PAPER

A Photocatalytic Building Façade for Improving Urban Air Quality

DANTE GIL RIVAS
Rice University

KYOUNG-HEE KIM
University of North Carolina at Charlotte

OK-KYUN IM
University of North Carolina at Charlotte

CHENGDE WU
Iowa State University

Keywords: photocatalytic facade, air depollution, urban air quality

Fossil fuel combustion generates various types of air pollutants. Nitrogen dioxide (NO_2) is the primary source of air pollution in populated urban areas, especially in developing countries. This study investigates an air pollutant reduction system that utilizes a photocatalytic substance on building facades. Titanium Dioxide (TiO_2), one of the most effective photo-induced catalysts, can be excited by UV-A rays with a wavelength shorter than 385nm. Excited TiO_2 can then break water vapor molecules in the air to form hydroxyl radicals. Due to its strong oxidation properties, hydroxyl radicals can subsequently react with air pollutants and form harmless substances, e.g., turning NO_2 into nitrates. In this study, we conducted experiments to test the effects of photocatalytic facades reducing air pollutants under UV rays. We fabricated a small scale (30cm x 30cm) building façade model and coated it with a thin layer of titanium dioxide. The model is then put into an airtight chamber filled with exhaust gas from an internal combustion engine. Inside the chamber, we installed a set of environmental sensors that measure NO_2, UV intensity, temperature, and relative humidity. The sensors were connected to a Raspberry Pi that is used to collect the sensor data. Natural sunlight was used as the UV source to activate the TiO_2 on the model. Under sunlight, the concentration of NO_2 dropped noticeably over time. In a controlled experiment, on the other hand, the concentration of NO_2 monotonically increased without the UV rays. This study shows that photocatalytic facades with titanium dioxide coating can reduce urban air pollutants through photocatalysis. In urban areas with severe air pollution and a large amount of building surface area, photocatalytic facades can be an effective passive system to improve urban air quality.

INTRODUCTION

Two thirds of the world population is expected to reside in cities by 2030 (UN 2005). The growing influx of city residents results in increasing pollutants from construction, automobiles, and energy production. Tall buildings will become a default building typology to accommodate urban populations and high-density development. Building enclosures as a threshold between indoor and outdoor spaces are directly exposed to sunlight year around. Capitalizing on sunlight and photocatalysis, our research focuses on photocatalytic building enclosures in improving urban air quality.

In 2019, according to the World Health Organization (WHO), 99% of the world population were living in places where air quality guideline levels were not being met (WHO, 2021). The effects of air pollution, whether outdoor or indoor, can be associated with affecting human health and the environment. The Environmental Protection Agency (EPA) Report on the Environment categorizes three different types of air pollutants including criteria pollutants, air toxins & other pollutants, and stratospheric ozone issues (EPA, 2021a). For criteria pollutants, the EPA has established the Clean Air Act which sets National Ambient Air Quality Standards (NAAQS) for the six principal pollutants in outdoor air that are considered harmful to public health and the environment (EPA, 2021c). The six pollutants are nitrogen dioxide (NO2), ozone, particulate matter, carbon monoxide, sulfur dioxide, and lead (EPA, 2021c). The research focuses on the reduction of criteria pollutants, specifically one of the six pollutants in this category, NO_2, caused by anthropogenic sources. The aim of the study is a photocatalytic building facade to improve the urban air quality issue by removing NO_2 in urban areas, thus improving human health and the environment.

The focus of NO_2 in this study is due to its immense negative impact on public health and the environment in urban settings. WHO categorizes NO_2 as one of the key air pollutants that pose health risks (WHO, 2021). NO_2 forms when fossil fuels such as diesel, oil, gas, or coal are burned at high temperatures (American Lung Association, 2021). There are two different concentrations, indoor and outdoor. Outdoor sources of NO_2 form from emissions of internal combustion engines such as cars and trucks (EPA, 2021b) while indoor sources of NO_2 include tobacco smoke, gas, wood, oil, kerosene, and poorly maintained appliances such as stoves, ovens, water heaters, and fireplaces (WHO, 2010). In an outdoor setting, high concentrations of NO_2 in a short period of time can irritate the human respiratory system causing coughing, wheezing, or difficulty breathing (EPA, 2021b). Longer exposures to NO_2 can contribute to the development of asthma and increase susceptibility to respiratory infections (EPA, 2021b).

