REVIEW ON THE EFFECTS OF AN ACTIVE LIVING WALL SYSTEM ON THE INDOOR ENVIRONMENT

Saskia Monen
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft
saskiamonen@gmail.com

ABSTRACT

To reduce the energy consumption buildings are designed airtight. This leads to the accumulation of indoor air pollutants, which causes multiple health and discomfort problems. Research has shown that plants can filter these indoor air pollutants out of the air, but an impractical amount of plants is needed to have a significant effect. Living wall systems can provide a space-efficient solution. An 'passive' living wall system however still has no significant effect on the indoor environment, but an active living wall system (ALWS) can be the solution. In a ALWS air is ventilated through the growing media and root zone for maximal air exposure. On top of the air purification effects, the ALWS can also humidify and cool the air. It has an aesthetic value that can have a positive mental effect and can be used for its acoustic benefits. In conclusion: if the ALWS is correctly designed, the ALWS can have a significant positive effect on the indoor living environment.

KEYWORDS: *Active living wall system, Indoor environment, Indoor air pollution, Benefits, Effects*

I. INTRODUCTION

Over the last couple of decades, climate change and energy crises have led to an increased interest in reducing the building energy consumption. During the energy crisis in the 1970's efforts to reduce the building energy consumption resulted into airtight buildings (Persily & Emmerich, 2010). In the last couple of years, climate change has led to a renewed emphasis on reducing building energy consumption to net-zero energy use. Reducing the building energy consumption contributes to the decrease in emission of the greenhouse gasses, which has a large impact on the climate. While building airtight has a positive effect on the outside environment, it has a negative effect on the indoor environment.

Our indoor environment has changed over the last couple of decades, because of new developments in materials and technology. New buildings materials like composite-wood, synthetic carpets and polymeric flooring emit an array of chemicals, but also new appliances such as washers, dryers, TV's and computers emit indoor air pollution. Building airtight has led to the accumulation of these indoor air pollutants. Buildings with a poor ventilation and moisture control have a significant effect on the human health. In some metropolitan areas, indoor air has been found up to 100 times more polluted than outdoor air (Weschler, 2009).

Concerns grew when researchers found a correlation between indoor air pollution, allergies and other chronic illnesses. Poor indoor air quality has been linked to number of health symptoms, like headache, nausea, dizziness, irritation of eyes and breathing problems, also known as the Sick Building Syndrome (EPA, 1991). Research even shows that in Europe 99,000 premature deaths were attributed to household air pollution (WHO, 2014). The negative effects of indoor air pollution are major, also given that people in industrialized nations spend an average of 80-90% of their time indoors (Aydogan & Montoya, 2011).

These negative health effects of the indoor environment have contributed to a renewed interest in green building practices. A couple of decades ago, NASA conducted a research where they found that plants could reduce indoor air pollution and have a positive effect on the indoor environment (Wolverton & Wolverton, 1993). Additional studies also showed that plants could effectively reduce levels of volatile organic compounds (VOCs) (Irga, Torpy & Burchett, 2013), carbon dioxide (CO_2) (Torpy, Zavattaro & Irga, 2017) and particulate matter (PM) (Gawronska and Bakera 2015).

Besides the ability to reduce indoor air pollution, research has shown that plants increase indoor humidity by releasing moisture into the air (Pérez-Urrestarazu, Fernández-Cañero, Franco & Egea, 2016). Other studies show that indoor plants are also beneficial for acoustic reasons (Akzorra et al., 2015; Davis et al., 2017). Finally, there are multiple researchers that conclude that plants could increase the well-being and even human health (Dijkstra, Pieterse & Pruyn, 2015).

This research will obtain knowledge on how much significant effect plants have on the indoor environment and how many indoor plants would be needed for this significant effect. Most research conclude that an impractical number of potted plants would be needed (Llewellyn & Dixon, 2011). A space-efficient method to deal with this problem is to use a living wall system (LWS). The objective of this research is to investigate the effects and the significance of these effects of a LWS on the indoor environment.

II. METHOD

2.1. Literature Review

The first part of the research contains a review of literature. This review focusses on the benefits of a LWS on the indoor environment. For this part of the research only scientific papers, found through online databases, like GoogleScholar, ScienceDirect and Scopus were selected. The more general papers showed the different benefits, like air purification by plants (phytoremediation), better relative humanity, acoustic values, but also the improvement of well-being and health. For each benefit of the living wall system scientific research has been selected to give more focus. To limit the selection, only recent scientific papers, not older than 2000, where used. The research papers are critically compared with each other to find if the benefits significantly influencing the indoor living environment.

