Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 5, 3260-3273
2025
Publisher: Learning Gate
DOI: 10.55214/25768484.v9i5.7677
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Effectiveness of indoor plants vs. HEPA purifiers in the removal of PM2.5 and PM_{10}

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Abstract: Particulate matter (PM) is a major contributor to air pollution in many countries, including Thailand. The use of high-efficiency particulate air (HEPA) filters in air purifiers is currently the most common solution. However, in the context of PM removal, it is worth exploring how nature-based technologies could be employed to combat indoor air pollution and support the broader goals of urban sustainability. This study compares the efficiency of HEPA air purifiers with selected dust-collecting indoor plants. For a day, incense sticks were burned nonstop in two enclosed rooms with air purifiers and another with plants that reduce dust. PM2.5 and PM10 levels were monitored until the air quality met safety standards. The results indicated that plants with rough, hairy surfaces, bush-like shapes, and large leaf surface areas collected the most dust. Among the tested species, Boston Fern and Monstera demonstrated the highest air-cleaning efficiency per square meter of leaf area per hour. By contrast, in heavily polluted conditions (e.g., due to incense burning), it took the plants approximately 1.67–3.55 times longer for PM2.5 and 2.0–3.6 times longer for PM10 to reach safe levels compared to the air purifiers. These findings provide valuable insights for individuals deciding between air purifiers and indoor plants for improving indoor air quality.
Keywords: *HEPA air purifier, Indoor plant, $PM_{2.5}$, Nature-based technology, PM_{10}, Sustainability.*

1. Introduction

According to research [1-8]. Indoor air pollution can be just as harmful as outdoor air pollution because most people spend more than 90% of their lives indoors [9, 10]. Both indoor and outdoor sources can now contribute to health-harming air pollution [11]. Numerous epidemiological studies have demonstrated that prolonged exposure to elevated particulate matter concentrations can considerably raise the morbidity and mortality rates of various illnesses [12-15]. Asthma, bronchitis, and tuberculosis (TB) are among the severe respiratory diseases that PM can cause [3]. Moreover, epidemiological research revealed that PM may contribute to the transmission of COVID-19 [11]. According to the Environmental Health Division, the following are the primary causes of indoor air pollution [5, 16]:

1) Pollutants, germs, and disagreeable odors build up inside buildings due to inadequate ventilation, which is brought on by poorly designed structures with few ventilation holes or outdated, broken ventilation systems, as well as a lack of routine cleaning and maintenance.

2) Smoke, vehicle exhaust, and construction dust are examples of external pollutants that can enter a building through gaps or leaks.

3) Indoor pollutants include those found in cleaning products, pesticides, cigarette smoke, incense burning, and office equipment.

4) Bacteria, particularly Legionella pneumophila, are biological contaminants that are present in central air conditioning systems' cooling towers.

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History: Received: 28 March 2025; Revised: 19 May 2025; Accepted: 22 May 2025; Published: 30 May 2025
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HEPA-filtered air purifiers are recommended since $PM_{2.5}$ and PM_{10} have detrimental effects on human health [5, 6]. Fibers of fiberglass, ranging in thickness and size from 0.5 to 2.0 micrometers (or microns), are arranged randomly to form HEPA filters [5]. These filters have been used in automobiles, airplanes, and medical equipment [6]. Despite their effectiveness, these electrically powered devices are more costly and energy intensive. Furthermore, a lot of individuals are unaware of how to make the most of them. The clean air delivery rate (CADR), noise level, energy consumption, and room size are all important considerations when selecting air purifiers for the house. Furthermore, to accomplish both indoor air quality and energy efficiency, air purification devices require an independent control mechanism [17]. Due of their inability to adapt to tenants' stochastic behavior, such as window usage patterns and $PM_{2.5}$ and PM_{10} emissions, traditional air purifier control approaches waste electricity. The amount of electricity used by an air purifier is directly related to its operating time. The purifier can save electricity by only running when required, such as when allergens are present, or the air quality is low. Because of this, a lot of contemporary air purifiers come with timers or other scheduling tools that allow users for setting up cycles to turn on and off at different times.

