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Literature review: Science behind nature-based air pollutant mitigation

Phytoremediation:

Phytoremediation is a bio-remedial process that uses various types of plants to remove, stabilize, and/or destroy contaminants in the soil, air, and groundwater.
In our case, we are leveraging the phytoremediation phenomenon in cleaning the air pollutants. Following bio-physical processes are involved in the typical phytoremediation process for air pollutant removal:

1. **Rhizosphere biodegradation:**
   - In this process, the plant secrets natural substances from its roots, and these are nutrients needed for the growth of microorganisms in the soil.
   - The micro-organisms grow speedily and stimulate the biological degradation of contaminants present in the soil.
2. **Phytostabilisation:**
   - The process in which certain plant species are used to immobilize the contaminants in the soil and groundwater is termed phytostabilization.
   - In this process,chemical compounds secreted by the plant immobilize contaminants, rather than degrade them.
   - This
   - takes place through absorption and accumulation in plant tissues, adsorption onto roots, or precipitation within the root zone prohibiting their migration in soil, as well as their transportation by erosion and deforestation.
3. **Phytoaccumulation (phytoextraction):**
   - The process of uptake/absorption and translocation of contaminants by plant roots into the plant shoots, that can be harvested and metabolized to gain energy and also for recycling the metal from the ash is termed as phytoextraction.
   - In this process, rhizosphere part of the plant roots functions to absorb the contaminants along with other nutrients and water.
   - Plant species selected for their ability to take up large quantities of lead (Pb) are seen to uptake water-soluble metals.
   - Generally, bioavailable metals for plant uptake include cadmium, nickel, zinc, arsenic, selenium, and copper.

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4. **Rhizofiltration:**
    - The process in which adsorption or precipitation of contaminants occurs onto plant roots or absorption and sequestration in the roots is known as rhizofiltration.
    - Typically hydroponic systems utilize an artificial soil medium, such as sand mixed with perlite or vermiculite.

5. **Phytovolatilization:**
    - The uptake and elimination of a contaminant by a plant, with the release of the contaminant or a modified form of the contaminant to the atmosphere from the plant during transpiration, is termed phytovolatilization.
    - It takes place when growing trees and other plants uptake water along with the contaminants present in water.
    - The contaminants pass through the plants to the leaves and vapor out into the atmosphere at comparatively low concentrations.

6. **Phytodegradation:**
    - In this process, specific plant species are used for a particular contaminant on the basis of the degradation capability of plant species.
    - In this process, plants actually metabolize and deteriorate contaminants within plant tissues.

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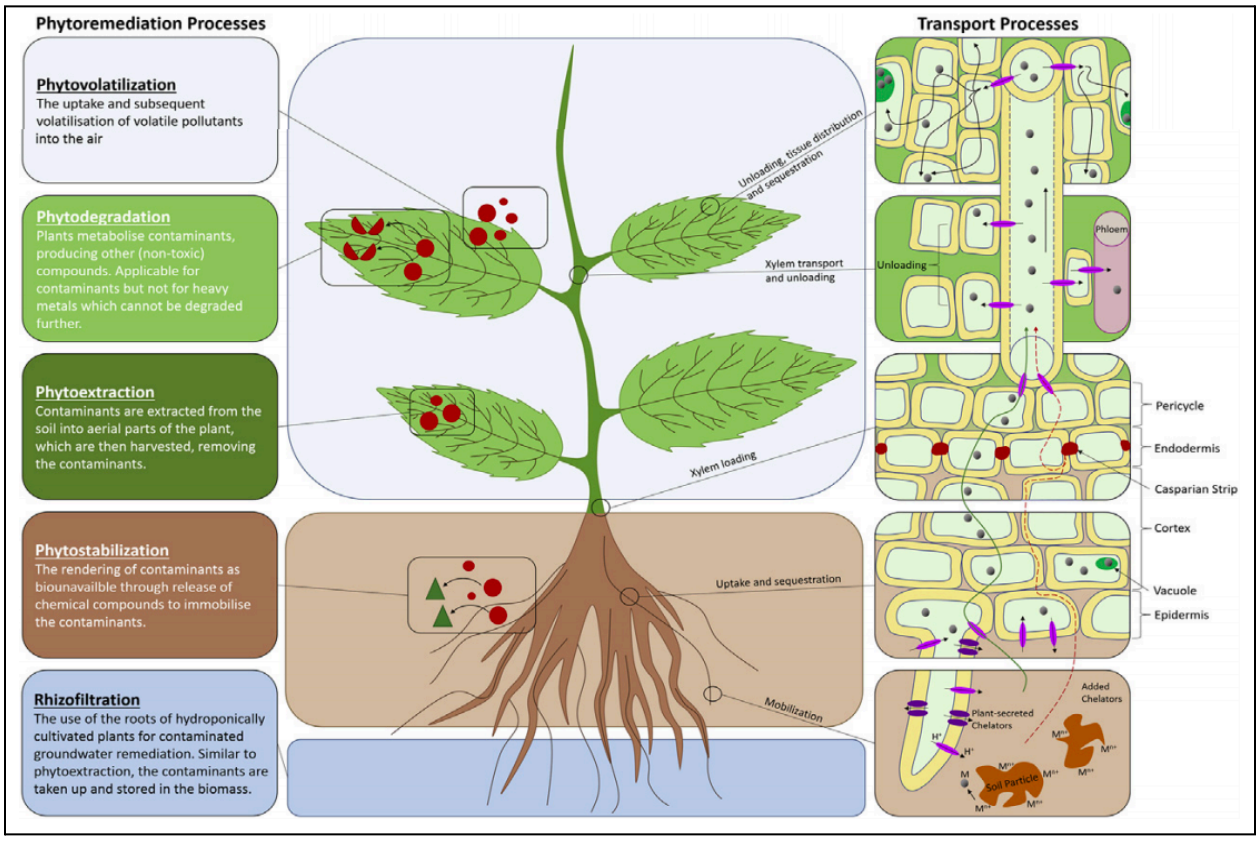

