Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 5, May 2024

Development and Efficacy study of UBreathe's Plant-Based Air Purification System for Mitigating in Door Air Quality Issues

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Abstract

Air pollution has become a major concern in modern cities, significantly impacting public health and productivity, particularly due to poor indoor air quality. Studies have shown that indoor air pollutant concentrations often exceed those outdoors, underscoring the need for effective indoor air purification solutions[1][2]. This research explores the development and commercialization of the uBreathe Mini Natural Air Purifier, a novel device that integrates the natural air-cleaning abilities of plants through phytodepuration with advanced purification technologies. The uBreathe Mini aims to enhance indoor air quality sustainably by leveraging optimized air-flow dynamics and a specially designed soil matrix that supports microbial growth and pollutant decomposition. The study's goals include developing a working prototype, testing and validating its effectiveness, securing intellectual property, preparing for production, ensuring regulatory compliance, refining its design, and formulating a market entry strategy. By combining cutting-edge technology with nature-inspired solutions, the uBreathe Mini represents a holistic approach to addressing indoor air pollution, promoting environmental sustainability, and establishing market leadership in air purification.

I. BACKGROUND

A WHO air quality model confirms that 99% of the world's population lives in places where air quality levels exceed WHO limits[3]. Some 4.2 million deaths yearly are linked to outdoor air pollution exposure. Indoor air pollution can be just as deadly, and an estimated 8 million deaths are associated with indoor and outdoor air pollution [4].Indoor air pollution consists of particulate matter (PM) and gaseous contaminants, including volatile organic compounds (TVOCs). Particulate matter varies by size: PM10 (10-2.5 µm), PM2.5 (2.5 µm or smaller), and PM1 (1 µm or smaller), each contributing to adverse health effects. HEPA filters in air purifiers can reduce PM exposure effectively, depending on particle size and filter type.

Gas-phase pollutants include inorganic gases like SO_2, NO, NO_2, CO, O_3, and organic TVOCs such as formaldehyde, benzene, toluene, ethylbenzene, xylene, and polycyclic aromatic hydrocarbons. TVOCs originate from outdoor sources (e.g., car exhaust, industrial activities) and indoor sources (e.g., building materials, household products, human activities). Indoor TVOCs concentrations often exceed outdoor levels, causing indoor air to be five times more polluted.[5]

Chronic exposure to TVOCs, even at low concentrations, can cause allergies, eye and throat irritation, aggravated asthma symptoms, and cancers, particularly affecting vulnerable groups like children and the elderly. TVOCs also impair cognitive functions, reducing problem-solving abilities and information usage at work.

However, the availability of purification systems for indoor arrangements may help control the air quality indoors [6] but at the expense of enormous power consumption, substantial recurring cost along with the utilization of unsustainable filtration methods.Currently, there are many indoor air purification devices currently on the market; however, these devices (e.g. mechanical filters, electronic air cleaners, ion generators, etc.) focus mostly on the removal of airborne PM particles only and struggle to remove TVOCs effectively. Current mitigation strategies include using low-VOC products and frequent ventilation, both of which have limitations. Further with the study of NASA it is also known that certain house plants support complex biological and bacterial processes within the plant, and also, within the growth medium surrounding the plant roots, within which the plant is embedded, all of which tend to biodegrade various airborne pollutants, especially airborne hydrocarbons and TVOCs. [7][8][9][10] The proposed indoor air purification system tries to maximize the air purification properties of indoor plants by building and combining several practical solutions to enable success of such a solution for a practical use-cases in indoor spaces like – houses, office cabins and restrained indoor spaces.

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II. THE LIMITS OF AIR PURIFIERS

As awareness of the negative impact of low air quality has increased over the past decades, efforts to find practical solutions have intensified. One prominent solution is the use of portable air purifiers, which have seen a significant rise in public demand and are expected to experience market growth in the coming years.

The technologies behind portable air purifiers vary according to the type of pollutants they are designed to address. HEPA filters are highly effective for capturing particulate matter (PM), but they are incapable of filtering out volatile organic compounds (TVOCs) because these compounds are typically smaller than 1 nanometer in diameter, while HEPA filters operate at the micrometer scale.

To address TVOCs, various technologies have been developed for new generations of portable air purifiers. These technologies, though promising, often come with significant drawbacks and, in some cases, can generate more pollution than they remove, as outlined in the Environmental Protection Agency (EPA) technical summary (Table 1).

