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Vertical Greenery Systems as Microbial Air Quality Filters for Community Houses Located Near the Landfill Site

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Abstract. Rapid urban development, along with high population growth in Indonesia, has forced some communities to move away from the city center. At the same time, the city needs space for its waste, which is typically deposited in landfill sites. In both cases, the city outskirts have become favored sites for development. As a result, some communities now find themselves living adjacent to a landfill site and must cope with its air pollution. This study assesses the application of a vertical greenery system (VGS) acting as a microbial air quality filter for community houses located near the landfill site in Kampung Nambo in South Tangerang, Indonesia. Six types of plants were selected for analysis. The study found that Hedera helix was the most effective plant for filtering microbes from the air; the highest recording was reaching 717.3 CFU/m^3 (day 10). The study also highlighted the presence of solar radiation, additional shading, and natural ventilation combined with the VGS help to improve air quality. Higher temperatures can reduce the microorganisms, thus impacting the number of bacteria and fungi. Every 1 W/m^2 increase in solar radiation can reduce bacteria by 1.98 to 2.16 CFU/m^3. Furthermore, the insights of this study should encourage both governmental decision-makers and the broader community to reexamine the importance of vertical greening in settlements adjacent to a landfill.

Keywords: Air quality; Dense settlement; Landfill; Vertical greenery system

1. Introduction

Indonesia experiences high humidity ranging from 55% to 100% along with daytime temperatures between 20°C to 32°C, and nighttime temperatures between 21°C to 27°C (Direktorat Jenderal Cipta Karya, 2020). These climatic conditions, together with Indonesia becoming one of the top twenty most polluted countries globally (The World Bank, 2022), can combine to produce potentially adverse health effects (Ahad *et al.*, 2020). Additionally, the country's population has experienced a 211% increase from 1960 to 2022, with significant growth occurring in urban areas (The World Bank, 2022). A growing population

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and increasing consumption levels have resulted in more waste production. Thus, landfill sites have grown. Some landfill sites are located close to nearby communities that are also extending their boundaries, sometimes through informal settlements, and this too will have potentially adverse consequences for the environment and health. Despite a key regulation stating that settlements must be at least 500 meters away from landfill areas (Minister of Public Works Republic of Indonesia, 2013), housing settlements and landfill areas still become unavoidably "close neighbors".

Building practitioners face challenges in considering future climate conditions in construction and retrofitting projects. Currently, there is a growing focus on developing models and gathering evidence to support the creation of more resilient buildings. One area of growing interest is in implementing Vertical Greenery Systems (VGS) to improve building envelope performance and address multifunctional benefits for dense settlements and nature (Ryan and Bristow, 2023; Rupasinghe and Halwatura, 2020; Hong, Ibrahim and Loo, 2019; Oluwafeyikemi and Julie, 2015). A VGS is a vegetated wall system that can be applied to interior areas or building facades (Fernández-Cañero, Urrestarazu, and Perini, 2018). VGS helps to improve external and internal air quality (Megahed and Ghoneim, 2021). In addition, there is potential to enhance the "green feel" within communities by transforming ecologically barren walls into vibrant green spaces. This is especially beneficial in metropolitan areas (Shaharudin, Khalil and Saleh, 2019), where the layer of leaves that grows on walls acts as traps for reducing dust and particulate matter (Axmalia and Mulasari, 2020). Previous applications of VGS, such as in Pasir Gudang, Malaysia, show that it can enhance thermal performance while lowering air pollution (Ghafar *et al.*, 2020). It has been claimed that if an inner-city area were greened on all potential facades, 4% of annual dust fall may be captured on the leaves (Köhler, 2008).

An early study on VGS by Zaid found that it can lower air pollution in a tropical context (Zaid *et al.*, 2018). Subsequent work by Megahed and Ghoneim on spaces in densely populated residential areas discussed the use of VGS on building facades for natural ventilation, air quality management, thermal comfort, and green spaces (Megahed and Ghoneim, 2021). A vibrant debate is emerging on the applicability and efficacy of VGS in various settings (Bustami *et al.*, 2018; Coma *et al.*, 2017; Pan and Chu, 2016). Important developments have taken place in understanding thermal performance, energy efficiency, and plant variety.

While other studies have made valuable contributions to the impacts of VGS on air quality (Yang *et al.*, 2023b) and cooling (Yang *et al.*, 2023a), less attention has been given to more marginal, densely populated communities where space is likely to be heavily contested and where environmental issues may be given only passing attention. Our study is to test if VGS could help improve the sustainability of waste concerns in our case study community and, more generally, around urban landfill sites in developing countries (Schlosser, Robert, and Debeaupuis, 2016). The contribution of our work, therefore, is to demonstrate that persuasive, evidence-based cases can be made for investments in VGS where they are sympathetic to community aspirations. VGS meets local community interests because it has minimal impact on space for homes and can help to improve air quality where there are concerns about respiratory health. Our study extends the role of VGS, which has typically adopted a planning-led approach (Fang, Li, and Ma, 2023) that underplays inequality in decision-making and outcomes. Kampung Nambo in South Tangerang City is selected as a case study to represent communities in a hot, humid climate. The research process is outlined in Figure 1 below. In Section 2, we develop our argument by combining insights into the negative health impacts of landfills with an understanding of VGS. This approach provides us with an opportunity to develop solutions that are more sensitive to the needs of the community and better address ongoing environmental problems. In Section 3 we outline our approach to data collection in our case study community and the selection of different types of plants to populate the box models that replicate potential VGS schemes. Section 4 reports on our results and shows the variability of different types of plants on air quality and thus supports our contention of the need for community-level analysis to maximize the benefits of green infrastructure investments. Finally, in Section 5 we draw together our insights and conclude that sympathetic plant selection plays a crucial role in the effectiveness of VGS. This is because, first different plant varieties perform an air cleansing function in variable ways at the local level; and second, where public and private funding is likely to be constrained community management of VGS will move to the fore, and communities need to be able to draw on their tacit knowledge of local plants to nurture their growth and care.

