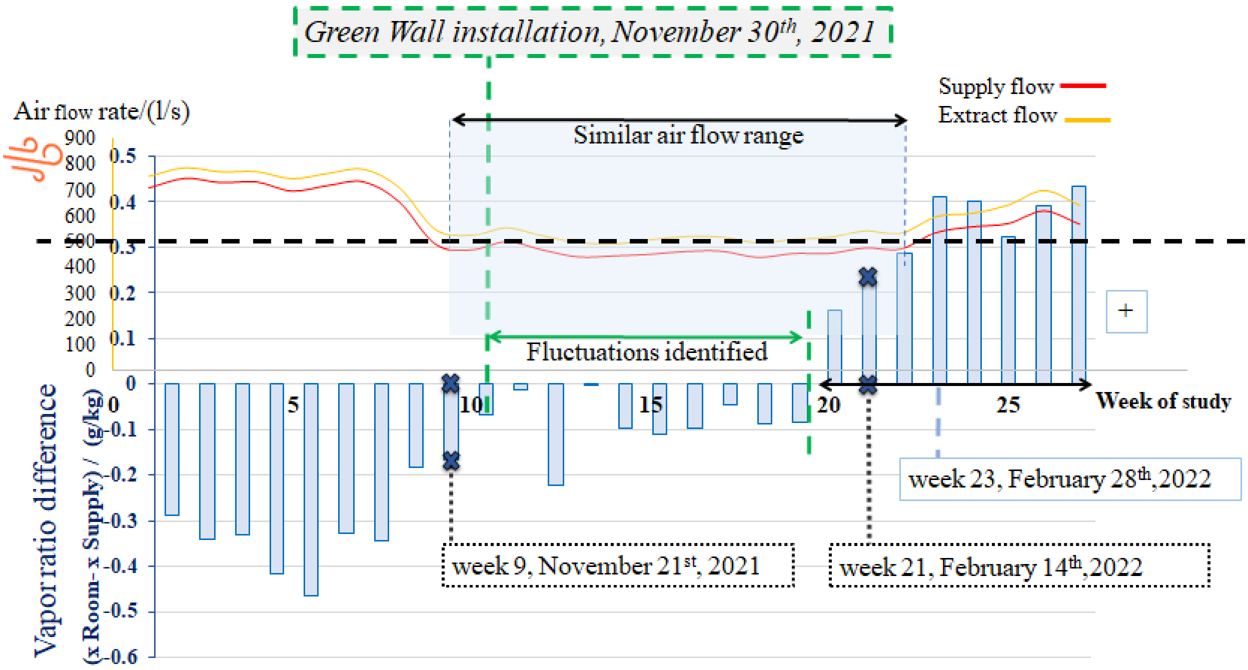

***Fig.16**: Airflow rates and vapor ratio difference between Room and Supply air. Week 1-27.*

3.1 Results of the comparison

The cases selected for comparison *before* and *after* GW installation and further analysis are presented in this chapter. Following the structure described in the method emphasizes a few particularities noticed throughout the study. However, a more bountiful interpretation of the results, including possible sources of error, was included later in the discussion.

3.1.1 *Before* the installation

Fig.17 shows the data collected *before* the green installation. More than 3600 measurements represent the week's outdoor, supply, and room air conditions collected from **November the 22nd to 26th, 2021**. According to the graph, while considering the outdoor temperature and evaluating the vapor ratio difference between the room and the supply conditions, the difference *before* installation fluctuates around 0g/kg. A slight negative vapor ratio difference is experienced at higher outdoor temperatures, particularly between five to nine degrees. Although some possible reasons for this unpropitious difference are later exposed, the difference suggests the room may remain dryer than the supply air conditions when negative.

