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Article

School sustainability: The implications of implementing living walls at schools for air purification

Jacklin Xie[1], Elisa Margarita[2]
[1] Brooklyn Technical High School, Brooklyn, New York
[2] Biology, Brooklyn Technical High School, Brooklyn, New York

SUMMARY

The average public school in the United States contains thousands of students, teachers, and staff. In a small, enclosed space with little ventilation, this can cause the circulation of unwanted pathogens, hazardous gases, and more. Previous studies have shown the benefits of plants in improving air quality under controlled laboratory conditions; however, these benefits have yet to be tested in real-world settings. In this study, we assessed the efficacy of integrating living walls in a school environment to enhance indoor air quality. We hypothesized that the presence of plants from the living wall would reduce the concentrations of air pollutants in the surrounding area. To test this hypothesis, we measured the concentrations of common air pollutants over a few months, utilizing the living wall at Brooklyn Technical High School and an air quality monitor. We analyzed the collected data using the Analysis of Variance (ANOVA) hypothesis test to determine whether air quality was improving. Our results showed that there was no statistically significant difference in particulate matter (PM2.5, PM10) concentrations with and without the living wall; however, formaldehyde (HCHO) and total volatile organic compound (TVOC) concentrations revealed statistical significance in both cases. Additionally, we observed lower standard deviations and maximums of air pollutant concentrations in the presence of plants, suggesting that living walls may play a role in regulating air pollutant fluctuations. Our study showed that the living wall can play an integral part in increasing the predictability and consistency of indoor air pollutants.

INTRODUCTION

Growing concerns regarding school air quality and a lack of transparency in schools' air quality reports are beginning to cast doubt on schools' abilities to provide adequate ventilation for their students' health and safety (1). In 2020, the United States Government Accountability Office stated that approximately 41% of school districts, around 36,000 schools nationwide, required updates or replacements for heating, ventilation, and air conditioning (HVAC) systems (2). Old school infrastructure often leads to poorly functioning air conditioning systems and, consequently, inadequate ventilation. The issue is worsened by significant foot traffic in small, enclosed spaces, inevitably contributing to poor indoor air quality. According to the United States Environmental Protection Agency (EPA), indoor air pollutants may be two to five times greater than outdoor air, sometimes even hitting 100 times greater, raising significant concern (3). Given the recent COVID-19 pandemic, there is a growing apprehension among parents regarding their children being exposed to unclean or contaminated air (4). This concern is particularly heightened due to the extended periods that children spend in classrooms where the availability of open windows is limited.

To address such concerns, New York City Schools have spent approximately $90 million on Intellipure Compact Air Purifiers in an effort to promote better air filtration (5). Despite these promising claims, there has been rising controversy surrounding the efficacy of these filtration systems as they do not use high-efficiency particulate air (HEPA) filters as recommended by the Centers for Disease Control and Prevention, but rather their own patented Disinfecting Filtration System technology (5). Analytical studies in response to these concerns conducted by the Built Environment Research Group at the Illinois Institute of Technology reveal that the Intellipure Compact Air Purifier was, in fact, among the least efficient in terms of its clean air delivery rate (CADR) compared to the dozen other air purifiers the team had tested (6, 7). On top of that, these Intellipure Compact Air Purifiers start at $549 per unit, and each replacement filter costs $220 (8).

Fortunately, some studies have shown that plants could be a cheaper alternative to air purification systems through a process known as phytoremediation. Phytoremediation is the use of plants to clean up contaminated environments (9). While mechanical filtration effectively eliminates larger debris particles, it lacks the ability to eliminate smaller chemical particles. Alongside carbon dioxide and oxygen, plants are also capable of absorbing a variety of other air pollutants such as particulate matter (PM2.5 & PM10), formaldehyde, and total volatile organic compounds (TVOC) (10). This proves to be significant because these air pollutants are associated with an adverse list of health problems.