2.2. Toolkit for Designers

In the second part of this research the results of the first part will be used to make a toolkit for designers. This toolkit is meant to give designers support when designing a building with an indoor LWS. It provides guidelines for designing a LWS and can be used to calculate the square meter living wall (LW) needed to have a significant positive effect on the indoor environment. Additional, two different activated living wall systems that are currently available on the market are shown.

III. RESULTS

3.1. Literature Review

3.1.1. Air Purification Effects

Extensive research has shown the positive air purification effects of plants on indoor air. The biological activities of plants combined with the substrate microflora has been shown to be capable of reducing many types of urban pollutants, including volatile organic compounds (VOCs) (Irga et al., 2013), carbon dioxide (CO_2) (Torpy et al., 2017) and particulate matter (Gawrońska & Bakera, 2015). Most research has been done with the use of potted plants, but more recently an interest has gone out to use hydroculture LWSs as an active botanical biofilter.

3.1.1.1. Effects on Volatile Organic Compounds

In the indoor environment the most important contaminates are Volatile Organic Compounds (VOCs). There is a wide range of VOCs identified. Some indoor VOCs are toxic at high levels and some have been proven to be carcinogenic, like benzene and formaldehyde. If we look at the concentration per VOC it is most times lower than the concentration known to cause health problems, but there are over 250 known VOCs (Aydogan & Montoya, 2011). The total concentration of all VOCs is therefore more important.

A couple of decades ago, the National Aeronautics and Space Administration (NASA) investigated the use of plants to reduce the VOC concentrations in outer space. Their research positively demonstrated that potted indoor plants could remove substantial amounts of gaseous VOCs in sealed chambers (Wolverton & Wolverton, 1993). The researchers initially believed that the foliage of the plant was the primary contributor to the VOC reduction, but it was later shown that the main mechanism for VOC reduction was the root-zone of the plants. These researches were however mostly done with unrealistically high concentrations and very small chambers (Llewellyn & Dixon, 2011).

Recent research has studied more realistic indoor concentrations. Research done by Irga et al. (2013) showed that hydroculture has a similar potential to deplete VOCs from chamber air as plants grown in potting mix. Aydoga and Montoya (2011) looked at the removal of formaldehyde by four plant types and three different hydroculture growing medias. They found that activated carbon as a growing media alone could remove 98% of formaldehyde, but this media was found to not properly sustain long-term plant growth. The other two growing medias, expended clay and growstone, had a removal percentage of 62,6% and 62,3%. The different plant species didn't show any significant differences.

For maximal phytoremediation, it is important to maximizing air exposure to the plants root-zone (Wolverton & Wolverton, 1993). Therefore, ventilators are used to create an airflow through the growing media and root-zone. These LWSs are called active living wall systems (ALWS) or active botanical biofilters. Wang and Zhang (2011) research such an ALWS. They found that potted plants alone are not efficient in realistic indoor conditions, but that the ALWS is very promising. Over a test period of 300 days the system had a removal efficiency of 90% for formaldehye and 33% for toluene. Lee, Choi and Chu (2015) also developed an ALWS. They found that the removal efficiency of total VOCs passed through the system were about 71,3 – 75,5%. For benzene and formaldehyde this removal rate was about 40%. Chen et al. (2005) also found that ALWS have a significant removal efficiency. They noted that the ALWS was more effective in removing VOCs than several mechanical systems.

3.1.1.2. Effects on Carbon Dioxide

Most research about ALWS is done in the field of VOCs removal, leaving carbon dioxide (CO_2) removal untested. Every time we exhale CO_2 is emitted. In airtight buildings the CO_2 concentration can go up to 1000 ppmv. CO_2 is not toxic per se, but in high concentrations it can be narcotic. It has therefore been associated with multiple health effect like mucous membrane and respiratory symptoms (Torpy et al., 2017).