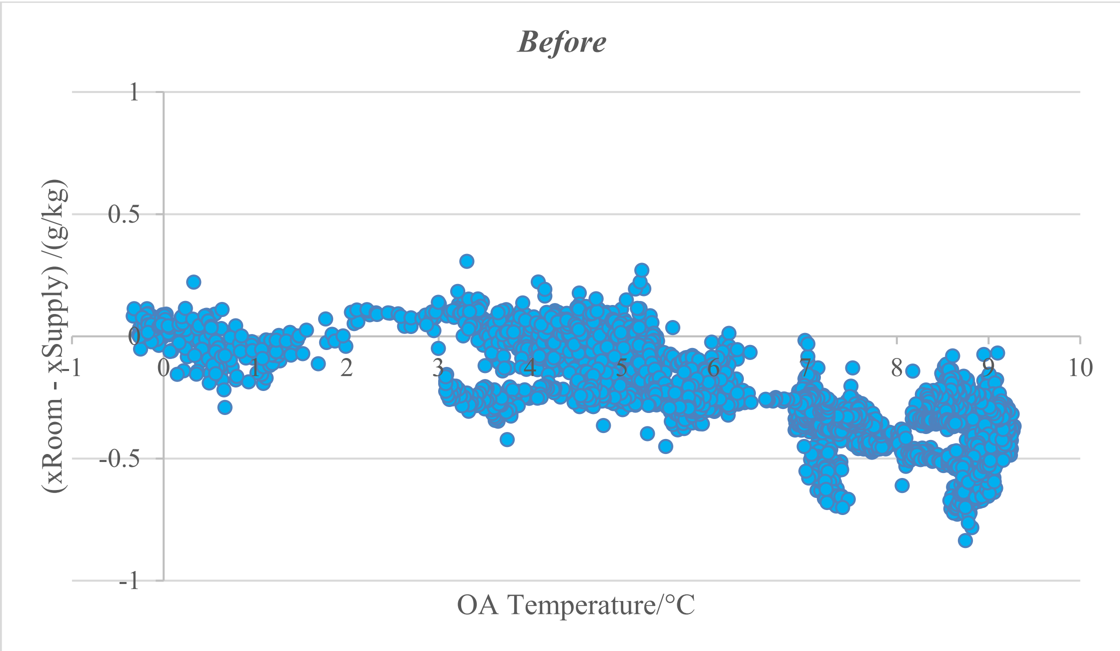

Fig.17*: Outdoor air temperature and vapor ratio difference (xRoom - xSupply) before GW*

However, it is pertinent to mention that as the outdoor temperature increases, the vapor ratio of the supply air might be expected to be higher. Although the room does not show significant alterations apart from the ventilation supply, which is due to the moisture buffering of the materials and furniture inside the office, sometimes registered negative differences. Thus, the vapor ratio difference experienced *before* the installation remains fluctuating. Furthermore, the vapor ratio difference between the room and the supply air conditions might become negative as the outdoor temperature increases. Although the difference peaked at roughly 0,7g/kg when the temperature rose, the overall difference during the study week remained around, or even less than 0,5g/kg.

3.1.2 *After GW* installation

The vapor ratio differences *before* and *after GW* installation are shown in ***Fig.18.*** *Before* the installation, represented by the red dots, the ratio difference between the room and supply *(xRoom – xSupply)* fluctuates around or below 0g/kg. On the other hand, *after* the GW, represented by the different green marks, the given difference shows predominantly positive values. After GW, during week 21, the vapor ratio difference reaches up to 0,9g/kg. Also, compared to the results attained before the installation, the difference is not predominantly negative anymore. Then, on week 22, the difference fluctuates from approximately 0,1 to 0,8 g/kg, peaking at almost 1g/kg when the outdoor temperature is five degrees. Next, along week 23, the vapor ratio difference fluctuated from roughly 0,2 to 1,1 g/kg, reaching its highest value when the outdoor temperature is around five, or six degrees. Overall, the vapor ratio difference reached the highest values, around 1,3g/kg, when the outdoor temperature is close to five degrees. Between zero to ten degrees, the difference between the room and the supply air conditions fluctuated around 0,7g/kg. Likewise, ***Table 2*** compares the averages from the selected weeks according to the results.

While considering the weekly averages *after* the GW, the vapor ratio difference remains with a positive (+) difference when comparing the room (xRoom) air, the supply air (xSupply), and the outdoor conditions. Even when comparing the results during week 23, despite the colder outdoor temperature and the lower vapor ratio conditions, the difference remained around 0,64g/kg. On the other hand, a negative average difference of 0,28g/kg was determined under similar conditions *before* the installation. Therefore, this vapor ratio difference might provide evidence that the moisture contribution experienced in the room can be an effect of the GW. Nevertheless, evaluating the data calibration can be advisable.