LITERATURE REVIEW

The proposed research is to develop a photocatalytic facade in improving urban air quality. Our photocatalytic facade uses titanium dioxide (TiO_2) and the UV rays in sunlight to improve air quality by reducing VOCs and NO_2 in the air. UV-A rays with a wavelength shorter than 385nm can excite TiO_2 (Madhusudan, 2003) and this photocatalytic oxidation processes break down NO_2 and organic pollutants into nontoxic gaseous matters such as nitrate, carbon dioxide, and water vapor.

Various other methods and technologies exist to improve air quality. Source reduction, generally speaking, can be a solution depending on the source of pollution. However, source reduction wouldn't lead to the elimination of the pollutants but releasing smaller amounts into the air. A common practice used to improve indoor air quality is to dilute the indoor pollutant concentrations with outdoor air but it has its own challenges. This requires outdoor air to be cleaner than indoor air but weather conditions and contaminants in outdoor air can affect the results. Besides minimizing the sources of pollutants and diluting the indoor pollutants with outdoor air, another method is to use air-cleaning devices which fall into two different categories: HVAC or furnace filters and other duct-mounted air cleaners installed in a central HVAC system and portable air cleaners (EPA, 2018). The EPA states there are commonly two types of air cleaning technologies used in duct-mounted and portable air cleaners. To remove particles in the air, fibrous media air filters and electronic air cleaners (electrostatic precipitators [ESPs] and ionizers) are used. Fibrous air filters remove particles in the air by capturing them on fibrous filter materials. ESPs remove particles in the air by a process that requires electricity to charge particles to become attracted and adhere to oppositely charged plates. Both methods to filter the air require an active system and need electricity.

Several architectural precedents were analyzed to understand the different design strategies deployed from the design of the facade, material selection, material application, program specification, building size, and the intended client to further investigate how TiO_2 is used in architecture.

Carlos Martinez Architekten is an architecture firm based in Switzerland that has designed a curtain wall system for the Raiffeisen Bank's branch in Upper Rhine Valley located in the municipality Oberriet in Switzerland. Completed in 2019, the firm worked with CRE Panel GmbH, an Austrian company specializing in precast concrete to develop an air-purifying wall system. The design of the facade has a strong three-dimensional effect made of fiberglass-reinforced concrete mixed with TiO_2 powder. The idea of adding titanium dioxide was for the wall to absorb the pollution created by cars as they drove to the drive-through ATM. Raiffeisen Bank sees the interior and exterior design of its bank as an important way to communicate its values. However, how much the wall offsets air pollutants is not reported.

Casalgrande Padana is an Italian-based company manufacturing ceramic tiles for over 60 years. Casalgrande has partnered with Japanese group TOTO to use their patented Hydrotect® technology, a photocatalytic purification technology. With this technology, Casalgrande has developed a facade cladding solution, Bios Self-Cleaning® ceramics. The ceramic tiles were used by formally Berlin-based architecture firm, Studio Libeskind in their 2017 project Sapphire in Berlin, Germany. The facade design is a signature design by architect Daniel Libeskind for Casalgrande Padana. Casalgrande claims that strict lab tests conducted have proven Bios Self-Cleaning® does not diminish over time. In an accelerated aging test conducted, results were comparable to conditions of 50 years of outdoor exposure. Casalgrande states that 1000 square meters (10,763 square feet) of Bios Self-Cleaning® can purify the air similar to a forested area the size of a football pitch. Removal is the equivalent of NO_2 emitted by 70 cars in one day. Though Casalgrande makes these claims, the exact reduction of the ceramic tiles used on the project Sapphire is not stated.

