A PHOTOCATALYTIC AIR CLEANING SYSTEM BREAKING DOWN VOLATILE ORGANIC COMPOUNDS TO IMPROVE HEALTH AND PRODUCTIVITY OF OCCUPANTS

by

Ketki Prashant Bapat

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Architecture

Charlotte

2022

Approved by:

____
Dr. Kyoung-Hee Kim

____
Dr. Andrew Harver

____
Dr. Brian Magi

ABSTRACT

KETKI PRASHANT BAPAT. A Passive Air Cleaning System Breaking Down Volatile Organic Compounds To Improve Health And Productivity Or Occupants. (Under the direction of Dr. Kyoung-Hee Kim)

Volatile Organic Compounds (VOCs) are one of the pollutants that impact indoor air quality, leading to many adverse health effects such as Asthma, and other breathing issues. Most of the VOCs are harmful and carcinogenic, usually emitted by indoor sources like disinfectants, insecticides, and building materials including wall paint, varnishes, and many more. As human beings spend 90% of their time indoors, it is necessary to maintain good indoor air quality by reducing harmful VOCs. Photocatalysis is one way to remove the VOCs in the air. A photocatalytic compound TiO_2 is activated in presence of UV light and breaks down VOCs in the air. The more the surface area is covered with TiO_2 and in contact with sunlight, the more effective it removes VOCs. Building facade is one of the building elements that is in direct contact with sunlight and interior space. Therefore, it can serve as a prime location to implement TiO_2 photocatalytic facade and remove VOCs. The facade configuration studied in this paper was chosen as a tetrahedron geometry to increase more surface area for coating TiO_2 under a unit volume. The radiation analysis simulations were run for all the orientations of east, south, west, and north. These radiation analysis simulations were run in 2 categories, one was annual radiation and second was seasonal radiation on each façade. The simulation indicated that south façade has most potential as the radiation on south façade is highest. While east and west has higher radiation in summer season. In both annual and seasonal radiation, north façade receives least amount of radiation, but it still has potential to activate titanium dioxide to reduce VOCs in the air. Further physical experiments were carried out to study the effect of TiO_2 coated facades

in reducing VOCs, the source of which was generated by hand sanitizer and silicone sealant. Two TiO_2 coated facades were tested: one is with TiO_2 powder and the other with TiO_2 spray. A controlled experiment was carried out as well, with the façade module with any coating, to ensure the reduction in TVOC levels is caused to activation of TiO2 in presence of UV light. In the controlled experiment, it was observed that there was 13% reduction in levels of TVOCs which was significantly less that spray and powder TiO2 which was 30-60% and 70-75% reduction accordingly.

ACKNOWLEDGEMENT

First and foremost, I am extremely grateful to my supervisor, Dr. Kyoung Hee Kim for the lessons and advice she provided in my complete academic years at UNC Charlotte, continuous support, and patience during my MS study. Her immense knowledge and plentiful experience have encouraged me in all the time of my academic research and daily life. I would also to thank Dr. Andrew Harver and Dr. Brian Magi who advised me in this paper. I would also like to thank Dr. Chengde Wu and Dr. Ok-Kyun Im for their technical and academic support on my study. I would like to thank Dante Gil Rivas for help he provided for making the chamber for physical testing. It is their kind help and support that have made my study and life at UNC Charlotte a wonderful time. Finally, I would like to express my gratitude to my parents, my friends. Without their tremendous understanding and encouragement in the past few years, it would be impossible for me to complete my study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

VOC	Volatile Organic Compounds
EPA	Environmental Protection Agency
REL	Reference Exposure Level
SBS	Sick Building Syndrome
TiO2	Titanium Dioxide
UV	Ultraviolet
ZnS	Zinc Sulfide
CdS	Cadmium Sulfide
ZrO2	Zirconium dioxide
DC	Direct Current
sm	Square meter
sf	Square feet
NOx	Nitrogen oxides
m	Meter
CO2	Carbon dioxide
NC	North Carolina
epw	Energy plus weather
kW/m2	Kilo Watt per square meter
TVOC	Total Volatile Organic Compounds
V	Voltage
ppb	Parts per billion
W/m2	Watt per square meter

1. Introduction

There are many air-polluting elements that are harmful to the environment as well as humans including particulate matter, ozone, Volatile Organic Compounds (VOCs), and many more. These harmful gases and matter cause many health issues in human beings. VOCs have short term effects on body like, eyes, nose and throat irritation or headaches but also long-term effects like asthma and other breathing issues, heart issues and a weight of newly born baby is also affected if the mother is exposed to VOCs during her pregnancy. The scope of this paper is to reduce the VOCs present in the air using a photocatalytic facade system. According to the EPA, it is estimated that humans spend 90% of their time indoors where the concentration of VOCs is 10 times higher than the concentration outdoors because of limited sources of natural ventilation indoors (Wallace 1989). Building materials like paints and other solvents, wood products, furnishings, carpets are some of the major sources of VOCs in the interior. Disinfectants, aerosol spray, pesticides, adhesives, and glues are a few other sources of VOCs.

VOCs are pollutants that cause different impacts on humans and the environment. VOCs are present in gaseous state at room temperature and are also responsible for increasing tropospheric ozone concentration that not only creates a greenhouse effect but also has carcinogenic properties. According to data collected of 100 random buildings from 37 cities, researchers found many different VOCs that are carcinogenic in the building (EPA 2020). It was found that different types of paints, carpets, gypsum boards, and glues emit VOC into the air, causing symptoms like headache, nausea, dizziness, and sometimes the damaging liver and kidney (Environmental Protection Agency, n.d.). Table 1 shows the sources of common VOCs and what are the consequences of the exposure to these VOCs are on humans. Research indicated that the indoor to outdoor ratio of VOC emission is greater than 2 to 5 (Environmental Protection

Agency, n.d.). Most commonly found indoor VOCs are formaldehyde emitted from wood-based products flooring and furnishings, Toluene from carpets, xylenes from planters, and adhesives (Yu and Kim 2011). It was also found that the drying process of paints, wallpapers, or even finger paints emit VOCs. Another research revealed that the emission of VOCs is higher in winter, except for a few VOCs like formaldehyde and acetaldehyde (Wallace et al. 1991). In addition to building materials, occupants contribute to VOC generation. It was found that VOCs like aldehydes, ketones, alkanes, and many more VOCs are released by human skin which is more in adults than children (Zou, He, and Yang 2020) (Stonner, Edtbauer, and Williams 2018).

Table 1: Commonly found VOCs, their sources, and consequence on the human body.

Source: (Environmental Protection Agency)

VOC	Acute REL target organs	Safe Harbour Level (Per day) (µg)	Occurrence
1,4 - Dichlorobenzene	The nervous system, respiratory system, alimentary system, kidney	20	Insecticide, germicide, space and garbage deodorizer; chemical intermediate inorganic chemicals, dyes, and pharmaceuticals
Acetaldehyde	Respiratory system, eyes	90	Fruit and fish preservative, flavoring agent, denaturant for alcohol; solvent; component of tobacco smoke
Acrylic acid	Respiratory system, eyes		Polymers, paint, leather, and paper coatings, detergents, and water treatment chemicals;
Benzene	Reproductive/development, immune system, hematologic system	13	Veterinary medicine (disinfectant); production of detergents, pharmaceuticals, and dyestuffs;
Chloroform	Reproductive/development, nervous system, respiratory system		Pesticides; chemical intermediate;
Formaldehyde	Eye irritation	40	Disinfectant (antibacterial, fungicide), plastics, adhesives, preservatives, pressed wood products, automobile components
Methanol	Nervous System	47,000	solvent, antifreeze; chemical intermediate (formaldehyde, acetic acid)
n - Hexane	Nervous system		Cleaning agent (degreaser), low-temperature thermometer filling; component of solvents (edible oil extraction, adhesives)
Toluene	The nervous system, eye, respiratory system	13000	Solvent, cement for polystyrene kits; production of polymers; chemical intermediate (benzene dealkylation);
Xylenes	The nervous system, eye, respiratory system		Solvent for paints, varnishes, inks, dyes, adhesives, pharmaceuticals, detergents, and rubber; production of polymer fiber

Temperature plays a role in the concentration of VOC levels in the air. Research indicated that the concentration of VOC at nighttime is higher than daytime during the winter period (Wallace et al. 1991). Thus, it can be said that the concentration of VOCs increases at lower temperatures (Wallace et al. 1991). The emission of VOCs is constant under the changes of ±2° C temperature and ±5% relative humidity. While formaldehyde emission is doubled with a 7° C increase in temperature or the increase in relative humidity from 30% to 70% (Wolkoff 1998). As the relative humidity increases, the emission of VOCs also increases. (Markowicz 2015).