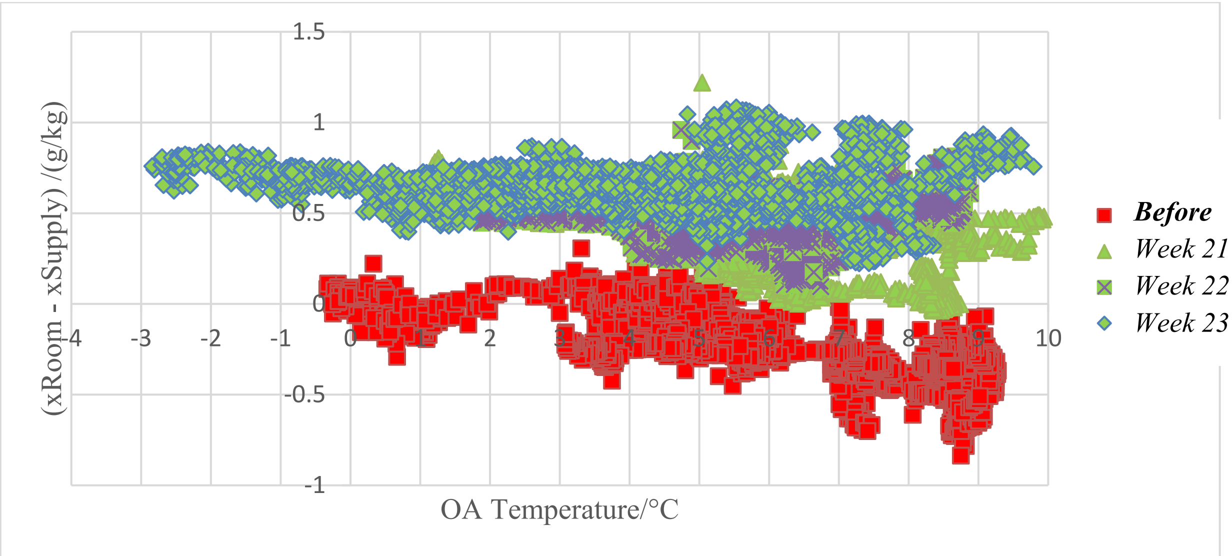

***Fig.18**: OA Temperature and Vapor ratio difference (xRoom - xSupply), before and after GW*

***Table 2**. Conditions comparison before and after GW installation. Weekly averages.*

	Outdoor air (OA) Temperature/°C	Vapor ratio difference (xRoom - xSupply)/(g/kg)	Supply flow/(l/s)	Extract flow/(l/s)
Before	6,6	-0,286	485	547
After GW week 21	6,2	0,410	473	543
week 22	5,8	0,506	465	531
week 23	3,9	0,644	533	597
After GW		**+0,6 to 0,9g/kg**		

The conducted calibrations determine the real vapor ratio difference by correcting the measurements using the trend line equations. In a similar vein, the collected measurements from the weeks *before* and *after* GW are re-computed according to the calibration results. ***Fig.21*** shows the vapor ratio difference *before* the GW but after the calibration. According to the graph, while considering the outdoor temperature and evaluating the vapor ratio difference between the room and the supply conditions, the difference *before* installation still fluctuates around 0g/kg. However, compared to the graph without calibration (*Fig.17*), the difference remains closer to 0g/kg. The negative vapor ratio difference experienced at higher outdoor temperatures disappears. Furthermore, the highest ratio difference between the room and supply is not higher than 0.4g/kg, compared to the negative value of 0.8g/kg experienced before the calibration at higher outdoor temperatures, particularly between five to nine degrees.