Fig. *Phytoremediation processes[1]*

Phenomenon	**Mechanism over time**	**Site**
Phytoextraction	Transfer of metal from soil to the stem and the leaves	Roots, Shoot & leaves
Rhizofiltration	Absorption & adsorption of the contaminants by the roots	Roots
Phytovolatilization	Absorption and release of volatile contaminants from the leaves	Leaves
Phytodegradation	Decomposition of the plant enzymes or by its metabolism	Roots
Phytostabilization	Precipitation of contaminant in the root zone, reduction of mobility & restriction	Roots

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	of metal in the root tissue	
Phytostimulation	Plant-assisted stimulation of microbial degradation of contaminants by release of exudates, in to the rhizosphere	Roots

***Table**: Pollutant removal through phytoremediation process [2]*

Inferences: Through the illustrated bifurcation of a highly complicated process of phytoremediation, we could narrowly derive that

- Micro-biome present in the root zone plays an important role in the degradation of the pollutants
- On the other hand, adsorption and volatilization at the leaf zone helps in removal of the pollutants
- The growth of the microorganisms is taken care by the secretion of the nutrients from the plants in the root zone

The micro-organisms play a vital role in the bio-chemical/physical processes taking place in phytoremediation as they are the key player in the breaking down of harmful pollutants. This degradation/conversion of the harmful substances takes place over a period of time while the accumulation of the pollutants on the leaf, soil-root zones happens in real-time. Thus, even during the night, the accumulation of the pollutants continues in the instant time response hence room air gets cleaned during the night as well, although the degradation of the pollutants happens over a period of time. The phytoremediation process and the cleaning process **doesn't get affected during the night.**

Plant-Soil-Microbial interaction:

Plants excrete into the root zone significant amounts of carbon that stimulates the development of microorganisms in the rhizosphere **(Kraffczyk et al., 1984; Schwab et al., 1998)**. The miro-organism growth happens with the exposed pollutants, greater the pollutants greater will be the micro-organism in the rhizosphere.

There are two fundamental research on plant leaves , roots and microorganisms roles in the phytoremediation that will supplement the above understanding for us:

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1-**Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air.** ***The Journal of Horticultural Science and Biotechnology***, [3]

Key takeaways:

- Initial dosage of pollutants saw less removal rate than the increased subsequent dosage of the pollutants. (With the chambers in dark both cases)

Inference:

1. Initial concentration of the dosage helps in activating the micro-organism and their activity. This is also coupled with excretion of carbon by plants in the roots, that aids to the growth/restructuring of the bacterial colony in the root zone. Thus, an enhanced rate of removal is observed even with increased subsequent dosage.
2. Pollutant removal doesn't get affected by the light , as it happens through a complicated combination of phenomena happening in the leaf and root zones due to the microorganisms.