As stated in an EPA reference guide of typical indoor air pollutants, common sources include pollen, soil, and some types of burning, such as tobacco smoke, cooking, diesel engines, etc. (11). While PM10 causes more minor health concerns, finer particulate matter (PM2.5) can cause lung disease, asthma, and a variety of other respiratory ailments (11). Furthermore, children tend to breathe in 50% more air per pound of body weight than adults making them particularly susceptible to these air pollutants (11). Therefore, long-term exposure to these particles can aggravate existing respiratory conditions, such as asthma and bronchitis, and lead to increased hospital admissions and emergency room visits (3, 12). Furthermore, long-term exposure to volatile organic compounds (VOC), such as formaldehyde, a human carcinogen,

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can not only damage our kidneys, liver, and nervous system, but also increase the risk of nasal and lung cancer (13). Thus, the implementation of an effective air filtration system is critical.

In one of the earlier studies conducted by National Aeronautics and Space Administration in 1989, Wolverton *et al.* demonstrated the role of plants in the removal of organic chemicals from indoor air, both through direct absorption through the stomata of its leaves and indirectly through the root/soil pathway (14). A subsequent study confirmed these findings, demonstrating the potential of potted plants to improve PM2.5 removal (15). Plants with a high leaf area index (LAI) increased PM2.5 removal rates to 71.46%, while the control group without plants only had a PM2.5 removal rate of 42.0% from gravitational sedimentation (15). Another study showed that plants removed ~80% of the formaldehyde in the air within four hours, compared to the approximate 7% removal without the presence of plants (16). These studies all indicated a positive correlation between the presence of plants and improved air quality (14-16). However, they shared a commonality: they were conducted in controlled laboratory settings which ensured that results reflected an ideal environment. Implementing phytoremediation in school settings presents challenges due to the numerous uncontrollable variables that may occur, including passersby and the natural airflow of an opened window, all of which can impact the plants' capacities to produce the desired results. As a result, more research will be needed to determine the true costs and benefits of implementing living walls in a real-world environment.

We aimed to determine whether integrating living walls, vertical gardens typically used as a form of decor, into public indoor spaces like schools can help to improve indoor air quality as a cheaper and more sustainable alternative to traditional air purifiers. We hypothesized that the presence of the living wall would result in lower concentrations of the indoor air pollutants tested due to the plants' air purifying abilities. This experiment was conducted at the living wall in the third-floor hallway of Brooklyn Technical High School in New York

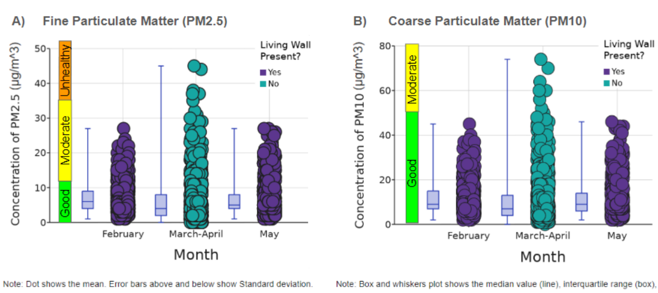

Figure 1: Effect of a living wall on PM2.5 and PM10 concentrations. Comparison of the levels of A) PM2.5 and B) PM10 in µg/m3 across three time periods: February, March-April, and May. Living wall was present in February and May, but not March-April. Each data point corresponds to a measurement taken at a 30-minute interval throughout a 24-hour day on a weekday within its respective month-long time period. The colored bar on the left displays the level of health concern as determined by the air quality monitor. Box and whiskers plot shows the median value (line), interquartile range (box), and the extent of the data (whiskers above and below at min/max data points). A one-way ANOVA was conducted to look for significant differences across the three time periods for PM2.5 (p = 0.50) and PM10 (p =0.31).

A) **Fine Particulate matter (PM2.5) in µg/m³**

Group	Mean	Std.dev.	SEM	Median	Min	Max	Range
February	6.740	3.820	0.123	6	1	27	26
March-April	6.460	6.330	0.210	4	0	45	45
May	6.600	4.670	0.164	5	1	27	26

B) **Coarse Particulate Matter (PM10) in µg/m³**

Group	Mean	Std.dev.	SEM	Median	Min	Max	Range
February	11.500	6.310	0.204	9	2	45	43
March-April	10.900	10.300	0.342	7	0	74	74
May	11.300	7.730	0.271	9	2	46	44

Table 1: Comparative Analysis of PM2.5 and PM10 Concentrations. Descriptive statistics for analyzing A) PM2.5 and B) PM10 concentration readings across three distinctive time periods in the presence and absence of the living wall. Std. dev. - Standard deviation; SEM - Standard error of the mean.