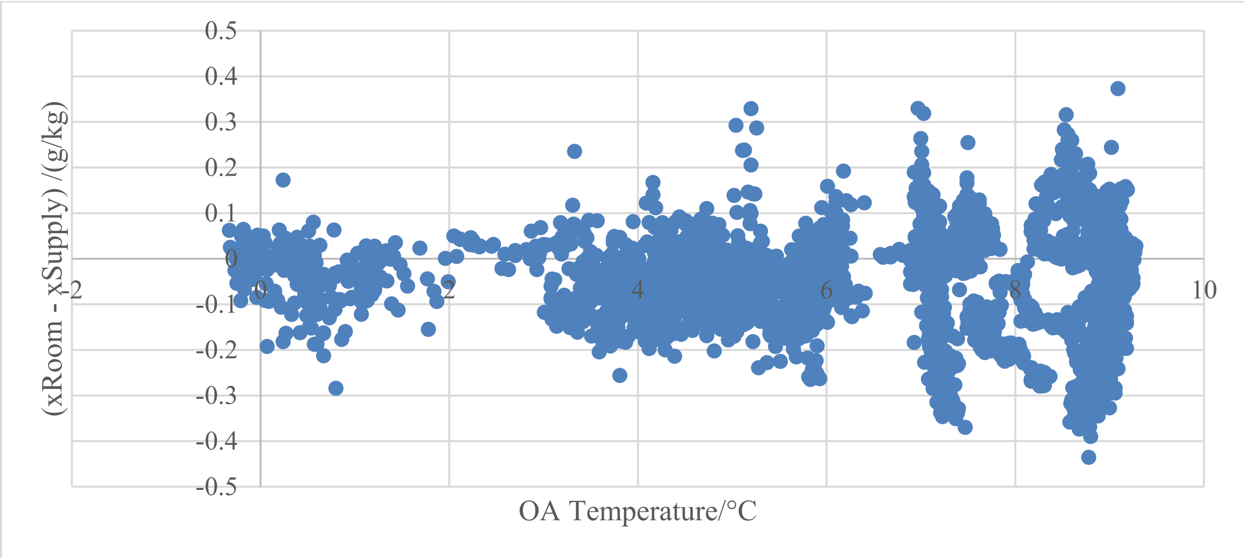

Fig.21: *Real vapor ratio difference before the GW installation*

Fig.22 shows the vapor ratio difference *before* and *after* GW installation. It is pertinent to mention that this comparison is conducted while analyzing the same room. It is then in *Zone 2*, the GW's common area. Thus, *after* GW installation, represented by the light color, the real vapor ratio difference remains to fluctuate around 0.5g/kg. Moreover, the difference between the room and the supply increases, peaking at 0.9g/kg, mainly when the outdoor temperature is between four to nine degrees. Nonetheless, the vapor ratio difference *after* the GW is never negative anymore.

Fig.23 shows the vapor ratio difference *after* GW installation when analyzing different zones inside the office. Thus, *Zone 1* and *Zone 2*, which correspond to the north-office area and the GW's common area, are compared to determine the humidity variations due to the proximity or remoteness of the green installation. Thus, according to the graph, the real vapor ratio difference remains to fluctuate around 0.1g/kg to 0.2g/kg for *Zone 1*. Furthermore, the difference between the room and the supply increases, peaking at 0.4g/kg when the outdoor temperature is between five to nine degrees. Perhaps both zones show a similar tendency; the GW's common area exceeds by 0,5g/kg the vapor ratio difference calculated in the north-office area. Evenly, although a lower vapor ratio difference peaks when the outdoor temperature is around 8 degrees, the difference between the room and the supply air remains at most 0.1g/kg. This difference suggests that *Zone 2* remains with a higher vapor ratio than *Zone 1* due to the presence of the GW.