The ability of plants to remove carbon dioxide (CO_2) has been analyzed in several studies [16, 18-22]. Subsequently, research was conducted to explore the use of plants in reducing air dust. As part of efforts to sustainably reduce air pollution using green plants, Sunakorn, et al. [23] proposed a study on the relative capacity of creeping plants to capture dust. According to the test results, creeping plants' capacity to capture dust was nearly equal to their percentage of leaf area. Furthermore, they contribute to the creation of beauty, fulfillment, and psychological advantages for people. Subsequently, research focused on identifying plant species that aid in lowering air pollution was conducted to incorporate them into Rangsit University's eco-friendly condominium project [20]. This study examined and categorized various plant species according to their ability to address pollution issues, such as dust capture, toxin absorption, oxygen production, and allergy reduction. Later, at King Mongkut's University of Technology North Bangkok, Witthayaphirom and Nuansawan [24] examined the use of decorative plants to enhance indoor air quality. Their findings revealed that plants can effectively reduce dust and carbon dioxide levels. The efficacy of plants for passive particulate matter removal had been investigated [25]. They compared PM removal rates in an environmental chamber to estimate size-resolved particle deposition velocities and clean air delivery rates (CADRs) for eleven distinct plant species. The CADRs of the plants ranged from 0.084 ± 0.009 m^3/h to 0.002 ± 0.004 m^3/h. Different plant species have the ability to absorb dust particles, according to a number of research studies. The surface area and arrangement of the leaves determine their capacity to collect dust. Data on indoor plant species with dust-capturing capabilities will be used to advance the study. In accordance with the guidelines [16] from the Department of Health, Ministry of Public Health, Thailand, this data can be used for comparative research with the use of air purifiers as an alternative to nature-based technology for creating dust-free rooms. To support the development of sustainable cities, this research attempts to address the issue of dust in indoor spaces using nature-based technology. By modeling a prototype room based on the Ministry of Public Health's recommended dust-free room, the study aims to compare the dust-catching effectiveness of selected plant species with that of High-Efficiency Particulate Air (HEPA) air purifiers. To generate pollutants for this experiment, incense sticks will be continuously burned for 24 hours in three closed rooms. This method was chosen because burning incense is a common practice in Thailand for reverence and worship, such as in temples or funeral ceremonies, and it significantly contributes to severe indoor air pollution. This study aims to assist individuals deciding between indoor plants and air purifiers by providing preliminary insights.

2. Methodology

2.1. Experiment Rooms

Three identically sized rooms, designated as Room1, Room2 and Room3, are set up as a closed system by sealing off the openings to prevent outside air from entering. Additionally, incense pots are

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placed on a table in the center of each room and lit to generate smoke and particulate matter (PM). The specification of these rooms is shown in Table1.

Table 1.
Room Specification.

Description	Details (width x length x height)
Room size	3m x 8m x 2m
Table size	1.2m x 2.4m x 1m

2.2. Plants

Various plant species with properties to address pollution issues, like collecting dust, removing toxins, generating oxygen, and reducing allergy symptoms, have been analyzed and categorized in a number of studies [18-20] as follows:

