Comprehensive Analysis of Volatile Organic Compounds (VOCs) and Particulate Matter (PM) in Indoor air: Effects of Nano-layering VOCs using Catalytic Metal Oxides

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ABSTRACT

Indoor Air Pollution causes 1.6 million premature deaths annually and puts 3.8 billion people at risk globally (1). Volatile Organic compounds (VOCs) are chemicals that vaporize and make indoor air unhealthy. These can vary from minor irritants to potentially carcinogenic compounds. This research is a multi-phase project concerning the effects of VOCs on Particulate Matter (PM). In the first phase of this research, it was established that VOCs significantly increased the PM concentration in the air. The current research focuses on reducing the impact of VOCs using metal oxides, mainly Titanium Dioxide, Magnesium Oxide, and Zinc Oxide. The VOC tested in this research was sodium hypochlorite, a common household cleaner and a very potent VOC. The metal oxides were tested both in non-nano and nano forms. The metal oxides powders were deposited on the VOCs using dip coating methods, involving an ethanol substrate. PM monitor data suggested that titanium dioxide was most efficient followed by Zinc oxide in reducing PM concentrations. The non-nano metal oxides, mainly titanium dioxide, showed a remarkable decrease in PM particles, by around 200 µg/m3 less. The presence of light impacted certain data trials, but especially titanium dioxide as it is photocatalytic. This research can be expanded to create safer household chemicals coated finely with metal oxides using the Lang-Muir-Blodgett method. The utilization of these coatings can result in the development of healthy building materials like paints, surfaces, and countertops that will limit the detrimental effects of VOCs. This project is an attempt to offer insight into this less recognized yet highly crucial aspect of Volatile Organic Compounds and their interaction with the indoor environment. The overall goal of this multiphase research is to contribute towards understanding and developing solutions to improve the quality of indoor air.

INTRODUCTION

Indoor Air Pollution is responsible for 4.1% global deaths annually (2). The issue of Air pollution has two contexts- Outdoor Air Pollution and Indoor Air pollution. Indoor Air pollution is generally attributed to use of fossil fuels like coal and wood for household purposes like cooking or warming the indoors. However, there are other less studied indoor air pollutants like Volatile Organic compounds (VOCs) and aerosols, commonly found in household cleaners, fresheners, varnishes, paints etc (3). VOCs refer to any solid or liquid chemical that emits vapours harmful to human health. Indoor spaces are crucial to human health considering that a major amount of individual’s day is spent within spaces like home, school, workplace, hospitals, businesses and so on. Yet, indoor air remains a relatively less researched topic despite its critical role in the human respiratory health at a global level.

Particulate Matter (PM)

Particulate Matter is defined as microscopic particles of solid or liquid matter suspended in the air (2). There are three magnitudes or diameter sizes of PM. These are PM_1, $PM_{2.5}$, and PM_{10}. These can also be represented as PM 1, PM 2.5, and PM 10. Varying sizes of PM particles are exposed to our lungs at varying levels as shown below[4] (Figure 1).