III. SUMMARY OF AIR CLEANING TECHNOLOGIES

Air-Cleaning Technology	Targeted Pollutant(s)	Advantages	Disadvantages
Fibrous Filter Media	Particles	High removal efficiency for many particle sizes; improved efficiency with loading	Requires regular replacement; used filters can emit odors; high pressure drops can affect HVAC systems; reduced efficiency in electric media with loading
Ionizers	Particles	Low power requirement; quiet; low maintenance	Generates ozone; typically low effectiveness due to low airflow and CADRs
Electrostatic Precipitation (ESP)	Particles	High removal efficiency for wide particle size range; low pressure drop	High ozone and NOx generation; efficiency decreases with loading; high power requirement
Ultraviolet Germicidal Irradiation (UVGI)	Microbes	Effective at high intensity; can inactivate microbes on surfaces	Can generate ozone; potential for eye injury; high power requirement; does not remove microbes
Adsorbent Media	Gases	High removal efficiency for many gases; no byproducts	Requires regular replacement; adsorption is reversible; efficacy of consumer-grade systems is uncertain; high pressure drops can affect HVAC systems
Chemisorbent Media	Gases	High removal efficiency; irreversible pollutant capture	Requires regular replacement; effectiveness of consumer-grade systems is unknown; high pressure drops can affect HVAC systems
Catalytic Oxidation	Gases	Degrades a wide array of gases; can be combined with adsorbent media	Can generate harmful byproducts (e.g., formaldehyde, ozone); low removal efficiency; catalyst lifespan is finite
Plasma	Microbes, Gases	High removal efficiency; can be combined	Generates harmful byproducts; high variability in removal efficiency;

		with other technologies	fewer studies on particle removal
Ozone Generators	Gases	Reacts with many indoor gases	High ozone generation; high byproduct formation; can degrade indoor materials

Table 1: Summary of air-cleaning technologies. Adapted from EPA residential air cleaners technical summary (EPA 402-F-09-002, July 2018, EPA Indoor Environments Division).

IV. TECHNOLOGIES ADDRESSING TVOCS IN AIR PURIFIERS

Air purifiers claiming to remediate TVOCs employ one or more of four main technologies for gas removal: catalytic oxidation, plasma, ozone generation, and adsorbent media.

Catalytic Oxidation

Also known as photocatalytic oxidation (PCO), this technology is prevalent in many modern air purifiers. It relies on the activation of compounds such as titanium dioxide by photons, typically in the UV range. These activated catalysts then oxidize air molecules they encounter. A significant drawback of PCO is its lack of specificity, which can result in the generation of harmful byproducts. For instance, the oxidation of ethanol can produce acetaldehyde, a Group 2B carcinogen, and other byproducts like formaldehyde .

Plasma

Plasma air purifiers utilize high-voltage discharges to ionize incoming gases, thereby breaking their chemical bonds. While plasma technology can achieve high removal efficiency, particularly against TVOCs, it may also produce several harmful byproducts, including carbon monoxide, ozone, and formaldehyde .

Ozone Generation

The intentional generation of ozone indoors is highly detrimental, as ozone is a potent lung irritant. The Environmental Protection Agency (EPA) explicitly advises against the use of ozone generators in occupied spaces, stating: "Do not use ozone generators sold as air cleaners in occupied spaces. No federal agency has approved ozone generators for use in occupied spaces".

Adsorbent Media

The most commonly used adsorbent media is activated carbon, also known as activated charcoal. This material features a large number of micropores, significantly increasing its surface area and allowing it to trap various chemical compounds. This property makes activated carbon a popular choice for water and air purification. However, the efficiency of activated carbon depends on several factors, including the type of TVOC and the design of the air cleaner. A critical limitation of this technology is that TVOCs are merely adsorbed on the surface of the activated carbon. This can lead to rapid saturation of the media and the potential release of these pollutants back into the indoor air under certain conditions, such as increased heat or inadequate filter maintenance .

V. POLLUTANTS REMOVAL MECHANISM IN THE PLANTS

Major indoor air pollutants and their removal phenomenon through phytoremediation:

Particulate Matters: PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope. They may occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray. Human activities, such as the burning of fossil fuels (petrol, diesel, kerosene, etc.)in vehicles, power plants, construction sites, unpaved roads, fields, smokestacks or fires, and various industrial processes also generate significant amounts of particulate matter.

Removal Process: Through the combination of phytoremediation processes taking place such as surface adsorption being facilitated due to waxes, large stomata size, high trichome density, etc. & phytoaccumulation.