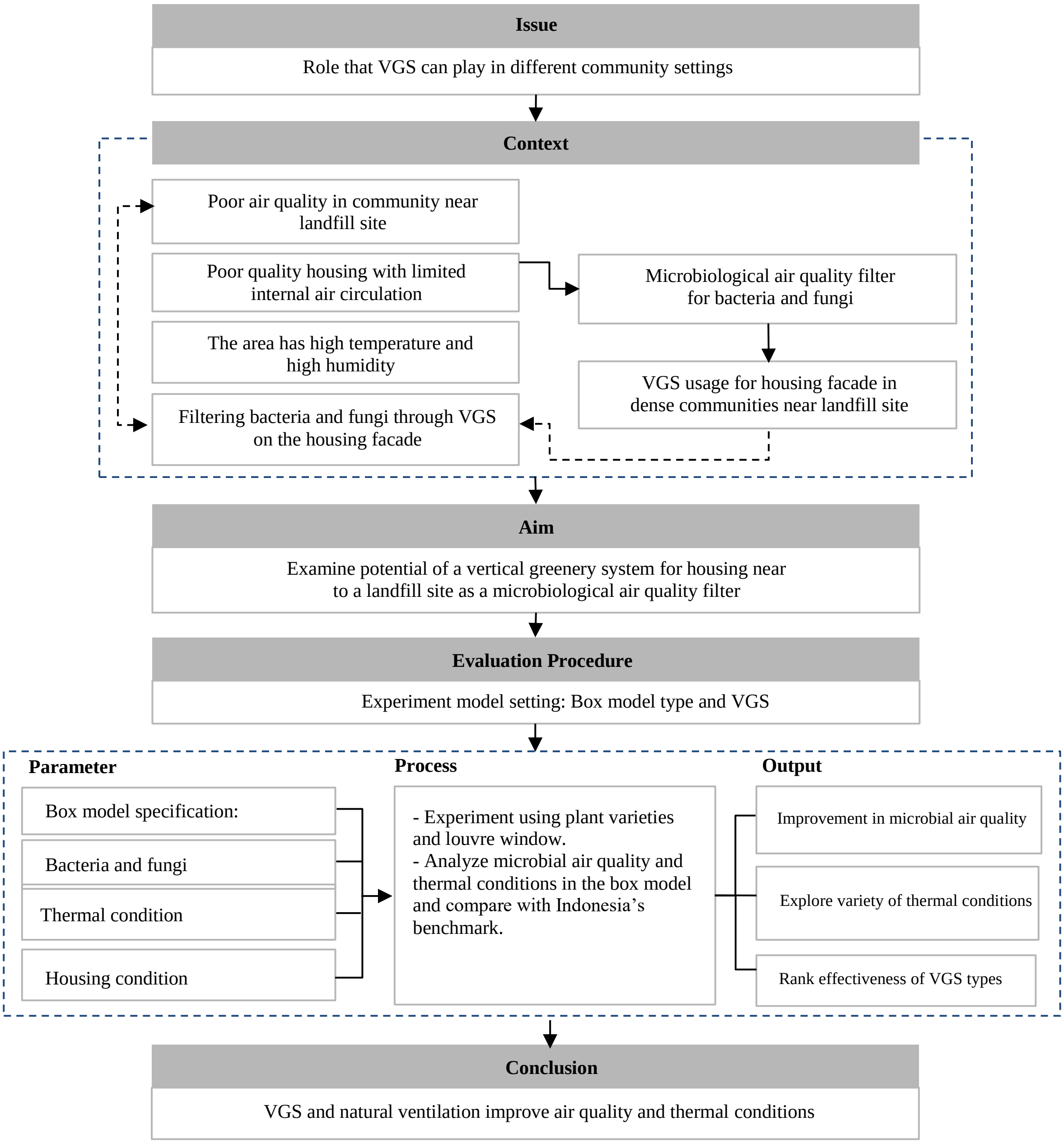


Figure 1 Study framework and keywords compilation

2. Literature review

In this section, we will discuss the issues surrounding landfill sites and their impact on the health and environment of local communities (Section 2.1). Since many landfill sites are expected to operate for the foreseeable future, it is crucial for neighboring communities to have the opportunity to enhance their air quality. We will explain our rationale for selecting specific plants in the study and present preliminary findings on the benefits of VGS (Section 2.2). Additionally, we will highlight how VGS can naturally assist in managing solar radiation (Section 2.3).

2.1. The impact of landfill sites, microbial air quality, and health

Landfill sites are formal locations to manage garbage responsibly for people and the environment. In practice, that may not always be the case. A landfill site near housing settlements and other sensitive locations, such as a market or a waterway, is considered unsafe and a threat to public health that needs to be adequately managed (Daniel *et al.*, 2021). Moreover, waste decomposition generates methane (CH_4) and hydrogen sulfide (H_2S), which have a bad odor and may attract rats, while ammonia (NH_3) causes respiratory illnesses, physiological abnormalities in the lungs, and elevated blood pressure (Axmalia and Mulasari, 2020). Along with chemicals, biological pollutants such as bacteria and fungi are transported by air circulation in the landfill area (Pepper and Gerba, 2015). As we are keen to emphasize throughout local conditions matter. In this case, local biometeorological factors such as temperature, pressure, relative humidity, wind direction, and the substance of waste and leachate create an impact on pathogenic agents' ability to survive and multiply (Schlosser, Robert and Debeaupuis, 2016). In addition, in an equatorial or tropical environment, like that of Indonesia, building design places a high priority on managing the amount of heat transfer and ventilation (Othman and Sahidin, 2016).

2.2. Vertical Greenery Systems (VGS)

The VGS is categorized as a green facade (GF) or a living wall (LW) based on its construction type and diversity of plants (Fernández-Cañero, Urrestarazu and Perini, 2018). A GF commonly consists of vines and hanging plants applied to walls or balconies at different heights from the building, while a LW is a complex VGS suitable to support the growth of various plants and may be aesthetically pleasing (Fernández-Cañero, Urrestarazu and Perini, 2018). The installation of VGS with the living wall on the exterior has several patterns, such as a mesh and trellis system with planters (Čekić, Trkulja and Došenović, 2020).

VGS can act as a natural air conditioner to absorb heat (Zaid *et al.*, 2018). Natural ventilation, air quality controllers, and thermal comfort with green spaces are part of a VGS system on a building's facade in highly populated settlement areas (Megahed and Ghoneim, 2021). To improve visual comfort inside the home, VGS is additionally utilized as a shield from direct solar radiation (Stephenson *et al.*, 2013; Funo, Yamamoto, and Silas, 2002). In short, depending on the scale at which it is implemented VGS can help mitigate local to wider Urban Heat Island (UHI) effects and reduce air quality problems.