1.1.Background

1.1.1. Sick Building Syndrome

According to the US EPA, "sick building syndrome" (SBS) is a situation in which occupants of the building suffer from acute health and comfort issues that are linked to the time spent in a certain building. It is caused due to inadequate ventilation and indoor sources of air pollution like VOCs emitted by-products used inside the building. These VOCs are carcinogenic, that is they cause cancer and other health effects (Wallace 2000; Theloke and Friedrich 2007). Even low or moderate concentrations can cause breathing or skin-related problems.

1.1.2. Research Statement

Photocatalytic façade system will help break down indoor VOCs with the help TiO_2 as a catalyst in presence of UV light of 360 nm wavelength. This study will aim to measure and analyze the reduction of VOCs generated by some common everyday products used indoor with the application of TiO_2 in presence of sunlight.

1.1.3. Research Question

- What is the effect of UV spectrum of sunlight on activation of TiO_2 and reduction of VOCs?
- What is the rate of breakdown of VOCs in the air?

2. Literature Review

2.1. Photocatalysis

To reduce or eliminate the concentration of VOCs, there are solutions such as reduction of VOC emitting materials and the use of low VOC products. Natural ventilation is also a passive design solution to reduce the concentration of indoor VOCs. However, natural ventilation is not a feasible option for thermal comfort in case of extreme weather. To this end, photocatalytic TiO_2 in presence of UV light can be an alternative solution to reduce VOCs indoors.

Photocatalysis follows the basic principle of the formation of electron-hole pairs by absorbing photons that have energy equal or greater to the semiconductor's material which excites the electrons producing reactive oxygen (Ameta et al. 2018). ZnS, CdS, ZrO_2 are a few of the semiconductors used for the process of photocatalysis (Yoneyama 1997; Fujiwara et al. 1997; Yoshida and Kohno 2001). TiO_2 is the most commonly used photocatalytic chemical. TiO_2 is a widely found, low-cost, and low maintenance material which also has strong oxidation properties (Weon et al. 2017). Fujishima Akira discovered the photocatalytic properties of TiO_2 in 1967 while he was graduate student at University of Tokyo. The efficacy of photocatalysis depends mainly on the intensity of UV rays and the amount of TiO_2 particles. TiO_2 is also included in many personal care products like sunscreens and shaving creams while also used as an additive to paints to give the bright white color with high refractive index and self-cleaning abilities. (Weir et al. 2012)

There is also a drawback that the UV rays have to be directly incident on the surface for maximum efficiency. Researchers are also focusing on using Vacuum UV which helps TiO_2 perform 70% better than UV irradiation (Shu et al. 2018). Researchers are working on the activation of TiO_2 in presence of visible light spectrum (Etacheri et al. 2015). There are researchers doping TiO_2 with noble metals like Palladium that helps TiO_2 perform in a visible light spectrum with much more efficiency. It is also proven that doping TiO_2 increases the efficiency of TiO_2 photocatalysis by 90% since it oxidizes VOCs in visible light (Fujimoto et al. 2017). For the purpose of our research, we are mainly focusing on pure TiO_2 that performs under UVA rays. In addition, TiO_2 coated products allow the self-cleaning traits along with reducing the growth of phototrophic bacteria which are the reason for mold formation (Graziani et al. 2014). Therefore, our research focused on photocatalytic degradation of VOCs with TiO_2.

2.2. TiO_2 Coating

TiO_2 is usually made by laser interaction of titanium and oxygen in anatase form. (Fathi-Hafshejani et al. 2020). The coating of TiO_2 on stainless steel is rough thus larger surface area is formed which is much more beneficial for photocatalytic oxidation. Nanoparticle deposition system is a widely used technique to coat TiO_2. (Chun et al. 2008). The temperature of the substrate also plays a crucial role in the application of TiO_2 coating. Fine crystals of TiO_2 are formed when TiO2 is coated on a cool substrate. The magnetron sputtering process for TiO_2

coating on TiO_2 films can be coated by heating the substrate. This is beneficial since the deposition of TiO_2 on low melting point substates will be cost-saving (Zeman and Takabayashi 2002). TiO_2 films can be deposited on a silica glass substrate with the use of arc ion plating with a pulsed DC power supply with heating of the substrate. Hydrothermal-seeded techniques are also one of the effective techniques for obtaining porosity and anatase TiO_2 (Kartini et al. 2018).

2.3. Architectural application

As the properties of photocatalytic materials were discovered, researchers and architects started using the photocatalytic compounds as a coating for different building elements especially façade.

Manuel Gea González Hospital (Figure 1) is one of the examples where a façade is coated with TiO2 to improve the air quality in Mexico City. Mexico City was singled out as the most polluted megacity in the world in 1992. The hospital was designed to neutralize the pollutants and improve the air quality in the area with many hospital patients. It was hypothesized the air pollution in Mexico City is causing 35,00 hospitalizations and 1000 deaths every year.

Figure 1: Manuel Gea Gonzalez Hospital

Source: Alejandro Cartagena

Mexican government initiated the “ProAire” program to reduce the escalating levels of air pollution. In 1992, the air quality in Mexico City was good only for 9 days in the whole year, while with the launch of program it increased to 248 days in 2012. It was still not enough, and there were many initiatives that were taken by government and other bodies to improve the air quality in Mexico City. Under the ProAire program, a hospital was redesigned and extended to improve the air quality by transforming air pollutants into harmless substances. The original building for the hospital was designed by Manuel Villagran in 1942. In 2013, Elegant Embellishments of Berlin, a new façade cladding was added to the existing building. It was 2,500 sm (26,910 sf) façade modules coated with proSolve370e spanning upto 100 m (328 ft). According to the proSolve370e inventors the chemical can neutralize the pollution created by 8,750 cars every day. The fine TiO_2 was coated on thermoformed plastic as a main façade material substrate for TiO_2. The modules (Figure 2) were coated with a special pigment which in presence of ambient ultraviolet light reacts with the pollutants in the air and breaks them down into less harmful compounds like carbon dioxide and water.

There was a third-party testing for the façade system, Daniel Schwaag, co-director of Elegant Embellishment mentioned that the façade will neutralize the smog produced by 1,000 vehicles in Mexico City. This façade project was funded by Mexico’s Ministry of Health which is one of the investments of $20 billion in Mexico’s health structure. This façade project focused mostly on reducing Nitrogen oxides (NOx), Volatile Organic Compounds (VOCs) and sulphur dioxide in immediate surroundings.

Figure 2: Facade modules of Manuel Gea Gonzalez Hospital

Source: Elegant Embellishment

The façade system for Manuel Gea González Hospital uses geometry called quasi pattern to maximize the surface area for coating that would be exposed to diffused light. The biomimetic quasi pattern was derived from the quasi crystalline or Penrose pattern found in sponges and corals. The tiles of the façade (Figure 3) were tested rigorously and prototyped at 1:1 scale patch installed wit steel frame assembly. The façade modules are light weight and didn't require any heavy machinery for installation.