Volatile Organic Compounds (TVOCs): are emitted as gases from certain solids or liquids. TVOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. Anthropogenic TVOCs include large groups of organic chemicals, such as formaldehyde, polycyclic aromatic hydrocarbons (PAHs), and BTX (benzenes, toluene, and xylenes).

Sources of TVOCs are Household products, including paints, paint strippers and other solvents, wood preservatives, aerosol sprays, cleansers and disinfectants, moth repellents and air fresheners, stored fuels and automotive products, hobby supplies, dry-cleaned clothing, pesticide, building materials, and furnishings, office equipment such as copiers and printers, correction fluids and carbonless copy paper, graphics and craft materials including glues and adhesives, permanent markers and photographic solutions.

Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
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Removal process: Plants absorb gaseous pollutants via leaf stomata. Some of the TVOCs are recognized as xenobiotics by plants, and they are detoxified through xenobiotic metabolism, involving oxidoreductase or hydrolases, bioconjugation with sugars, amino acids, organic acids, or peptides, and then removed from the cytoplasm for deposition in vacuoles [9]. In addition to plant leaves, rhizosphere microbes also contribute to the reduction of TVOCs under interior environments [10].

VI. PLANTS AS AN AIR PURIFIER

In 1989, NASA initiated a research project led by B.C. Wolverton to investigate biological life support systems for long-duration space missions. The results of this study indicated that certain plants, in conjunction with their associated root-zone microorganisms, possess notable capabilities for removing specific volatile organic compounds (TVOCs) from the air (Wolverton et al., 1989). This discovery catalyzed a widespread belief in the efficacy of houseplants in improving indoor air quality, supported by numerous articles extolling the virtues of "the best plants to purify the air in your home.

Despite the enthusiasm, the practical impact of potted plants on indoor air quality in real-world settings remains contentious. Laboratory studies have documented the ability of plants to absorb TVOCs such as benzene, formaldehyde, and trichloroethylene under controlled conditions (Wolverton et al., 1989)[11]. However, subsequent research has highlighted significant limitations when these findings are applied to typical indoor environments. For instance, studies by Cummings and Waring (2019)[12]and Torpy et al. (2017) [13]suggest that while plants can remove TVOCs, the rate of removal is too slow to have a meaningful impact in a standard living space without an impractically large number of plants.

To achieve a significant reduction in TVOCs concentrations in a room, one would need dozens of plants per square meter, which is impractical for most indoor settings (Cummings and Waring, 2019). Additionally, factors such as plant species, soil composition, light availability, and ventilation play crucial roles in determining the effectiveness of phytoremediation (Irga et al., 2018)[14]. For example, certain species like the spider plant (Chlorophytum comosum) and the Boston fern (Nephrolepis exaltata) have shown higher efficiency in VOC removal in controlled studies (Orwell et al., 2004) [15].

Furthermore, it is important to consider the role of the rhizosphere—the region of soil in the immediate vicinity of plant roots—which is rich in microorganisms that can enhance the degradation of TVOCs. This microbial activity, however, is highly dependent on environmental conditions that are difficult to replicate consistently in indoor settings (Cousins et al., 2022)[16].

VII. ACTIVE PHYTOREMEDIATION THROUGH UBREATHE MINI

The uBreathe Mini, a portable plant based air-purifier developed by Urban Air Labs, Gurugram, India represents a significant advancement in air purification technology by integrating phytoremediation, a process that utilizes the natural ability of plants to absorb and degrade indoor air pollutants, including particulate matter (PM), volatile organic compounds (TVOCs), and gaseous contaminants. This approach offers a holistic and sustainable solution compared to traditional air purifiers that rely solely on mechanical or chemical filtration.

Central to the uBreathe Mini's innovation are its novel air-flow dynamics, which have been meticulously engineered to optimize pollutant removal. The chassis design creates an optimal air-flow path that efficiently directs air through the leaf zone before it interacts with the soil matrix. Research has demonstrated that the leaf zone can effectively remove 5-10% of total pollutants.[17] Ensuring that pollutants interact precisely with the leaves is crucial for maximizing this removal efficiency. However, the majority of pollutants are removed through the soil-root zone via microbial activity, highlighting the importance of the soil matrix in the overall purification process (Giese et al., 1994)[18].