- The test was carried out with plants in the soil and in the hydroponic state . Further after initial results (once the bacterial growth has happened) ,the plant was removed and test was carried out with just the growing media i.e. soil and water media . In the soil case, the pollutant removal was observed with a declining removal rate with time that ended to zero . In hydroponic media , the removal rate was obtained to be very-very slow as compared to just the soil case.

  Inferences:

  1. Pollutant removal is a biological response, not merely an adsorption or absorption process, which would tend towards a saturation.
  2. Plant + Soil media , helps in growth and sustaining of the microorganisms when exposed to the pollutants. Since, after removing the plants the pollutant removal took place for a period of time before stopping to zero. Suggesting the declination of the micro-organisms without the nutrients from the plants.

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2- **Efficiency of volatile formaldehyde removal by indoor plants: contribution of aerial plant parts versus the root zone. *Journal of the American Society for Horticultural Science***[4]

Key takeaways:

- The test was carried out to understand the percentage of pollutant removal happening through the leaf and the root zone. The aerial part of the plant & the roots were exposed to the pollutant in separate chambers in day as well as night condition. During night, the removal rate obtained through just the aerial plants drastically reduced whereas in the root cases, it remained the same. Furthermore, it was found that the root zone was responsible for removing 90% of the polluant.

Inferences:

1. Stomatal and cuticle opening aids to the absorption and adsorption of the pollutants in the leaf , which gets hampers when stomata remains closed during the night. Although,the cleaning through the aerial part continues due to the cuticular absorption.
2. When working with the plant-root system together , the enhanced pollution removal rate is observed with exposed time to pollution. This shows the involvement of the microorganisms present in the root zone, which grows with increased pollution concentration.
3. The root zone , in a plant-soil system accounts for about 90% of the pollutant removal

Key pollutants removal mechanisms in the plants

Major indoor air pollutants and their removal phenomenon through phytoremediation:

- **Particulate Matters**: The term for a mixture of solid particles and liquid droplets found in the air. PM 2.5, PM10, atmospheric particulate matter, or fine particles, are tiny particles and gas. 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.

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- **Nitrogen oxides (NOx):** are a group of air-polluting chemical compounds, comprising nitrogen dioxide (NO2) and nitrogen monoxide (NO).

  Removal Process: A group of bacteria like Azotobacter and Rhizobium and fungi such as mycorrhizas are capable of fixing atmospheric N. Cyanobacteria are able of using a variety of inorganic and organic sources of combined N, like nitrate, nitrite, ammonium, urea or some amino acids. These microbes are often associated with plant roots. Nitrifying bacteria including species from the genera Nitrosomonas, Nitrosococcus, Nitrobacter, and Nitrococcus oxidize ammonia to hydroxylamine, and nitrite oxidoreductase oxidizes nitrite to nitrate.

- **Sulfur oxides (SOx):** are a group of pollutants that contain both sulfur and oxygen molecules. Sulfur dioxide, SO2 is the most common form in the lower atmosphere. The majority of sulfur oxides are produced when fuels that contain sulfur undergo combustion. Natural sources include volcanoes. Coal-burning power plants that burn high-sulfur coal are some of the main sources of SOx. Vehicles are also a source of sulfur oxides.

  Removal process: Plant leaves absorb SO2 via stomata. Sulfur oxidizing bacteria such as *Beggiatoa* and *Paracoccus* are able to oxidize reduced sulfur compounds like H2S to inorganic sulfur, and thiosulfate to form sulfuric acid [5]. Sulfate-reducing bacteria like Archaeoglobus and Desulfotomaculum can convert sulfur compounds to hydrogen sulfide (H2S). Oxidation of H2S produces elemental sulfur (S°), which is completed by the photosynthetic green and purple sulfur bacteria and some chemolithotrophs. Additionally, sulfate-reducing bacteria have been shown to use hydrocarbons in pure cultures, which can be used for bioremediation of benzene, toluene, ethylbenzene, and xylene in contaminated soils [6]. Such bacteria may also colonize leaf surfaces and could be used for the remediation of air pollutants.

- **Carbon monoxide (CO):** is formed by the incomplete combustion of carbon-based fuels. Carbon monoxide is emitted to the atmosphere from natural and artificial sources. Examples of natural sources are natural gas, volcanic activity, forest fires, and lightning. The main part of artificial emissions comes from transports, working machinery, and heating of buildings.