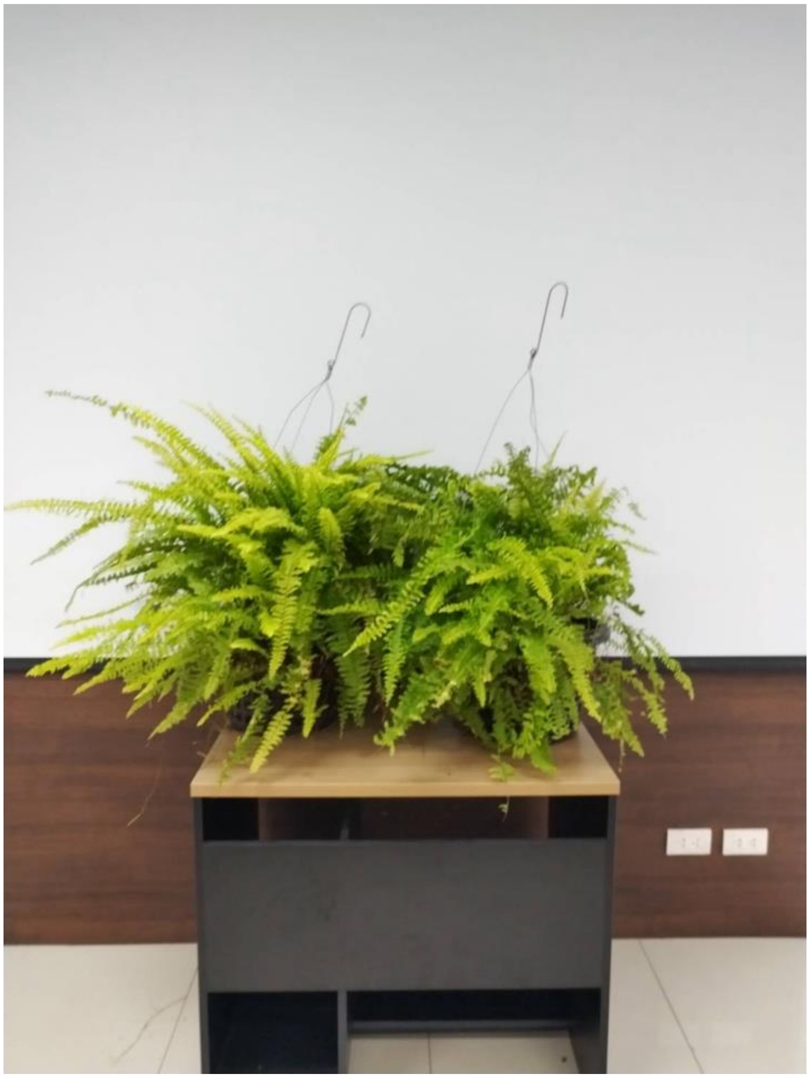

Figure 1.
Boston Fern.

ISSN: 2576-8484
Vol. 9, No. 5: 3260-3273, 2025
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The Boston Fern is one type of ornamental plant that is commonly used to adorn buildings on the inside as well as the outside. It can be grown in hanging pots or placed on shelves. It also purifies the air, increases the humidity in the building, and absorbs toxins.

Figure 2.
Rubber Plant.

A Rubber Plant has a dark, upright stem. The glossy, solitary leaves are multicolored, ranging from bright green to red and black. In addition to its aesthetic value, it effectively reduces dust and acts as a home air purifier.

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Figure 3.
Lady Palm

The Lady Palm, which belongs to the palm family, is a popular plant in China, Japan, and Malaysia. It is commonly used as a plant for decoration. The tree grows in clumps, just like bamboo. The dark green, glossy leaves are separated into lobes that resemble fans. The leaf stem has five to ten small leaves attached to it. Its trunk is straight and robust. It is a decorative plant that helps purify the air in the building.

Figure 4.
Monstera.

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The Monstera, which reduces dust, is renowned for its exquisite shape. By capturing dust particles that are floating in the air, it has qualities that aid in air purification. Additionally, it has the ability to absorb a variety of toxins, including formaldehyde, alcohol, and ammonia.

Figure 5.
Fiddle Fig.

The Fiddle Figure is a common ornamental plant used to decorate buildings and homes. Nothing compares to the elegance and beauty of its leaves. It can also aid in air purification in the area by absorbing dust and pollutants.

Figure 6.
Snake Plant.

People often use the Snake Plant as an ornamental plant to liven up their bedrooms because it can absorb carbon dioxide and release oxygen at night. Additionally, it has properties that help purify the air and create a feeling of freshness.