There are some studies done to examine the potential of traditional indoor plants for reducing CO_2. Plants can remove CO_2 through the process of photosynthesis. Research done by Irga et al. (2013) showed that indoor plants could remove significant amounts of CO_2 with light intensities commonly found indoors. With an increased light intensity more than 60% of CO_2 can be removed. Pennisi and Van Iersel (2012) also show the potential of plants to remove CO_2, but concluded that an impractical amount of potted plants would be needed to make a worthwhile difference to the indoor environment, as did Llewellyn and Dixon (2011). The solution for this is to use a ALWS, because they are space efficient.

Plant selection for the removal of CO_2 is of great importance. Plant species can have a different capacity to remove CO_2, because of different light intensities requirements and different photosynthetic behavior (Torpy, Irga & Burchett, 2014).

With the removal of CO_2 another aspect has to be taken into account. Other parts of the plant like non-photosynthetic parts and plant-growth substrate microorganisms release CO_2 into the air. Torpy et al. (2014) shows that light levels usually encountered in office buildings are too low for plants to remove any CO_2. Plant CO_2 removal will often be zero or in many cases even release CO_2 because of the growing substrate and plant respiration. Further research by Torpy et al. (2017) concluded that for a highly functional ALWS sufficient light levels (250 μmol m^{-2} s^{-1}) are needed to ensure effective CO_2 removal. Some CO_2 will still be removed at light levels of 50 μmol m^{-2} s^{-1}, but below 15 μmol m^{-2} s^{-1} the ALWS will increase the indoor CO_2 levels.

3.1.1.3. Effects on Particulate Matter

Plants are also known to reduce particulate matter (PM) in the outdoor environment. PM are particles smaller than 10 micrometers. PM in indoor air can come from domestic burners, heaters, fireplaces and of course outdoor sources like exhaust gases. The smaller the particles the more harm they can bring to the human health, because these particles can penetrate deeper into the respiratory system where it is taken up into the blood (Ottelé, 2011). Over 2 million premature deaths around the world are the responsibility of $PM_{2,5}$ alone (Silva et al. 2013). PM causes health problems like damage to the circulatory and respiratory system and it is also the second largest cause of lung cancer (Gawrońska and Bakera, 2015).

In literature there is almost no knowledge about the reduction of PM in indoor environments by plants, phytoremediation. Gawrońska and Bakera (2015) conducted one of the only researches on PM in the indoor environment. Their research concluded that spider plants, which are known to reduce VOCs and CO_2 (Wolverton & Wolverton, 1993), could also reduce levels of PM by accumulating it on the leafs. It was found that smaller particulate matter were more firmly attached to the leaves. This means that the risk to human health is even lower, because the smaller the particles the more harm they can cause.

A later research about the PM uptake by Spider plants studied the efficiency of the PM reduction (Irga, Paull, Abdo & Torpy, 2017a). They found that with an air flow rate of 11, 25 L s^{-1} through a 0.25 m^2 filter the efficiency for total suspend particles was 53.51 ± 15,99%. The system is currently less efficient than a conventional HVAC filter, but shows potential for further development.

3.1.1.4. Effects on Bioparticulate Matter

With the incorporation of ALW systems indoor, questions are raised whether these systems have the potential to emit airborne bioparticulate matter, like fungal spores or bacteria into the indoor environment. Multiple researches see the possibility that with the presence of plants indoor the risk of health hazards due to fungi could be raised. Especially occupants with immune system disorders and allergies could be affected, for example in hospitals or child care centers. This risk could be even higher for ALW systems, because they force air through the vegetation layer (Irga, Abdo, Zavattaro & Topry, 2017b).

For this reason, Darlington, Chan, Malloch, Piger and Dixon (2000) researched the biosafety of the Nedlaw Living wall system. They concluded that there is a moderate increase in bioparticulate matter, but the magnitude is too low to cause any health concerns.

Wang and Zhang (2011) were unable to culture microbial growth successfully from their DBAF, but they concluded that more research was necessary before the problem of bioparticulate matter could be ruled out.

Irga et al. (2017b) did a similar research for an ALWS. The findings indicated that the modules are unlikely to be a major source of fungal bioparticulate matter or legionella bacteria. They do however see a problem when the ALWS maintenance conditions are extremely poorly. Finally, for legionella no components of the Breathing Wall system should reach a temperature of 37 degrees or above to minimize the risk.

3.1.2. Effects on Relative Humidity

Plants could not only have a positive effect on purifying air, but can also for their cooling and humidifying effects. This means that the ALWS can cool, purify and humidify the air (Pérez-Urrestarazu et al., 2016).