Grass and ornamental plants in VGS, such as *Cordyline fruticosa, Phyllanthus cochinchinensis, Nephrolepis exaltata*, and ornamental plants like *Philodendron burle-marxii* can reduce heat and air pollution (Ghafar *et al.*, 2020). While other plant species can also be used with VGS to filter airborne particles, like *Dracaena deremensis, Neomarica gracilis, Philodendron cordatum, Schlumbergera truncata Hybrids, Monstera deliciosa, Nephrolepis biserrata, Hoya pubicalyx, and Cissus rhombifolia* (Ghazalli *et al.*, 2018). In addition, *Hedera helix* plants with a ≥ 20 cm thickness are not only capable of reducing heat but also acting as a wind barrier (Kraus, Žáková and Žák, 2020; Castellanos-Arévalo *et al.*, 2016; Minister of Health Republic of Indonesia, 2011). The density of Passiflora plants is expected to impact the thermal experience (Widyahantari, Alfata, and Nurjannah, 2020).

Biochar is frequently used to boost the viability and efficacy of VGS (Kraus, Žáková and Žák, 2020). Based on a preliminary study from Puteri (2016), 59 plant species were examined to see which had the best pot systems for VGS. *Alternanthera ficoidea* stood out for having the highest index value for plants' capacity to produce the maximum supply of 18 O_2/m^2 with a leaf area of 44 cm^2. As well as *Codiaeum variegatum* and other plants with an index of 12. In addition, *Philodendron sp.,* with a leaf area of 363 cm^2 and an index value of 8, performs well. It is, though, important to evaluate plant performance in a variety of local settings to be confident of their effectiveness, including their acceptability to communities and this will often mean that they are plants recognized locally. For our study, it involves examining the purification abilities of plants in close proximity to a landfill site, taking into account the hot and humid climate of Indonesia.

The anaerobic decomposition of microorganisms in landfills produces ammonia gas (NH_3), which encourages the growth of bacteria, especially from organic waste (Yang *et al.*, 2023a). According to the Indonesian health standard, the upper range for germ threshold with harmful fungi and bacteria is 700 CFU/m^3 (Minister of Health Republic of Indonesia, 2011). International standards, such as the American Conference of Governmental Industrial Hygienists (ACGIH), are stricter and set a threshold of 500 CFU/m^3. This more demanding requirement has become mandatory for some tropical countries, such as Brazil and Singapore (Castellanos-Arévalo *et al.*, 2016). Another challenge for many landfill sites in Indonesia, including our case study, arises from biological activity brought on by sewer decomposition and stagnant water. This results in the formation of hydrogen sulfide gas (H_2S), which has a strong odor (Elwood, 2021; Azima, 2016). Previous research has suggested that vegetation can be used to reduce high levels of bacteria and fungi in settlement areas near landfills (Fithri, 2021; Kumar *et al.*, 2019). However, where land is scarce, as in our case study, there are limited opportunities to create traditional vegetation barriers.

A previous study by Rakhshandehroo mentioned that VGS is primarily applied on the façade with varying degrees of installation complexity to support building performance, such as reducing noise and insulating the building's envelope through solar reflection, heat transfer from the leaves and photosynthesis or evapotranspiration, among other things (Rakhshandehroo, Mohd-Yusof, and Deghati-Najd, 2015). Additionally, VGS has been found to reduce energy usage from 9.5% to 18% in commercial buildings and decrease the harmful effects of UV light on the building's (Rakhshandehroo, Mohd-Yusof, and Deghati-Najd, 2015; Sathien, Techato and Taweekun, 2013).

2.3. VGS and shading: reducing solar radiation

The range of optimal daylight intensity for housing in a tropical climate is about 3–7 W/m^2 (DKI Jakarta Provincial Government, 2012). Lighting and ventilation are frequently connected. Therefore, external improvements, such as adding shade in the form of trees or air bricks and patterned tiles, can lower temperatures in settlements to between 18°C and 30°C and ameliorate internal comfort (Kusumawardhani, 2011; Minister of Health Republic of Indonesia, 2011). Well-planned shade can increase a city's aesthetic appeal lessen the consequences of heat generation (Macher, 1989) and reduce the risk of illness (Hollands and Korjenic, 2021).

In addition to lowering surface temperatures, VGS can also enhance air circulation, air quality, visual comfort, and indoor thermal conditions (Shuhaimi *et al.*, 2022; Abdul-Rahman *et al.*, 2014). However, the reality of the situation for many fast-growing urban areas in developing countries is that green space is continually being challenged, and so efforts to maximize the effectiveness of VGS need to pay particular attention to installation, maintenance, placement, density, and plant types (Abdul-Rahman *et al.*, 2014). Little, though, is known about how VGS may work for poorer quality buildings and in more marginal communities. Our case study, therefore, fills an important gap in the literature.

3. Methodology

3.1. Case Study: Kampung Nambo, South Tangerang, Indonesia

South Tangerang City is one of the fastest-growing cities in Indonesia and is close to Jakarta. South Tangerang's landfill is located in Kampung Nambo. The community next to the landfill site is home to 40% of the households in Kampung Nambo (Dewi *et al.*, 2019). The area was chosen as a case study due to its environmental issues.

Figure 2 depicts the Kampung Nambo settlement with the landfill site visible in the background. Spanning an area of 2.5 hectares, the landfill receives approximately 300 tons of waste daily. The sheer volume of waste deposited has caused the landfill to surpass the height of the surrounding community, with reports indicating that the waste has reached a staggering 16 meters in height (Renaldi, 2020). It is claimed that "The foul smell emanating from the site has been reported as far as 6 kilometers away" (Renaldi, 2020).

Figure 2 The vicinity of Kampung Nambo Serpong with the view of a landfill as background

The average temperature is measured daily for the whole year during the study to be between 27.46°C and 28.04°C. Climate change is likely to lead to further increases in average temperature, making efforts to improve cooling within the community even more important. Like other tropical areas, local weather has a rainy season. This means that there is a high average annual humidity of around 80%. The average wind speed is between 1.44 and 1.57 m/s (BMKG, 2022) so might potentially blow air pollution into the neighborhood, which is only 500 meters away from the landfill.

3.2. Data Collection

Data sets were collected during the 'shifting season' in Indonesia - the time between dry and rainy seasons – for six weeks between March and April 2022. This study captured data from wet to dry seasons and our measurements took place during high rain precipitation, drought, and strong wind speed. The sampling was done outdoors, using one control box, and six VGS box models. Within the timeframe of the study, microbial air quality tests in the laboratory were done twice a week.