  Removal process: Through photosynthesis & transpiration along with other phytoremediation processes

- **Ozone (O3):** ground-level ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC). This happens when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources chemically react in the presence of sunlight.

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Removal process: Plant absorption of O3 is mainly through stomata, O3 is easily dissolved in water and reacts with apoplastic structures and plasma membranes to form reactive oxygen species (ROS), such as O−2, H2O2, and OH radical.

O3 can be removed from the air by chemical reactions with reactive compounds emitted by vegetation, particularly monoterpenes [7]. Second, semi-volatile organic compounds, such as different diterpenoids exuded by trichomes on leaves are an efficient O3 sink [8].

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

  Sources of VOCs 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.

Removal process: Plants absorb gaseous pollutants via leaf stomata. Some of the VOCs 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 VOCs under interior environments [10].

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UBreathe Rain

'A nature-inspired and HEPA-free , wall mounted, modular air purification system for a large semi-open region having heavy population influx.

The existing air-purification technologies mostly rely on a stack of HEPA based mechanical filtration, charcoal filtration, etc. These filtration techniques require a fan-based suction system to channel airflow in and out of these systems. The application of these air-filtration techniques leads to the following critical limitations:

- Huge power consumption due to heavy suction systems that increases with the size of the coverage area.
- Regular replacement of the unsustainable filter media
- Unsustainable filters get disposed of in the landfills, ultimately leading to soil & water pollution
- The drastic increase in noise and size of the system with the coverage area
- Inefficient and infeasible available technologies for the outdoor applications

To overcome these limitations, Urban Air Labs have developed a self-sustaining air purification system in the form of modules which can be stacked together and mounted on the wall to cater to the large air-volume. The air-purification method backing this system is an innovative sustainable development over our patent filed 'Breathing Roots Technology' also hereby called as bio-filtration.The bio-filtration i.e. plant's phytoremediation capabilities coupled with our novel and patent filed 'Rain Shower Technology'. The rain shower technology mimics the wet deposition phenomenon that happens during rainfall which has been proven to reducing suspended pollutants in the air.[11] This is further supported by a novel self-regenerating filter made of sodium alginate, this filter needs not to be replaced and is also sustainable in development and usage.

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Thus, through modular design incorporating the three stacks of filters the developed air-purification system can be easily used effectively in outdoor, semi-open, and indoor spaces due to the availability of huge exposed surface areas. These modular wall mounted purification systems can be easily customized as per the requirements and aesthetics.

Technical Insights on the Design & Innovation

1. **Modular:** The design is made in the form of small units that can be joined together and scaled for any volume of air or for any size of the sweeping area. Each single unit is defined as a module, each module has been designed with specific size , flow rate (cfm), energy consumption, number of plants and arrangements to be joined with next modules either horizontally or vertically.
2. **Wall Mounted:** The modules integrated with the stacks of sustainable filters are mounted on the wall to utilize the maximum space of the wall and improve the efficacy of the air-purification system for the semi-open spaces. Through this the area available for the air-purification system fittings increases to many-folds which is not possible in conventional floor/table-top indoor air-purification systems.
3. **Novel Sustainable Filtration Stacks: The first layer is of the bio-filters through our 'Breathing Roots Technology'**. There are numerous researches backing NASA's study of plants species cleaning ability of the pollutants. The phenomenon known as Phytoremediation , through which plants can degrade the pollutants (PM, TVOCs, Gaseous pollutants) through the leaf and plant root zone.

Since the plant's roots contribute to 90% of the pollution degradation and only 10% of the pollution cleaning happens through leafs , our innovative patent filed technology 'Breathing roots' increases the breathability of the soil-root zone and increases the volume of air getting into the root zone, thus increasing overall efficacy of the phytoremediation. The plant's through photosynthesis also improves the oxygen levels and controls the carbon dioxide levels.

The next filtration is done by mimicking the showers of the rainfall and passing the air through it. It has been always observed that on rainy days, most of the air's common air pollutants and pollen are washed away, helping to improve the air quality. This phenomenon is called Wet deposition. To be more scientific: 'Wet deposition' refers to the natural processes by which material is removed ('scavenged') by atmospheric hydrometeors (cloud and fog drops, rain,

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snow) and delivered to the Earth's surface. These phenomena are also mainly discussed as 'precipitation scavenging', 'wet removal', 'washout', and 'rainout'.