Italcementi is an Italian company acquired by HeidelbergCement that produces and sells cement, ready-mix concrete, and aggregates. Italcementi has a patented product i.active that has photocatalytic properties due to its formula. One of the projects that used their technology is the Italy Pavilion Milan Expo completed in 2015 designed by Italian-based architecture firm Nemesi. The project consists of over 700 panels made from i.active BIODYNAMIC concrete which has patented TX Active technology, the photocatalytic principles for cementitious products. In the project, 2,000 tons of i.active cement was used resulting in 9,000 square meters of external surfaces. Italcementi claims that 1,000 square meters of TX active products are equivalent to 100 deciduous trees, eliminating the pollution caused by 22 petrol vehicles or 16 diesel vehicles. Based on Italcementi's estimation, the Italy Pavilion Milan Expo is calculated to be equivalent to 900 deciduous trees eliminating the pollution caused by 198 petrol vehicles or 144 diesel vehicles.

DESIGN INTERVENTIONS

With an imperative to address anthropogenic pollutants and climate emergencies, our photocatalytic building facades can play an important role in improving urban air quality. A considerable amount of research has shown the effect of photocatalytic air-purifying materials in reducing NO_2 for architectural applications such as concretes, paints, and mortars (Carssar et al. 2003 and Carssar et al. 2007), in which UV induced photocatalytic effect from material surfaces eventually breaks down harmful gases into benign matters such as CO_2 and vapor. This paper explains a feasibility study of photocatalytic facades coated with a thin layer of nanocrystalline titanium dioxide (TiO_2) for air pollution abatement.

Our system was configured as a photocatalytic window system that offers multiple benefits including NO_2 reduction, solar regulation, daylight penetration, and view-out. The NO_2 removal rate varies depending on TiO_2 coated area, airflow rate, and air turbulence (Chen and Poon 2009). For maximum TiO_2 contact areas with minimum material usage, our photocatalytic system utilized tetrahedron geometry, an exterior surface shape of which is an equilateral triangle. Another design consideration was to accommodate view-out and daylight penetration, resulting in porous surfaces with open and closed triangles. The inclusion of porosity within this 3D tetrahedron façade system is expected to slow down airspeed and lengthen TiO_2 contact time. The porosity level and size of the equilateral triangles were the balance between different performance goals such as NO_2 abatement, solar control, daylighting transmission, and occupant view-out.

As shown in Figure 1, our photocatalytic system can turn into two façade applications: a single façade system and a double façade system. The single façade system is to install the photocatalytic system in front of a window, allowing direct exposure to outdoor conditions. The double façade system is to integrate the air depolluting system in an air cavity separated by an inner window and outer glass panel. The distinct difference between the single façade and double façade applications lies in the controllability of outdoor environments. While the single façade application cannot regulate airflow behaviors, the double skin façade can control the target volume and the speed of intaking air flows depending on sunlight intensity. Relative humidity is another known factor that affects photocatalytic efficiency (Beeldens 2010). The double façade system can also maintain the optimum relative humidity in the air cavity environment.

Research on evaluating the durability of photocatalytic efficiency has shown debatable results. Hassan et al. studied the durability and photocatalytic performance of concrete pavement samples with 3% and 5% content of TiO_2 (Hassan et al. 2010). The study indicated no wearing sign of TiO_2 under 20,000 loaded-wheel and abrasion tests. In addition, the NO_2 removal efficiency from the original sample with 3% and 5% TiO_2 concentration was measured at 18% and 26.9% respectively. The photocatalytic efficiency after weathering the samples showed similar photocatalytic performance. Cedello-Gonzalez et al., on the other hand, reported that dramatic reductions of the durability and photocatalytic efficiency of TiO_2 were measured after different weathering conditions were applied (Cedillo-González et