3.3. The Box Model

South Tangerang is at -6.31113, South Longitude: 106.65893, altitude 32.06 m, 105.20 ft. The area chosen for data collection was based on the accessibility of the likely contamination point nearest to the community (see Figure 3). A box model was developed to incorporate the VGS. This enabled us to investigate the amounts of bacteria and fungi, temperature, and humidity in dense populations next to the landfill. The box model with the VGS acts as a filter for contaminated air.

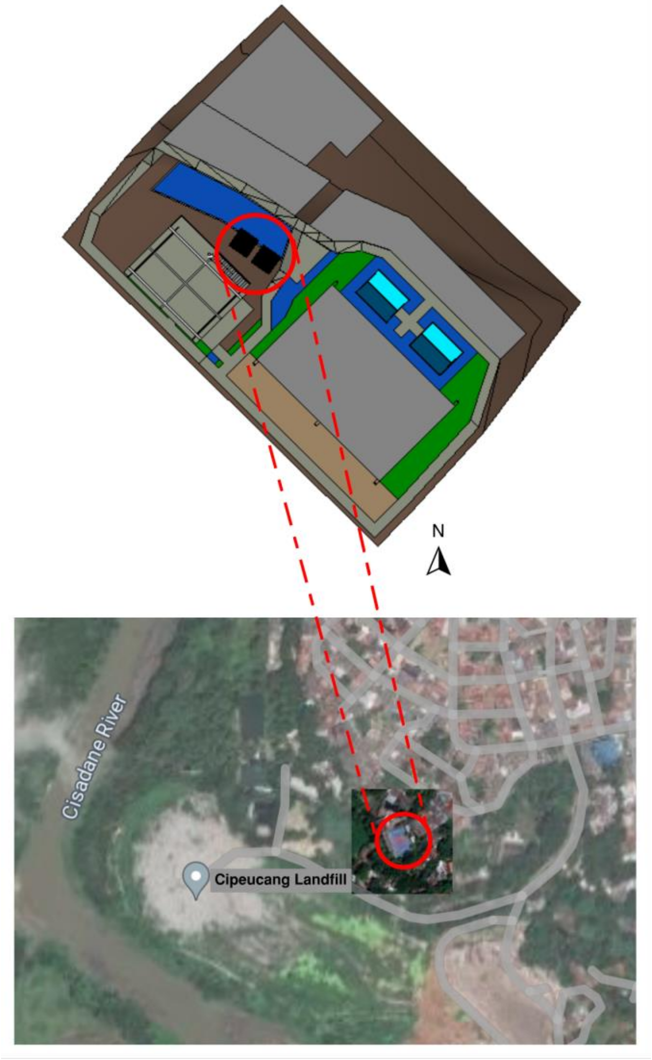


Figure 3 Experiment Box Model Placement in Kampung Nambo Serpong, RT 03 RW 04, South Tangerang City

3.3.1. Plant Selection

Six box models with different plants (boxes 1-6) and a box control (C) were set up. The control box had no plants but was fitted with louvre glass windows (see Figure 4). The selected six plants that local growers offer are low-maintenance plants suitable for tropical conditions. They are *Hedera helix, Alternanthera ficoidea, Nephrolepis cordifolia, Vernonia elliptica, Sansevieria trifasciata,* and *Philodendron sp.* (Ghafar *et al.*, 2020; Charoenkit and Yiemwattana, 2016). They encompass climber, creeper, succulent, and herbaceous plants. These plants were evaluated and ranked by consideration of climatic conditions such as humidity, temperature, wind speed, and solar radiation. The effectiveness of each plant as a microbial air quality filter was then ranked.

Figure 4 Experimental box model with six selected plants and one control box experimented over a period from day 1 to day 12

3.3.2. The Box Model Material and the Measuring Tools

The box model consists of opaque walls, a corrugated roof in white color, and a louvre window as an opening. Our on-site observations of the community noted that dwelling windows had restricted openings, and the average of dwelling size is 21 m^2 - 36 m^2 (Minister of Settlement and Regional Infrastructure Republic of Indonesia, 2002). Although we would have liked to replicate a typical dwelling in our study, due to restrictions on the available space for the study, the box model is smaller than the average dwelling size in the community (see Figure 5). Where necessary, we have been cautious in our interpretation of the data to take account of the size differences.

For each box model, VGS with planting media was installed in the outer part of the opening alongside gravity-fed drips (Corson-Knowles, 2012). The study employed data loggers, anemometer, FLIR thermal imaging, a solar meter, and the Impactor EMS E6 400-holes as measuring tools. These tools were also installed in the control box. Figure 5 shows the tool placement within a box model. Data loggers were used to record the temperature, and humidity, and were located within the box. The anemometer was used to measure the outside air temperature, humidity, and wind speed. The solar meter was used to measure the solar radiation within the model, and FLIR thermal imaging captures the surface temperature. The Impactor EMS E6, which has 400 holes, and a vacuum pump were utilized to collect data on the parameters of bacteria and fungi in the air, specifically related to air pollution (Macher, 1989). In the laboratory, the plants were assessed for their effectiveness in reducing the levels of fungi and bacteria in the air.