Darlington, Dat & Dixon (2001) found that operating their ALWS with cooler water temperatures could benefit the humidity of the surrounding air. If the system was operated at higher temperatures this could lead to a high humidity that could negatively influence the indoor environment and potentially damage the building.

Wang and Zhang (2011) researched a ALWS with 50% active carbon as growing media. They combined the ALWS with the HVAC system of a newly constructed office room (volume: 265 m^3) to test the system with more realistic conditions. The research shows that the return air had a humidity increase from 13.5% to 31.2% (+17.7%) and a temperature decrease of 0.5 degrees. They also conducted a classic chamber test where an average of 11.3% of humidity increase was found. Due to the low humidity of office room, more moisture was generated in comparison to the chamber test. The higher increase in moisture in the test room is seen as a positive effect, because the humidity of the room was too low.

Other research conducted in Spain shows a temperature drop between 0.8 (in the middle of the room) and 4.8 (near the ALWS) at different distances of the ALWS. With this decrease of temperature an increase of relative humanity is shown. Finally, it was found that the system worked better with warm and drier indoor conditions (Pérez-Urrestarazu et al., 2016).

Torpy et al. (2017) found for the Breating Wall system an increase in humidity of ~10% during chamber tests, but further research is required to test the effects on the indoor environment.

3.1.3. Acoustic Effects

LWS could also be used as an acoustic element inside the building. Unfortunately research about the acoustic performance of a LWS is limited. More extensively research is done for vegetation on the ground and recently also in the field of rooftop gardens. Research about ground vegetation mostly concerns the acoustic effects of belts of trees near roads and trains. For example, researchers found that sound levels from passing trains where 8-9 dB lower behind a dense 50 m wide tree belt. Research also found that sound energy was absorbed mainly by the leaves of trees and not their trunks (Wong, Tan, Tan, Chiang & Wong, 2010).

There are however a few studies that do investigate the acoustics of a LWS. Wong et al. (2010) conducted a research to determine the sound absorption coefficient of a LWS in a reverberation chamber. The LWS was constructed with two wooden frames were potted plants could hang in. The reverberation time for the system was researched for the system with 0%, 43%, 71% and 100% greenery coverage. Their research shows that the sound absorption coefficient of the studied LWS has one of the highest values compared with other building materials and furnishes. They also concluded that the sound absorption coefficient increases with a higher greenery coverage. The average sound absorption coefficient found with 100% coverage for this LWS is 0.37. However, the plant used in this research, the Nephrolepis exaltata, has a high leaf area index. So this result reflects the maximum performance of this system and not the medium.

Another research studied the acoustic behavior of a modular LWS. They found a sound absorption coefficient 0.40 for the researched system. The result shows a similar or better acoustic absorption coefficient than other common building materials. Especially interesting was the observed sound absorption coefficient for low frequencies, because these where better than some current sound absorbent materials (Azkorra, Pérez, Coma, Cabeza, Bures, Álvaro, Erkoreka & Urrestarazu, 2015).

Finally, both studies conclude that a LWS could be used very effectively in public places for instance restaurants and hotels, because the frequency of voice is the same frequency where the LWS has the highest sound absorption coefficient.

There are many different LWS. Many factors such as the construction, moisture content of the substrate as well as the various plants species all have an impact on the acoustic performance. These factors need to be analyzed individually to determine their influence on the other factors and overall acoustics performance of the LWS. However, every research shows the great potential to use LWS inside a building. The LWS showed a similar or better acoustic absorption coefficient than other common building materials and is even better at low frequencies than some acoustic materials.

3.1.5. Effects on Well-being and Health

The effects of ALW systems that are discussed up till now are all physical effects, but plants could also have a mental effect on human well-being and health. Sight on the plants is for these effects important. The perception of foliage plants could simply improve human well-being, as is shown by Blaschke, O'Callaghan and Schofield (2017). In this research artificial plants where used to make a living wall in a hospital waiting room. From the responders 71% was positively affected and 81% agreed that the greenery brightens the waiting room. This indicates that the artificial living wall has a positive effect on human well-being. Although, it should be noted 62% preferred real plants.

A different research by Dijkstra et al. (2015) shows that plants also have a stress-reducing effect. The study concluded that indoor plants create a higher perceived attractiveness of the hospital room. This higher attractiveness leads to a reduced feeling of stress in patients. This indicates that simply making the environment more attractive could have a positive effect on the health and well-being of the patient. An attractive color of paint could then also be enough. While, all people vary in their preference of color, people generally prefer natural elements.