Figure 3: Prototype of façade module for Manuel Gea González Hospital

Source: Elegant Embellishment

Form finding:

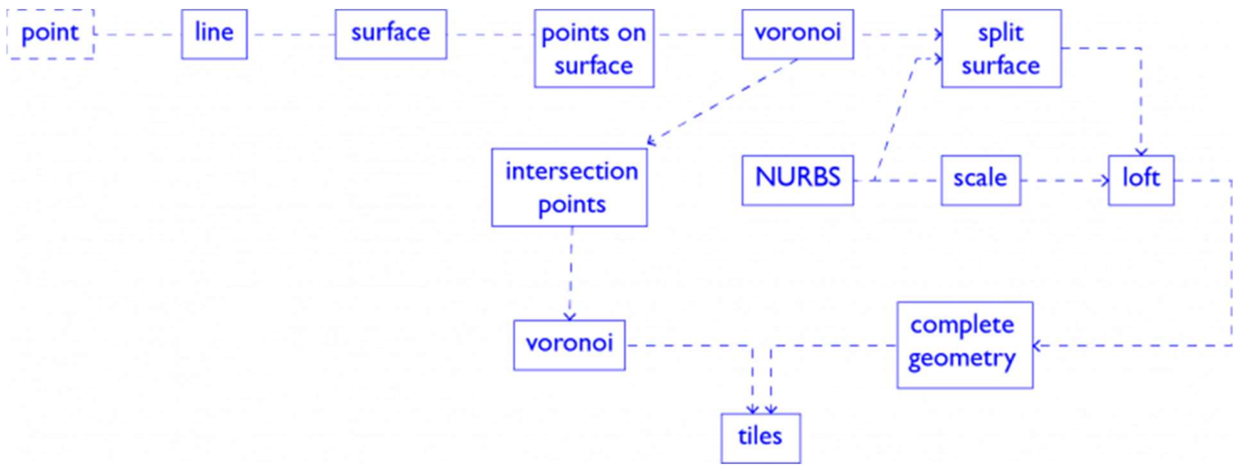


Figure 4: Pseudo code

Source: IAAC Blog

The façade geometry was created in grasshopper plugin in rhino software with certain set of commands (Figure 5) which is shown in the simplified version as a Pseudo code (Figure 4)

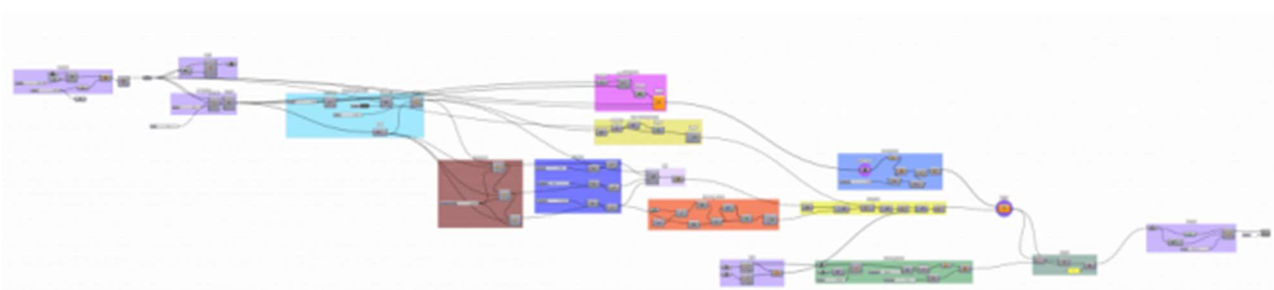


Figure 5: Grasshopper code

Source: IAAC Blog

Figure 6: Palazzo Italia

Source: Heidelberg Cement

Another example of photocatalytic façade is Palazzo Italia (Figure 6). The building was originally designed for Milan Expo 2015. It is the only permanent structure in the Expo standing 35 m high. Building was designed by Nemesis architects inspired by the concept of urban forest resembling the branches of the tree that are intertwining together to form the mesh like structure. Not only the concept of forest was applied to the structure of façade but also the façade absorbs CO2 and other air pollutants and neutralizes it and sends it back to atmosphere. The façade cladding is almost 97,000 sf (9,000 sm) and is made from patented TX Active technology by Heidelberg Cement Group who did the research to neutralize CO2 by photocatalytic titanium dioxide within the concrete. This concrete mixed with titanium dioxide uses sun’s light energy creating oxidizing reactants that further breaks down harmful air pollutants to clean the outdoor air.

The cladding is made from 80% recycled materials of marble and aggregate. Also, in addition to that, photovoltaic glass was used for roof to further help producing electricity to make Palazzo Italia energy neutral.

Figure 7: Jubilee Church, Rome, Italy

Source: Andrea Jomolo

Jubilee Church (Figure 7) designed by Richard Meier is another example in Italy that uses photocatalysis to clean the air. An Italian concrete manufacturer Italcementi developed TX millennium concrete mix especially for this project. This façade also makes use of titanium dioxide that activates in presence of ultraviolet light of sunlight to break down air pollutants in the air. Titanium dioxide is also the self-cleaning material; thus, it retains the white appearance.

Along with permanent and concrete substrates are used as substrate to coat TiO_2 for its photocatalytic properties, Saint Gobain created the tensile roofing structure called “Ever Clean” architectural membrane which uses photocatalytic coating of TiO_2 on architectural tensile fabric materials. These photocatalytic tensile structures are used in AT&T Stadium in Arlington, Texas (Figure 8).

Figure 8: AT&T Stadium

Source: Sheerfill website

3. Façade Design

3.1. Tetrahedron Geometry

The primary purpose of any façade is the separate the indoors from outdoors. By doing this protecting the interiors from sun, rain, wind, and other natural and man-made factors. In addition to that, the façade should provide shading from sun to reduce the cooling load caused by greenhouse effect in the building due to glass, and also to provide view out for the occupants of the building.

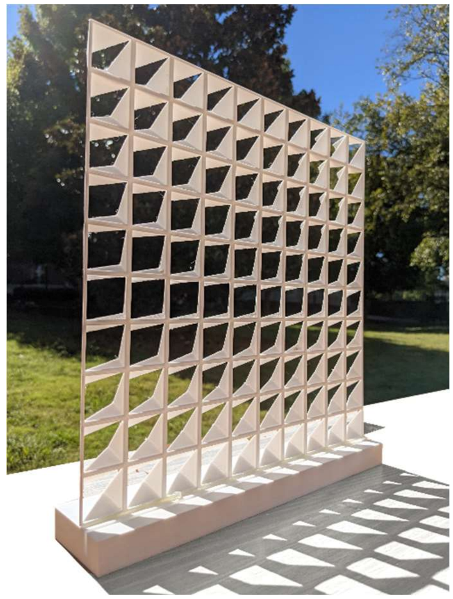


Figure 9: 3d printed facade panel (a)

Source: Author

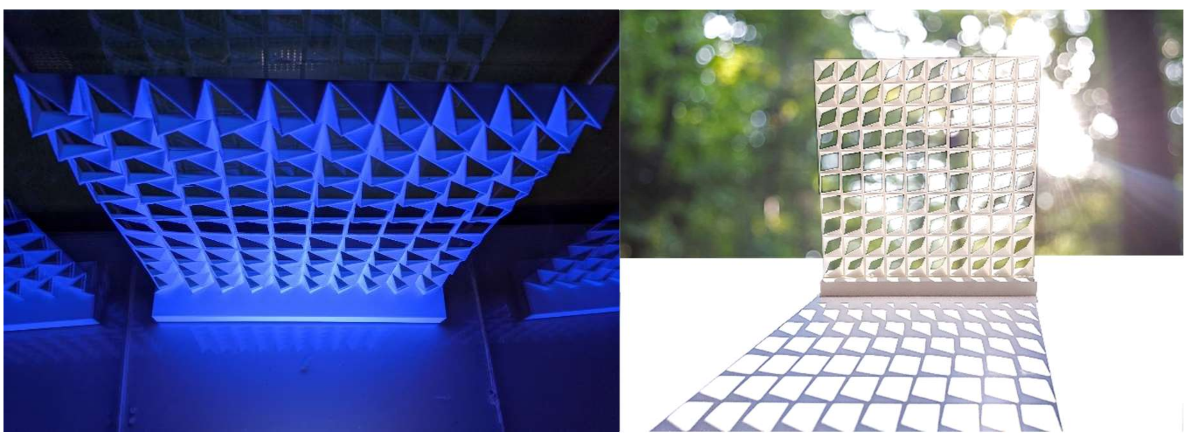


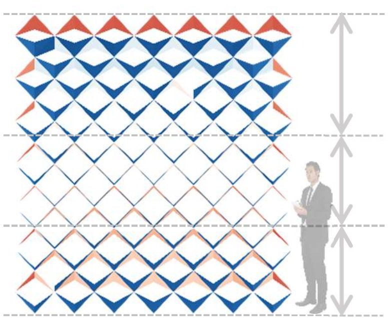
Figure 10: 3d printed facade panel (b)

Source: Author

The purpose of the proposed façade is also to increase the surface area for coating TiO_2 to maximize the exposure to UV light coming from sun to effectively break down indoor VOCs (Figure 12 and 13). The façade with also provide the shading by providing more depth to the tetrahedron cells in the from higher part of façade panel. While the depth of tetrahedron cells will be less to provide view out for the occupants at their eye levels. In addition to that, the lower part of façade will also have higher depth to provide more surface area to coat TiO_2.

Figure 11: Interior render-1

Source: Author



- Maximum sun exposure (or solar radiation for improving TiO_2 activation.
- Shading the interiors to avoid heat in and reducing the cooling load.