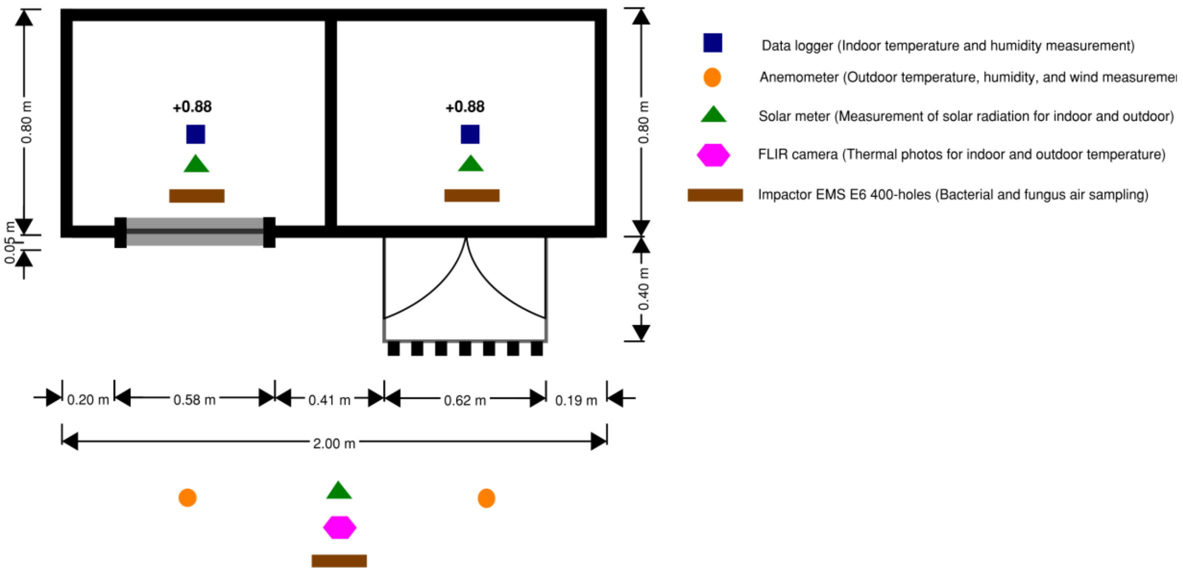


Figure 5 The placement of measuring tools, including a data logger, an anemometer, a solar meter, a FLIR camera, and an Impactor EMS E6-400, for tested the experimental box from day 1 through day 12

3.4. The Microbial Air Quality Test

This study also collected sampling data on bacteria and fungus to see if it fell within the Indonesian Health Standard of 700 CFU/m^3, for the total number of germs (Minister of Health Republic of Indonesia, 2011). The microbial air quality tests were conducted in the laboratory at the Universitas Indonesia. Due to the restricted availability of media manufacturing and the laboratory's capacity to examine germ sample growth, data collection was limited to two days a week. However, this regularity provides for consistent and accurate findings. Also, during our study period, air pollution from the landfill site tends to stay within its bounds.

The microbial air quality test system used the NIOSH 0800 and 0801 techniques and ACGIH recommendations (Odonkor and Mahami, 2020; Er *et al.*, 2015). To assess the amount of particle deposition in the container and the number of microbial colonies of air pollutants per unit of air volume, the culture of bacteria and fungi must also be tested 48 hours after the sampling.

The number of bacterial colonies in samples that had been cultured for 48 hours was then counted. The 400 holes in the Correction Factor Table (Macher, 1989), were used to adjust the number of bacterial colonies to the standard deviation. The method can then be used to determine the extent of bacterial and fungal bioaerosol samples with the following formula (Universitas Indonesia, n.d.):

$$\text{Range bacterial or fungal colonies} = \frac{Number\ of\ colonies}{Qp\ .t}$$

CFU/m^3 = Bacterial and fungal concentration
Qp = Vacuum pump airflow rate (liter/minute)
t = Pumping time (seconds)

4. Results and Analysis

4.1. Outdoor air quality and VGS

This study undertook twice weekly air quality monitoring during the study period (March 21, 2022, until April 27, 2022). The 12 observations of outdoor air quality are indicated in Figure 6 and show that in Kampung Nambo Serpong, there was an Air Quality Index (AQI) value of between 65-158 for PM2.5, which means the air quality there reached an unhealthy level (Weather, 2022; United States Environmental Protection Agency, 2014). The AQI is an index used to report daily air quality and it shows how clean or polluted air is, as well as the health implications that may be present (United States Environmental Protection Agency, 2014). Box models 4-6 recorded notably poorer air quality than Box models 1-3, illustrating the difference that plants can make. It is also important to note, though, that as the recording progressed over time there was higher rainfall experienced and this increases the possibility for the spread of germs and fungi.

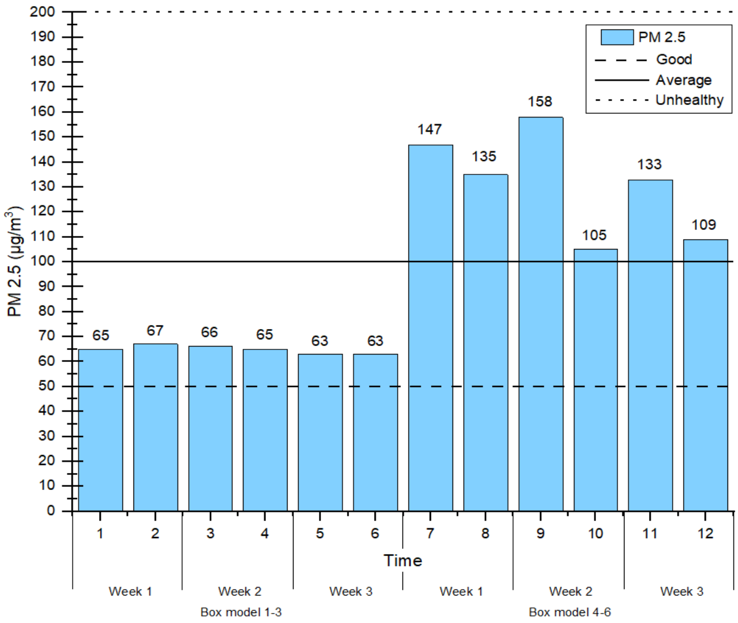


Figure 6 Average Outdoor Air Quality in Serpong-Banten, Indonesia, was evaluated from week 1 through week 6 during the experimental period

This index, as shown in Figure 6, indicates high air pollution for weeks 4-6, especially for PM 2.5, which is up to 6.5 times higher than the WHO standard (WHO, 2021). As a result, asthma, lung, heart, and other medical conditions may develop (Izzatuljannah and Zakiah, 2021). The presence of a settlement near the Cipeucang Landfill, the growth of industries, factories, and businesses with high pollution intensity, as well as the reduction in green open space have all contributed to a considerable rise in pollution over time (Izzatuljannah and Zakiah, 2021).

Bacterial colonies were measured by an Impacter EMS-E6 400 holes device and validated with a correction table (see Appendix 1 for further details). The total range of bacterial colonies outdoors = (485.86 – 556.53) CFU/m^3 (these numbers mean that there were 485.86 – 556.53 bacterial colonies in 1m^3) and the bacterial colonies were in the acceptable range for Indonesia at <700 CFU/m^3 (Minister of Health Republic of Indonesia, 2011) but higher than more stringent regulations to be found in other tropical countries such as Brazil and Singapore.