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The leaves and stems of the experimental plants will be measured in order to determine the tree's potential dust-trapping surface area. When calculating the leaf surface area of a shrub with many leaves, the shrub's height and width will be measured. To calculate leaf area (LA), the width (W) and length (L) of six plants are assessed using two approaches: (A) measuring the width and height of each individual leaf (when there are only a few leaves) and (B) measuring the width and height of the entire bush as illustrated in Figure 7 [26]. Rubber Plants, Monstera, Fiddle Figs, and Snake Plants are treated with method A, whereas Boston Ferns and Lady Palms are treated with method B.

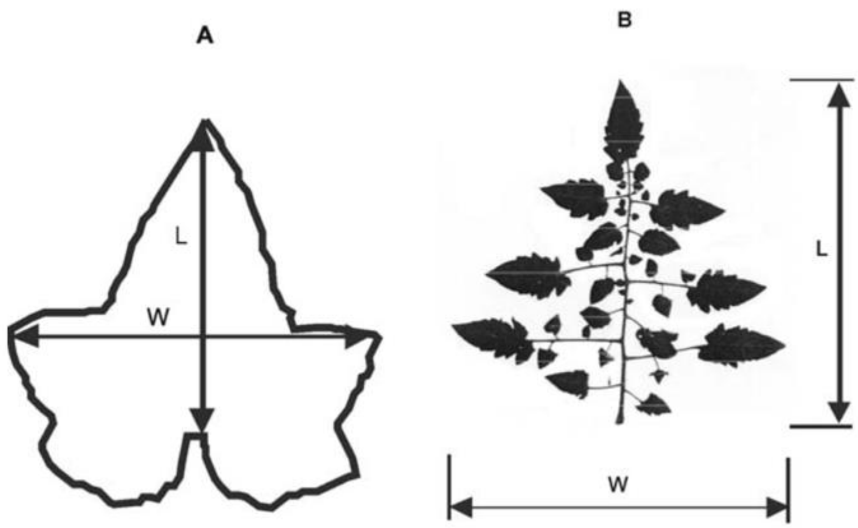

Figure 7.
Method of measurement the width and height of plants.
Source: Blanco and Folegatti [26]

The following formula can be used to estimate leaf area (LA):

$$LA\ (m^2) = \alpha * W * L \quad (1)$$

where α is the coefficient that depends on the form of the leaf, while W and L are width and length measurements. Table 2 displays the total leaf surface area of every plant with $\alpha = 0.75$.

Table 2.
Plant and leaf surface area.

Name	Leaf surface area (m^2)
Boston Fern	1.0546
Rubber Plant	1.5010
Lady Palm	13.4512
Monstera	1.0282
Fiddle Fig	1.3080
Snake Plant	12.1338

2.3. Sensors

Fifteen $PM_{2.5}$ and fifteen PM_{10} sensors were used in the experiment. In compliance with Kotzias [27] and the Department of Health's directive to track daily using the average value generated from measurements taken every hour [16] this study employs the concept of getting $PM_{2.5}$ and PM_{10} readings by averaging from five sensors in each room.

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2.4 Air Purifiers

In accordance with the Thai Department of Health's guidelines [16] HEPA air purifiers are used to reduce indoor dust levels. HEPA filters can effectively capture particles as small as 0.3 microns [28] and can reduce particulate matter (PM) by up to 99% [28, 29]. In this study, two HEPA air purifiers with power ratings of 60 and 70 watt-hours (Wh), designed for rooms ranging from 25 to 43 square meters, will be used.

2.5. Experimental Method

The experiment is divided into the following two categories.

1) To ensure the proper functioning of the laboratory, these three rooms will stay sealed throughout the five-day experiment, during which PM values will be monitored in a controlled setting. The procedure will be repeated three times to determine the average values from the collected data.
2) To generate pollutants for this experiment, incense sticks will be burned continuously for 24 hours in a closed space. To eliminate of pollutants, Room 1 will use the first air purifier, and Room 2 will use the second one. For the same reason, Room 3 will be dependent on plants. $PM_{2.5}$ and PM_{10} will be monitored until the air quality satisfies the safety standards established by the Thai Department of Health [16] as indicated in Table 3, The following is the experimental pairing of two air purifiers and a plant:

a. Air purifiers and Boston Fern
b. Air purifiers and Rubber Plant
c. Air purifiers and Lady Palm
d. Air purifiers with Monstera
e. Air purifiers with Fiddle Fig
f. Air purifiers with Snake Plant.