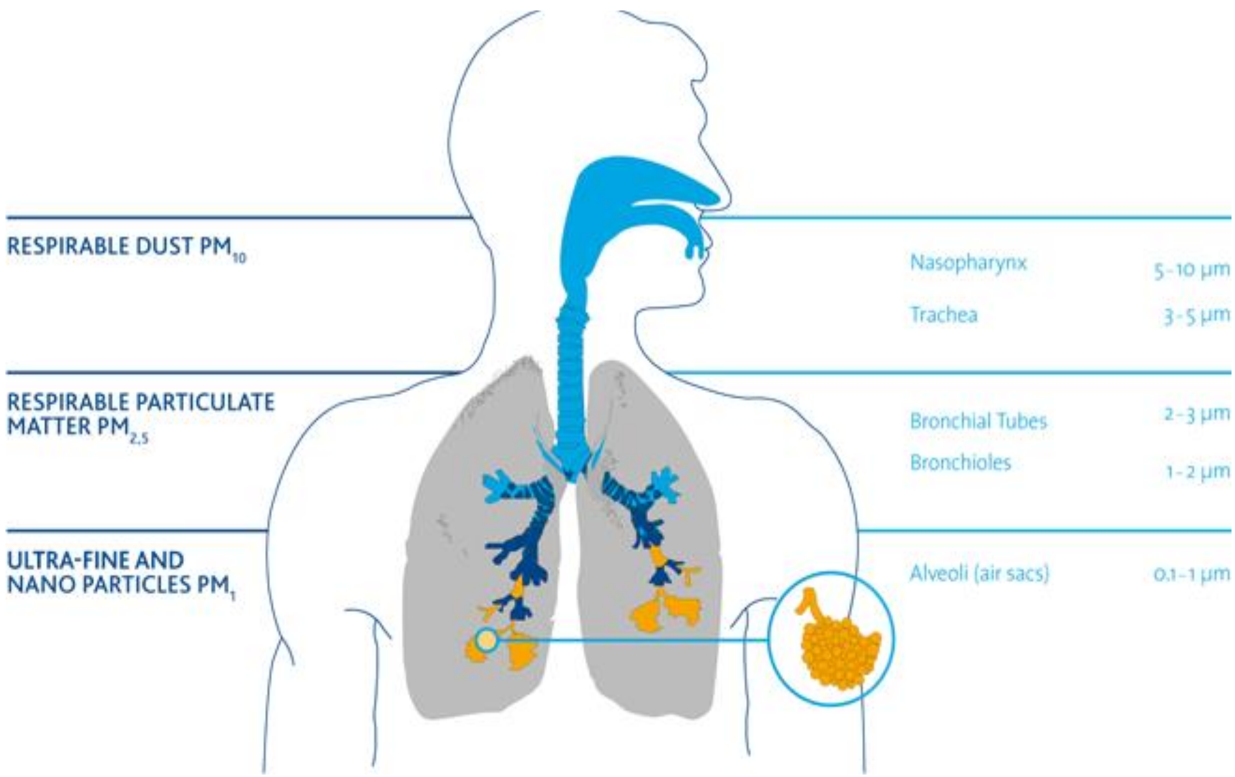


Figure 1: Particulate Matter Types

Volatile Organic compounds (VOCs)

Volatile Organic Compounds (VOCs) can be defined as organic chemicals that have a high vapor pressure at ordinary room temperature (4). This means that chemicals used in processes like wood furnishing or polishing, over time can turn into fumes and then be inhaled. Some VOCs, toxic in nature like Formaldehyde, are becoming a part of our daily lives. Some extremely common, and potentially hazardous VOCs include Alcohol, Butanal, Ethanol and Acetic Acid.

Phase 1 Research

The phase 1 of this research established that VOCs have a direct impact on the PM concentration in the air. This phase also established that VOCs are more potent than aerosols in driving the PM concentration to higher levels. Hence, with this as the basis a very potent VOC was taken as the base for conducting the Phase 2 of this project.

Purpose of Current research (Phase 2)

Several indoor activities like vacuuming, cooking, cleaning and disinfecting result in release of dust particles and/or potent chemicals into the indoor air. These can vary from minor irritants to chemicals that are potentially carcinogenic. The current research expands on the previous finding and focuses on the prevention and oxidation of these vapours using metal oxide nano coatings. The scope of this research is to reduce VOCs through the modern technology of nano-layering (7), specifically of Titanium Dioxide, Magnesium Oxide, and Zinc Oxide (5, 6). These metal oxides were chosen after meticulous research and because of their poor reactivity with VOCs and other chemicals or surfaces. The specific purpose of this phase is to test various metal oxides in both nanopowder and non-nano powder forms to determine the best formulation that prevents the oxidation of VOCs and consequently reduces PM buildup in the indoor air. The findings can have strong implications for the way these chemicals are produced and making them safer for indoor air.