City. As a control, air quality measurements were also conducted without the presence of the living wall. The obtained results partially aligned with the hypothesis, revealing a few noteworthy observations. Rather than drastically reducing indoor air pollutant concentrations, the presence of the living wall may have functioned more as a regulator of air quality, helping to maintain air pollutants below the threshold of being unhealthy or dangerous.

RESULTS

To examine the real-world benefits of integrating plants into a school environment, an air quality monitor was set up in front of the living wall to periodically record the particulate matter (PM2.5 and PM10), formaldehyde, and TVOC concentrations in 30-minute intervals. We collected data both when the living wall contained plants and when it did not, allowing for a comparative analysis of the groups. While this meant that the experiment would be conducted in an uncontrolled space with a lot of noise that could have influenced our results with extraneous variables, we still expected that the school air quality would improve with the presence of the living wall as seen across the trends of numerous studies conducted under more controlled settings (14-16).

We observed a visual trend toward a lower concentration of particulate matter as well as formaldehyde and TVOC in the presence of the living wall compared to the absence of the living wall; however, we later determined that these differences were not statistically significant **(Figure 1-2)**. We speculate that this was due to the large variation among our data points because our experiment was conducted in an uncontrolled space, the school. While it appeared that some of the data points reached the higher concentrations for each pollutant in the absence of the living wall, the majority of the data clusters were still located towards each pollutant's lower concentrations **(Figure 1-2)**. Hence, the descriptive statistics provided further insight into the air quality data: there generally seemed to be slightly higher average concentration of air pollutants across the board in the presence of a living wall compared to the absence of it **(Figure 1-2)**.

The increase in average air pollutant concentration was particularly true in the case of particulate matter. The absence of the living wall correlated with a lower average PM2.5 of 6.460 µg/m³ compared to the 6.740 µg/m³ and 6.600 µg/m³

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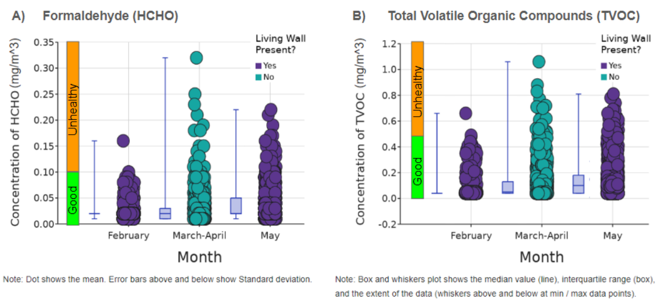

Figure 2: Effect of living wall on formaldehyde and TVOC concentrations. Comparison of the levels of A) formaldehyde and B) TVOC in mg/m3 across three time periods: February, March-April, and May. Living wall was present in February and May, but not March-April. Each data point corresponds to a measurement taken at a 30-minute interval throughout a 24-hour day on a weekday within its respective month-long time period. The colored bar on the left displays the level of health concern as determined by the air quality monitor. Box and whiskers plot shows the median value (line), interquartile range (box), and the extent of the data (whiskers above and below at min/max data points). A one-way ANOVA was conducted to look for significant differences across the three time periods for formaldehyde ($p < 0.01$) and TVOC ($p < 0.01$).

in February and May, respectively, when the living wall was present **(Table 1)**. This trend was observed for PM10 concentrations as well with 10.900 μg/m^3 in the absence of the wall as opposed to 11.500 μg/m^3 and 11.300 μg/m^3 in February and May, respectively, when the living wall was present **(Table 1)**. This contradicts the results of prior studies conducted under controlled environments (14-16). To further investigate this unexpected trend, we conducted an Analysis of Variance (ANOVA) test to assess the relationship between the presence of the living wall and the concentration of particulate matter. By weighing the difference between the means of the three groups, we were able to determine whether the difference was likely to be a result of random chance. The ANOVA test results indicated *p*-values of 0.50 and 0.31 for PM2.5 and PM10, respectively. These values suggest the differences in the concentration of particulate matter across the three-month periods (February and March-April, May and March-April, February and May), were not statistically significant, as confirmed by post-hoc tests **(Figure 1)**.

