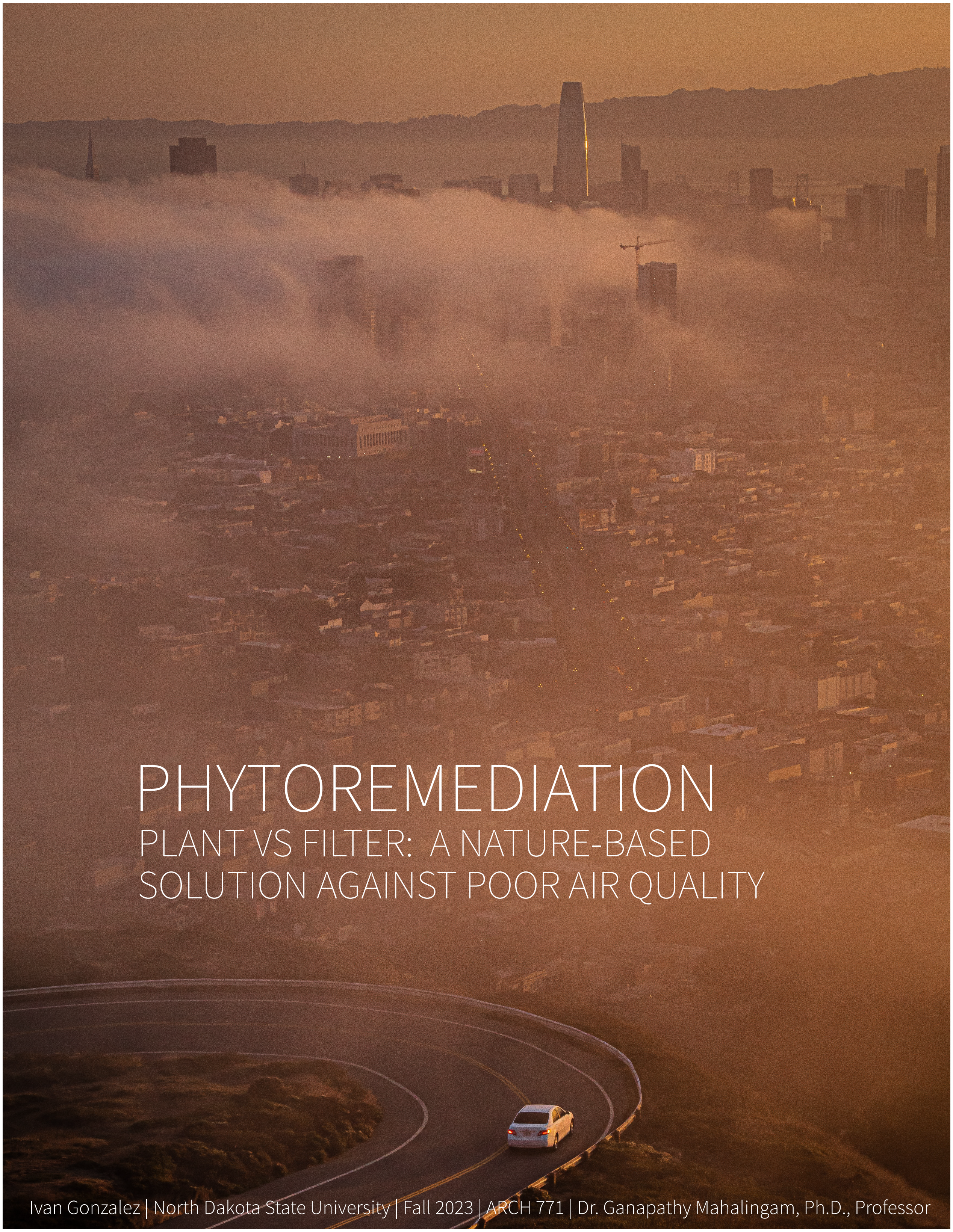

PHYTOREMEDIATION

PLANT VS FILTER: A NATURE-BASED SOLUTION AGAINST POOR AIR QUALITY

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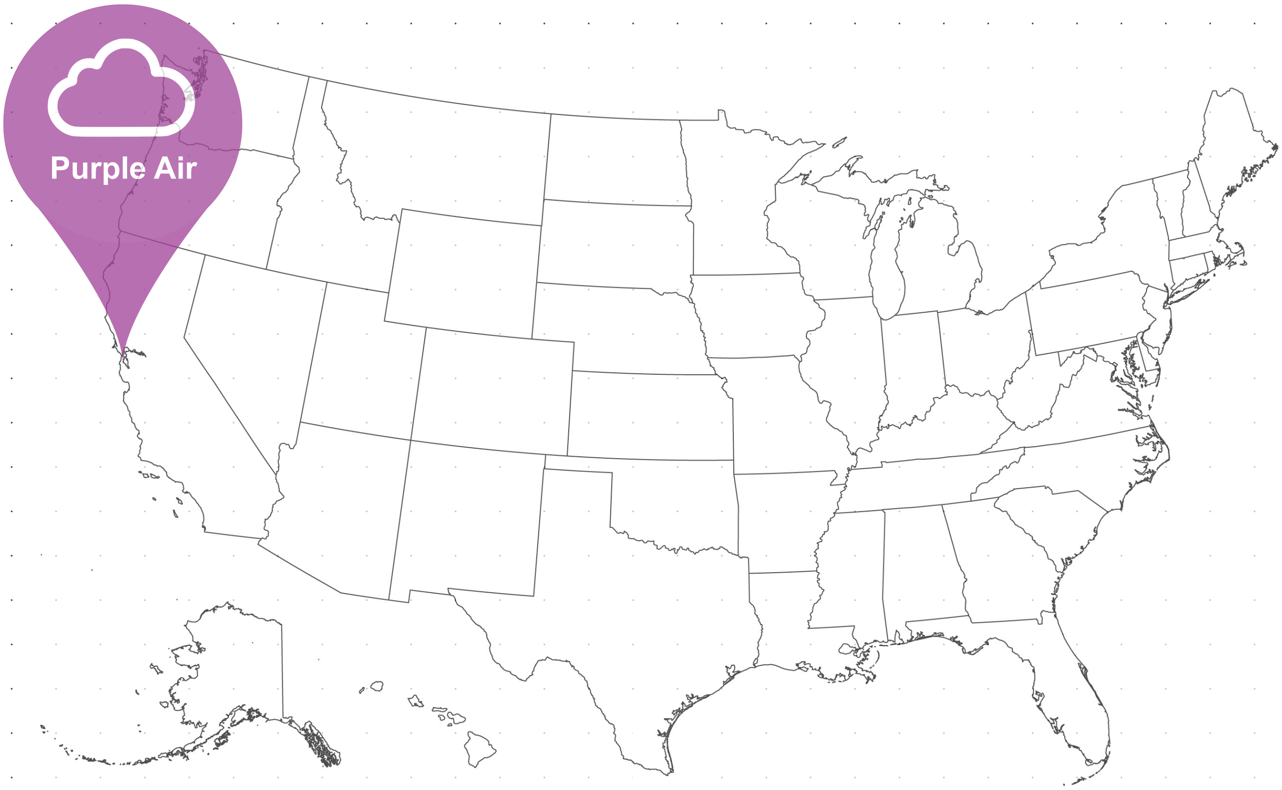
Introduction

With an increasing number of wildfire events occurring year after year in California, one of the challenges many cities face today is the exposure to smoke produced by fires that spread faster and burn more intensely. This heavy smoke comprises gaseous pollutants, water vapor, and particle pollution, or particulate matter (PM). Particles generally 2.5 µm in diameter or smaller represent the primary pollutant in wildfire smoke and the leading health threat. People at greater risk include those with cardiovascular or respiratory disease, older adults, children 18 years and younger, pregnant women, outdoor workers, and those of lower socio-economic status. According to the California Air Resources Board (CARB), PM2.5 contributes to 5,400 premature deaths due to cardiopulmonary causes per year, in addition to 2.800 hospitalizations for cardiovascular and respiratory diseases and 6,700 emergency room visits for asthma each year.

The most common advice during a wildfire smoke event is to remain indoors. For this to be effective, buildings should have a tightly closed, air-conditioned space in which the air conditioner recirculates indoor air. According to the 2021 American housing survey released by the U.S. Census, San Francisco has become the least air-conditioned metro area in the U.S. The survey states that about 45% of the 1.8 million housing units have a primary air conditioning source, compared to a national average of 92%. Of those 45%, only about 34% of homes are equipped with central air, while 11% use room air conditioning.

This research aims to provide an alternative nature-based solution to today's conventional HVAC systems. This research will integrate the benefits of phytoremediation, a plant's ability to remediate soil, water, and air, with a building HVAC system to combat poor air quality in the urban environment.