In a research done by Fjeld (2000) three different work-spaces were studied with and without foliage plants. Health and discomfort symptoms, like fatigue, headaches and mucous membrane symptoms such as dry and hoarse throat, were found to be 21% to 25% lower when plants were present in the working environment. Fjeld concluded that this decrease in health and discomfort symptoms could be due to the improvement of air quality by the plants, an increase in general well-being due to the perception of foliage plants, an appreciable influence from establishing more nature-like indoor light environment ad an effect of increased attention towards the employees. Recent studies show that the quality of air cannot be improved significantly by 'passive' plants. The decrease of symptoms therefore need to be mental effects caused by the plants.

3.2. Toolkit for Designers

3.2.1. Guideline for Designing an Efficient Active Living Wall System

Volatile Organic Compounds Removal

- Air ventilation through the growing media and root zone is required to efficiently let the microbes remove the VOCs (phytoremediation).
- A velocity speed of 0.1 m^3_{air} per $m^2_{biofilter}$ per second is most efficient purifying air, but noise by the fans has to be taken into account.
- With air speeds over 0.15 m^3_{air} per $m^2_{biofilter}$ per second the ALW system will saturate.
- The age of the active LWS does not matter to the efficiency rate.
- Activated carbon has the highest formaldehyde removal rate, but does not properly sustain long-term plant growth. Therefore, expanded clay, growstone or felt layers are better growing medias.

Carbon Dioxide Removal

- Light needs to be 250 μmol m^{-2} s^{-1} for a highly efficient CO_2 removal ALW system.
- For small CO_2 removal light intensity needs to higher than 50 μmol m^{-2} s^{-1}.
- Air ventilation through the growing media is recommended for better CO_2 removal.

Particulate Matter Removal

- Chlorophytum comosum (Spider plants) have a removal efficiency of 53.35 ± 15.99% for PM with an air flow of 11.25 L s^{-1}.
- Air ventilation through the growing media is recommended for better PM removal.

Bioparticulate Matter Removal

- Good maintenance needs to be done to reduce the risk of bioparticulate matter.
- ALW system components should not reach temperatures above 37 degrees to minimize risk of legionella.

Relative Humidity

- The water temperature of the LWS needs to be lower than indoor air temperature.
- The humidity effects of plants work better for dry and warm indoor conditions.

Acoustic Behavior

- The average sound absorption coefficient found is ~0,4.
- Soil-thickness of 8–10 cm is the minimum thickness that results in a good sound absorption.
- For better low-frequency absorption soil thickness of the ALW system can be expanded

Well-Being and Health

- Sight on the ALW system is important.

Seize of Active Living Wall System

- One square meter of ALW can accommodate a space of 100 m^2 space (Brochure Nedlaw Living Walls).
- One square meter of ALW is needed to reduce VOC values to outside levels for 5 people (Brochure Nedlaw Living Walls).
- Sixty square meters of ALW with spider plant is needed to produce 'fresh air' from which the CO_2 has been removed (Torpy et al., 2017).
- To remove the respiratory CO_2 from one occupant, 6.25 m^2 of ALW with spider plant is needed (Torpy et al., 2017).

Plant Selection

Table 1: Removal rate for VOC, CO_2 and PM per plant species.

Plants	VOC removal rate	CO_2 removal	PM removal
Spider plant	10.4% - Formaldehyde	5.49 g/h Air flow: 3.5 m/s	53.35 ± 15.99% Air flow: 11.25 $L\ s^{-1}$
Golden Pothos	73.2% - Benzene 9.2% - Trichloroethylene	1.36 g/h Air flow: 3.5 m/s	
Englisch Ivy	89.8% - Benzene 10.9% - Trichloroethylene		
Janet Craig	77.6% - Benzene 17.5% - Trichloroethylene		
Peace lily	79.5% - Benzene 23.0% - Trichloroethylene		
Marginata	79.0% - Benzene 13.2% - Trichloroethylene		
Mother-in-law's tongue	52.6% - Benzene 13.4% - Trichloroethylene		
Warneckei	70.0% - Benzene 20.2% - Trichloroethylene		