As per the study of scientists from MIT USA, there are two main parameters that govern the wet deposition capabilities of the rain: a) Size of the droplets b) Charges present in the droplets.[11]

For the size of droplets, the smaller the size of the droplet greater will be its surface area to dissolve the particles in itself. Hence through our experiments an optimized size of droplets was achieved giving the maximum effectiveness in the wet deposition capabilities. We have done several experiments and numerical analysis to determine a balance of positive and negative charge that the droplets should be fed with in-order to form the free [H+] and [O2-] ions from the droplets and the air. These free ions in the droplets help in increasing the coagulation capacity of the droplets for removing the particles. The gases are absorbed by the charged droplets and broken down into simpler and non-harmful gases.

The **'Rain Shower Technology**' is achieved by facilitating the above phenomenon inside the module. For this, a series of holes with washers are made horizontally in a single row in the pipe mounted on a sump, the pipe is fed continuously with water through a submersible pump from the collecting tank. The sump has two layers of equidistant holes made horizontally keeping the diameter of the washer equal to the required droplet diameter.The holes are made as per the optimized diameter of the droplets and this whole arrangement of water shower is kept across the air-flow after the bio-filtration layer in 90 degree. Thus, all the air coming after interacting with the biofilters get passed through the series of drops falling vertically down into a collecting tank.

The ion-generating system i.e. ion-splasher is also placed inside the module in a strategic position such that it emits the ions and charges the rain drops with a balance of positive and negative ions. The charge carrying droplets falling vertically across the air flow path coagulates with the suspended particles and absorbs the harmful gases. The drops with the dissolved pollutants are collected in the collecting tank and the water is fed again to the pipe for the rain-shower.

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Our innovation, **Breathing Roots Technology and Rain Shower Technology** is capable of removing all prominent air-pollutants and hence can tackle air pollution in an enhanced and more effective way with all sustainable arrangements.

4. **Self-Sustaining:** The modular purification system self -sustaining in nature. Once implemented and attached to the power supply the system takes care of itself autonomously. The sensor after checking the humidity level in the roots triggers the irrigation system, the water used from the collecting tank is fed through a drip irrigation system to all the plants. The grow light attached with each module gets ON as per the LDR (Light dependent resistor) response and hence the plants always gets ample amount of light for their health and growth. The filtration layer integrated with the modules are all sustainable and need not to be replaced after usage. The water level sensor senses the level of the water in the collecting tank and activates the alarm for the replenishing of the tanks.

5. **Advanced Air-flow design:** The design consideration in the module has been made in such a way that the air gets the least resistance path towards the area of interest thus facilitating the less flow losses around plant root and water shower area. The air combination of air-inlets are strategically designed to facilitate more flow rate without additional power consumption by utilizing the first principle of physics.

There are two pairs of inlets kept for sucking in foul air:

- Primary inlet- These are small holes of particular diameter kept around the plant pot on the front surface
- Trigger inlet- These are small holes of particular diameter made on the center of the module at the top surface

When the suction system is activated the foul air starts getting sucked in from the front and top holes . Since the trigger holes are less in number hence the volume of air getting through the trigger inlet is very less as compared to the primary inlet. Since air enters through the small holes, to conserve the volume its velocity increases to some multiples just after the inlet.

This air-flow pattern thus helps in sucking in more foul air through the same power consumption unit. The phenomena happening as a combination of both the physics is termed henceforth as **‘Urban Tunnel Effect**