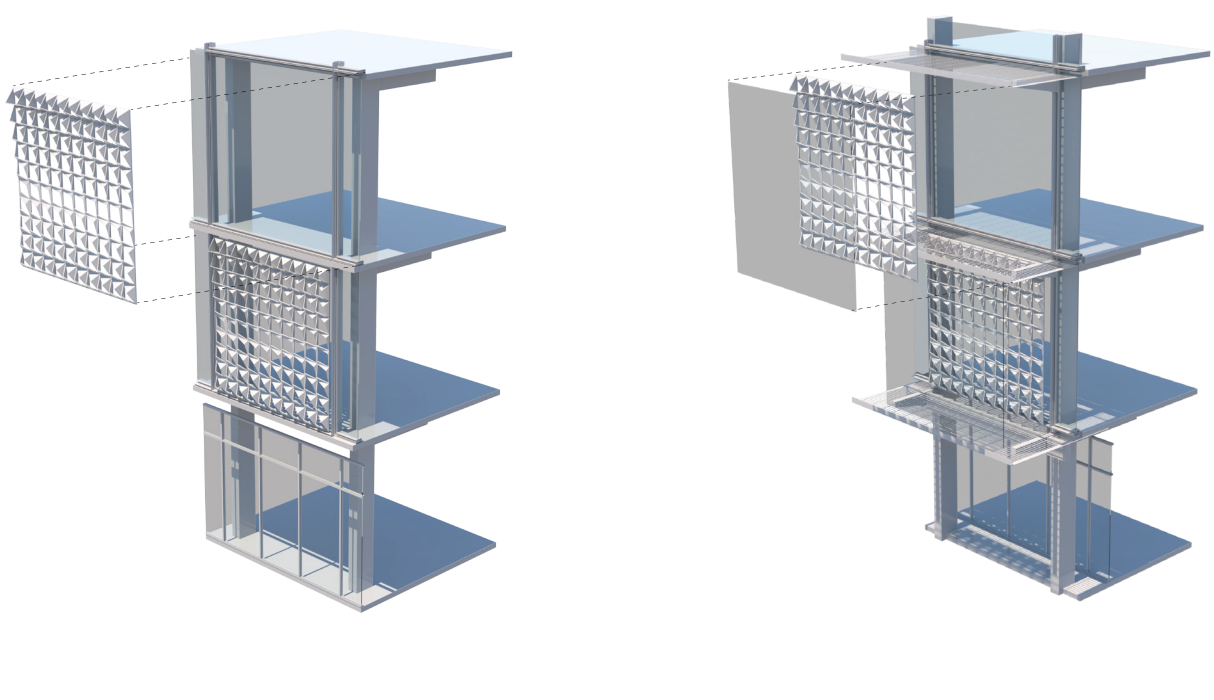

Figure 1 Architectural applications of photocatalytic facades: (a) single facade consisting of a photocatalytic system installed in front of the window and (b) double facade consisting of a photocatalytic system installed in an air cavity separated by inner window and outer glass panel.

al.2018) We plan to carry out further research on the long-term durability of NO_2 removal efficiency for outdoor applications.

PHYSICAL EXPERIMENTS

4.1 EXPERIMENT SETUP

There are five essential elements to conduct the experiments: photocatalytic facade samples, testing chamber, sensors & data logger, pollutant gases, and UV light (Figure 2). For the facade sample preparation, we coated 3D printed models (30cm x 30cm in PLA) with TiO_2 paste made by mixing TiO_2 powder with water. The facade samples were left dry naturally to remove moisture content from the facade.

Five sides of the testing chamber are made of 36cm x 36cm acrylic panels sealed with low-VOC silicone sealant. The lid is made of 6mm thick single pane clear glass to maximize UV light penetration. A rigid foam board is placed between the glass panel and the five acrylic panels to ensure air tightness while having the convenience of easily taking on/off the lid for conducting experiments.

A set of sensors was used to monitor the testing chamber. An Enviro+ sensor by Pimoroni is used to measure temperature, humidity, and NO_2 concentration.UV-A intensity from the sunlight is measured by the VEML6075 light sensor made by Sparkfun. Data from each sensor was collected at a 10-second interval by a Raspberry Pi Zero and the arithmetic mean over one minute period is used for analysis. The entire system is powered by a solar-powered rechargeable battery.

To closely represent the air pollution in reality by the internal combustion engines, we used car exhaust from a 2014 passenger car with a total mileage of 116,000 miles. A flexible aluminum hose is used to hook up the car exhaust pipe on one end and the testing chamber on the other to directly supply pollutant gases for the experiments. An 80mm fan powered by the same battery is used to circulate the air in the chamber for a more even air mixture. The experiments were conducted under a partly cloudy sky to utilize the UV-A rays in the natural sunlight to activate the TiO_2 on the facade samples.