In comparison, data points of formaldehyde and TVOC have different distributions. The concentrations of formaldehyde and TVOC are the lowest in the presence of the living wall in February (0.0213 mg/m^3 and 0.055 mg/m^3, respectively), followed by the concentrations in the absence of the living wall in March-April (0.0292 mg/m^3 and 0.115 mg/m^3, respectively), while they are the highest in the presence of the living wall in May (0.0363 mg/m^3 and 0.148 mg/m^3, respectively) **(Figure 2)**. The standard deviations are also the lowest in February for formaldehyde and TVOC (0.0117 mg/m^3 and 0.060 mg/m^3, respectively), intermediate in March-April (0.0284 mg/m^3 and 0.123 mg/m^3, respectively), and the highest in May (0.0297 mg/m^3 and 0.140 mg/m^3, respectively) **(Table 2)**. Once again, an ANOVA test was conducted to determine whether there was a relationship between the two groups. The obtained *p*-value of <0.01 for both formaldehyde and TVOC indicated that the groups, February with March-April and May with March-April, were indeed different and statistically significant. The post-hoc test demonstrated statistical significance across all three-month periods, namely between February and March-April, May and March-April, and February and May. This outcome introduces uncertainty in our ANOVA results, highlighting the need for additional research to ascertain the precise extent of the living wall's influence on formaldehyde and TVOC.

We also noticed that, in the presence of plants, the particulate matter concentration data had a smaller spread, as indicated by a lower standard deviation and a lower maximum. In February and May (living wall was present) the standard deviation for PM2.5 was 3.820 μg/m^3 and 4.670 μg/m^3 compared to 6.330 μg/m^3 in March-April (living wall was not present) and the lowest maximums were in February and May at 27 μg/m^3 compared to the 45 μg/m^3 in March-April **(Table 1)**. For PM10, the standard deviation was 6.310 μg/m^3 and 7.730 μg/m^3 for February and May compared to 10.300 μg/m^3 in March-April and the lowest maximum was in February at 45 μg/m^3 with May close behind at 46 μg/m^3 compared to the 74 μg/m^3 in March-April **(Table 1)**. Similarly, the formaldehyde and TVOC concentration data also displayed lower maximum concentrations in the presence of the living wall. The maximum concentration of formaldehyde was 0.16 mg/m^3 in February and 0.22 mg/m^3 in May compared to the 0.32 mg/m^3 in March-April **(Table 2)**. The maximum concentration of TVOC was 0.66 mg/m^3 in February and 0.81 mg/m^3 in May compared to the 1.06 mg/m^3 in March-April **(Table 2)**. The data suggest a potential stabilizing effect of the living wall on air quality metrics. Further research with a larger sample size and more controlled variables may be necessary to determine the impact of living walls on indoor air quality conclusively.

DISCUSSION

At first glance, our results appeared to match the conclusions of these previous studies, indicating that plants may improve indoor air quality; however, the descriptive statistics did not support the claim that the presence of plants was associated with reduced concentrations of air pollutants. The computed statistics seemed to indicate that there was a more complex set of underlying variables that was impacting our results due to the real-world environment as opposed to controlled laboratory environments. Thus, the difference in concentrations with and without the presence of the living wall

A) **Formaldehyde (HCHO) in mg/m^3**

Group	Mean	Std.dev.	SEM	Median	Min	Max	Range
February	0.0213	0.0117	0.0004	0.02	0.01	0.16	0.15
March-April	0.0292	0.0284	0.0009	0.02	0.01	0.32	0.31
May	0.0363	0.0297	0.0010	0.02	0.01	0.22	0.21

B) **Total Volatile Organic Compounds (TVOC) in mg/m^3**

Group	Mean	Std.dev.	SEM	Median	Min	Max	Range
February	0.055	0.060	0.002	0.04	0.04	0.66	0.62
March-April	0.115	0.123	0.004	0.05	0.04	1.06	1.02
May	0.148	0.140	0.005	0.10	0.04	0.81	0.77

Table 2: Comparative Analysis of Formaldehyde and TVOC Concentrations. Descriptive statistics for analyzing A) formaldehyde and B) TVOC concentration readings across three distinctive time periods in the presence and absence of the living wall. Std. dev. - Standard deviation; SEM - Standard error of the mean.