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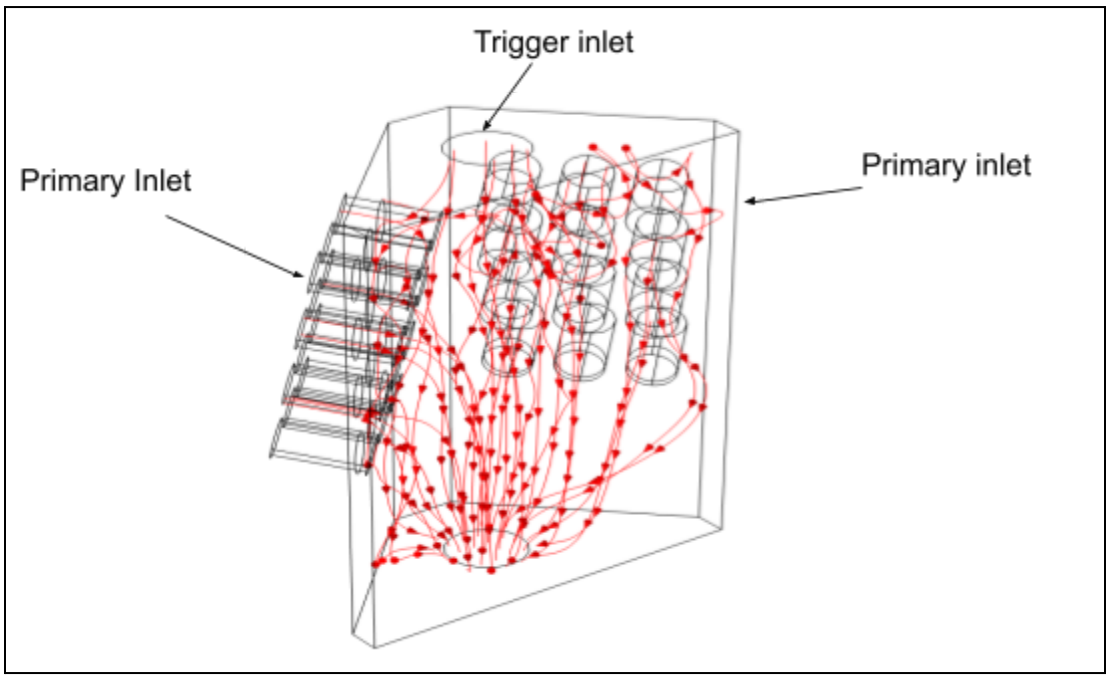

Fig1. *Module with primary & trigger inlet*

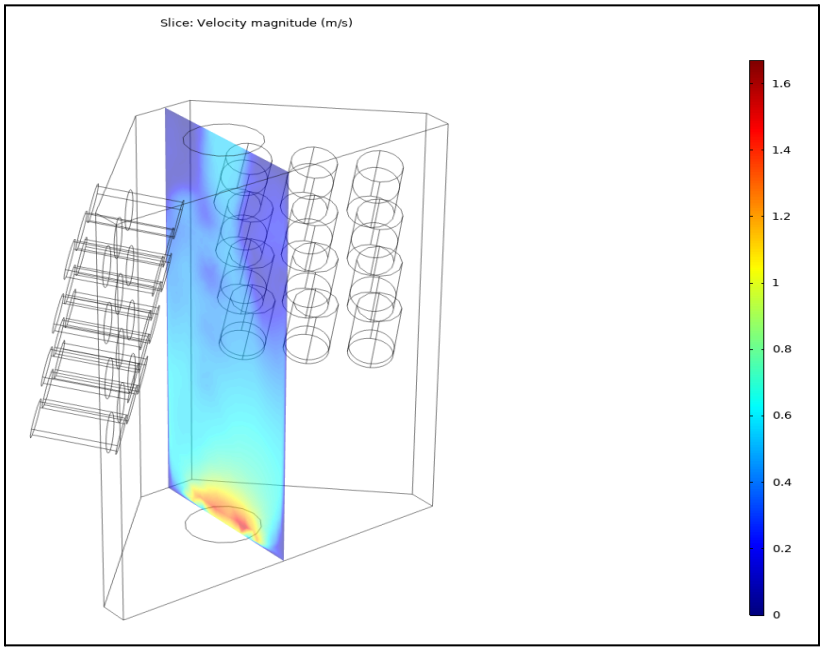

Fig2. *Velocity gradient depicting velocity increase near the center cross section region due to Urban Tunnel Effect*

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6. **Biophilic Design:** The Biophilia is attached to the sole theme behind the design of the modules through plants, water drops, sustainable material apart. This Biophilic design apart from reducing CO2 levels and improving Oxygen levels has added advantages like:

- Reduce a development's carbon footprint
- Regulating the temperature of building
- Regulating the humidity of the building
- Improved health
- Increased mood and feeling of well-being
- Improved productivity
- Increased employee engagement
- Reduced stress levels
- Mental restoration & reduced fatigue

The novel technology developed is capable of controlling the air-quality of the semi-open spaces where air volume is huge, air-infiltration is prominent and pollutant load is very unpredictable. The modules with all the filtration stacks get mounted on the wall and joined together to scale up as per the requirement. The energy requirement per unit module is very less as compared to the conventional air-purifiers for the same specification and sweeping area.