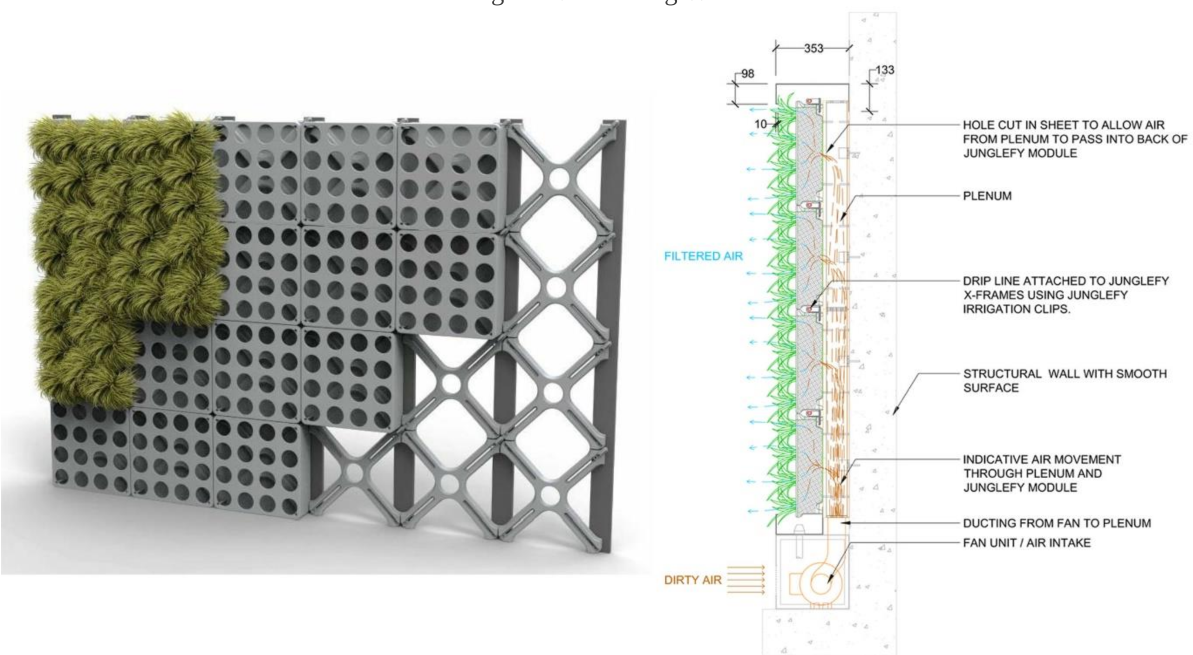
VOC removal rate (Wolverton & Wolverton, 1993), CO_2 removal (Torpy et al. 2017) and PM removal (Irga et al., 2017a)

3.2.2. Two Examples of Active Living Wall Systems Currently Available.

Two ALWSs, the Nedlaw Living Wall system and the Breathing Wall, are currently on the market.

The first ALWS is the Breathing Wall (Figure 2). This system is made out of modular elements filled with potted plants. The system focuses on the reduction of CO_2.