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may be due to random chance. While the data did not show that the living wall decreased the overall levels of pollutants in the air, they did show that the presence of the wall could help with pollutant concentration fluctuation.

The presence of the living wall did not seem to have much effect on reducing the average concentration of particulate matter for both PM2.5 and PM10; rather, the average concentrations were slightly greater, contradicting the many previously conducted studies that had concluded that plants help to remove particulate matter in the surrounding air **(Table 1)**. We suspect this is because these previous studies were typically conducted in small, enclosed environments, whereas our experiment was done under real-world conditions. This means that passersby and air flow could have stirred up dust and dirt particles from the soil which could have impacted the particulate concentration readings. It is also reasonable to deduct that the presence of the living wall may have encouraged more foot-traffic in the area.

Although the average particulate concentration was slightly higher in the presence of the living wall, it still generally remained well within the healthy concentration range of 0.0-12.0 μg/m^3 for PM2.5 and 0-54 μg/m^3 for PM10 **(Figure 1)** (17). Additionally, most, if not all, of the PM10 readings remained in the healthy zone and most of the PM2.5 remained within the healthy and moderate zones in the presence of the wall, whereas without the wall, some readings skyrocketed towards unhealthy levels resulting in unpredictable fluctuations of air quality levels **(Figure 1)**. Although there are possibly data anomalies within our datasets, we included all the data points into the statistical analysis to prevent the potential distortion of the data. Such inclusion aims to maintain the integrity of the dataset, acknowledging the possibility of certain days exhibiting poorer air quality than others. A recent study investigating how indoor air quality affects strategic decision-making based on data collected from official chess tournaments concluded that a 10 μg/m^3 increase in the indoor concentration of fine particulate matter (PM2.5) was correlated with a 26.3% increase in a player's probability of making a wrong move (18). Sudden fluctuations and unpredictable air quality can impair our ability to function properly, and this is particularly alarming in learning environments such as schools. Thus, having the presence of plants to help regulate indoor air pollutant concentrations can be much more reassuring for students, staff, and parents/guardians.

Mixed results were also found in formaldehyde and TVOC concentrations. In the month of February when the living wall was present, average formaldehyde and TVOC concentrations were lower than when the wall was not present from mid-March to mid-April **(Figure 2)**. This supported our hypothesis that the presence of plants helped to reduce air pollutants; however, in the month of May when the wall was present, the opposite was true. The average formaldehyde and TVOC concentrations were higher than when the wall was not present **(Table 2).** Again, there are many variables that could have led to such results. Further research revealed that varying temperatures may be the underlying cause for such inconclusive results. For instance, an increase in temperature promotes the release rate of VOCs such as formaldehyde and TVOC (19). This explains why the average concentration of formaldehyde and TVOC may be higher in a summer month like May than in a winter month like February despite the living wall being present in both periods. Regardless, the concentrations of formaldehyde and TVOC consistently remained within the healthy range of 0-0.1 mg/m^3 and 0-0.5 mg/m^3, respectively, for the majority of the observation period (17).

While there is not any definite evidence proving that the presence of the living wall improves air quality drastically, one thing that remains consistent throughout all the collected data is that the presence of the living wall is associated with a lower maximum concentration of air pollutants. In combination with observed lower or similar standard deviations, we have greater support for the notion that the presence of plants increases the predictability and consistency of air pollutant levels. Although this observation may be a result of random chance, the pattern was sustained across two different months (February and May), hence indicating reproducibility and providing greater plausibility to our conclusion. Therefore, while this real-world study may not illustrate a direct correlation between plants and improved air quality, it does provide some evidence that the presence of plants may provide long-term benefits in maintaining indoor air quality levels to minimize the effects of fluctuations in air pollutants on an individual's physical and mental health.