- Maximum View out for improving
- Occupant's visual comfort

- Maximum sun exposure for improving TiO_2 activation

Figure 12: Design Intent for facade panel

Source: Author

Figure 13: Interior Render-2

Source: Author

Thus, the façade provides shading and view out, while also maximizing the area to coat TiO_2 that will be directly exposed to UV light. While ensuring maximum surface area, it also provides daylight inside, by not completely blocking the daylight to increase the surface area. As daylighting is also one of major factors that could affect the productivity of occupants along with improving air quality.

4. Methodology

4.1.Simulations:

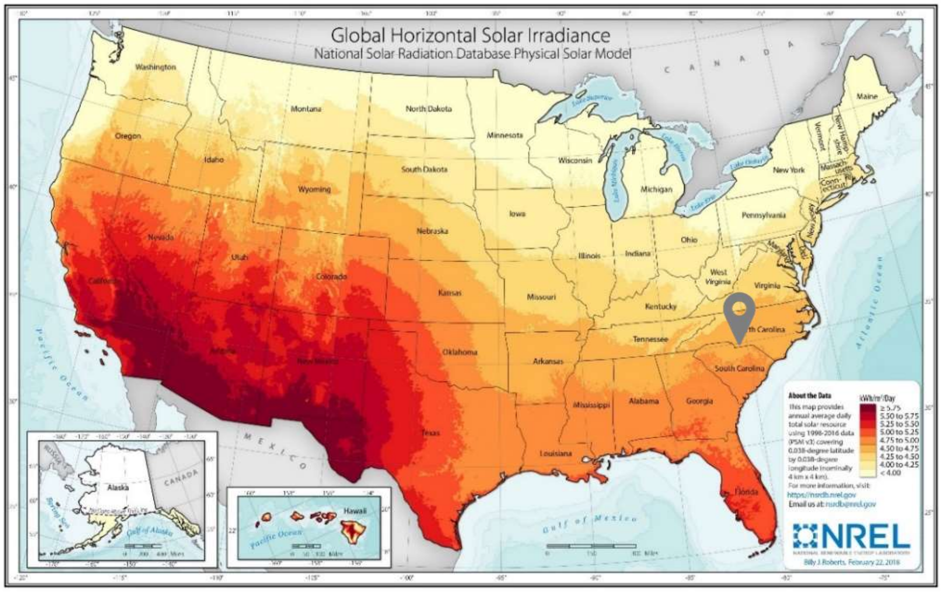


Figure 14: Location of Charlotte on the map of USA

Source: NREL

The radiation analysis was simulated based on the .epw file collected from energy plus website for the location of Charlotte, North Carolina, USA (Figure 14). The latitude and longitude of the Charlotte is 35.23° N and 80.84° W.

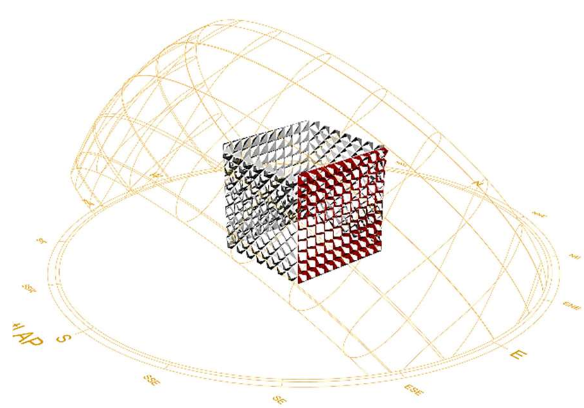


Figure 15: The sunpath for the Charlotte, NC location

Source: Author (ladybug plugin)

According to the Sun Path (Figure 15) derived from the ladybug plugin for grasshopper in rhino software, the sun travels from east to south to west. So, for the southern façade, when the sun is at its higher altitude angles, the horizontal shading is more effective in reducing the solar exposure (Figure 16). While in east and west, when the sun is rising and setting the altitude angles of the sun at lower, so it is necessary to shade the indoors with vertical devices. It is

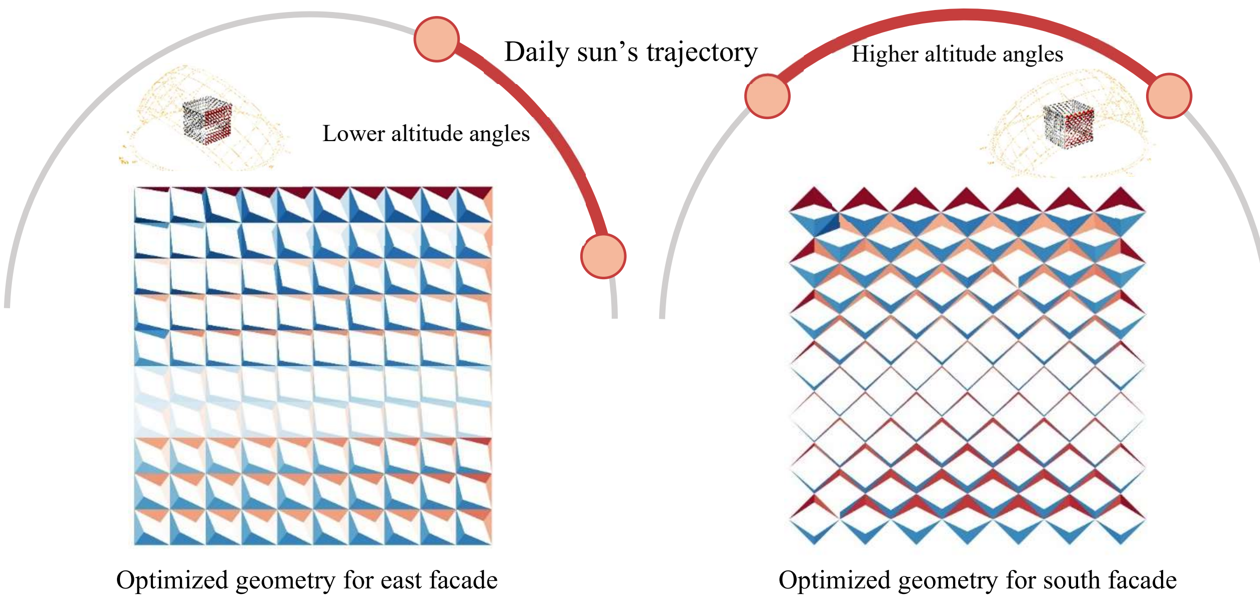


Figure 16: Design Intent for facade geometry on east and south façade

Source: Author

shown in figure 16.

The simulations were run for annual radiation of the façade surface to determine which side receives most of the radiation annually.

Based on the simulations and the graph (Figure 17 and 18), shows that south façade receives mostly of the radiation of about 2600 kW/m2 annually. While east and west façade receives almost the same amount of radiation of 2412 kW/m2 and 2404 kW/m2 accordingly per year. The least amount of radiation is falling on north façade with 1738 kW/m2, since north faced only receives the diffused radiation as sun is mostly present in south.