HYPOTHESIS

1. *If the source of VOCs is evenly coated with metal oxides, then the resultant Particulate Matter concentration in air will decrease.*
2. *Titanium Dioxide would be the most effective metal oxide in reducing PM concentration.*

Independent Variable	Dependent Variable	Constants	Control Tests
Visible Light (lux)	Particulate Matter (μ/m^3) - Pm 1 - Pm 2.5 - Pm 10	Temperature (Celsius)	No VOC- baseline test- included results of humidity, temperature, and all three PM magnitudes
Metal oxides (g): Nanoparticle for TiO_2, MgO, ZnO Non-nanoparticle powders for the same metal oxides.		Humidity (%): humidity can impact PM readings, and thus must remain constant	Only VOC – to be contrasted to when the VOC is accompanied by metal oxides or presence of light.
Sodium Hypochlorite (VOC, ml)		Controlled environment	Only ethanol- ethanol was used as a base to mix the nanoparticle metal oxides. To ensure it had no impact on the PM readings, it was tested separately as a control.

Table 1. Variables and Constants

The Particulate Matter concentration is measured in µg/m^3 (Table 1). One of the most potent VOC used on household cleaning, Sodium Hypochlorite was used for this research. In the first phase, this VOC increased PM concentrations as high as 415 µg/m^3.

RESULTS AND DISCUSSION

Baseline and control tests

The graphs below show the Particulate Matter concentration for PM 10 particles on the y-axis and time in seconds for trials on the x-axis. It was observed that only PM 10 particles were the most significant when studying the impacts of VOCs on PM, and thus to represent data more clearly, the graphs included only PM 10. The changes to PM 1 and PM 2.5 can be described as extremely similar, but less dramatic. This observation was in line with phase 1 of the study.

The control tests are used to define baseline conditions. The control test was to characterize the conditions in absence of any VOCs (Figure 2).

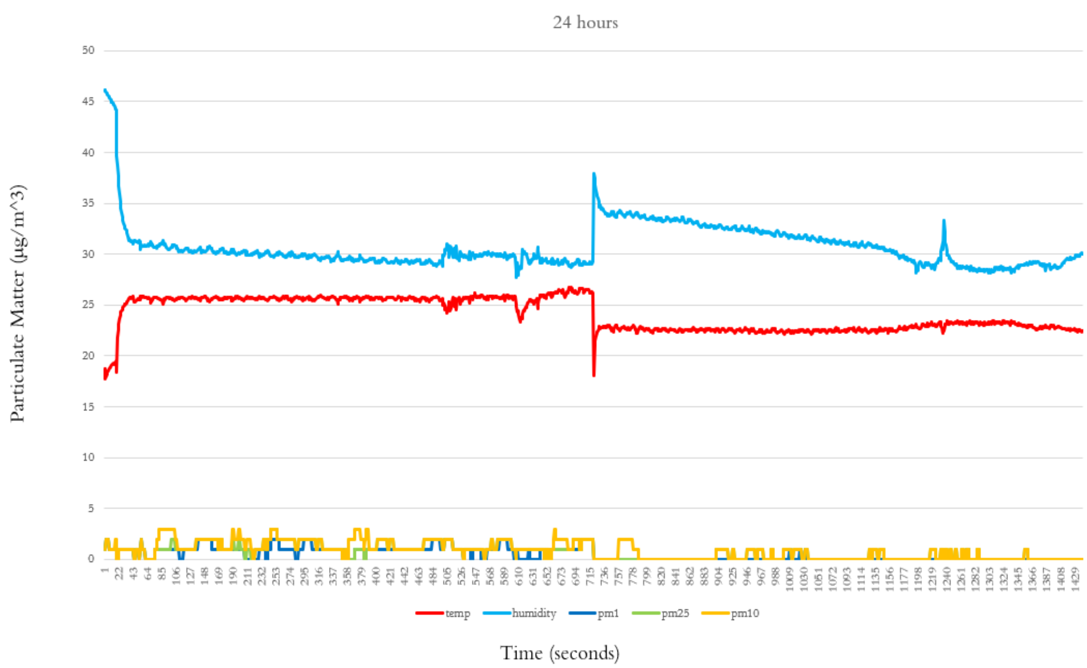


Figure 2: Control Test (No VOC exposure)