Methodology



Collection of plants: A plant's ability to remediate VOC, CO_2, and PM2.5 will determine the selection of plants. Based on the studies from Irga P.J. (2017) and Matheson S. (2023), plants will be selected from the proven remediation record, either in a laboratory setting or in situ. Investigations will include past data to determine the single pass removal efficiency (SPRE).

Collection of past data on air quality index (AQI) and city selection: In order to find the clean air delivery rate (CADR) of each pollutant, determining the AQI measurement of a chosen city will be conducted by examining a series of maps and data from AirNow, which shows the average and extremes of AQI readings. 4CAir Collection of past data on indoor air quality (IAQ): After the AQI is collected, data from PurpleAir will be used to collect the readings of indoor air pollutants. For this research report, the study from Liang Y. (2021) will provide various readings from PurpleAir, specifically from San Francisco, California, regarding indoor air quality (IAQ).

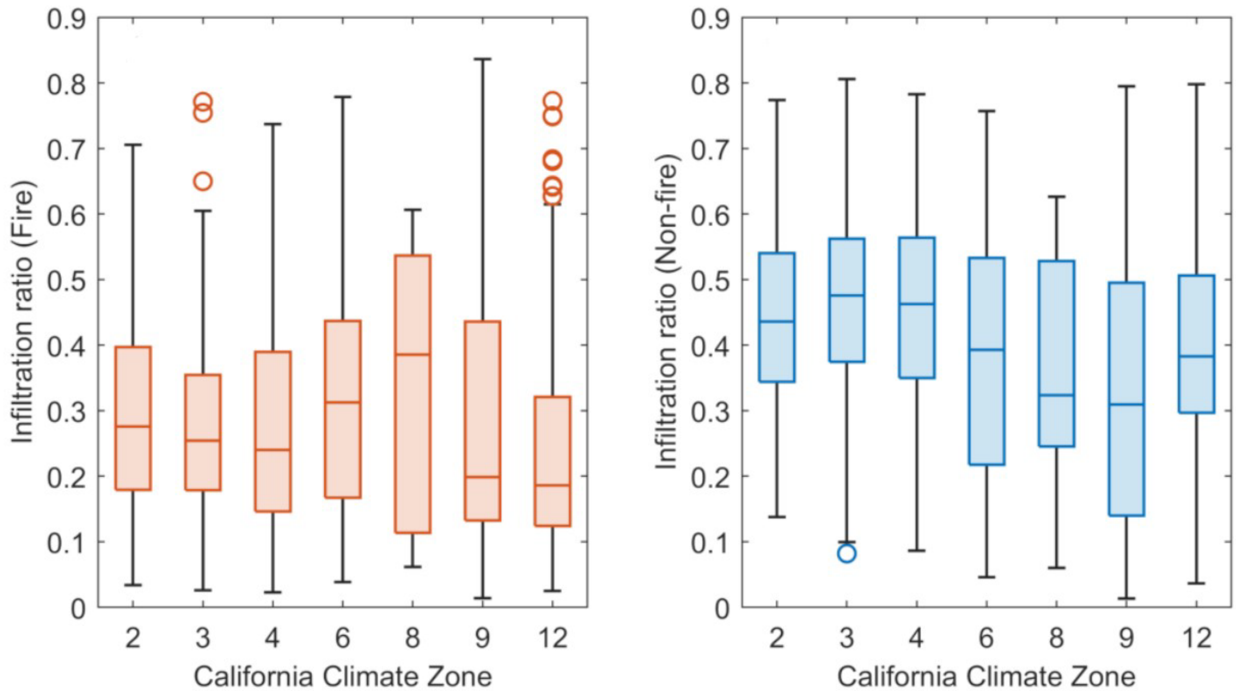


Figure 1. "Infiltration Ratio of buildings in different climate zones of California" In the graphs shown above the infiltration ratio is shown for climate zones with at least 10 indoor sensors. Each climate zones if referenced by cities; Zone 2 – Napa, Zone 3 – San Francisco & Oakland, Zone 4 – San Jose, Zone 6 – Los Angeles (LAX), Zone 8 – Long Beach, Zone 9 – Los Angeles (Civic Center), Zone 12 – Sacramento.
Note: Infiltration ratio graphs from Liang, Y.,(2021) study.