4.2 SENSOR CALIBRATION

The Enviro+ sensor uses a MiCS 6814 chip by Sensortech to measure NO_2 concentration. Each sensor needs to be calibrated by end users using NO_2 gas with known concentration. For this experiment, we used a 5ppm NO_2 gas canister from Macurco to calibrate the sensor. The sensors were exposed to 5 ppm NO_2 gas in an airtight compartment for more than five hours until the sensor values were stabilized. The sensor measured a mean resistance of 49.8kOhm with a standard deviation of 1.3 kOhm.

4.3 EXPERIMENT PROCEDURE

Before conducting each experiment, the sensors and the Raspberry Pi had been operated for 30 minutes continuously

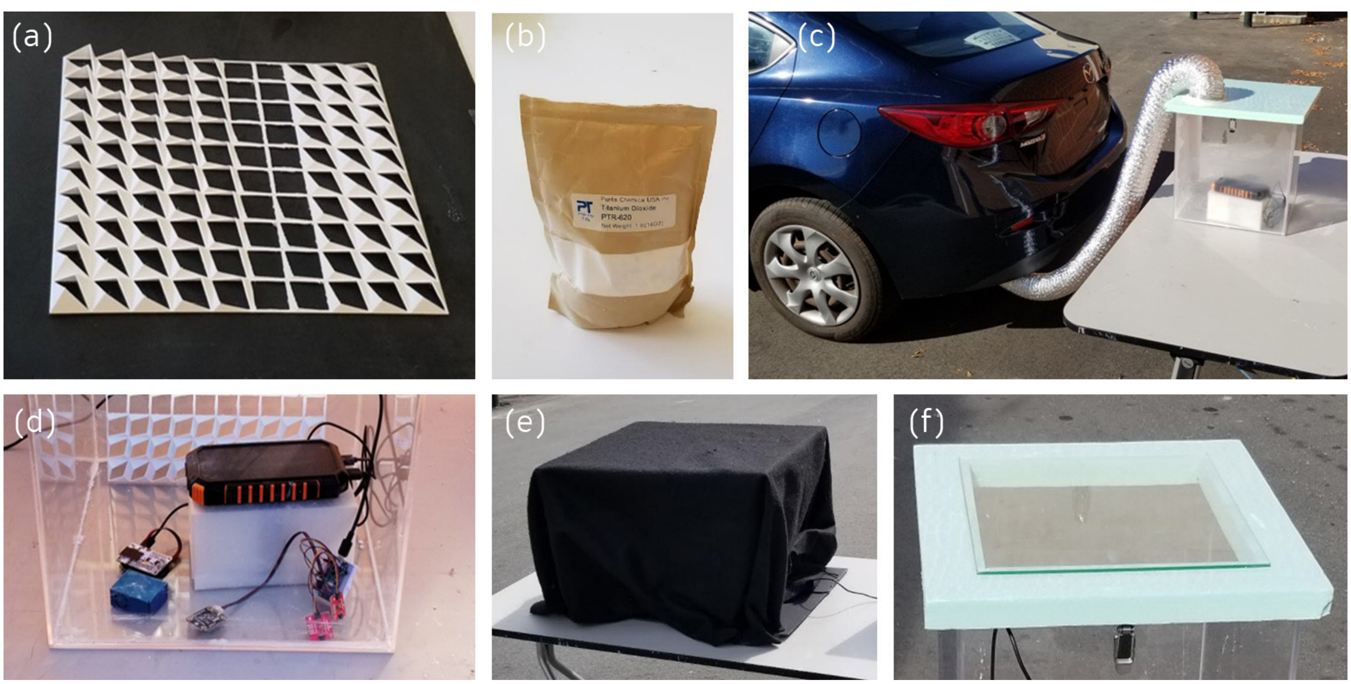

Figure 2 Experiment Setup. (a) Photocatalytic facade sample, (b) TiO2 Powder, (c) Testing chamber and pollutant gases, (d) Sensors and data logger, (e) Black cloth for the control experiment, (f) Glass lid with rigid foam

to warm up the sensors. Then the facade sample coated with TiO_2 was placed in the testing chamber alongside the sensing/data logging system, the fan, and the battery. The car was then started and idled for roughly a minute until the engine rotation speed dropped under 1000 RPM to prevent the initial gasoline-rich exhaust from entering the testing chamber. The flexible aluminum pipe hooked up to the car exhaust on one end was then connected to the test chamber to fill in the pollutant gases for one minute. The lid was capped immediately after the aluminum pipe was unplugged. A cardboard box was put on the testing chamber, and a black cloth was put on the top of the cardboard box to prevent the UV rays from activating the TiO_2 on the sample facade. The control experiment was run for 28 minutes to observe the NO_2 concentration without catalytic reaction. The black cloth and the cardboard box were then removed to expose the facade sample to sunlight for 24 minutes to test NO_2 reduction.