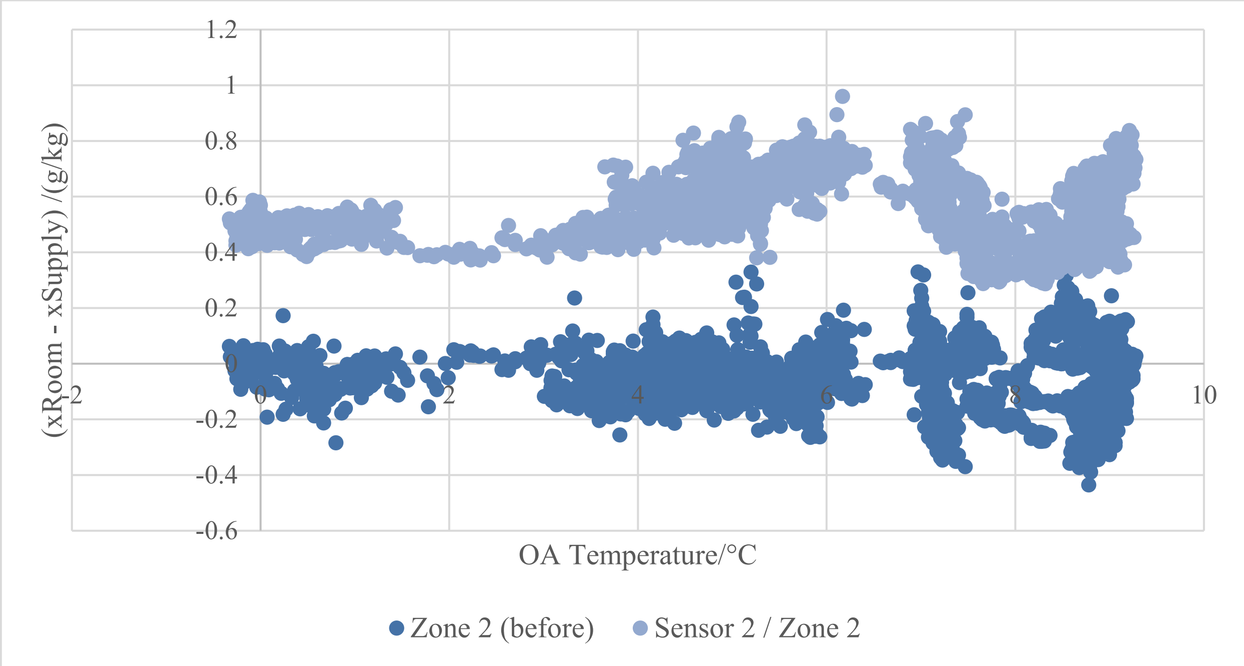

Fig.22: *Real vapor ratio difference* ***-comparison before and after GW (Zone2)***

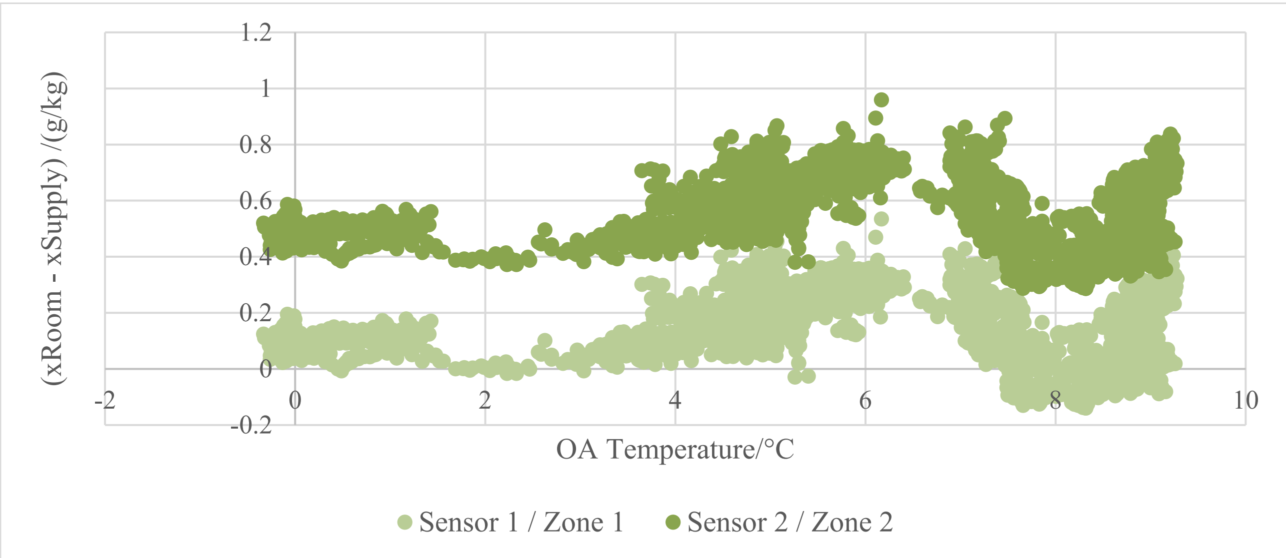

Fig.23: *Real vapor ratio difference after GW* ***-comparison between sensor's location.***

Fig.24 shows the vapor ratio difference *before* and *after* GW installation while it compares the humidity variations due to the proximity or remoteness of the green installation. The differences are notable. According to the graph, the vapor ratio difference *before* installation remains fluctuating around 0g/kg. However, it shows some negative differences that suggest the room remains with a lower humidity content than the supply conditions. Nonetheless, *after* GW installation, the vapor ratio difference remains around 0.5g/kg, peaking at most 1g/kg when the outdoor temperature is between five to seven degrees. Furthermore, the vapor ratio difference *after* GW is seldom harmful anymore, even when evaluating *Zone 1*. In a similar vein, *after* GW installation, the humidity contribution is so that the ratio difference between the room and the supply conditions is not harmful anymore.