Collection of past data on plants to find the CADR: Due to this emerging topic, limited research that describes the CADR for specific plants is available. CADR = SPRE x biofilter airflow rate. For example, as discussed in the trials from Australia, Pettit, T. (2020), during the "Black Summer," there was an average SPRE of 24.84% for PM2.5 using a volumetric flow rate of 884.8 m3/h. The CADR would then be 218.8 m3/h. On the other hand, during a controlled experimental trial, Irga P.J. (2017), the SPRE had a higher result. The SPRE was 48.21. Five airflow rates were tested during these trials: 3.75, 7.50, 11.25, and 15.0 L s−1. Out of the five, it was demonstrated that the most effective flow rate was 11.25 L s−1. This research report will use an airflow rate of 11.25 L s−1.

Inputting data and validation of measurements to develop design simulations: To truly understand the benefits of integrating phytoremediation with a building's HVAC system, a simulation will be created using Anylogic. In this simulation, a standard HVAC system with the help of a biofilter will demonstrate full clean air ventilation. Further explained in the research results, a flow rate is needed to initialize a simulation model in Anylogic. Figure 1 shows different infiltration rates that can be entered as a flow rate to test different scenarios and infiltration rates of a typical building in San Francisco. An infiltration rate of 18% will be used throughout this research investigation. This 18% is the lowest infiltration rate in Table X.

Inputting data and validation of measurements to develop design simulations: Continuing to use past data in studies from Irga P.J. (2017) and Matheson S. (2023), the last part of this investigation includes finding the minimum ventilation rates for typical spaces found in a four-star hotel. Additionally, to use biofilters as standalone air filtration systems, with the assistance of the study Irga P.J. (2017), there will be five different scenarios in which calculations will be made to find an estimate in the sizing of a standalone air filter, assuming each space accounts for at least four air changes per hour.

Research Results

3.1 Anylogic Software

Anylogic is a leading simulation modeling software that allows professionals from across various industries to gain a deeper understanding of complex systems and processes. A user can choose from six different types of libraries, including process modeling, pedestrian, road traffic, rail, fluid, and material handling. This research report will mainly use components from the fluid library. The fluid library will allow the simulation to have various characteristics of flows, such as rate and throughput, which is an essential part of the desired standalone biofilter. In addition to the fluid library, some components of the process modeling library were used. Some limitations of this software include a sole one-way flow and the under supply of accurate representation of some components in a biofilter.