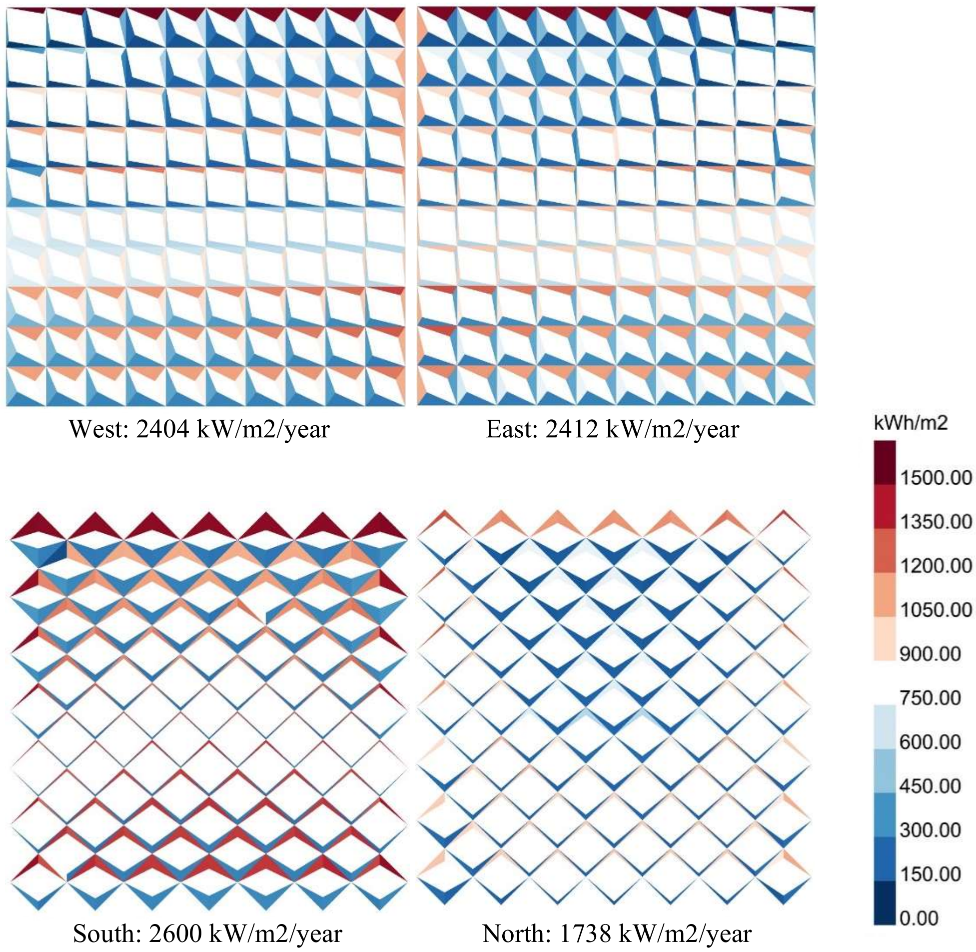


Figure 17: Annual Radiation on facade on each side

Source: Author

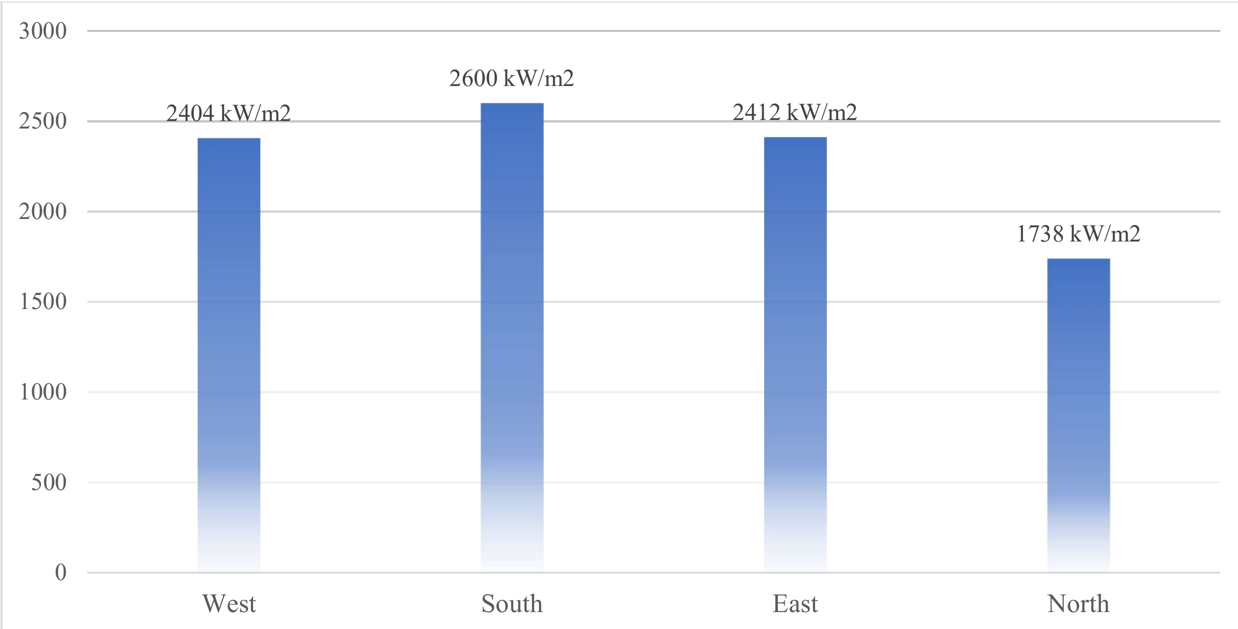


Figure 18: Annual Radiation visual graphics

Source: Author

For further information, the simulations for seasonal radiation analysis (Figure 19) were ran on each façade to know which season will receive most radiation to effectively reduce VOCs in the air.

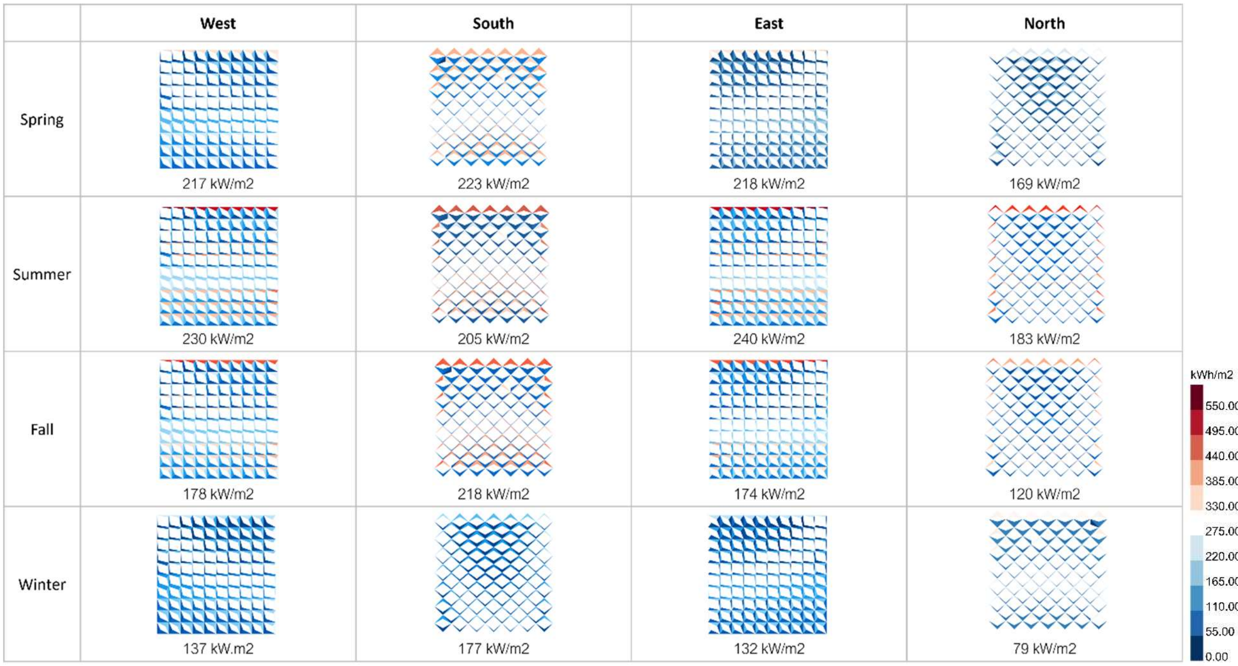


Figure 19: Seasonal Radiation on facade panels on each side

Source: Author

The simulation results (Figure 19 and 20) also demonstrated that south façade receives highest amount of radiation combined. Though the radiation in summer is lowest in summer that fall and spring, compared to east and west façade, the rest of the year balances it out to receive highest amount of radiation. Simulations also demonstrated that east and west receives highest radiation in summer than south. As per the reason mentioned for the annual radiation, the north façade receives least amount of radiation in any season compared to other facades.

While this being the case only for the locations in the norther hemisphere. This case will be completely reversed in case of locations in southern hemisphere of the globe.

This radiation analysis is helpful is designing the system according to seasonal necessity of the place. Since the concentration of VOCs is more in lower temperature (Wallace et al. 1991). The seasonal radiation analysis can help design the system to have higher intensity in winter than summer. Likewise, the system can be optimized for the colder locations considering its latitude for shading as well.