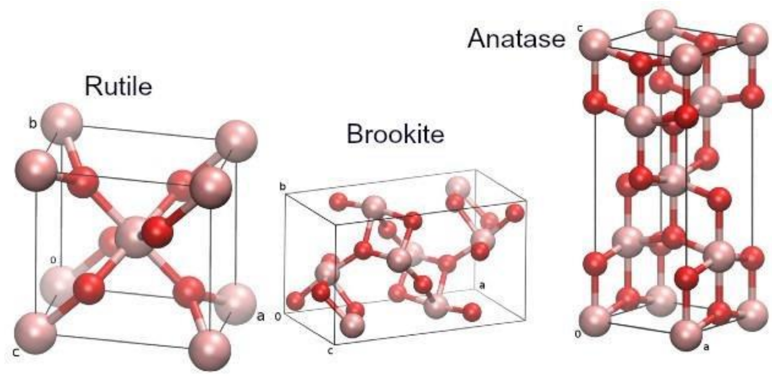
Effects of Nano-layering Titanium Dioxide (TiO_2) on VOC

Characteristics

Non-nano powder Specifications

Texture: Coarse powder **Color**: white **Observations**: Used as a colorant. Insoluble in water, results in a viscous slurry. **Purity:** 100% pure

Nanoparticle Specifications (8)

Titanium Dioxide (Anatase) 15nm, Purity 99% **Structure**: O = T = O **Color**: White **Form**: Powder **Morphology**: spherical **Bulk density**: 0.04 - 0.06 g/cm3 **True density**: 3.9 g/cm3 Usually used in paints or as a coloring agent.	

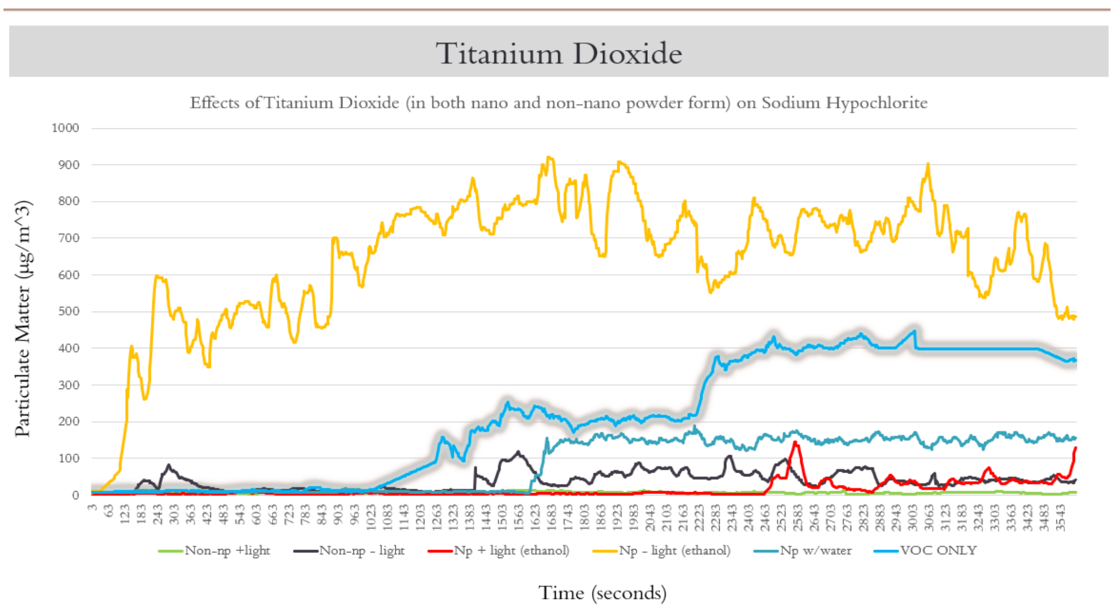


Figure 3: Effect of Titanium Oxide on PM Concentrations

Titanium dioxide trials showed that all variations of trials reduced PM readings in response to VOC exposure, except the trial with nano form of Titanium dioxide without light (Figure 3). This extreme increase in PM readings in this trial was difficult to explain. The only possible explanation will be the absence of light in this trial. All other trials showed a strong potency of this metal oxide in reducing VOCs.