Following three iterations of the experiment, the room configurations will switch between two air purifiers and plants. For analysis, the average values will be computed.

Table 3.
Guidelines for indoor air quality.

Pollutants	Acceptable value
$PM_{2.5}$	≤ 50 μg/m³
PM_{10}	≤ 120 μg/m³

3. Results and Discussion

3.1. Results

Table 4 shows the average of the PM values for fives days after data collection from three rooms that were closed under normal conditions. Room2 exhibits the highest average $PM_{2.5}$ concentrations (35.2 μg/m³). Room1 displays the highest average PM_{10} level (47.2 μg/m³) and features the most extensive range for both $PM_{2.5}$ and PM_{10} measurements. Room3 presents the lowest average $PM_{2.5}$ and slightly reduced PM_{10} levels compared to Room1, although it has higher PM_{10} levels than Room2.

Table 4.
Rooms with normal circumstances for fives days.

Room No	Average $PM_{2.5}$ (μg/m³) [min.-max.]	Average PM_{10} (μg/m³) [min.-max.]
Room1	34.8 [32-42]	47.2 [36-61]
Room2	35.2 [30-40]	42.2 [33-54]
Room3	33.4 [31-39]	45.8 [32-60]

Table 5 compares how long it takes two air purifiers and different plants to get rid of dust from the moment the incense is lit until the dust is in an acceptable level. The duration required for removal is expressed in hours, with lesser times indicating faster air purification. The second air purifier is the

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most efficient, with the quickest removal times (22 hours for $PM_{2.5}$ and 20 hours for PM_{10}). The first air purifier also surpasses all the plants in performance, but it takes longer than the second purifier. All the plants require significantly more time (60 to 78 hours) to eliminate particulate matter. Among the plants, Boston Fern and Lady Palm are relatively more efficient (60 hours for both $PM_{2.5}$ and PM_{10}), whereas Fiddle Fig is the slowest (78 hours for $PM_{2.5}$ and 72 hours for PM_{10}). Figure 8 provides a visual comparison of the average removal times (from best to worst) for PM2.5 and PM10 for various air-cleaning options.

Table 5.
Comparison of air purifiers and plants in terms of PM removal time.

Alternatives	Average $PM_{2.5}$ removal time (hours)	Average PM_{10} removal time (hours)
1st air purifier	36	30
2nd air purifier	22	20
Boston Fern	60	60
Rubber Plant	72	66
Lady Palm	60	60
Monstera	66	60
Fiddle Fig	78	72
Snake Plant	66	60