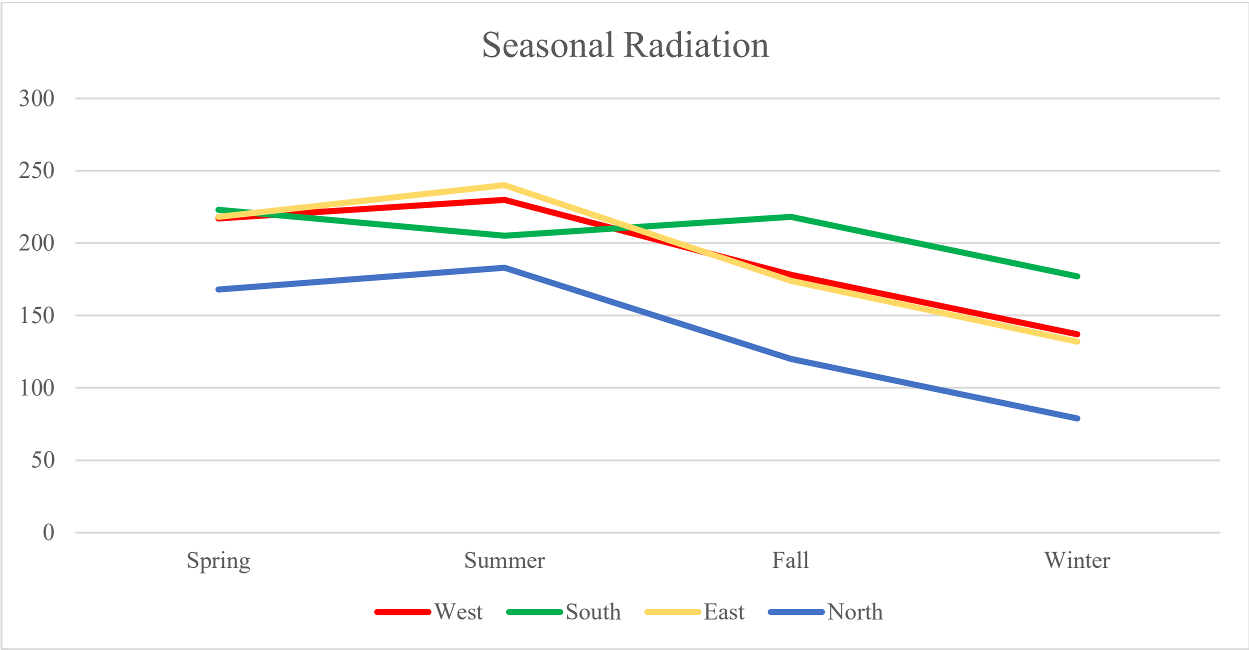


Figure 20: Seasonal Radiation visual graphics

Source: Author

Figure 21: Interior perspective

Source: Author

4.2. Actual Testing

4.2.1. Testing Chamber

A testing chamber (Figure 22 and 23) was made from transparent acrylic sheets, as it would be beneficial to monitor the testing process and measure experiments. The size of the testing chamber is 14”x14”x14” with 10 mm thick acrylic sheets (Figure 22). All the acrylic sheets were joined together with 100% low-VOC silicone sealant. The top lid was made from glass attached to a foam board and was removable for positioning the samples and sensors. Since TiO_2 on the facade surface can be activated by UVA, it is important to let UV light penetrate the testing box with minimal absorption. We found that acrylic absorbs about 80~90% of UVA light through tests. Thus, 6 mm single pane glass was used instead of acrylic for the lid considering the altitude of the sun at the testing time (Figure 22). In addition, VOC sources and a fan were housed in a material holder box with 3.5” (w) x 7” (d) x 3.75” (h) dimension installed inside the testing chamber. After applying formaldehyde sources on woodblock, it was placed in front of the fan to circulate the indoor air evenly. The power required to operate the fan was provided by the solar power bank.

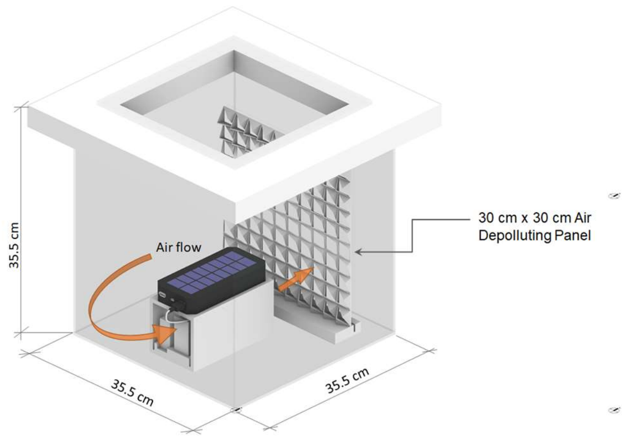


Figure 22: Testing Chamber – Isometric View

Source: Author

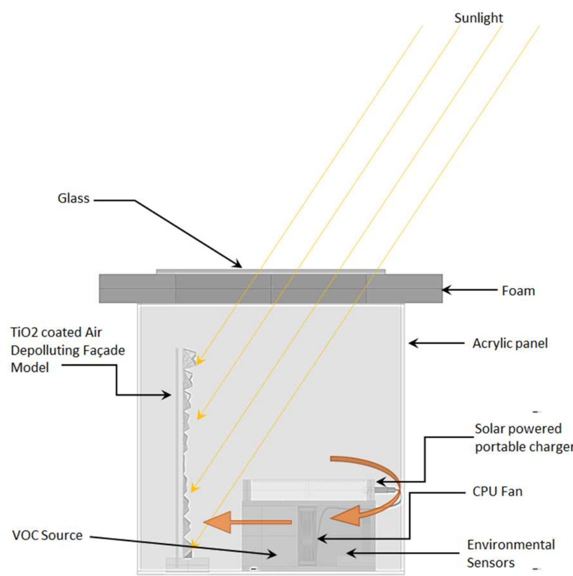
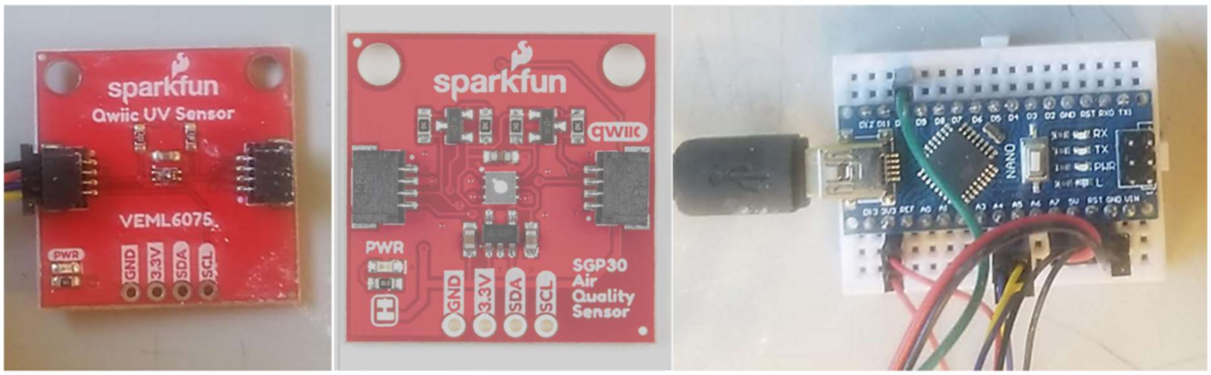


Figure 23: Testing Chamber - Side View

Source: Author

4.2.2 Air quality and UV light Sensor

In this experiment, UV and TVOC sensors were connected to an Arduino Nano board to collect data. The UV sensor (Figure 24a) was used to measure the intensity of UVA light entering the testing box in the range of 320 to 400 nm. This sensor was made by Sparkfun using a VEML 6075 light sensor. The second sensor is spark fun SGP30 air quality sensor (Figure 24b) that can measure TVOCs emitted from building materials such as carpet, glue, etc. Both sensors were connected to the Arduino Nano (Figure 24c) and sensor data were collected at one-second intervals.



a) UV sensor　　b) TVOC sensor　　c) Arduino Nano

Figure 24: Air quality, UV light Sensor, and Arduino Nano

Source: Author

Table 2: Sensors' specifications

Source: Author

	UV sensor (Sparkfun)	TVOC sensor (Sparkfun)
Operating voltage range (V)	1.7-3.6 V	1.62-1.98 V
Resolution	0.93 counts/µW/cm2	13 ppb
Detect range	UVA: 320~400 nm	0~60,000 ppb
Operating Temp	-40 °C ~ +85 °C	-40 °C ~ +85 °C

4.2.3. Photocatalytic Façade

Two TiO_2 facade (Figure 9) specimens with a size of 30 cm x 30 cm were fabricated using a 3d printer. One specimen was coated with TiO_2 paste that was made from a mixture of power and water, applied with a brush to the facade panel. The other sample was prepared with TiO_2 spray that was applied on the facade and air-dried. Figure 25a shows the powder mixed with water and Figure 25b shows the spray type applied by spraying it on the facade surface.