From reducing urban heat island effects to increasing biodiversity in the local ecosystem, living walls can do so much for our environment and wellbeing (20). While a few living walls in a school may not have much effect outside of their local environment, we can change this if people become more aware of the value of living walls and begin implementing them throughout various public spaces, including office buildings, libraries, local shops, or even cafes. Further research directly comparing the effectiveness of an air purifier versus the air purifying abilities of a living wall in real-time could better demonstrate the pros and cons of choosing one air purifying method over the other. Given additional time and resources, it would also be helpful to conduct a comprehensive analysis of air quality in the more distant vicinity surrounding the living wall. Extending the study duration to a full year would offer a better understanding of air quality trends over time both in the presence and absence of the living wall. The identification of consistency is imperative for establishing confidence in our research outcomes. This comparative assessment would help determine the extent of its influence in contrast to conventional air purifiers, and it could also be extended to different locations, encompassing various schools and public indoor spaces. From getting a better understanding of how plants absorb air pollutants to determining the best combination of plants for targeting a specific air pollutant, there are many more questions that remain unanswered; however, this study brings us one step closer to a future of better air quality.

MATERIALS AND METHODS

This study was conducted in a high school in downtown Brooklyn, New York. Situated in one of the most frequented neighborhoods of Brooklyn and surrounded by various commercial and residential areas, meeting the conditions of an established metropolitan public school appropriate for our research. With almost 6,000 students in the building, this experiment took place at the newly installed living wall located in the center of the third-floor hallway, right between the most populated floors and directly outside the school's environmental lab.

The living wall was installed with a variety of plants namely: the Rare Black Cardinal Philodendron (*Philodendron erubes-*

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cens 'Black Cardinal'), the Prince of Orange Moonlight Philodendron (*Philodendron erubescens* 'Prince of Orange'), the Moonlight Philodendron (*Philodendron hederaceum* 'Moonlight'), the Golden Devil's Ivy Pothos (*Epipremnum aureum*), the Heart Leaf Philodendron (*Philodendron scandens*), and more. These plants were chosen based on their durability and simple maintenance. The various philodendrons require minimal lighting and infrequent waterings and feedings. Their large leaf surface area also allows them to maximize their air purifying abilities making them some of the best plants for the wall. The installation comprises a 22'4" x 4' x 9" living wall designed in a four-plant system utilizing 77 plant socks, each accommodating four plants, resulting in a total of 308 plants encompassing eight different species. Maintenance involves watering every 10 days, and the plants are exposed to LED growing lights with a full spectrum and a voltage of 120 volts.

To measure the concentration of air pollutants in the surrounding air, the Temtop LKC-1000S+ 2nd Generation Air Quality Monitor was chosen as the optimal measuring tool due to its focus on some of the most common indoor air pollutants: particulate matter (PM2.5 & PM10), formaldehyde, and TVOC. It was set up within close proximity to the living wall and approximately two meters from the ground to limit human interference as much as possible. From there, the air monitor was left to run such that the concentration of air pollutants was collected in half-hour intervals in a full 24-hour period through the monitor's data collection function. Readings were taken on every weekday of the month. The collected data was then uploaded to a spreadsheet and the process was repeated for the next three months.

In order to assess the true benefits of a living wall in improving indoor air quality, it was necessary to include a control sample of air quality data from when the living wall was not installed. Midway through March and into April, the plants in the living wall had to be taken out for a maintenance check, which gave us the opportunity to do so. This enabled us to collect air quality data in the same location whilst the living wall was empty of plants. The air monitoring system continued to run as it previously had, constantly monitoring the air quality levels for approximately a month before plants were eventually reinstalled into the wall. Afterwards, the air monitor continued collecting data for another month before the data collection was finally complete.

Once the data collection process was complete, the collected data for the months of January to May was cleaned up by removing days with missing data, holidays, and weekends which were vulnerable to inaccurate readings due to sanitation work. To evaluate the true impact of installing a living wall on air quality in an indoor school environment, a statistical analysis was conducted through an ANOVA test comparing the months of February with March-April and May with March-April to identify consistent findings that may suggest the correlation between the presence of plants and reduced air pollutant concentrations.

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