Furthermore, the strategic placement of the suction system in the uBreathe Mini prevents any short-circuiting of exhaust air into the soil matrix. By channeling the exhaust air away from the soil matrix, this design significantly enhances pollutant removal efficiency, addressing limitations observed in previous designs (Fisk et al., 2002)[19]. The introduction of a vacuum chamber or tunnel within the system also creates a streamlined pathway for air to flow towards the exhaust port, ensuring a consistent and undisturbed air-flow pattern. This feature not only enhances the overall energy efficiency of the system but also maintains high pollutant removal performance (Weschler, 2009)[20].

Fig. 1 uBreathe Mini and it’s sectional view depiction

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 5, May 2024

The soil matrix used in the uBreathe Mini plays a pivotal role in its functionality, offering a unique composition that boosts its performance. Unlike conventional soil matrices, this specially developed composition provides optimal nourishment for plants, promoting robust growth even in indoor environments with limited natural conditions (Aydogan and Montoya, 2011)[21]. The soil matrix also fosters the growth of a unique rhizospheric microbial colony. These microbes exhibit exceptional capabilities in breaking down contaminants absorbed in the soil matrix, thereby detoxifying the surrounding air (Mahmoud et al., 2011)[22].

In terms of pollutant adsorption and absorption, the recommended proportion and composition of the soil matrix optimize its permeability, allowing contaminated air to enter the matrix easily upon activation of the suction system. Dust particles settle and are locked on the surface, while gaseous pollutants are absorbed into the substrate's intricate structure, ensuring efficient pollutant removal (Wang and Zhang, 2011)[23]. Additionally, the combination of the soil matrix and the rhizospheric microbial colony facilitates the decomposition of various pollutants, including heavy metals, gaseous pollutants, and TVOCs. This interaction promotes the conversion of harmful substances into less toxic forms, further enhancing air quality (Bishop et al., 2010)[24].

The uBreathe Mini leverages the principles of phytoremediation through innovative air-flow dynamics and a specially composed soil matrix increases the breathability of soil and offers an advanced and sustainable air purification solution. This integration of natural processes with technological innovation which has been patent filed as ‘Breathing Roots Technology’ marks a significant step forward in addressing indoor air quality challenges.

VIII. UBREATHE MINI COMPARED TO EPIPREMNUM AUREUM

The comparative efficacy of the uBreathe Mini and a single potted Epipremnum aureum in reducing PM2.5 and PM10 pollutants was evaluated under controlled conditions. The uBreathe Mini integrates advanced phytoremediation techniques with optimized air-flow dynamics, offering a promising alternative to traditional air purification methods.

Experimental Conditions

- Pollutant Levels: PM levels were artificially increased to their maximum, with PM2.5 measurements peaking at 999 and TVOCs at 650, the highest value detectable by the monitoring equipment.
- Testing Area: The tests were conducted in a 72 cubic ft. volume chamber without any external air circulation.
- Monitoring Equipment: Air quality measurements were performed using an Aurassure Care air quality monitor, ensuring high accuracy and reliability.
- Testing Environment: A sealed chamber was used to prevent external air interference, ensuring controlled and consistent conditions.

Fig. 2 Experimental set up of Epipremnum aureum in test chamber for testing PM2.5 and TTVOCs

Fig. 3 Experimental set up of uBreathe Mini in test chamber for testing PM2.5 and TTVOCs

IX. RESULTS & DISCUSSION

The performance results presented in the previous section demonstrate a significant disparity in efficacy between uBreathe Mini and conventional houseplants (Epipremnum aureum) known for air-purifying properties. This disparity is particularly evident in the pollutant drop rate, where uBreathe Mini exhibits markedly superior capabilities.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 5, May 2024

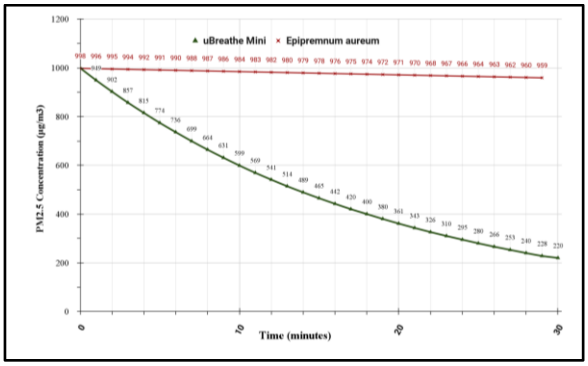

Fig. 4 The comparison of PM2.5 concentration reduction with time by uBreathe Mini and Epipremnum aureum