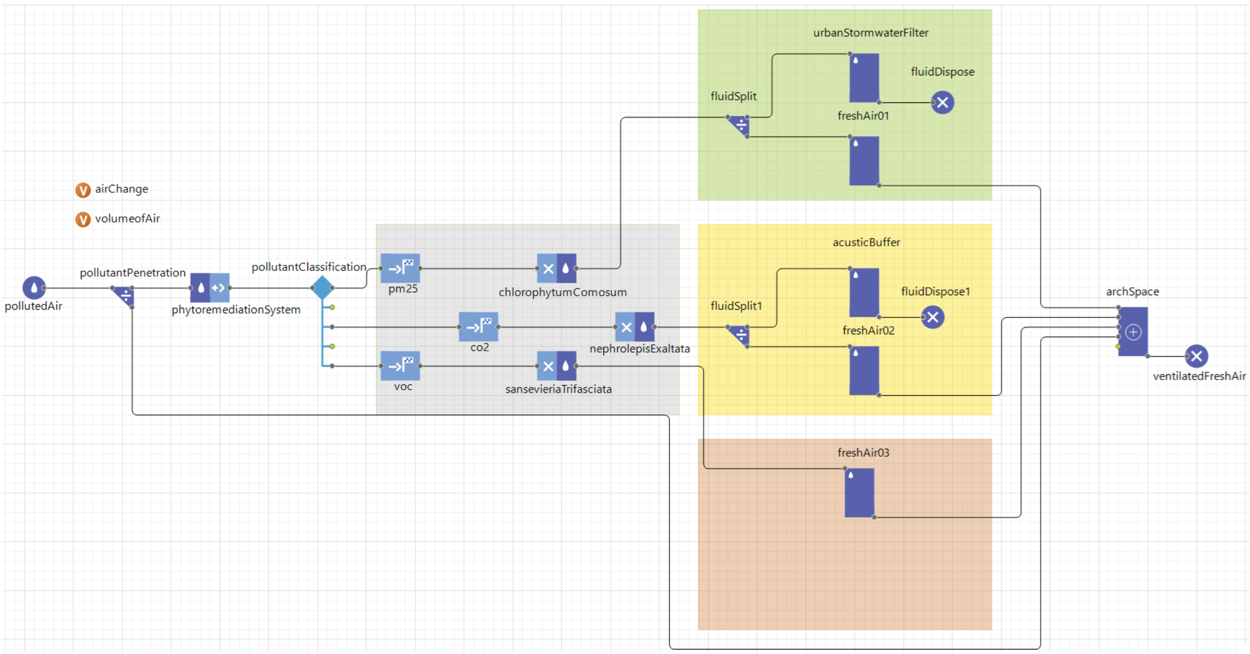


Figure 2: Anylogic Simulation Model

3.2 Development of simulation model

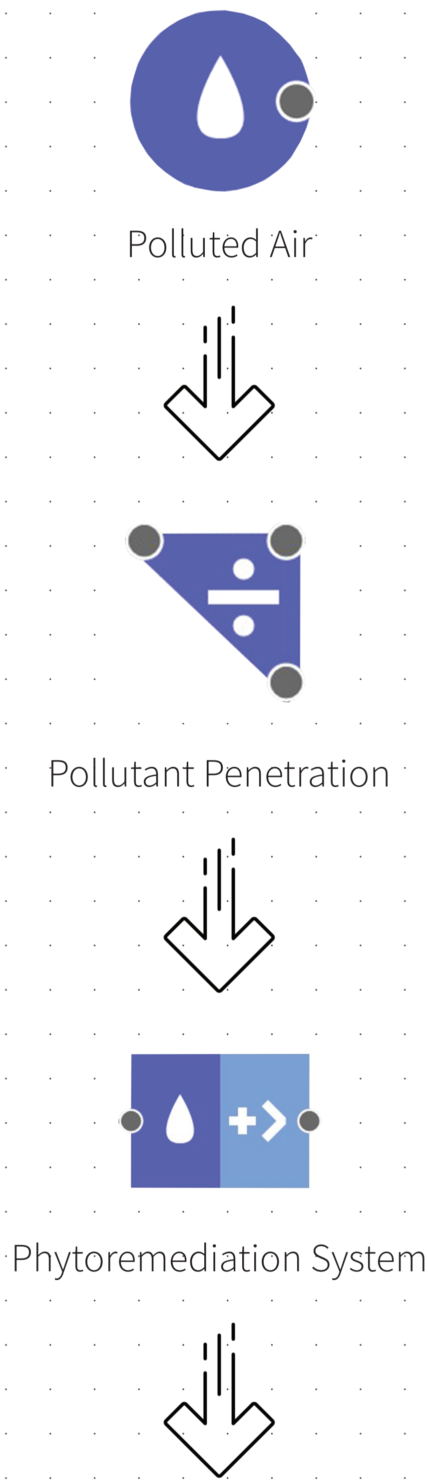
To develop the simulation model in Anylogic, it was essential to enter a flow rate at the start of the simulation. The units in Anylogic for the flow rate were decided to be entered as cubic meters per second. For this reason, the volume of air was entered as cubic meters at the beginning of the simulation model using the ***fluid-source*** block named polluted air.

Entering a flow rate by using the following equation:

$$\frac{(\text{volume of air, } m^3)(\text{ air change per hour})}{3600}$$

As the simulation progressed, the ***fluid-split*** block was used from the fluid library to represent the separation of air infiltration named pollutant penetration. This block allows users to separate the flow rate by entering the desired fractions. To determine an accurate infiltration rate, data from Liang, Y. (2021) was used to determine that about 18% of polluted air is what enters a typical building, which means that in the usage of conventional HVAC systems and filters, about 82% gets effectively filtered. These percentages were taken from California studies, focusing on the Bay Area, as this will be the area of study for a potential building that could solely use an active green wall filter for indoor air quality monitoring.

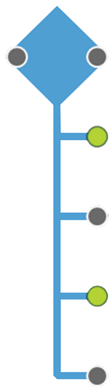
Assuming 18% of polluted air enters a building, the polluted air continues through the ***fluid-to-agent*** block. This block, named the phytoremediation system, is where the phytoremediation system process begins.



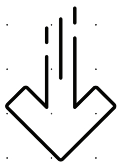
The polluted air is then separated even further into three different pollutants. These pollutants include particulate matter (PM2.5), carbon dioxide (CO2), and volatile organic compounds (VOC). The ***select-output-five*** block, labeled as pollutant classification, has five outputs that can make five different distinctions. For this simulation model, three outputs were used out of the five to represent each pollutant.

Moving forward through the model, the ***move-to*** block represents each pollutant and advances towards the *agent-to-fluid* block. Labeled as PM2.5, CO2, and VOC.