The six VGS plants were able to effectively filter microbiological air. Therefore, they have the potential to achieve similar results in settlement areas near the landfill. As shown in Table 1, the plants are capable of filtering microbial air with a range of 1,162.59 to 1,790.96 CFU/m^3. These are significant differences that highlight the importance of understanding local geographic conditions when establishing VGS. As expected, the *Hedera helix* can provide a higher-level filter for microbial air than other plants at a range from

1,636.38 to 1,790.96 CFU/m³. It is followed by *Alternanthera ficoidea* with a range from 1,545.16 to 1,703.11 CFU/m³, and *Nephrolepis cordifolia* with a range from 1,522.92 to 1,677.91 CFU/m³. However, it was found during plant testing that the control box with a louvre window was also efficient and could filter the air with a range from 1,472.37 to 1,593.07 CFU/m³. These conditions occurred due to the inlet and outlet in the louvre window, as it encouraged airflow to indoor space, harnessed natural ventilation patterns to filter the incoming air, captured larger particles, and created a continuous flow of fresh outdoor air.

Table 1 Ranking of the best plants for reducing microbial populations

Rank	Box No.	Plants	Type of plant-leaf density	The number of reduced germs (bacteria and fungi) (CFU/m³)
1	*6*	*Hedera helix*	Climber, Creeper	1,636.38 ₋ 1,790.96
2	*4*	*Alternanthera ficoidea*	Herbaceous, Creeper	1,545.16 ₋ 1,703.11
3	*5*	*Nephrolepis cordifolia*	Herbaceous	1,522.92 ₋ 1,677.91
4	*1*	*Vernonia elliptica*	Creeper	1,182.73 ₋ 1,271.56
5	*3*	*Sansevieria trifasciata*	Succulent	1,169.75 ₋ 1,253.27
6	*2*	*Philodendron sp.*	Climber, Creeper	1,162.59 ₋ 1,243.77

The remaining three plants that can perform as an air filter are *Vernonia elliptica, Sansevieria trifasciata,* and *Philodendron sp. Vernonia elliptica* has a range of 1,182.73 to 1,271.56 CFU/m³, *Sansevieria trifasciata* ranges from 1,169.75 to 1,253.27 CFU/m³, and *Philodendron sp.* ranges from 1,162.59 to 1,243.77 CFU/m³. As a result, the VGS with a mesh and trellis system type on an orientation facing the landfill area had the potential to improve the air quality, and from previous studies, we know it can also help reduce heat (Shuhaimi *et al.*, 2022; Perini *et al.*, 2011). Plants ability to develop, as seen in Table 1, demonstrates that their high leaf density makes them more effective at filtering microbes such as bacteria and fungi in the air.

4.2. Germs and air quality

Figures 7 and 8 show the lower and upper ranges of the germ numbers, an indicator of air quality, which fluctuates for 12 days for which measurements took place over the six-week study. The reason for the shortened time frame for the measurement of the germs is because of the two-day time period that was required to prepare the culture before it could be used to test the samples from the box models. Days 1,3-4, 6, 9-10, and 11 showed that the germ intensity was above the safe limits, which range from 700 to 2,300 CFU/m³. Days 4 and 9 had the highest levels at 2,300 CFU/m³. In contrast, during days 2, 5, 7-8, and 12 the intensity of germs fell below the limit of 700 CFU/m³. During day 4, Box Model 2 showed the highest level of bacteria at 2,000–2,300 CFU/m³. Box model 6 had the lowest concentration at 100–200 CFU/m³ on day 11. Additionally, the outside area on day 9 had a germ index of around 1,700 to 1,800 CFU/m³, while day 7 had a germ index of under 100 CFU/m³. Weather affects how many and how few germs are present; for example, sunny weather tends to have fewer germs than overcast or wet weather. Considering various weather conditions is critical for understanding the variability in the results and highlights the value of detailed local studies. The figures below indicate that germ levels in the box model varied over a short period of time. It can be observed that sunny weather generally resulted in fewer germs (Figure 7) compared to overcast or wet conditions. Despite this, both figures demonstrate similar patterns throughout the study period. The variation between the lower limit (Figure 7) and upper limit (Figure 8) for germ levels remains consistent, highlighting the significance of local climatic conditions.

Figures 7 and 8 also display the changes in the control box model and Box model 2 that housed *Philodendron sp.* plants. Data for box model 2 shows it is the weakest performer (i.e.

the lowest ranked of the six plants) but does illustrate the minimum gain that can be made by green infrastructure. Looking at the figures in more detail shows that over the three weeks for data collection the trend on day 4, for Box model 2 showed an increase in the number of germs, as it rose from 2,004.4 to 2,308.29 CFU/m^3. Meanwhile, data from the control box model shows that on the same day, a lower figure was recorded for the number of germs of 555.65 and ranged up to 640.45 CFU/m^3. This is an unexpected finding because other studies show that plants will filter germs (Kumar *et al.*, 2019). It is essential to understand why such an anomaly may arise as it illustrates the challenges of undertaking community-level work in which the environment can only be partially controlled. During the observation periods when the researchers were on site, we noticed that chickens began moving in and out of Box Model 2 before recording data on day 4. However, this situation cannot happen in the Control Box model due to the louvre window which blocks chickens from entering the box. We assumed the chickens would have brought germs into the box, which explains the surprisingly high level of germs recorded. However, this assumption needs to be further investigated (see Appendix 2).

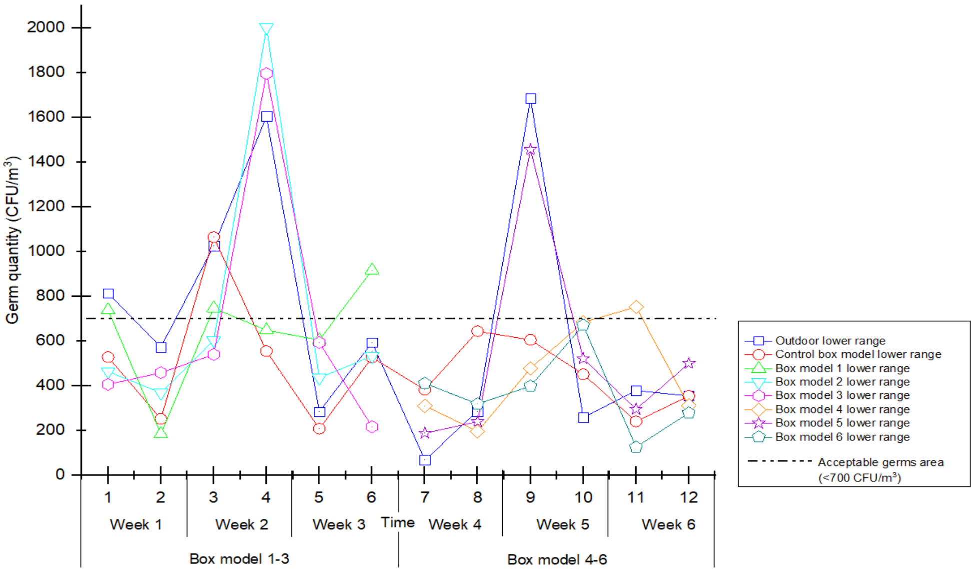


Figure 7 The lower range of germ quantities graph in an outdoor, control box model, and box models 1-6 for 6 weeks

