Photocatalytic Oxidation for Air Sanitization using Anatase Ti0_2 Coating Exposed to UV Irradiation: An Overview

Alpine Innovative Research Inc.

Nov 2021

1 Introduction

Air Sniper products dramatically reduce the concentration of airborne contaminants such as volatile organic compounds (VOCs), bacteria, and viruses, using two distinct technologies: germicidal ultraviolet light, and a chemical process called photocatalytic oxidation (PCO). This chemical process occurs when titanium dioxide (TiO_2) is exposed to ultraviolet (UV) light. It allows volatile organic compounds and pathogenic bio-aerosols to be cleansed from the air and rendered harmless. PCO air sanitization can be deployed in a wide variety of contexts to improve indoor air quality. This article describes and motivates for the effectiveness of PCO air sanitization in neutralizing VOCs and harmful airborne pathogens by elaborating on the chemical principles by which the technology works.

2 Titanium Dioxide

Titanium dioxide (TiO_2) is a versatile mineral naturally found in various ores and sands. It is mainly found in one of two crystal forms, called anatase and rutile respectively. Most TiO_2 is produced by refining ilmenite mineral ore, which is mined all around the globe, with Australia leading as the world's top producer.

TiO_2 is used in a wide variety of applications, especially as a pigment. According to the US Geological Survey, "approximately 95% of titanium is consumed in the form of titanium dioxide (TiO_2), a white pigment in paints, paper, and plastics" ("Titanium Statistics and Information", 2021). In the 1960s, researchers Akira Fujishima and Kenichi Honda discovered a new application of TiO_2, reporting on a photocatalytic effect of TiO_2 nanoparticles exposed to UV light in their article published in the Journal Nature in 1972. Since this early report, the photocatalytic activity of TiO_2 has been an important subject of research, and various applications of this process have been discovered. Both rutile and anatase forms of TiO_2 exhibit this behaviour when exposed to UV light, but anatase has been found to be the most effective at producing a photocatalytic effect (Huang et al., 2016).

3 Photocatalytic Oxidation

One of the most promising applications of photocatalytic oxidation with TiO_2 is as a sanitizer. For this purpose, TiO_2 nanoparticles have been incorporated into a variety of substrates from cement blocks to paints, providing these materials with a passive air-sanitization property. In a dedicated air sanitization reactor, TiO_2 nanoparticles are typically used to coat a mesh substrate that air can pass over, such as the stainless steel mesh used in Air Sniper products. According to Huang and Colleagues (2016), "titanium dioxide (TiO_2) is known as the most extensive [sic] studied photocatalyst due to its excellent stability, high photo-activity, and suitable band gap

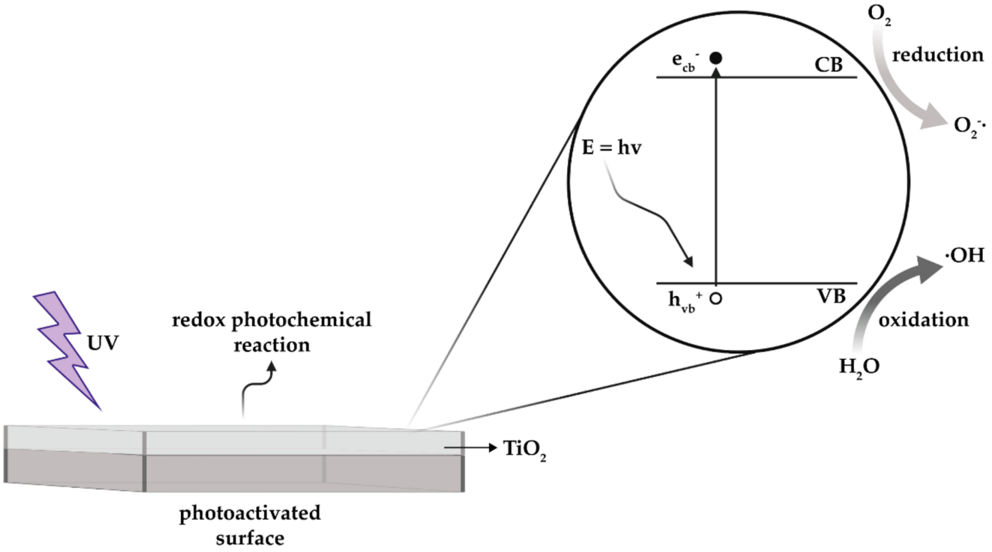

Figure 1: Graphical depiction of the PCO process (from Bono et al., 2021).