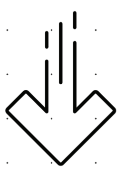
For each pollutant, there is an *agent-to-fluid* block. Each ***agent-to-fluid*** *block* is then associated with a specific plant that has demonstrated the efficiency to remediate its according pollutant. *Chlorophytum Comosum* can remediate PM2.5, *Nephrolepis Exaltata* to CO2, and *Sansevieria Trifasciata* to VOC.



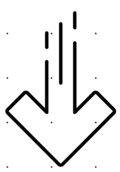
Pollutant Classification



PM2.5 | CO2 | VOC

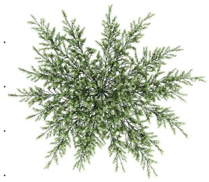


“Plant Name”



Chlorophytum comosum

Nephrolepis Exaltata

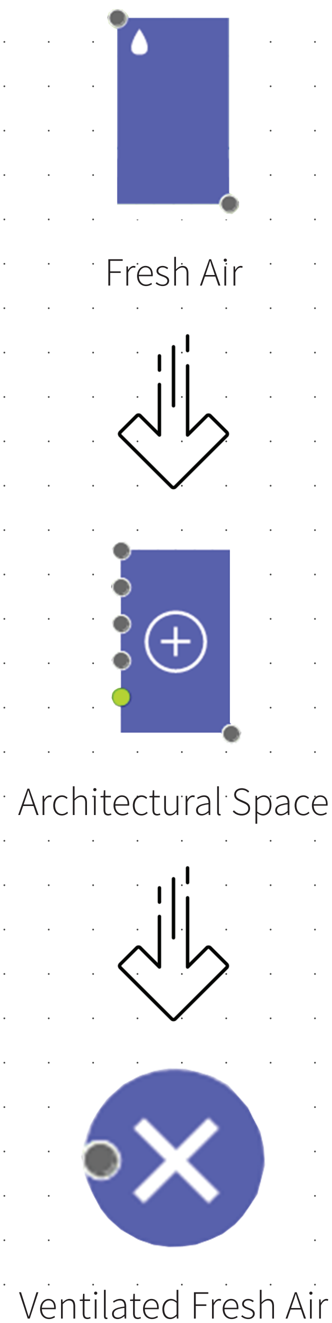


Sansevieria Trifasciata

As the polluted air goes through the simulation, it can do more than transform into fresh air. After leaving the *agent-to-fluid* block, the fluid gets diverted by another *fluid-split* block. This step shows the other benefits of an active green wall. From the review paper of the Matheson, S. (2023) study, the other benefits include the performance of acting as an acoustic buffer and urban stormwater filter. These benefits then go through a ***tank*** block, representing all the benefits of a biofilter.

Towards the end of the simulation model, the ***fluid-dispose*** block is introduced. For some *tanks*, such as the urban stormwater filter and the sound buffer tank, a *fluid-dispose* block is shown to demonstrate the effect. As for the remediated fresh air, it ends in the designated architectural space, which represents a building.

At the end of the simulation model, all the fresh air finally reaches the architectural space. The ***mix-tank*** block is assumed to reach an entire filtered space, firstly by an effective HVAC filter and secondly by integrating a biofilter. At the very last step, the last block is another ***fluid-dispose***. This last block shows the ventilated fresh air and concludes the simulation model.



3.3 Minimum Ventilation Rates for spaces in a four star hotel

Two studies were analyzed to estimate a single pass removal efficiency, Irga P.J. (2017) and Matheson S. (2023). One study was realized in situ while the other was realized in a laboratory. In the study realized in the laboratory, the SPRE was realized to be 48% with a flow rate of 11.25 L/sec for PM2.5. In comparison, in the in situ study, the SPRE Was only 24.84% with a flow rate of 12.29 L/sec, assuming a 0.25 m2 biofilter using Chlorophytum comosum or spider plant as previously used for PM accumulation. For this simulation, the SPRE of 36.53% was used with a flow rate of 11.25 L/sec.

Looking at the equation found in ASHRAE Standard 62.1 2022 and with the square footage from Table 6.1 in Figure 3, we can conclude the necessary amount of clean air needed where a biofilter could act as a standalone filtration system. At this point, conceptual spaces in a typical four-star hotel were used for each calculation.