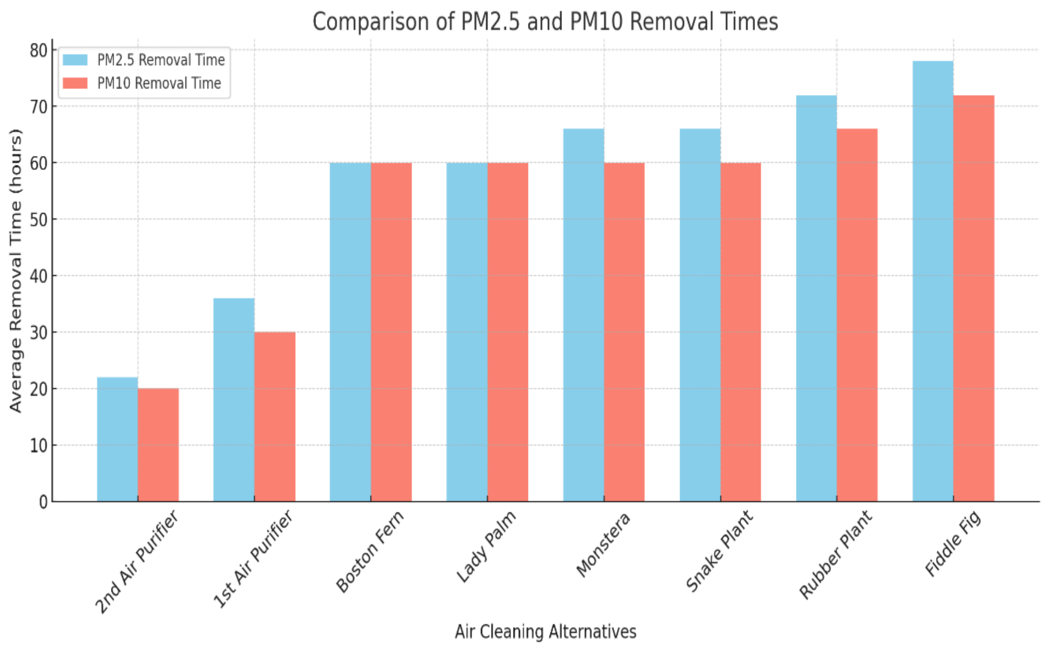

Figure 8.
Comparison of the average removal times for PM2.5 and PM_{10}.

3.2. Discussion

According to the analysis results in Table 4, pollution levels, $PM_{2.5}$ and PM_{10}, fluctuate even in closed environments, and the values in the three rooms differ slightly. The $PM_{2.5}$ values in Room1 range from 32 to 42 μg/m³, while those in Room2 and Room3 range from 30 to 40 μg/m³ and 31 to 39 μg/m³. Similarly, PM_{10} levels in Room 1 range from 36 to 61 μg/m³, while Room 2 and Room 3 show ranges of 33 to 54 μg/m³ and 32 to 60 μg/m³, respectively. Therefore, to reduce variability between rooms, one approach is to alternate the use of rooms during experiments to determine the average. These slight variations may result from microenvironmental factors such as differences in airflow patterns, prior accumulation of dust, or minor variations in room sealing. Thus, alternating room use not only helps

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reduce spatial bias but also enhances the reliability of the experimental outcomes by averaging out these subtle environmental discrepancies.

Practically, efficiency is the speed and effectiveness with which a technique may bring the concentration of pollutants, such as $PM_{2.5}$ and PM_{10}, in a specific area down to acceptable levels. Efficiency is measured using two metrics: removal time and energy consumption. The Boston Fern and Lady Palm were the plants that eliminated the most dust during the experiment. Their performance was consistently high across all rooms, reinforcing their potential as effective natural air purifiers in indoor environments. Generally, the leaf area determines how well dust is removed. The time required to clear dust will decrease with increasing leaf area and increase with decreasing leaf area. The Lady Palm can trap a significant amount of dust due to their leaves having the largest surface area. Despite having the smallest leaf area, Boston ferns are nonetheless quite good at removing PM because of their bush-like structure and rough, hairy surface, which efficiently capture dust and make them more effective than plants with glossy, smooth skins [30]. This finding supports previous studies suggesting that not only the total leaf area but also specific leaf morphology and texture—such as hairiness, surface roughness, and branching pattern—play crucial roles in particulate matter capture. During testing with incense burning in a closed room without air purifiers or plants, the highest average values of $PM_{2.5}$ and PM_{10} detected by sensors in all three rooms were 1951 and 2853 micrograms per cubic meter (µg/m^3). These peak values highlight how everyday indoor activities can lead to significant pollution in enclosed spaces, emphasizing the importance of practical and accessible solutions like indoor plants. In order to analyze the PM removal efficiency of plant leaves, efficiency ratios can be calculated as follows:

$$PM_{2.5}\,Efficiency = \frac{1951}{Leaf\ Surface\ Area\ *\ PM_{2.5}\ Removal\ Time} \quad (2)$$

$$PM_{10}\,Efficiency = \frac{2853}{Leaf\ Surface\ Area\ *\ PM_{10}\ Removal\ Time} \quad (3)$$

Table 6.
Plants efficiency per square meter of leaf surface area per hour.