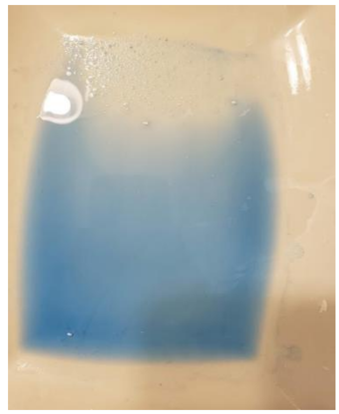
		
Titanium in water, non-nano	Titanium nanopowder, water	Titanium nanopowder, ethanol
Uneven layering	The texture is different from ethanol, thicker solution, even coating	Most successful with the lights ‘on’, photocatalytic property exhibited. Even coating

Table 2: Nano layering Titanium Oxide on VOC

Results of Nano layering Zinc Oxide (ZnO) on VOC

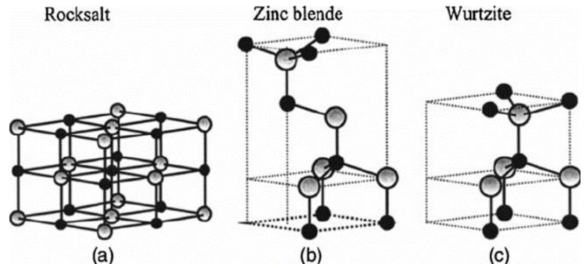
One of the metal oxides tested for the reduction of VOCs was Zinc Oxide. It was tested in both nano and non-nano powder form.

Characteristics

Non-nano powder Specifications

Texture: Coarse powder **|** **Color**: white **Observations**: USP pharmaceutical, non-nano, uncoated. Great for salves, creams, lotions, and ointments. **Purity:** 100% pure

Nanoparticle Specifications (9)

Zinc Oxide, 20 nm, Purity 99% **Structure**: Zn = O **Color**: White **Form**: Powder **Morphology**: spherical **Bulk Density:** 0.1-0.2 g/cm3 **pH value:** 6.5-7.5 ZnO rocksalt formation, closest to powder	

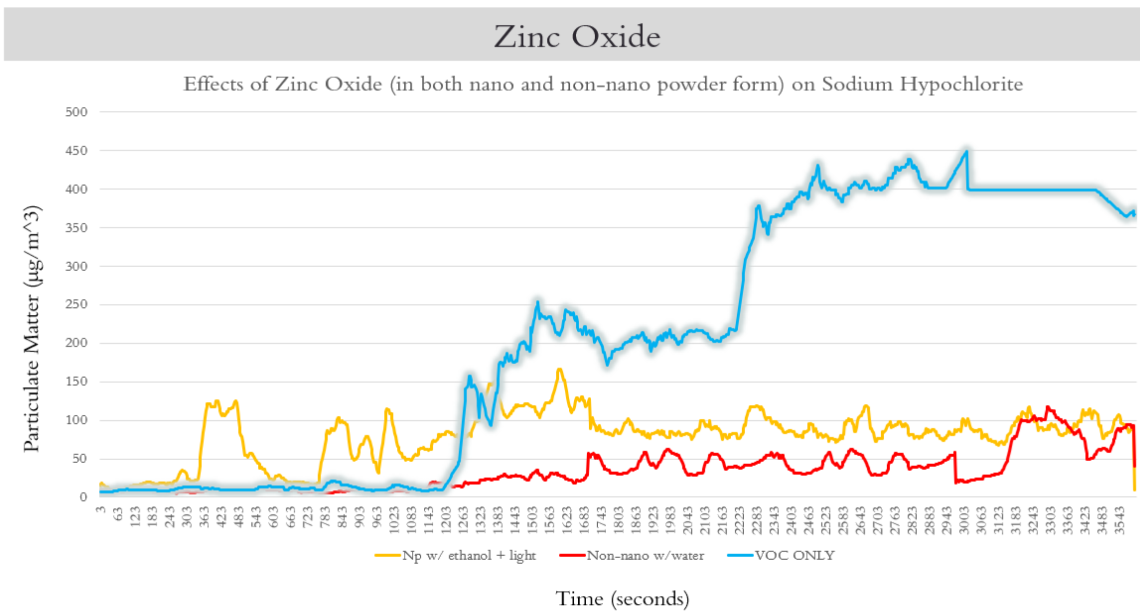


Figure 4: Effect of Zinc Oxide on PM Concentrations

All trials for zinc oxide (figure 4) showed dramatic reductions in PM readings indicating the effectiveness of this metal oxide. Both regular and nanoforms of zinc oxide were effective in the presence of light, again suggesting the role of photocatalysis. Zinc oxide like Titanium dioxide was also a promising solution to catalyzing VOCs.