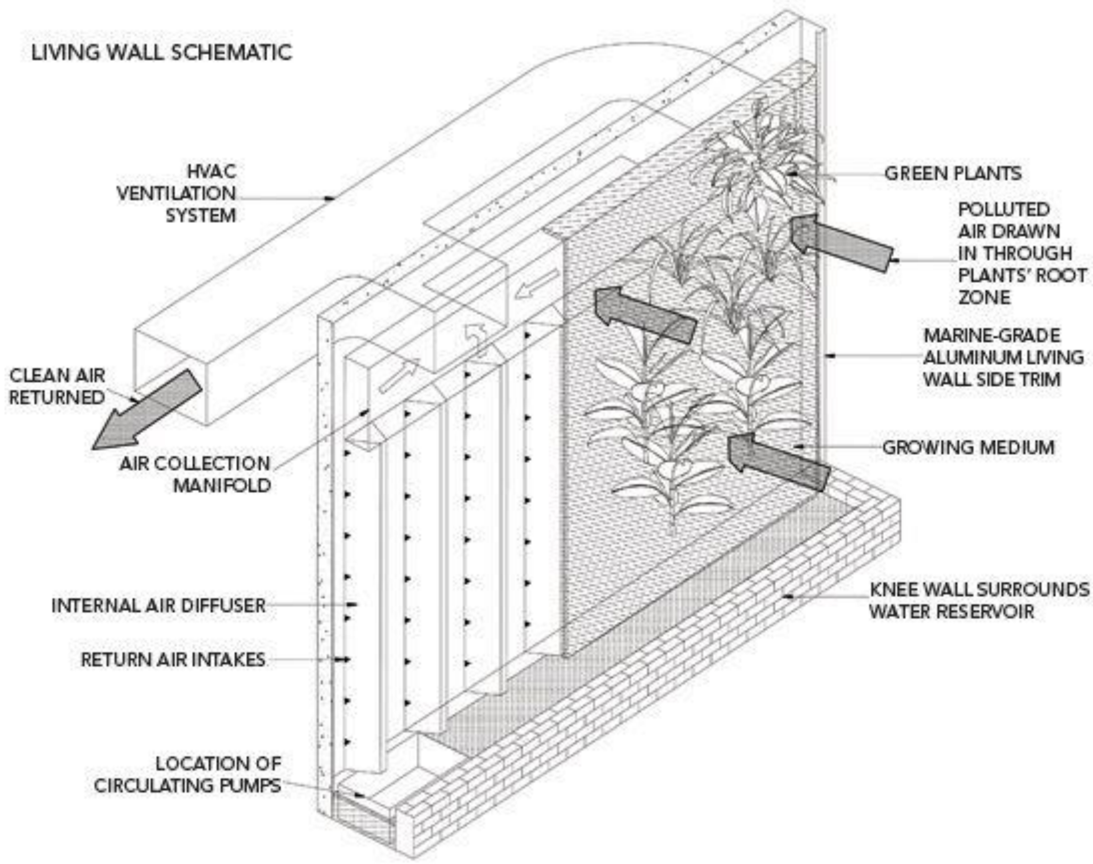
Figure 1: Breathing Wall



The second ALWS is the Nedlaw Living Wall system (Figure 1). This system is developed with aim to reduce the VOCs out of the indoor environment. The Nedlaw Living Wall is constructed with plants that are hydroponically grown inside felt layers. Air is ventilated through the wall so the

VOCs can come in contact with the root zone. The root zone of these plants provides microbes that actively remove the VOCs, this is called phytoremediation.

Figure 2: Schematic Nedlaw Living Wall system



These two ALW systems have a different focus. The Nedlaw Living Wall system focusses on VOC removal, while the Breathing Wall focusses on the decrease of CO_2. A combination of these two systems could provide an even better effect on the indoor environment. The Nedlaw Living Wall system does not need large m^2 of wall to have a significant effect, while the Breathing Wall system needs a large wall to have a significant effect on the CO_2 removal.

IV. CONCLUSION & DISCUSSION

The literature review has showed the great potential of the ALWS. A ‘passive’ LWS has no effect on the indoor environment. This is because too little air is coming in contact with the root zone of the plants, where the phytoremediation is taking place. Air needs to be ventilated through the LWS to increase the efficiency of the phytoremediation process. This way the ALWS can provide significant amounts of ‘fresh air’ for occupants that is purified, humidified and cooled within one system. The active ALWS’ ability to remove VOCs, CO_2 and PM, humidify and cool the air, makes the device superior to most non-biological systems used as general air quality maintenance devices. On top of the physical effects, the aesthetic value can also have a positive mental effect. In conclusion, a correctly designed ALWS can have a significant improvement on the indoor environment and the overall human health and well-being.