Plants	$PM_{2.5}$ Efficiency	PM_{10} Efficiency
Boston Fern	30.83	45.09
Rubber Plant	18.05	26.40
Lady Palm	2.42	3.54
Monstera	28.75	42.04
Fiddle Fig	19.12	27.96
Snake Plant	2.44	3.56

As shown in Table 6, Boston Fern has the highest efficiency by a significant margin, whereas Monstera comes in second, not far behind Boston Fern. It is perfect for tiny spaces because it has good performance per leaf area per hour. Rubber Plants and Fiddle Figs perform rather well, though not as well as the top two, especially when structural or aesthetic appeal is also important. Despite having a large raw leaf surface area, Lady Palms and Snake Plants perform poorly on a per-area per hour basis. This suggests that efficiency depends not just on leaf area but also on leaf structure and texture, with hairy leaves like those of Boston Fern capturing particles better than smooth and waxy leaves like those of Snake Plants.

In comparison to air purifiers, plants take 1.67 to 3.55 times as long to reduce PM2.5 to acceptable levels (50 µg/m3). Similarly, plants take about 2.0 to 3.6 times longer than air purifiers to reduce PM10 to within the acceptable range (120 µg/m3). This clearly reflects the slower action of phytoremediation compared to mechanical filtration, especially in enclosed spaces where pollutant concentrations can rise rapidly. When rapid remediation is required (for example, following cooking, cleaning, or smoke exposure), or in high-pollution areas, air purifiers are appropriate. Phytoremediation is the process by

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which plants absorb contaminants through their leaves. They are more suited for passive, long-term air quality enhancement. This long-term benefit makes plants an ideal complement to air purifiers in creating a more sustainable indoor air management strategy.

To equal the impact of an air purifier, a large number of plants must be placed in a room due to their comparatively low air-cleaning capability per unit. Table 7 displays the approximate quantity of each plant species needed to achieve the second air purifier's $PM_{2.5}$ removal efficiency (22-hour removal time). These calculations are theoretical and assume additive effects; however, in reality, interactions between plants and microenvironments can alter this efficiency. This assumes that plant removal effects are additive and simultaneous, which may not be perfectly accurate in practice due to space, airflow, and plant health. However, because of airflow and distribution constraints in the actual world, it might require even more plants. Proper plant placement is crucial to optimize air circulation and exposure, and grouping plants near pollutant sources or high-traffic areas can enhance overall efficiency. Moreover, regular leaf cleaning is necessary because dust can build up on leaves and reduce their efficiency. For plants to remain healthy, they require pest management, pruning, and watering. Therefore, while plants offer a low-energy, aesthetically pleasing option for improving indoor air quality, they come with maintenance demands that must be consistently addressed to sustain their effectiveness.

Table 7.
The approximate amount of each type of plant required.

Plant Type	Estimated Number of Plants Needed
Boston Fern	2.73 (~3 plants)
Lady Palm	2.73 (~3 plants)
Monstera	3.0
Snake Plant	3.0
Rubber Plant	3.27 (~4 plants)
Fiddle Fig	3.55 (~4 plants)

The following formula can be used to determine energy usage (in unit) Energy Research and Development Institute of Nakornping [31] and Customer Service Information System Development Division Provincial Electricity Authority [32].

$$Energy\ Usage\ (unit) = \frac{Energy(Wh)}{1000} * hour \quad (4)$$

Table 8.
Comparison of air purifiers and plants in terms of energy usage (unit).

Alternatives	Energy usage for $PM_{2.5}$ removal	Energy usage for PM_{10} removal
1st air purifier	2.16	1.8
2nd air purifier	1.54	1.4
Boston Fern	0	0
Rubber Plant	0	0
Lady Palm	0	0
Monstera	0	0
Fiddle Fig	0	0
Snake Plant	0	0