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Fig. *UB Rain Team*

Key Benefits

- **Removes Air- Pollutants:** UBreathe Rain captures dust pollutants(PM 2.5, PM10) and removes gaseous(NOx, SOx etc.) as well as build-up volatile organic compounds(Benzene, formaldehydes etc.)
- **Deactivates Virus and Bacterias:** UBreathe Rain efficiently deactivates micro-biological pollutants from indoor spaces.
- **Reduces CO2 build-up:** Plant based air purification degrades hazardous concentrations of CO2 build up at places of public gatherings
- **Improves Physical & Mental Well being:** UBreathe Rain also provides biophilic benefits such as supporting cognitive function, physical health, and psychological well-being.
- **Increases Productivity:** UB Rain utilizes the essence of mother nature through plants & raindrop trickles which has been proven to improve productivity at work
- **Mitigates Noise:** Reduces the reflected noise more efficiently than the normal used building materials
- **Reduces cooling load of the building:** Reduces the temperature of the building or the spaces and aids to reduction in building cooling load

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Key novelties in the developed UBreathe Rain

1. State-of-the-art sustainable air filtration with "RAIN SHOWER TECHNOLOGY". Inspired from the rainfall, the technology mimics the physics of rainfall at quantum level to wash out the air-pollutants in the air.
2. 'Urban Tunnel Effect', Advanced Air-flow pattern mimicked from the air-flow pattern observed in the tunnel to leverage the fluid flow phenomenon through design and strategic placements of the vents to improve the suction of the system without increasing the power consumption of the suction system
3. Designed for semi-open areas ranging from 150 sq. feet for a single module. Each module can be clubbed together to cater to the size of any area
4. A Modular design for customer-company synergy, providing complete flexibility for personalization.
5. Eco-friendly and aesthetically designed to control the hazardous carbon-dioxide concentration in the crowded areas
6. 'Self-sustaining' air-purification system, fully automated system of irrigation and AQI control

Patents filed for UBreathe Rain

A. RAIN SHOWER TECHNOLOGY(Indian Provisional Patent Filed)

TITLE OF THE INVENTION- A SELF-SUSTAINING WALL MOUNTED AIR PURIFICATION SYSTEM

Owner: Shubham Singh, Sanjay Maurya

B. BREATHING ROOTS TECHNOLOGY (Indian Full Patent Filed & European PCT Filed)

TITLE OF THE INVENTION- A SYSTEM FOR SMART TECHNOLOGY ENABLED BIODEGRADABLE PLANT POT THAT MONITORS AND FILTERS INDOOR AIR

Owner: Akhil Gupta, Inderjeet Rao, Akshay Goyal

C. URBAN MUNNAR EFFECT (Indian Full Patent Filed)

TITLE OF THE INVENTION- Purifier System and method Thereof

Owner: Sanjay Maurya, Shubham Singh

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Trademarks for UBreathe Rain

Trademark	Category	Class
RAIN SHOWER TECHNOLOGY	WORD	11
URBAN TUNNEL EFFECT	WORD	11

Limitations of Conventional & Existing Technologies & competitive advantage of UBreathe Rain

1) **Maintenance Requirements:** Conventional mechanical filters (HEPA-based) require regular maintenance and filter replacement to maintain their air cleaning capacity. Over time, the filters become clogged with captured pollutants, reducing their effectiveness.
2) **Energy Inefficiency:** The current air purification technologies consume high levels of electricity, making them energy-inefficient and contributing to increased energy costs and environmental impact.
3) **Space Utilization:** Conventional air purifiers are often bulky and occupy a large footprint, making them challenging to integrate into existing spaces. They suffer from insufficient space utilization, hindering their widespread adoption.
4) **Limited Effectiveness:** Current air purification technologies are limited to closed spaces and are ineffective in larger or semi-open spaces. This is due to their reliance on a sealed environment to recirculate the air and capture pollutants.
5) **Inadequate Coverage of Pollutants:** Conventional air purifiers do not cover the full spectrum of pollutants, including PM particles, gaseous pollutants, volatile organic compounds, and microbial pollutants, highlighting the need for new and innovative air purification technologies
6) **Elevated CO2 Concentrations:** In crowded spaces, such as large public gathering areas, conventional air purifiers may struggle to compensate for elevated levels of CO2. This can lead to hazardous concentrations of carbon dioxide in the air, posing health risks to occupants.
7) **Lack of Sustainability:** The production and disposal of conventional mechanical filters (HEPA-based) have a negative impact on the environment, making them unsustainable and contributing to environmental degradation.

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