Equation 1:

Vbz = (Rp)(Pz) + (Ra)(Az)

Table 6-1 Minimum Ventilation Rates in Breathing Zone

	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Default Values Occupant Density		
Occupancy Category	cfm/ person	L/s· person	cfm/ft^2	L/s·m^2	#/1000 ft^2 or #/100 m^2	Air Class	OS (6.2.6.1.4)
Cafeteria/fast-food dining	7.5	3.8	0.18	0.9	100	2	
Kitchen (cooking)	7.5	3.8	0.12	0.6	20	2	
Restaurant dining rooms	7.5	3.8	0.18	0.9	70	2	
General							
Break rooms	5	2.5	0.06	0.3	25	1	✓
Coffee stations	5	2.5	0.06	0.3	20	1	✓
Conference/meeting	5	2.5	0.06	0.3	50	1	✓
Corridors	—	—	0.06	0.3	—	1	✓
Occupiable storage rooms for liquids or gels	5	2.5	0.12	0.6	2	2	
Hotels, Motels, Resorts, Dormitories							
Barracks sleeping areas	5	2.5	0.06	0.3	20	1	✓
Bedroom/living room	5	2.5	0.06	0.3	10	1	✓
Laundry rooms, central	5	2.5	0.12	0.6	10	2	
Laundry rooms within dwelling units	5	2.5	0.12	0.6	10	1	
Lobbies/prefunction	7.5	3.8	0.06	0.3	30	1	✓
Multipurpose assembly	5	2.5	0.06	0.3	120	1	✓

Figure 3. ASHRAE Standard 62.1 - 2022

Where:

Vbz = the outdoor airflow required in the breathing zone

Az = zone floor area, the net occupiable floor area of the ventilation zone, m2

Pz = zone population, the number of people in the ventilation zone during use

Rp = outdoor airflow rate required per person as determined from Table 6-1

Ra = outdoor airflow rate required per unit area as determined from Table 6-1

Main Space	Typical Size (sq ft)
Guest Room	300 – 400
Suite	430 – 3,000
Bathroom	50 – 100
Lobby	1,000 – 5,000
Restaurant	1,000 – 2,000
Bar	500 – 1,000
Fitness Center	1,000 – 2,000
Meeting Room	500 – 1,000
Pool	1,000 – 5,000
Business Center	50,000 – 100,000

Figure 4. Generated by Google Bard

Biofilter calculations

Situation A.)
Bedroom with 2 beds and an area of 30m2 with a maximum of 4 people.

Situation B.)
Bedroom with 1 bed and an area of 30m2 with a maximum of 2 people.

Situation C.)
Hotel lobby with an area of 185m2 and a maximum of 10 people.

Situation D.)
Multipurpose Assembly with an area of 100m2 and a maximum of 154 people.

Situation E.)
Restaurant seating area of 190m2 and a maximum of 136 people.

Assuming an air change per hour of 4 each situation was calculated into equation (x) for sizing of biofilter.

Scenario A.)
Vbz = (2.5)(2) + (0.3)(30) = 14 Ls-1

Scenario B.)
Vbz = (2.5)(4) + (0.3)(30) = 19 Ls-1

Scenario C.)
Vbz = (3.8)(10) + (0.3)(185) = 93.5 Ls-1

Scenario D.)
Vbz = (2.5)(154) + (0.3)(100) = 415 Ls-1

Scenario E.)
Vbz = (3.8)(136) + (0.9)(190) = 687.8 Ls-1

3.4 Sizing of Biofilter

A metric used to indicate the effectiveness of the biofilter in an in-situ application is the air cleaner effectiveness. Irga, P. J. (2017) This tells us the capacity of the biofilter to serve as a standalone ventilation system for the main spaces of a hotel. Four air changes per hour will be used to size the biofilter to serve as a stand-alone ventilation system for all scenarios. Based on the calculation of Irga, P. J. 2017 the biofilter in its most effective operational setting would require 0.1872 modules per m3 to supply a ventilation equivalent of 4 air changes per hour. Assuming all this for each scenario, throughout this study, a conceptual volume of spaces in a hotel was used to estimate the biofilter size required to replace mechanical ventilation fully.

Scenario A.)
Assuming a room volume of 90 m3 and four air changes per hour, the required modules to fully replace mechanical ventilation would be 0.1872 x 90 m3 = 16.848 modules (4.21 m2).

Scenario B.)
Assuming a second room will have the same room volume as the room in scenario a, the required modules to fully replace mechanical ventilation would be 0.1872 x 90 m3 = 16.848 modules (4.21 m2).

Scenario C.)
Assuming the hotel lobby has a volume of 62.85 m3 and four air changes per hour, the required modules to fully replace mechanical ventilation would be 0.1872 x 62.85 m3 = 11.77 modules (2.94 m2).