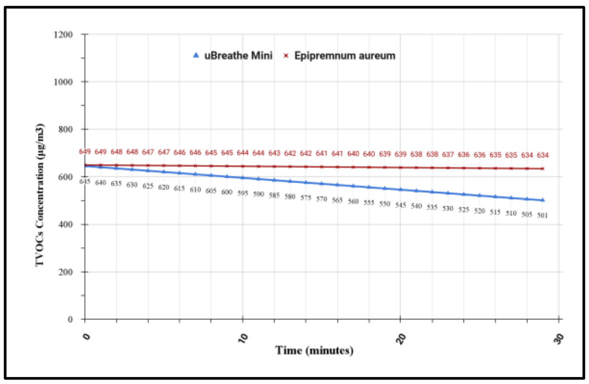

Fig. 5 The comparison of TVOCs concentration reduction with time by uBreathe Mini and Epipremnum aureum

In this controlled environment, both the uBreathe Mini potted with Epipremnum aureum and a single Epipremnum aureum were tested for their ability to reduce PM2.5 and TVOCs concentrations over a period. The results were significant: the uBreathe Mini reduced PM2.5 levels by approximately 77%, whereas the single plant achieved only a 4% reduction. For TVOCs pollutants, the uBreathe Mini achieved a 23% reduction, compared to a 2.5% reduction by the single plant.

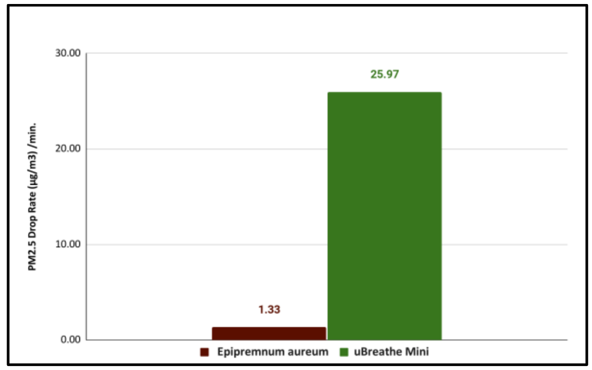

Fig. 6 The comparison of PM2.5 drop rate by uBreathe mini and Epipremnum aureum

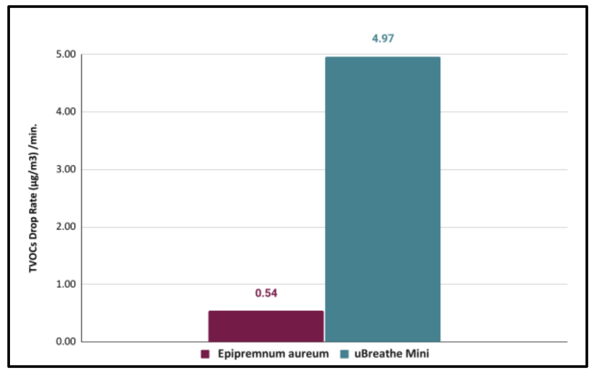

Fig. 7 The comparison of TTVOCs drop rate by uBreathe mini and Epipremnum aureum

Specifically, in the context of PM2.5 & TVOCs bioremediation, the drop rate for uBreathe Mini is twenty times higher than the average drop rate of Epipremnum aureum for PM2.5 & is nine times higher the average drop rate of Epipremnum aureum for TVOCs pollutants.

These results underscore the enhanced efficacy of the uBreathe Mini, which is attributed to several key design features. The optimized air-flow path ensures that air is effectively funneled through the leaf zone and soil matrix, facilitating efficient pollutant capture and degradation at both the zones. The pollutant drop with Epipremnum aureum can mostly be attributed to surface adsorption on the walls of the testing chamber and on the surface of leaves through wax.

The advanced exhaust system placement in the uBreathe Mini prevents short-circuiting of air back into the soil matrix, ensuring a consistent and effective removal of pollutants. The design incorporates a leak-proof chamber that streamlines air-flow, improving energy efficiency and pollutant removal efficacy.

X. CONCLUSION

The research underscores the potential of combining biological and mechanical filtration techniques to enhance indoor air quality. The uBreathe Mini's innovative approach not only harnesses the natural abilities of plants but also addresses the limitations of traditional air purifiers through sophisticated engineering solutions. This study supports the viability of the uBreathe Mini as a more effective and sustainable option for indoor air purification compared to conventional methods. Future research could further explore the long-term efficacy and practical applications of this technology in various indoor environments.

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