		
Testing ZnO, non-nano, water	ZnO nanoparticles, water	ZnO nanoparticles, ethanol
Uneven coating	Uneven Coating	Even coating

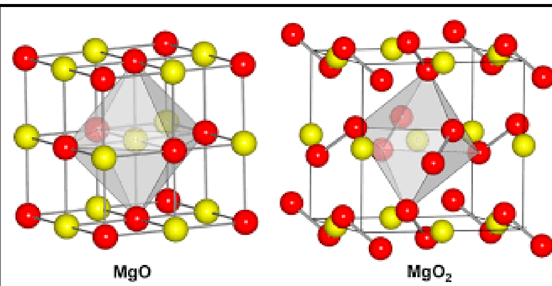
Table 3: Nano layering Zinc on VOC

Results of Nano layering Magnesium Oxide (MgO) on VOC

The third metal oxide tested for the reduction of VOCs was Magnesium Oxide. It was tested only in nanopowder form. This is because the non-nano powder is used as antacids and for other medical purposes and is hard to get in pure form.

Characteristics

Nanoparticle Specifications (10)

Magnesium Oxide 20nm, Purity 99% **Structure**: Mg = O **Color**: White **Form**: Powder **Morphology**: spherical **Bulk Density:** 0.1-0.3 g/cm3 **pH value:** 7.5-8.5 ZnO rocksalt formation, closest to powder	

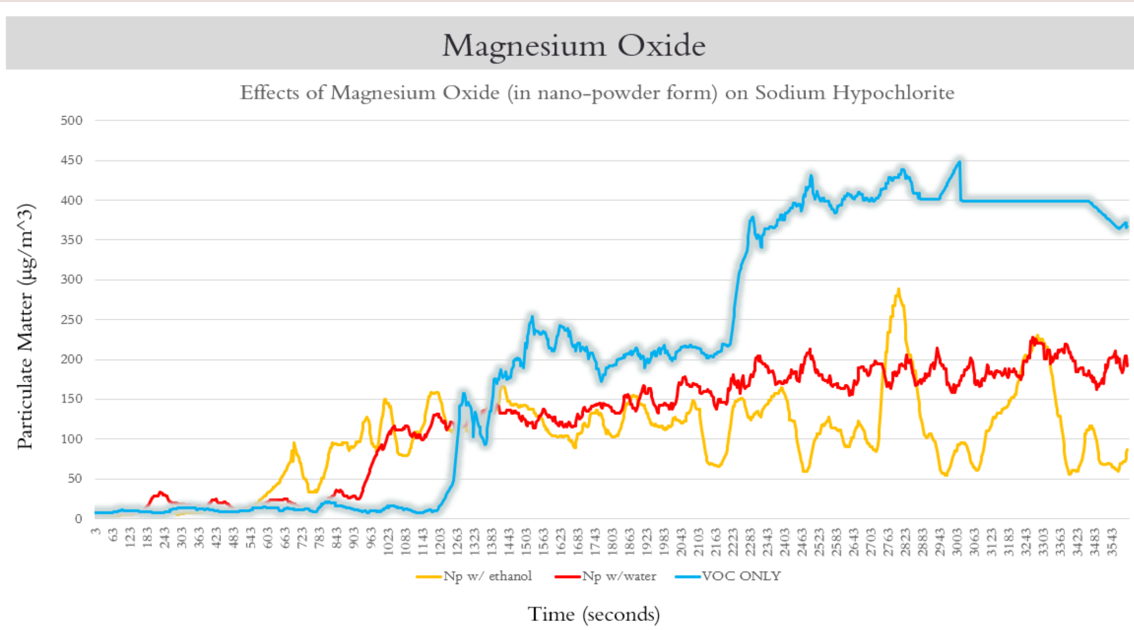


Figure 5: Effect of Magnesium Oxide on PM Concentrations

All trials of the Magnesium oxide nanopowder (figure 5) indicated moderate to almost mild impact on reducing VOCs. As can be seen in graphs, the PM readings were considerably high suggesting that Magnesium oxide might not be a potent oxidizer of this VOC.