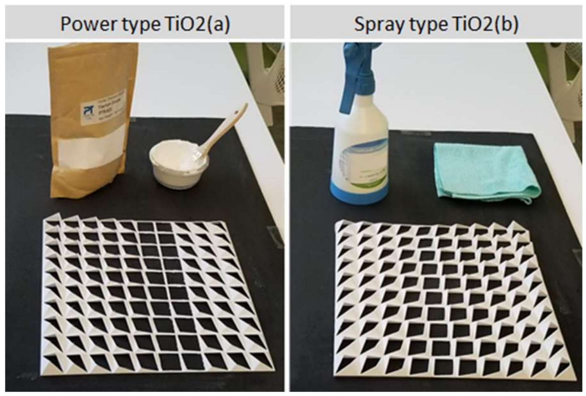


Figure 25: TiO2 coatings

Source: Author

4.2.4. Sources of VOCs

For the sources for VOCs, the readily available materials were used. The first source of VOC was a hand sanitizer (Figure 26a) provided by university during pandemic which contains 80% of alcohol. Another source of VOC used was an old nail paint (Figure 26b).

Figure 26: Sources of VOC

Source: Author

4.2.5. Experimental procedure

The experiment was carried out in 2 phases. In first, facade samples, VOC source was applied on the small 1 x 2” wood sheet, and sensors were placed inside the testing chamber. Next, the testing chamber was covered with a black curtain (Figure 27a) for 30 minutes to prevent TiO_2 from being activated by the sunlight. After 30 minutes, the black curtain was removed to expose the testing chamber to the sunlight (Figure 27b). The experiment was run for one hour and the sensors in the testing chamber measured the Total Volatile Organic Compounds (TVOC) level (ppb) and UVA intensity (W/m^2). In second phase and control experiment was carried out. In this experiment, the same procedure was carried as mentioned above. But for this experiment, the façade modules used in this experiment was not coated with TiO2 and the experiment was carried out. For this experiment, only hand sanitizer was used as a source of VOC. It is necessary to note that the experiments were carried out in different atmospheres and subjected to changing temperature and humidity and different UV intensities, different amount of source of VOCs.

Figure 27: Testing procedure

Source: Author

5. Results and Discussion

In this study, hand sanitizer and nail paint were used as the VOC sources, and a total of four experiments were carried out by applying two types of TiO_2 samples, powder, and spray. And another experiment with the façade modules without TiO2 coated onto it with hand sanitizer as a source of VOC was used. Table 3 summarizes the experimental setup of four different conditions.

Table 3: Five experiments for TiO2 photocatalytic facade

Source: Author

Testing	Experiment conditions
A	Photocatalytic facade with TiO_2 spray / TVOC source from hand sanitizer
B	Photocatalytic facade with TiO_2 spray / TVOC source from nail paint
C	Photocatalytic facade with TiO_2 powder / TVOC source from hand sanitizer
D	Photocatalytic facade with TiO_2 powder / TVOC source from nail
E	Façade without TiO_2 coating / TVOC source from hand sanitizer

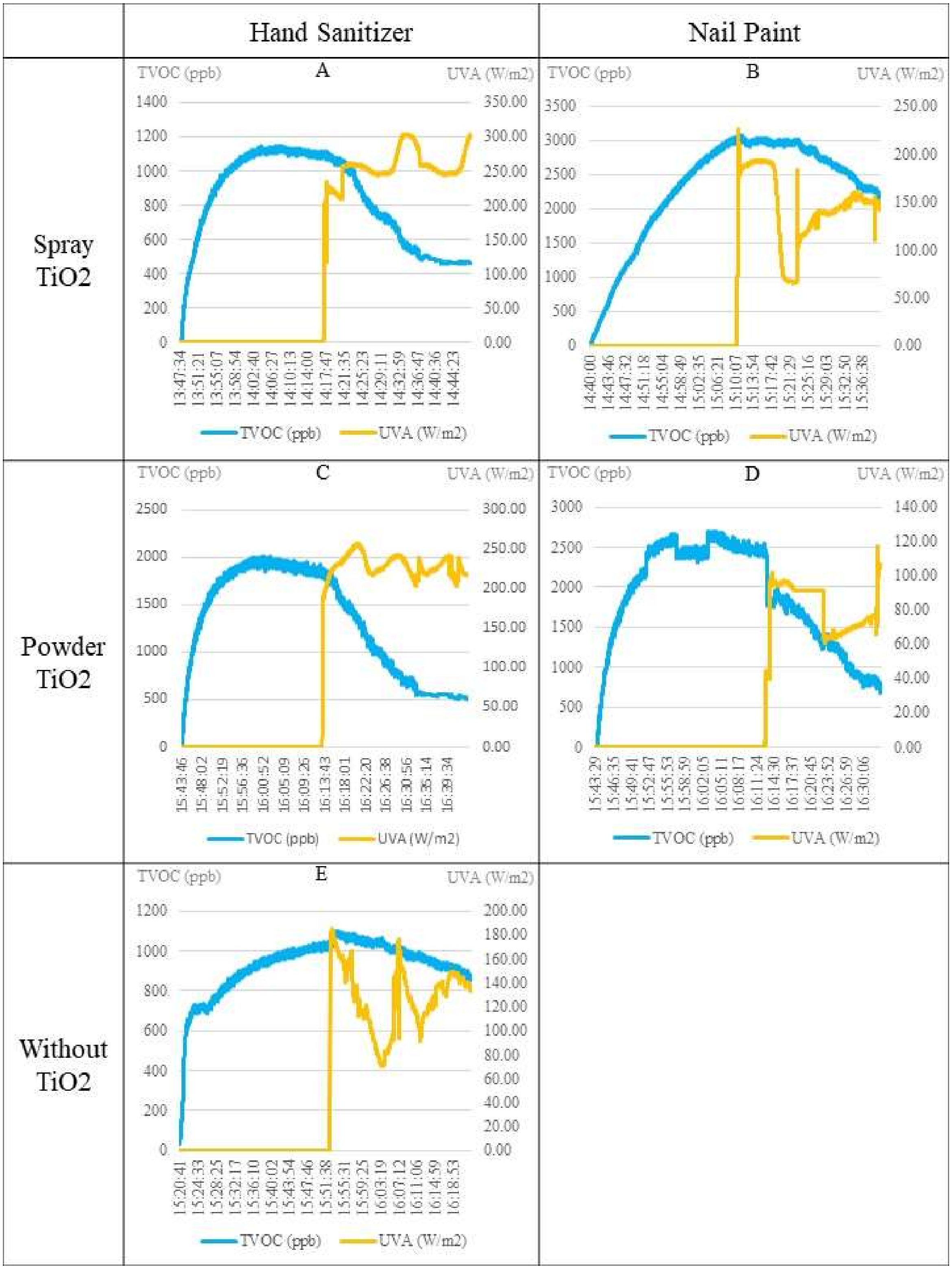


Figure 28: TiO2 experimental results

Source: Author

Figure 28 shows experimental data in measuring the effect of photocatalytic facades in reducing air contaminants. First of all, it can be seen that both powder and spray types of TiO_2 on the facade surfaces are effective in reducing the TVOC emitted from the hand sanitizer and nail paint. Although each experiment was exposed to different UVA intensity due to the natural variation from the sunlight, all experiments showed that the TiO_2 photocatalytic facades noticeably reduced the TVOC concentration.

Table 4: Maximum, minimum, and average values for all the experiments

Source: Author

	TVOC (ppb)			UVA (W/m2)		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Controlled Experiment E	1101	877	989	184.82	71.27	128.04
Experiment A	1148	460	804	303.10	118.17	210.65
Experiment B	3088	2161	2624	226.24	65.56	145.95
Experiment C	2010	509	1260	256.83	183.26	220.04
Experiment D	2700	670	1685	117.28	26.60	71.94

When comparing the result from experiment A and C, the reduction rate of TVOC in experiment C using the TiO_2 powder from 2010 ppb (Table 4), the maximum amount of concentration that is reduce to 509 ppb 30 minutes after powder TiO2 was exposed to UV light which was about 70% reduction with the rate of 47 ppb reduction per minute that is greater than the reduction rate of 22 ppb per minute in experiment A using the TiO_2 spray from highest concentration of 1148 ppb to 460 ppb at the end of experiment which was 60%. In the case of B and D, the powdered TiO2 beat the sprayed TiO2 since in experiment B there was 30% reduction at about 30 ppb per minute rate in TVOC while 75% reduction which is about 67 ppb per minute reduction in TVOC with powdered TiO2 (Table 4).