4.4 RESULTS

Test results show that NO_2 concentration increased steadily in the control experiment without UV exposure (the first 28 minutes). When the photocatalytic facade was exposed to sunlight, NO_2 concentration noticeably decreased over time. The speed of NO_2 reduction and the UV-A intensity showed a positive correlation, i.e. the stronger the UV radiation, the faster the NO_2 reduction. More specifically, the experiment was conducted under a partially cloudy sky and the UV-A intensity fluctuated between 10 and 30 w/m2. When clouds were temporarily cleared for a few minutes in the 31-36 minutes section, the UV-A intensity was increased to over 30 w/m2 where the NO_2 showed a steeper reduction rate.

CONCLUSION

Air pollution has become more prevalent in the built environment and protecting human health has increased in priority. We have carried out a prototyping and performance verification of a photocatalytic façade system in mitigating urban air pollutants. With potential architectural applications in single façade or double façade systems, our TiO_2 photocatalytic system aims to abate urban air pollutants such as NO_2 or other organic pollutants. In addition to photocatalytic efficiency, the system also incorporates additional environmental benefits from solar control, daylight penetration, and occupant view-out. The tetrahedron geometry of the photocatalytic system allows the maximum TiO_2 contact area using the least amount of materials. The integration of the photocatalytic system within an air cavity of the double-skin façade allows the control of optimum environments for photocatalytic performance including pollutant concentration, airflow velocity, and humidity level. In our lab experiments, a small-scale photocatalytic facade coated with TiO_2 has shown noticeable NO_2 reduction with the presence of sunlight. In addition, the intensity of the UV rays is positively correlated with the reduction rate of NO_2. Future studies include longevity testing, different coating methods, and different substrate materials. This study is conducted as proof of concept that building facades coated with TiO_2 can reduce air pollutants emitted from car exhaust.