		
MgO in ethanol, nanopowder	MgO nanopowder in VOC, ethanol base	MgO nanopowder in water
Turned green-ish on reaction	Even coating	Mixed well, even coating

Table 4: Nano layering Magnesium Oxide on VOC

The comparison of all metal oxide trials shows that Titanium dioxide showed the most promising results and PM reduction. It was noticed that within the nanoparticles, the ethanol base was the most effective. Titanium dioxide was also extremely photocatalytic, especially in the nanopowder version. Zinc Oxide also yielded a good reduction in PM levels. These results indicate that metal oxides are effective in reducing the detrimental effect of VOCs on indoor air.

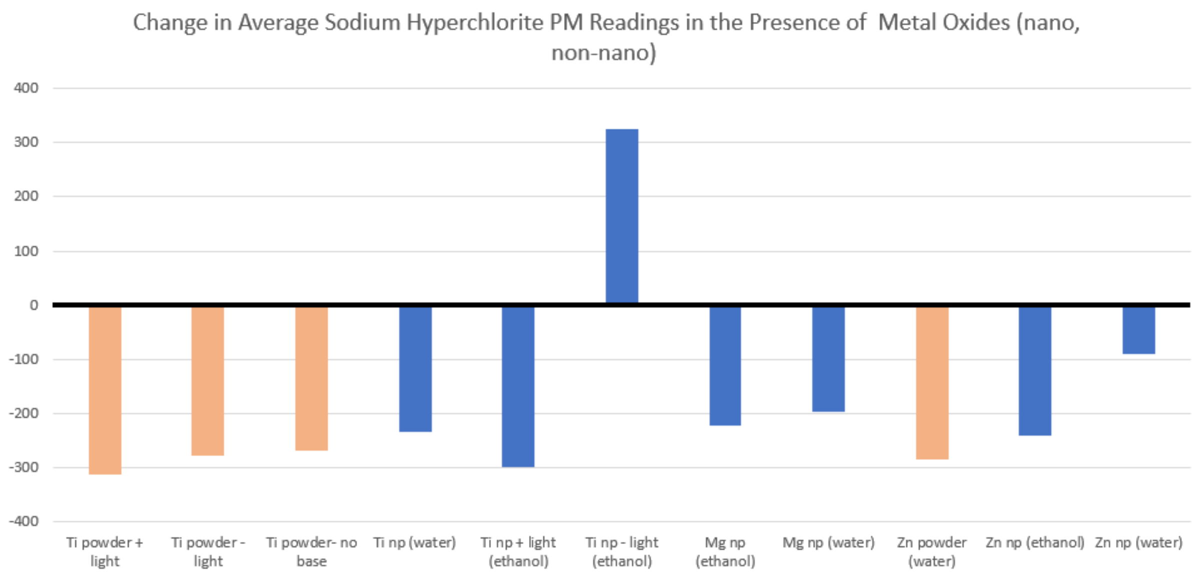


Figure 6: Comparison of Metal oxides for their reduction of PM concentrations (y-axis: PM 10 concentration (microgram/meter cube) | x-axis: the trials)

CONCLUSION

The current project focused on the reduction of PM particles caused by VOCs using metal oxide nano coatings The main findings are summarized below-

1. The non-nano powders were more effective and practical, with Titanium dioxide being the most effective, especially in the presence of light due to its photocatalytic property. The hypothesis was proven.
2. Zinc Oxide and Magnesium Oxide both decreased the PM readings, but not as significantly as Titanium Oxide.
3. The presence of light was important for Titanium Dioxide. Natural light was used and was sufficient for the purpose and UV light was not needed.