Scenario D.)
Assuming a multipurpose assembly room has a volume of 1200 m3 and four air changes per hour, the required modules to fully replace mechanical ventilation would be 0.1872 x 1200 m3 = 224.64 modules (56.16 m2).

Scenario E.)
Assuming a restaurant seating area has a volume of 2280 m3 and four air changes per hour, the required modules to fully replace mechanical ventilation would be 0.1872 x 2280 m3 = 426.82 modules (106.7 m2).

Conclusion

Although several studies have been conducted to analyze the effectiveness of a biofilter, in situ studies on a large-scale trial still need to be conducted. Additionally, only a few tests are being conducted for indoor spaces. Green walls have been previously used in buildings to treat urban stormwater or act as an acoustic buffer. However, only a few have been used to tackle the emergence of particulate matter in the urban ambient air. Many indoor biofilters have been shown to "scrub" the air but have only focused on VOCs. Biophilic design has also been primarily associated with green walls as it has been shown to have a substantial psychological impact on the inhabitants of urban areas. Although this research report only lays out a strong foundation for a standalone biofilter, it also lays out an opportunity to conduct a large-scale in situ study. One limitation that is clearly shown in this research report is a loop flow in the simulation model. A biofilter is also incomparably effective against a conventional HVAC filer. Where in a biofilter, the SPRE is maxed at 48%, an HVAC filter has a maximum read of 86%. Irga, P.J. (2017) Nonetheless, further indoor in situ experiments are needed to provide more data on performance and to use this in more highly accurate simulations; as for the desire to use a biofilter as a standalone filter in a hotel, a smaller boutique hotel could be better suited to provide a more feasible alternative.

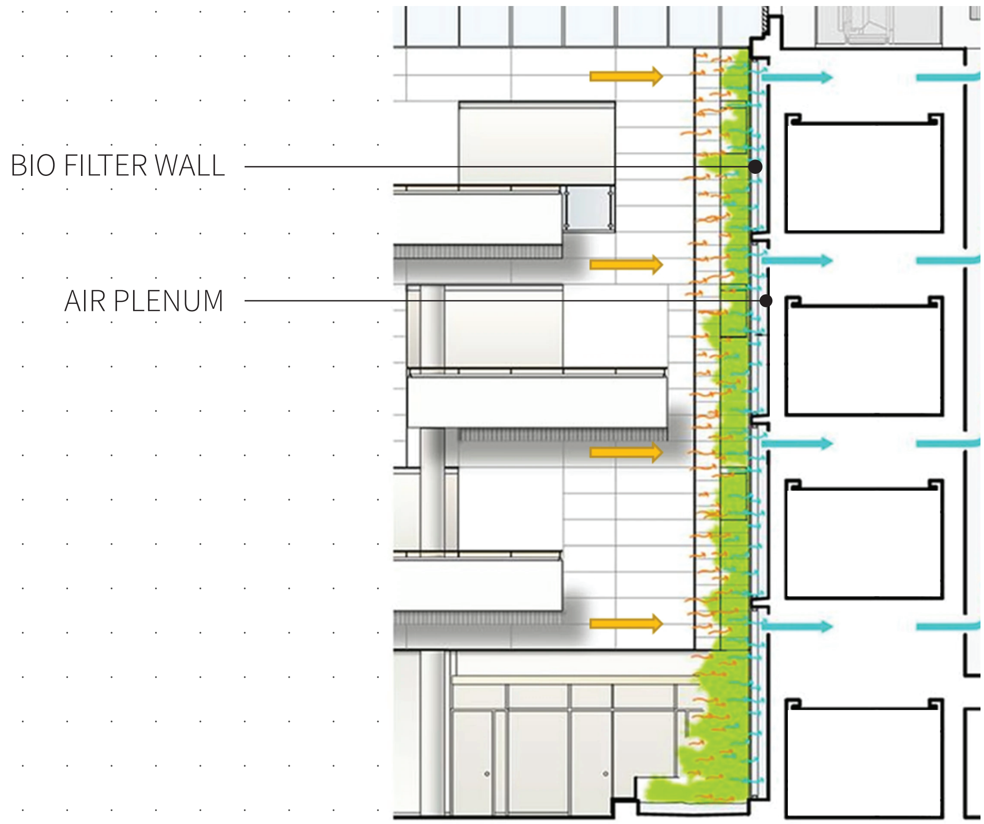


Figure 5. Conceptual drawing of a standalone biofilter. Orange arrows show polluted air through the green wall, while the blue arrows show clean air going out to occupied spaces. Matheson, S. (2023)

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