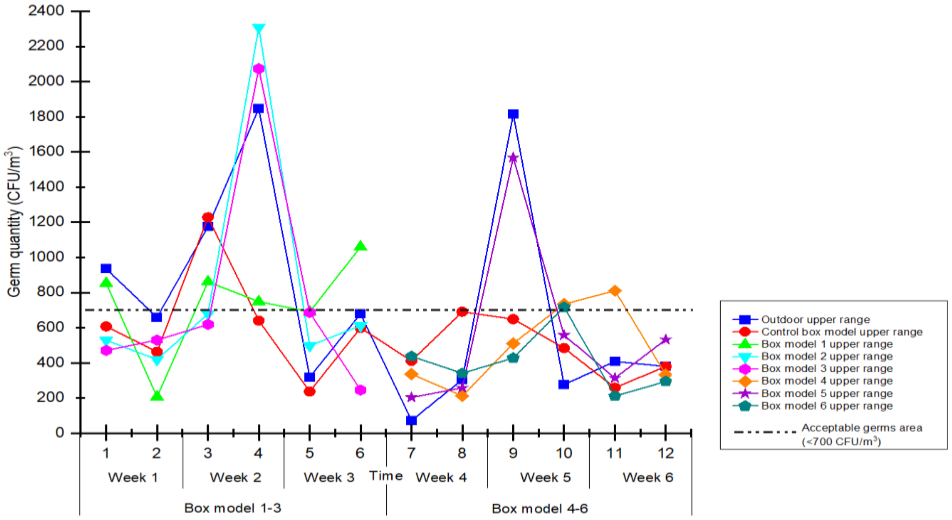
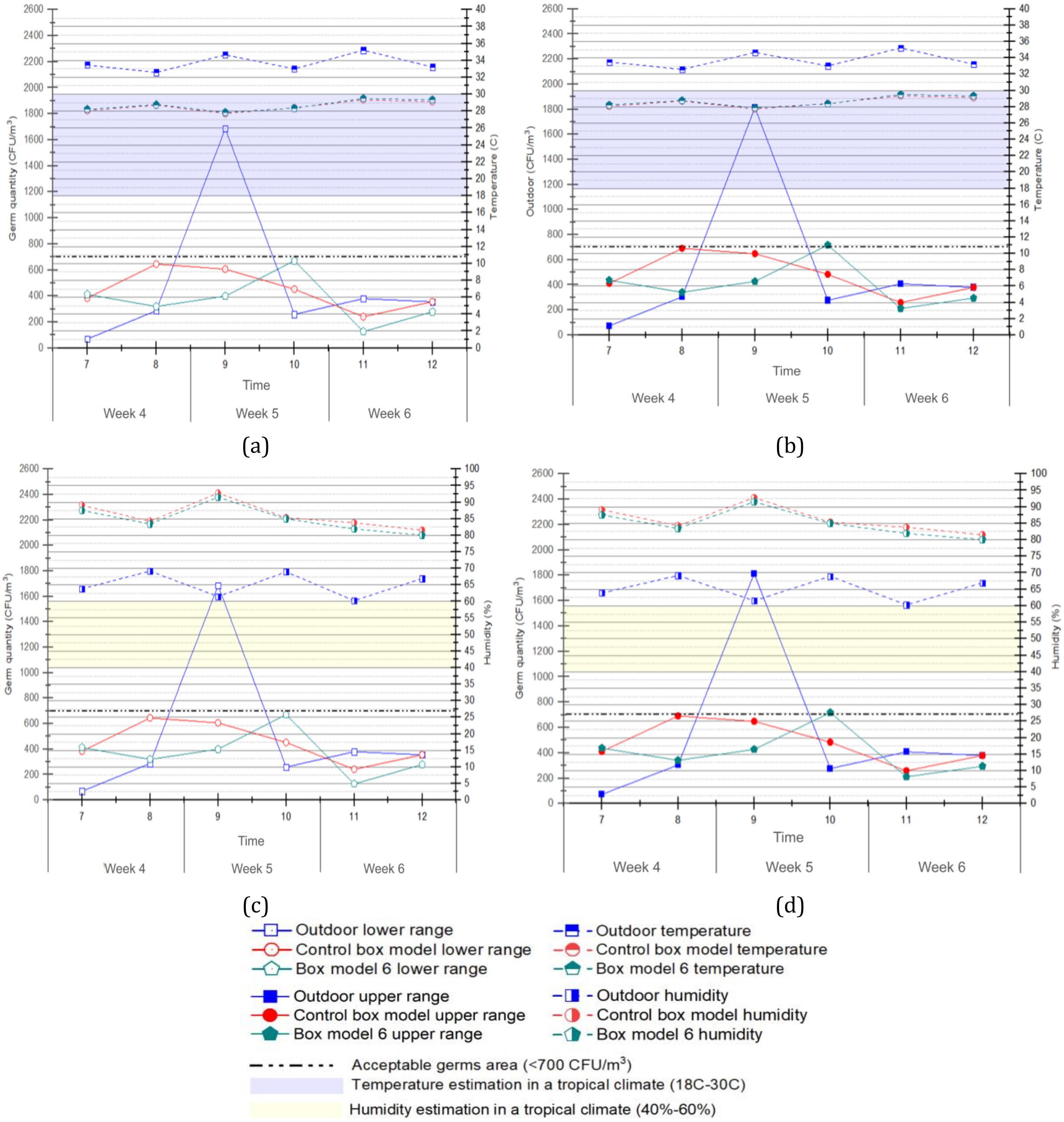


Figure 8 The upper range of germ quantities graph in an outdoor, control box model, and box models 1-6 for 6 weeks

As shown in Figure 9, Box Model 6 (*Hedera helix*) has lower germ trends than the other box models. The highest recording was on day 10, reaching 717.3 CFU/m^3. Additionally, changes in germ density between days 7–12 revealed a range from 100 to 700 CFU/m^3, which was lower than the other box models. The humidity in box 6 model was between 60–100%, while the temperature ranged between 30–38°C. The survival of airborne microorganisms is significantly influenced by temperature and humidity levels (Pepper and Gerba, 2015). Nevertheless, the type of microorganisms, the duration of exposure, and the surrounding environment all have varying impacts (Pepper and Gerba, 2015). BKMG data for 2022 shows that in Serpong-Banten, Indonesia the average temperature was 37°C and the relative humidity almost 80% (BMKG, 2022), and these conditions constrain the spread of germs.