4. These findings can be used to inform the ways to create safer household products that do not deteriorate indoor air.

Future Research and applications

1. Testing more types of VOCs, especially Toluene, which has common use in households.
2. Testing more kinds and combinations of metal oxides that have similar potential.
3. Coating of nano-metal oxides on VOC molecules using the Lang-Muir-Blodgett method, which requires technical equipment (11).
4. Developing commercial techniques for safely and effectively coating the nanolayers of these metal oxides on surfaces, building materials like paints, countertops, etc. with the overall aim of developing healthier products, buildings and indoor spaces (12, 13).

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SUPPLEMENTAL INFORMATION

Materials

Raspberry Pi Monitor (developed last phase)
Metal Oxide Powders (15-20g/trial):
Titanium Dioxide
Zinc Oxide (non-nano)
Water (30-40 ml/trial)
Oil (30-40 ml/trial)
Ethanol (30-40 ml/trial)
Beakers: 50 ml and 100 ml
VOC source: Sodium Hypochlorite (10-12%) strong with other similar vocs
Magnetic Stirrer with hot plate
Nano powders: (5-7 g/trial)
Titanium Dioxide (Anatase) 15nm, Purity 99%
Zinc Oxide 20 nm, Purity 99%
Magnesium Oxide 20nm, Purity 99%
Glass plate for testing
Safety equipment: gloves, goggles, towels, water,
first aid
Excel®: for graphing
MobaXterm®: SSH and data collection

Procedure

Main Setup:

1. Set up the monitor from the last phase using the prosecute established then. Amend the code if needed.
2. In a controlled room, take a base test to ensure the accuracy of the monitor. The base test, if accurate, will also help form a control test without VOCs.
3. Then take a base test using Sodium Hypochlorite only. This is the main focus of the project.
4. Now set up the area for testing.
5. Set up a plate for the chemicals, and next to it an area for the monitor.
6. Use MobaXterm for the SSH connection and data collection, and Excel to graph the readings.

Testing Metal Oxide Non-nano Powders:

7. For the testing of metal oxide non-nano powders, first, test the nature of Sodium Hypochlorite in oil and water.
8. Using this information to make sure there is no reaction, now set up the trials for TiO_2 and ZnO respectively.

9. Then test the TiO_2 mixed with oil, and then water. Also, switch between be light on and light off as there are instances of photocatalysis in titanium dioxide.
10. This will be done by pouring 30-40 ml of Sodium Hypochlorite on the plate. This plate must be glass so that there is no reaction.
11. Stir the metal oxide, around 15 grams in 30 ml of water or oil, and then evenly spread on the surface of the VOC.
12. Leave the lights on or off depending on the trial and leave the controlled area undisturbed.
13. Most trials will run for around 4 hours, even though the data set aimed for is one hour. This will help collect the most data possible, and ensure that the timing is not limiting the observations.
14. Do the same for zinc oxide.
15. Collect the readings and conduct multiple trials.
16. **Note**: ensure the constants like temperature and humidity do not change.

Testing Metal Oxides Nano Powders:

17. For the nanopowders, a similar process will be followed although there will be more variations. These are the different bases, which are water and oil. The other variation is with the light on and lights off.
18. There is also an additional metal oxide, magnesium oxide, which was not tested as a non-nano powder as that is used for medical purposes and would be unideal to use in chemical contexts.
19. Take a base test for VOC and only ethanol.
20. For the preparation of the solution, use the nanopowder and mix it in the base using the magnetic stirrer.
21. Use 5-7 grams of nanopowder with around 15-30 ml of water/ethanol.
22. As the base thins the VOC, it does not need to mix using a magnetic stirrer. The magnetic stirrer just makes the solution more even.
23. If a magnetic stirrer is not being used, then stir using a stirring rod.
24. Now pour the VOC, and then evenly pour the nano-mixture and record the findings.
25. If the nanopowder gets deposited unevenly use a fork or a thin rod to evenly distribute the liquid.
26. Similarly, graph these findings using Excel.
27. **Note**: keep thorough track of the readings, variations, and time. Label materials well.

Certain variables were not included for certain metal oxides for specific reasons. There is no non-nano powder for MgO as that is used in medical contexts. There is also no light-off, as the light did not impact the readings. There is no water base for ZnO np as the water was determined as a weak base through other trials. The significance of the variables was decided throughout testing and observing. For example, within trials, changes made would be tested to see if that variable was actually impacting the data set.