Although air purifiers are effective, they generate waste due to frequent filter replacements and electricity consumption as shown in Table 8. When compared to air purifiers, all plants are extremely energy-efficient because they require no energy to remove $PM_{2.5}$ and PM_{10}. It was discovered that when two air purifiers were compared, the 2nd air purifier (70 Wh) requires more energy power per hour than the 1st air purifier (60 Wh). However, the 2nd air purifier removed contaminants faster. As a result, the 2nd air purifier used less energy unit than the 1st one. An air purifier's electricity consumption is closely correlated with how long it runs. For instance, the study's two air purifiers consume 60 and 70 watts of electricity each hour. Operating them continuously will result in monthly electricity consumption of

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around 45 and 51 units [31] with an estimated cost of 176.5 and 200 baht for electricity, respectively [32]. This illustrates that energy efficiency depends not just on power ratings but also on performance and run time, making both energy use and purification speed key to cost-effectiveness. By only operating when necessary—for example, when allergens are present or the air quality is low—the purifier can conserve electricity. Because of this, many air purifiers come with timers or other scheduling devices that allow users to set up cycles to turn on and off at different times [33]. Nevertheless, the integration of plants into indoor environments presents a highly sustainable and cost-effective complementary approach. Moreover, costs can be reduced by using plants to help mitigate pollution. Increased humidity from plants can speed up dust settlement and lessen airborne particles. The natural transpiration process of plants contributes not only to improved humidity levels but also to enhancing indoor comfort, potentially reducing the need for other energy-intensive climate control methods. For the best interior dust and PM management, plants should be used in addition to air purifiers, not in instead of them. This hybrid approach leverages the rapid removal capabilities of purifiers and the passive, low-cost, and continuous support provided by plants, leading to a more environmentally conscious and economically viable air quality control strategy.

4. Conclusions

This study examines how successfully air purifiers and plants remove PM particles while accounting for energy usage and purification speed. For this study, the following plants were chosen because they have the capacity to eliminate dust pollution: Boston Fern, Rubber Plant, Lady Palm, Monstera, Fiddle Fig, and Snake Plant. The experiment showed that both $PM_{2.5}$ and PM_{10} can be effectively removed by plants and air purifiers. Plants are a great way to add visual appeal, affordability, and environmental responsibility to interior spaces. However, using air purifiers is a superior option for noticeable improvements in air quality, particularly for people who reside in a region with high pollution levels or have allergies or respiratory sensitivities. Boston Fern and Monstera are the best and second-best for cleaning air per square meter of leaf per hour, respectively, based on the results of all experiment plants. Because they are small but effective, both are space-efficient purifiers. However, the rate at which plants purify is slower than that of air purifiers. They eliminate $PM_{2.5}$ and PM_{10} dust 1.67–3.55 and 2.0–3.6 times slower, respectively. Despite their effectiveness, air purifiers require electricity to operate. Since no electricity is needed to remove $PM_{2.5}$ and PM_{10}, all plants are incredibly energy-efficient when compared to air purifiers. Additionally, plants can provide long-term benefits beyond PM removal, including increased humidity, improved psychological well-being, and aesthetic enhancement of indoor environments. Their passive operation and low maintenance cost (aside from watering and occasional pruning) make them an ideal supplement to mechanical air purification systems.

The amount of electricity used by an air purifier is directly related to its operating time. Higher runtime leads to higher energy costs, especially in households where air purifiers run continuously due to health concerns or poor outdoor air quality. Therefore, selecting models with efficient purification speeds and appropriate room coverage is critical to balance air quality improvement with energy consumption. Continuous operation will increase monthly electricity expenses and consumption. The most effective approach is frequently a hybrid one that uses air purifiers to rapidly reduce PM levels, particularly in high-risk locations like bedrooms, kitchens, or spaces close to windows. Plants can then serve as a sustainable, low-energy strategy for maintaining air quality during periods of lower pollution or when purifiers are turned off. To ensure consistent, background improvement, place plants in vents or in corners. This combination improves the space's general health and well-being in addition to the air quality.

Since this study focused on plant groups with the ability to dust pollution, the potential of plants to eliminate other pollutants, including odors, bacteria, viruses, and volatile organic compounds (VOCs), should be investigated further.

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Funding:
This study was supported by Thammasat University Research Fund, Contract No TUSDG 1/2565.

Transparency:
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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