(a) (b)

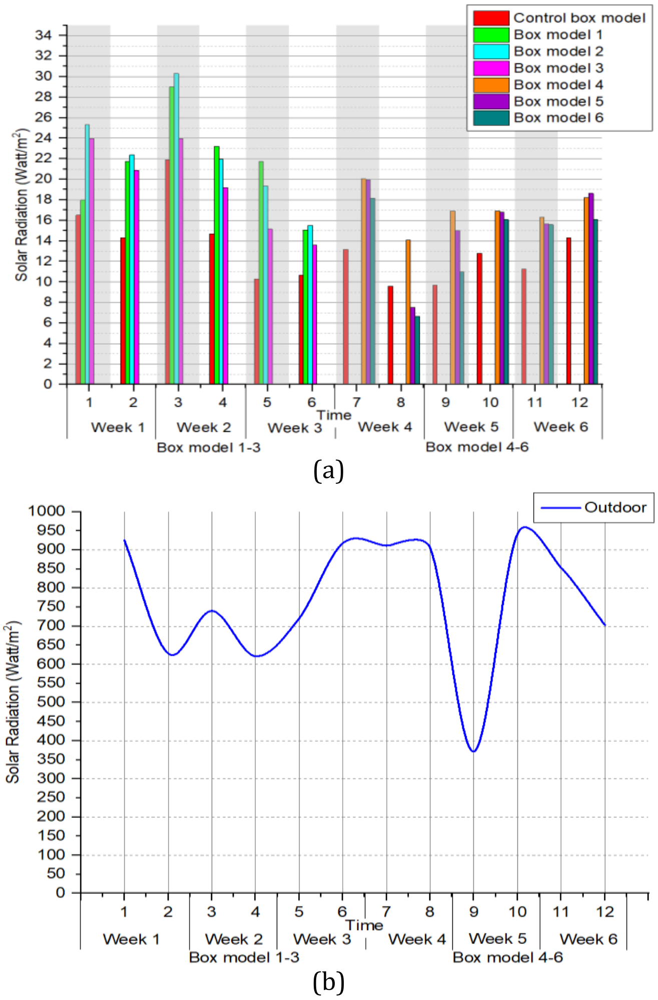
(c) (d)

Figure 9 The comparison graph between the lower and upper range of germ quantity with temperature (a & b) and humidity (c & d) in an outdoor, control box model, and box model 6 filter better than other box models

4.3. Solar radiation and air quality

Solar radiation substantially impacts the growth of germ intensity in the field (Pepper and Gerba, 2015). This study analyzed the amount of sun radiation over 12 days in 6 weeks. The 12-day recording of sun radiation is because measures were taken on visits to the site. Figure 10 shows the impact of incoming radiation levels on the box models for 12 days and the changing solar radiation outdoors. The outdoor solar radiation intensity ranges from 628.75 to 925.25 W/m^2 on days 1, 6, 8, and 10. A comparison of these two graphs (Figure 10 a & b) also demonstrates that each box type has successfully lowered the amount of incoming radiation by 900 W/m^2; however, compared to box models 4-6 and the control box model, box models 1-3 have lower barrier effectiveness. As an outcome, the control box model and boxes 5 and 6 are more effective than boxes 1 to 4 in the reduction of solar radiation intensity.

Weather variables influenced solar radiation levels significantly during the observation days. For instance, days 1, 6, 8, and 10 show high intensity of solar radiation up to 925.25 W/m^2 because of hot weather with high temperatures. In contrast, day 9, rainy day conditions, and low temperatures show low solar radiation of about 600 W/m^2. Moreover, hot weather conditions could reduce germs but substantially increase temperature, and cloudy or rainy weather increases germs but initiates low temperatures. Therefore, adding a vertical greenery system could improve the effectivity of shading for temperature but not lower the germ count.



(a)

(b)

Figure 10 Solar radiation graphs a) control box model, box models 1-6 for 3 weeks and b) outdoor for consecutive 6-week

The data shows that the density of the bacteria and fungi in the air is also impacted by factors related to climate conditions (Pepper and Gerba, 2015). The tropical environment in Kampung Nambo Serpong results in high temperatures and a lot of solar radiation. Higher temperatures can reduce the microorganisms; every 1 W/m^2 increase in solar radiation can reduce bacteria by 1.98 to 2.16 CFU/m^3, considerably impacting the number of bacteria and fungi.

5. Conclusions

The study evaluated the effectiveness of various plant species in vertical greenery systems (VGS) to enhance air quality in areas near landfills, where green infrastructure is limited. The findings demonstrate that VGS can significantly reduce air pollution, with Hedera helix emerging as the most effective plant for filtering microbes from the air. External factors, such as solar radiation, positively influence VGS performance by promoting plant growth and air filtration, thus further improving air quality. The study underscores the importance of considering local geography, climate, and community needs when implementing green infrastructure. Additionally, it emphasizes the value of a bottom-up approach that involves community participation and accounts for local lifestyles to effectively interpret data and manage unforeseen challenges. These findings are particularly relevant for tropical regions like Indonesia and suggest the need for further research involving a broader range of plants and extended data collection.

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Declaration of competing interest

The authors state that they have no personal relationships that might influence the research reported in this paper.

Statement of authors roles

Natasia Heindri: Conceptualization, Writing an original draft, Methodology, Resources, Investigation, and Analysis. Ova Candra Dewi: Methodology, Validation, Supervision, Writing, Review, and Editing. Nandy Putra: Methodology, Data Curation, Supervision, Writing, Review, and Editing. Andrew Flynn: Writing, Review, and Editing. Tika Hanjani: Writing an original draft, Writing, Review, Editing, and Data Curation. Kartika Rahmasari: Visualization.

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