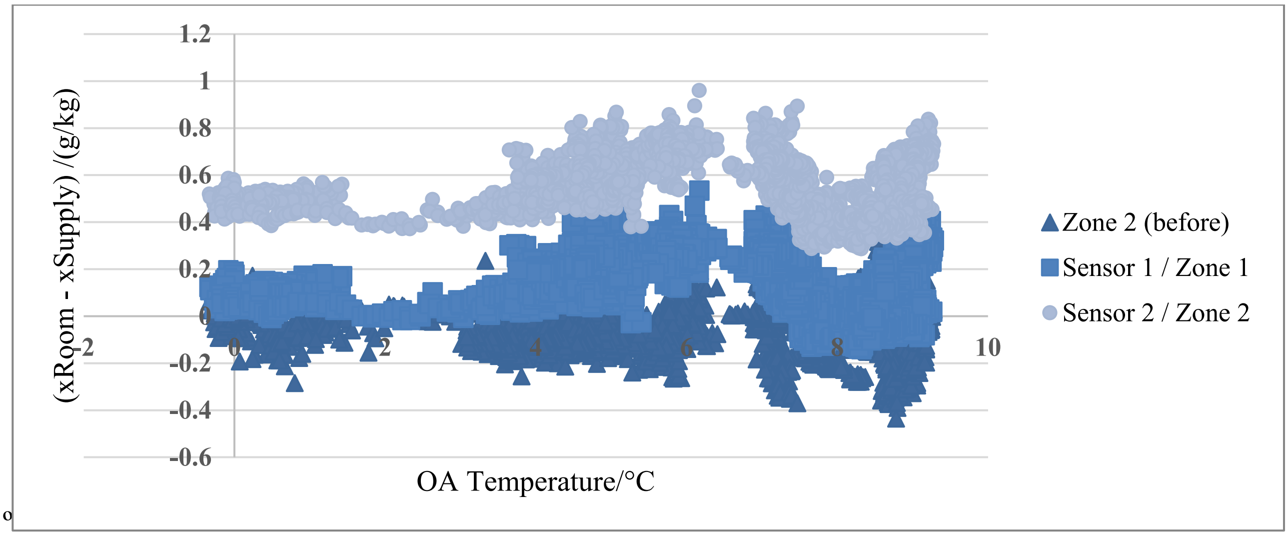

Fig.24: *Real vapor ratio difference -**comparison before, and after GW by considering sensor's location.***

3.2 Indoor carbon dioxide concentration

Regarding the results of the CO_2 concentration, measured in particles per million (PPM), the concentration in the room air *before* the installation was about 462 PPM. Although the carbon concentration was lower *after* the GW, about 453 PPM, the difference experienced is so minuscule, representing less than ten particles per million according to the foreseen measurements. Even though the result may not be enough evidence to suggest a positive impact on indoor carbon reduction due to the GW, the concentration difference, at least, provides evidence about the occupancy inside the office. Thus, according to the CO_2 difference experienced, a similar occupancy can be assumed during the selected period of study.

4 Discussion

The results obtained, the graphics and the diagrams provided along the content of this thesis suggested the impact of the GW installation and its effect on indoor humidity (vapor ratio). However, this section concentrates on some limitations, omissions, and sources of error identified during the study. Any inaccuracy might have always affected the analysis and, therefore, the results and conclusions. Some of them can be listed as follows:

1. Measurements and data collection. The measurements generally consist of a sequence of operations or steps that simultaneously introduce a potential source of uncertainty, in which its effect must be contemplated. Whether the person doing the measure, or the precision of the measuring device employed, just by mentioning some of them, there is always a source of error embodied in the surveying practice. Regarding the data logging on site, as probably mentioned before, the evidence was collected continuously from Monday to Friday from approximately 6:20 hrs. to 19:00 hrs. The ventilation airflow was reduced due to the lack of occupancy at night and on weekends. This airflow rate reduction might result in variations on site, especially each morning or after the weekend. Evenly, the ventilation schedule might represent a possible source of error while limiting a continuous 24-hour analysis.