The purpose of experiment E was to ensure the reduction in TVOC due to activation of TiO2. Since, formaldehyde, which is one of most commonly found VOC decomposes even in presence of sunlight, it was necessary to ensure that the reduction in VOC level is happening due to activation of TiO2 on the façade module in presence of UV light. In experiment E, it is observed that there is reduction in levels of TVOCs from 1101 ppb to 877 ppb at the rate of 7 ppb per minute which is 13% reduction (Table 4). But this reduction level is significantly less than compared to the sprayed and powder TiO2 which is 60% and 75% respectively. The 13% reduction is TVOC could have been caused due to the VOCs such as formaldehyde which breaks down in sunlight. As a result, this research found that both TiO_2 types on the facade surface were activated by UVA with a certain intensity level and effectively reduced indoor TVOC emitted from building materials.

6. Conclusion

People spend the majority of their time indoors. There is a correlation between indoor air quality and adverse health impacts. Common air pollutants are from building materials. The pandemic increased the use of sanitizing and cleaning products, making these sources of indoor pollution more relevant. This research focused on TiO_2 photocatalytic facades as an air quality control method. With the simulation it was noted that south facing façade receives most of the annual radiation while north façade receives least amount of annual radiation. While seasonal radiation analysis showed that in summer east and west façade receives most amount of radiation which will help activate TiO_2 to break down VOCs. In any case, though north façade receives least amount of annual and seasonal radiation, it still has potential to activate TiO_2 to break down VOCs in the air. The effect of TiO_2 photocatalysis removing TVOC was studied by physical experiment. In both cases of powder based and sprayed TiO_2 coating, a significant reduction of formaldehyde was observed. The TiO_2 powder reduced the TVOC by 70-75% while sprayed TiO_2 reduced the formaldehyde by 30-60%. These reduction levels may vary based on temperature and humidity and on the intensity of UV light. Though a few VOCs breaks down in presence of sunlight, the reduction rate is significantly lower and a few of VOCs do not break down in sunlight which are decomposed by activation of TiO2 in presence of UV light. Our experiment revealed that varying UV intensity has less effect on the reduction of VOC. Therefore, it can be concluded that TiO_2 photocatalytic facade can improve indoor air quality.

6.1. Further scope

This project can be further studied with 1:1 scale prototyping and testing with actual building material that emits VOCs like carpets, plywood, paints, etc. The efficiency of system can be tested at a practical at a building which has building material that emits VOCs. For the practical studies and testing, different glazing system like double glazing or low E glass that supports further energy efficiency can be used to check the activation of TiO2 and reduction in VOCs. As mentioned above the testing and simulation were carried out for the Charlotte location, thus the system was optimized for shading, viewing out and enhanced activation if

TiO2. This system can be optimized for any location in the world based on its latitude as shown in Figure 29.

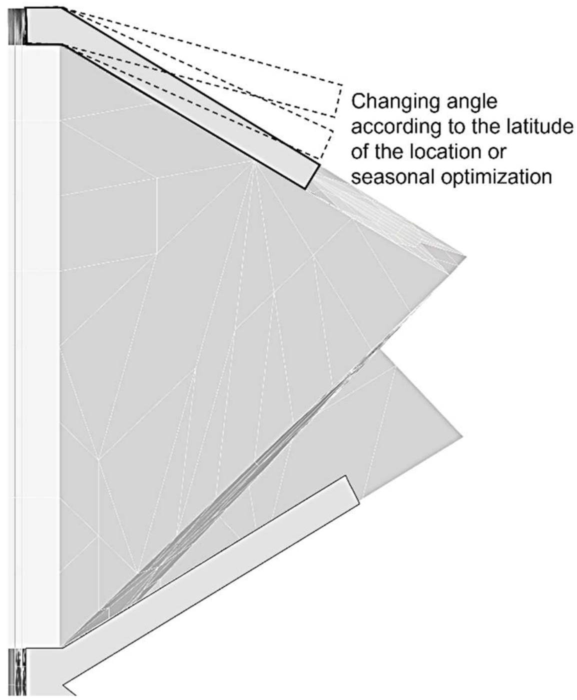


Figure 26: Angle optimization

Source: Author

REFERENCES

Ameta, R., M. Solanki, S. Benjamin, and S. Ameta. 2018. Advanced Oxidation Process for Waste Water Treatment. Chennai: Candice Janco.

Environmental Protection Agency. n.d. "Volatile Organic Compounds' Impact on Indoor Air Quality." Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality.

Environmental Protection Agency. 2020. Summarized Dala of Building Assessment Survey and Evaluation Study. 16 July. http://www.epa.gov/indoor-air-quality-iaq/summarized-da-ta-building-assessment-survey-and-evaluation-study.

Etacheri, V., C. Valentin, J. Schneider, D. Bahnemann, and S. Pillai. 2015. "Visible-light activation of TiO2 photocatalysts: Advances in theory and experiments." Journal of Photochemistry and Photobiology C: Photochemistry Reviews 25:1-29.

Fujiwara, H., H. Hosokawa, K. Murakoshi, Y. Wada, S. Yanagida, T. Okada, and H. Kobayashi. 1997. "Effect of surface structures on photocatalytic CO2 reduction using quantized CdS nanocrystallites." Journal of Physical Chemistry B 101, no. 41 (October): 8270-8278.

Shu, Y., Y. Xu, H. Huang, J. Ji, S. Liang, M. Wu, and D. Leung. 2018. "Catalytic oxidation of VOCs over Mn/TiO2/activated carbon under 185 nm VUV irradiation." Chemosphere 208:550-558.

Stonner, C., A. Edtbauer, and J. Williams. 2018. "Real-world volatile organic compound emission rates from seated adults and children for use in indoor air studies." Indoor Air 28.

Theloke, J., and R. Friedrich. 2007. "Compilation of a database on the composition of anthropogenic VOC emissions for atmospheric modeling in Europe." Atmospheric Environment 41 (19): 4148-4160.

Wallace, L., W. Nelson, R. Ziegenfus, E. Pellizzari, L. Michael, R. Whitmore, H. Zelon, T. Hartwell, R. Perritt, and D. Westerdahl. 1991. "The Los Angeles TEAM Study: personal exposures, indoor-outdoor air concentrations, and breath concentrations of 25 volatile organic compounds." Journal of Exposure Analysis and Environmental Epidemiology 1, no. 2 (April): 157-192.

Wallace, L. A. 1989. "The Total Exposure Assessment Methodology (TEAM) Study: An Analysis of Exposures, Sources, and Risks Associated with Four Volatile Organic Chemicals." Journal of the American College of Toxicology 8, no. 5 (September): 883-895.

Wallace, L. A. 2000. Assessing human exposure to volatile organic compounds., in Indoor Air Quality Handbook. New York: n.p.

Weir A, Westerhoff P, Fabricus L, Hristoski K, Goetz N. 2012. "Titanium Dioxide Nanoparticles in Food and Personal Care Products." Environmental Science & Technology 46 (4): 2242-2250. doi:10.1021/es204168d.

Weon, S., J. Choi, T. Park, and W. Choi. 2017. "Freestanding doubly open-ended TiO2 nanotubes for efficient photocatalytic degradation of volatile organic compounds." Applied Catalysis B: Environmental 205:386-392.

Wolkoff, P. 1998. "Impact of air velocity, temperature, humidity, and air on long-term VOC emissions from building products." Atmospheric Environment 32 (14-15): 2659-2668. https://doi.org/10.1016/S1352-2310(97)00402-0.

Yoneyama, H. 1997. "Photoreduction of carbon dioxide on quantized semiconductor nanoparticles in solution." Catalysis Today 39 (3): 167-175.

Yoshida, S., and Y. Kohno. 2001. "A new type of photocatalysis initiated by photoexcitation of adsorbed carbon dioxide on ZrO2." Catalysis Surveys from Japan 4, no. 2 (July): 107-114.

Yu, C., and J. Kim. 2011. "Long-term Impact of Formaldehyde and VOC Emissions from Wood-based Products on Indoor Environments; and Issues with Recycled Products." SAGE journals 21, no. 1 (September): 137-149.

Zou, Z., J. He, and X. Yang. 2020. "An experimental method for measuring VOC emissions from individual human whole-body skin under controlled conditions." Building and Environment 181.