REFERENCES

1. Aydogan, A., Montoya, L.D. (2011). *Formaldehyde removal by common indoor plant species and various growing media.* Atmospheric Environment(45). 2675-2682
2. Azkorra, Z., Pérez, G., Coma, J., Cabeza, L.F., Bures, S., Álvaro, J.E., Erkoreka, A., & Urrestarazu, M. (2015). *Evaluation of green walls as a passive acoustic insulation system for buildings.* Applied Acoustics(89). 46-56
3. Blaschke, S., O'Callaghan, C.C., Schofield, P. (2017). *"Artificial But Better Than Nothing": The Greening of an Oncology Clinic Waiting Room.* Health Environments Research & Design Journal(10). 51-60
4. Darlington, A.B., Chan, M., Malloch, D., Piger, C., & Dixon, M.A. (2000). *The biofiltration of indoor air: implications of air quality.* Indoor Air(10). 39-46
5. Darlington, A.B., Dat, J.F., & Dixon, M.A. (2001). *The Biofiltration of Indoor Air: Air Removal of Toluene, Ethylbenzene, and Xylene.* Environmental Science Technology(35). 240-246
6. Darlington, A.B. *Sizing of Nedlaw Indoor Air Biofilters.* (Brochure). Retrieved from: www.nedlawlivingwalls.com
7. Dijkstra, K., Pieterse, M.E., & Pruyn, A. (2008). *Stress-reducing effects of indoor plants in the built healthcare environment: The mediating role of perceived attractiveness.* Preventive Medicine(47). 279-283
8. EPA. (1991). *Indoor Air Facts No. 4 – Sick Building Syndrome.* Air and Radiation(6609J).
9. Fjeld, T. (2000). *The Effect of Interior Planting on Health and Discomfort among Workers and School Children.* Horttechnology(10). 46-52
10. Gawrońska, H., & Bakera, B. (2015). *Phytoremediation of particulate matter from indoor air by Chlorophytum comosum L. plants.* Air Qual Atmos Health(8). 265-272
11. Irga, P.J., Torpy, F.R., & Burchett, M.D. (2013). *Can hydroculture be used to enhance the performance of indoor plants for the removal of air pollutants?* Atmospheric Environment(77). 267-271
12. Irga, P.J., Paull, N.J., Abdo, P., & Topry, F.R. (2017a). *An assessment of the atmospheric particle removal efficiency of an inroom botanical biofilter system.* Building and Environment(115). 281-290
13. Irga, P.J., Abdo, P., Zavattaro, M., & Topry, F.R. (2017b). *An assessment of the potential fungal bioaerosol production fron an active living wall.* Building and Environment(111). 140-146
14. Lee, H.L., Choi, B., & Chu, M.Y. (2015). *Stabilizing soil moisture and indoor air quality purification in a wall-type botanical biofiltration system controlled by humidifying cycle.* Korean Journal of Horticultural Science and Technology(33). 1951-1956
15. Llewellyn, D., & Dixon, M.A. (2011). *Can Plants Really Improve Indoor Air Quality?* Guelph: University of Guelph
16. Ottelé, M. (2011). *The Green Building Envelope – Vertical Greening.* Thesis. 25
17. Pennisi, S.V., & Van Iersel, M.W. (2012). *Quantification of carbon assimilation of plants in simulated and in situ interiorscapes.* Hortscience(47). 468-476
18. Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco, A., & Egea, G. (2016). *Influence of an active living wall on indoor temperature and humidity conditions.* Ecological Engineering(90). 120 – 124.
19. Persily, A.K., & Emmerich, S.J. (2010). *Indoor Air Quality in Sustainable, Energy Efficient Buildings.* Syracuse, NY
20. Silva, R., West, J.J., Zhang, Y., Anenberg, S.C., Lamarque, J., Shindell, D.T., Collins, W.J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L.W., Nagashima, T., Naik, V., Rumbold, S., Skeie, R., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R.M., Eyring, V., Josse, B., Plummer, M.D., Righi, M., Stevenson, D.S., Strode, S., Szopa, S., &Zeng, G. (2013). *Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change.* Environ Res Lett(8). 2

21. Torpy, F.R., Irga, P.J., & Burchett, M.D. (2014). *Profiling indoor plants for the amelioration of high CO_2 concentrations.* Urban Forestry and Urban Greening(13). 227-233

22. Topry, F.R., Zavattaro, M., & Irga, P.J. (2017). *Green wall technology for the phytoremediation of indoor air: a system for the reduction of high CO_2 concentrations.* Air Qual Atmos Health(10). 575-585

23. Wang, Z., & Zhang, J.S. (2011). *Characterization and performance evaluation of a full-scale activated carbon-based dynamic botanical air filtration system for improving indoor air quality.* Building and Environment(46). 758-768

24. Weschler, C.J. (2009). C*hanges in indoor pollutants since the 1950s.* Atmospheric Environment(43). 153-169

25. WHO. (2014). *Burden of disease from Household Air Pollution from 2012.* Switzerland

26. Wolverton, B.C., & Wolverton, D.J. (1993). *Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment.* Journal of Mississippi Academy of Sciences(32). 11-15

27. Wong, N.H., Tan, A.Y.K., Tan, P.Y., Chiang, K., & Wong, N.C. (2010). *Acoustic evaluation of vertical greenery systems for building walls.* Building and Environment(45). 411-420