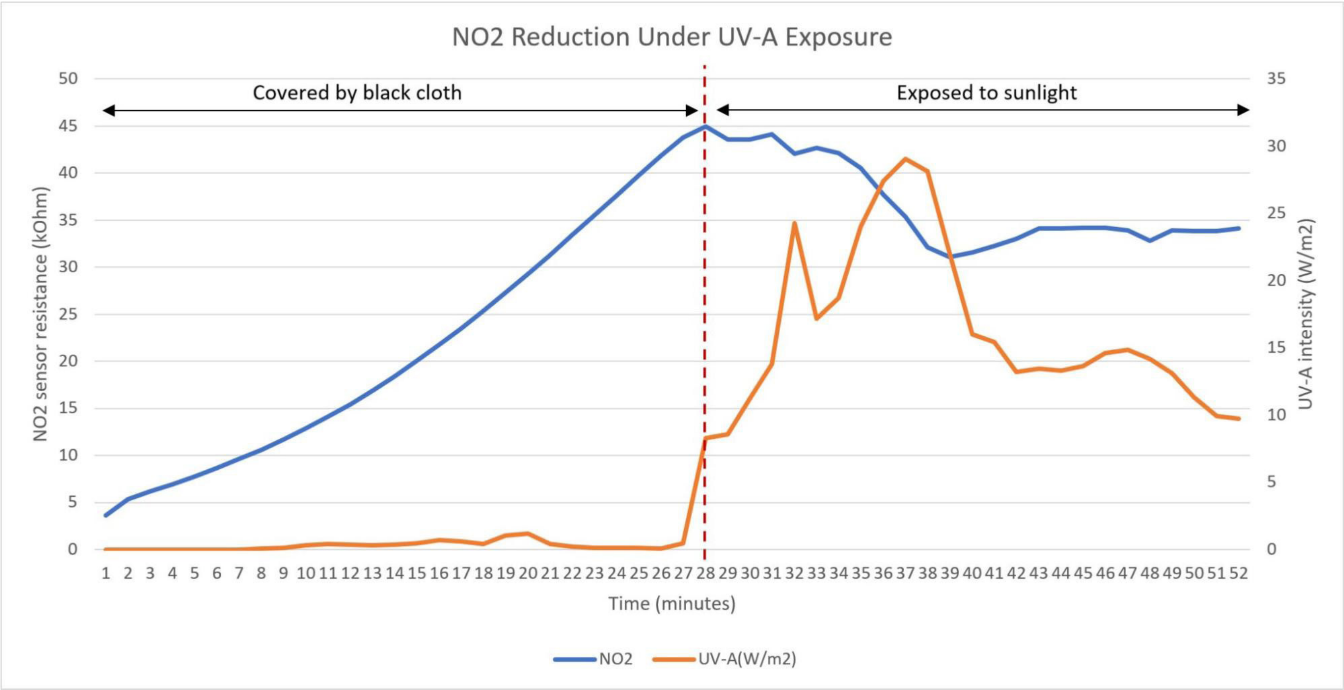

Figure 3 NO2 reduction under UV-A exposure

ACKNOWLEDGMENT

This research is funded by the 2020 NSF I-Corps Team program.

REFERENCES

1. American Lung Association. "Nitrogen Dioxide." Lung. American Lung Association. Accessed October 11, 2021. https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/nitrogen-dioxide.
2. Beeldens, Anne. "An environmental friendly solution for air purification and self-cleaning effect: the application of TiO2 as photocatalyst in concrete." Proceedings of transport research arena Europe–TRA, Göteborg, Sweden (2006).
3. Cassar, L., A. Beeldens, N. Pimpinelli, and G. L. Guerrini. "Photocatalysis of cementitious materials." In International RILEM symposium on photocatalysis, environment and construction materials, vol. 1, pp. 131-45. RILEM, 2007.
4. Cassar, Luigi, Carmine Pepe, Giampietro Tognon, Gian Luca Guerrini, and Rossano Amadelli. "White cement for architectural concrete, possessing photocatalytic properties." In Proceedings of the 11th International Congress on the Chemistry of Cement, vol. 4, pp. 2012-2021. 2003.
5. Cedillo-González, Erika Iveth, Virginia Barbieri, Paolo Falcaro, Leticia M. Torres-Martínez, Isaías Juárez-Ramírez, Laura Villanova, Monica Montecchi, Luca Pasquali, and Cristina Siligardi. "Influence of domestic and environmental weathering in the self-cleaning performance and durability of TiO2 photocatalytic coatings." Building and Environment 132 (2018): 96-103.
6. EPA. (2018, July). Residential Air Cleaners. EPA. Retrieved October 12, 2021, from https://www.epa.gov/sites/default/files/2018-07/documents/residential_air_cleaners_-_a_technical_summary_3rd_edition.pdf.
7. EPA. "Basic Information about NO2." EPA. Environmental Protection Agency. Accessed September 30, 2021b. https://www.epa.gov/no2-pollution/basic-information-about-no2
8. EPA. "NAAQS Table." EPA. Environmental Protection Agency. Accessed October 20, 2021c. https://www.epa.gov/criteria-air-pollutants/naaqs-table
9. EPA. "Outdoor Air Quality." EPA. Environmental Protection Agency. Accessed September 30, 2021a. https://www.epa.gov/report-environment/outdoor-air-quality
10. MAGGOS, Th, J. G BARTZIS, M LIAKOU, and C GOBIN. "Photocatalytic Degradation of NOx Gases Using TiO2-Containing Paint : A Real Scale Study." Journal of hazardous materials 146, no. 3 (2007): 668–673.
11. United Nations World Population Estimates, and Projections. Department of Economic. World Population Prospects: the 2004 Revision. Vol. 2. UN, 2005.
12. WHO Guidelines for Indoor Air Quality : Selected Pollutants. Geneva: World Health Organization, 2010.
13. WHO. "Ambient (Outdoor) Air Pollution." WHO. World Health Organization, September 22, 2021. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.