2. Building airtightness/losses. One of the assumptions taken during the case study was the airtightness of the building office where the GW installation is, coupled with having some control of the conditions in the room according to the ventilation details, office activity, and occupancy. However, the absence of losses and leakages on site seemed challenging to achieve fully; sometimes represented by an open window but sometimes by other minuscule openings where the transfer from the interior to the exterior might have occurred.

3. Greenery/plant selection: Usually, these green installations follow aesthetic design purposes that commonly choose and set a variety of plant species on them. The GW installed in Malmö's office was not the exception, including greenery that could have a different humidity contribution and, consequently, to the whole GW indoor structure. Perhaps, the plants set in the installation obeyed some particularities that helped lessen the variations by considering a small size and similar daylighting and watering requirements. Nevertheless, the greenery selection could result in humidity deviations.

4. Green wall's water consumption: The water inlet the GW installation received throughout some of the weeks of the study was not entirely accurate. Since its installation, a constant water consumption was assumed according to the personnel in charge of the GW. Similarly, the amount of water drained by the wall represents a rough estimation/calculus provided by the same source. However, it might be suggested that the water consumption was not as constant as it was initially assumed by considering the soil dryness reported in early January in some of the compartments of the GW, which might affect the planting irrigation, and, therefore, their effect and contribution to indoor humidity. Nevertheless, after the mentioned incident regarding the GW's water consumption, special care by the personnel was given up assuring the appropriate water inlet and the correct functioning of the irrigation system to avoid any future dryness issue in the soil or in the greenery.

5. Outdoor conditions and AHU/ ventilation supply: The outdoor temperature and vapor ratio highly influenced the room conditions. There were few options available when it came to the weeks chosen for the comparison since the ventilation settings were not the same except for one week before the GW installation. Thus, to set the correct boundaries for the comparison and avoid any other possible alteration that may not be directly due to the GW, the week selected as *before* must be as close as possible to the installation's date. This is to ensure that the determined impact of the GW is due to the wall itself and not to changes in other sources that might contribute to the humidity indoors. Consequently, the weeks to conduct the comparison *after* GW was selected to satisfy similar conditions to the one previously chosen while considering airflow rate, outdoor temperature, and vapor ratio. This is even though the meteorological conditions' fluctuations hinder holding identical situations for comparison. Nevertheless, the results after calibration provided a higher accuracy of the actual scenario.

6. Occupancy: Although the occupancy during the study remained steady at around twelve people per week, according to the office's personnel, the detailed schedule of every person involved at the office was entirely out of knowledge, and it may provoke variations and affect the indoor conditions, such as

humidity. Nevertheless, those variations are not expected to hugely influence the results since the indoor carbon concentration remained with no big difference within the study period, suggesting a constant or similar occupancy.

5 Conclusions

This thesis aimed to test and analyze the effect of a Green Wall (GW) on indoor air humidity in an office building, in a case study. The field measurements executed, excluding the effect of other changes and alterations influencing the building and the indoor environment, attempted to isolate the impact of the GW. The green wall's ability to increase humidity was testified and might indicate a positive indoor contribution through the results of this study.

While evaluating weekly averages *before* the installation, a negative vapor ratio difference of 0.286g/kg was calculated according to the room and supplied air conditions. By comparing the results *after* GW, the results of this study suggested an estimated contribution that oscillates between 0.5g/kg to 1g/kg (water/air content) attributed to the GW installed in Malmö's office. Perhaps a slight but notable difference. Nonetheless, if roughly considering the GW's area to the office's heated floor area, 8 m^2 Vs. 450 m^2, respectively, means that installing a green structure that roughly satisfied a relation close to 1.5% of the office area provoked the conditions to fluctuate up to 1g/kg when evaluating similar outdoor scenarios and supply air conditions.

To conclude, according to the analysis, the results obtained after the GW installation have suggested sufficient evidence of the GW's humidity benefit when evaluating the vapor ratio difference between the room and the supplied air, according to the outdoor conditions.

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