1. $(TiO)_2 + hv \rightarrow h_{VB} + e^-_{CB}\, (TiO)_2 + hv \rightarrow h_{VB} + e^-_{CB}$
2. $(TiO)_2 + hv \rightarrow h_{VB} + e^-_{CB}\, (TiO)_2 + hv \rightarrow h_{VB} + e^-_{CB}$
3. $O_2 + e^-_{CB} \rightarrow \cdot O^-_2 O_2 + e^-_{CB} \rightarrow \cdot O^-_2$
4. $HCHO + \cdot OH \rightarrow \cdot (CHO + H)_2\, O$
5. $\cdot CHO + \cdot OH \rightarrow HCOOH \cdot CHO + \cdot OH \rightarrow HCOOH$
6. $\cdot CHO + \cdot O^-_2 \rightarrow HCO^-_3 \overset{+H^+}{\rightarrow} HCOOH \overset{+HCOOH}{\rightarrow} HCOOH \cdot CHO + \cdot O^-_2 \rightarrow HCO^-_3 \overset{+H^+}{\rightarrow} HCOOH \overset{+HCOOH}{\rightarrow} HCOOH$
7. $HCOOH \overset{(-H)^+}{\rightarrow} (HCOO)^- \overset{h^+}{\rightarrow} H^+ + \cdot CO^-_2 HCOOH \overset{(-H)^+}{\rightarrow} (HCOO)^- \overset{h^+}{\rightarrow} H^+ + \cdot CO^-_2$
8. $\cdot CO^-_2 \overset{[O]\,[\cdot OH]\,[h^+]}{\rightarrow} (CO)_2$

Figure 2: The PCO reaction (Huang et al., 2016)

structure. Low cost and non-toxicity are also the main advantages for its application."

The TiO_2 in these products acts as a catalyst, causing an accelerated chemical reaction with the UV light and water vapour in the air; these two components, the UV light and titanium catalyst are the "photo-" and "catalytic" part of the process. The energy in UV radiation allows electrons in the outmost orbital of the titanium molecules (the valence band) to detach from the molecules and move freely through the material (the conduction band). These free electrons react with water vapour near the surface of the catalyst to create hydroxyl radicals and other highly reactive forms of oxygen (Huang et al., 2016, Bono et al., 2021); this step is the "oxidation" part of the chemical process.

4 Hydroxyl Radicals

Reiter et al., (1995) describe the hydroxyl radical as "the radical's radical", writing that it "is fearsomely reactive and highly toxic." Hydroxyl radicals are generally recognized as the most reactive species of oxygen; they are able to damage essential cell components including proteins, carbohydrates, lipids, and DNA (Kehrer et al., 1993, Block 2001).

Besides being produced by photocatalytic oxidation of TiO_2, hydroxyl radicals are also produced when hydrogen peroxide reacts with organic compounds, and are responsible for the antiseptic effect of this common disinfectant molecule. According to Seymour S. Block (2001), hydrogen peroxide (HP) is naturally found in milk and honey, where it prevents spoilage, in the human mouth, as an oxidant, and it is produced by the immune system, where white blood cells use it to kill invading pathogens before absorbing them. hydrogen peroxide, in all these cases, is leveraged by natural processes to kill pathogens. The method of action of hydrogen peroxide is through the production of hydroxyl radicals (Block 2001).

Photocatalytic oxidation can therefore be considered as producing a cleansing process analogous to hydrogen peroxide; both act as powerful sanitizers by producing hydroxyl radicals that oxidize the organic molecules found in pathogens and VOCs.

5 Safety of Photocatalytic Oxidation

Reading the previous section about the powerful antiseptic properties of hydroxyl radicals, which are produced by photocatalytic oxidation (PCO), one might reasonably express concern for what should happen if these oxidant molecules were to be introduced into the air by an air sanitization system. Thankfully, this concern is completely unnecessary. The hydroxyl radicals produced by photocatalytic oxidation are unstable molecules formed on the surface of the TiO_2-coated substrate found in a PCO air sanitizer. Their presence is relatively short-lived, and they exist only on or near the surface of the TiO_2 catalyst (Huang et al.,2016) before decaying. Because of this, there is no risk of introducing

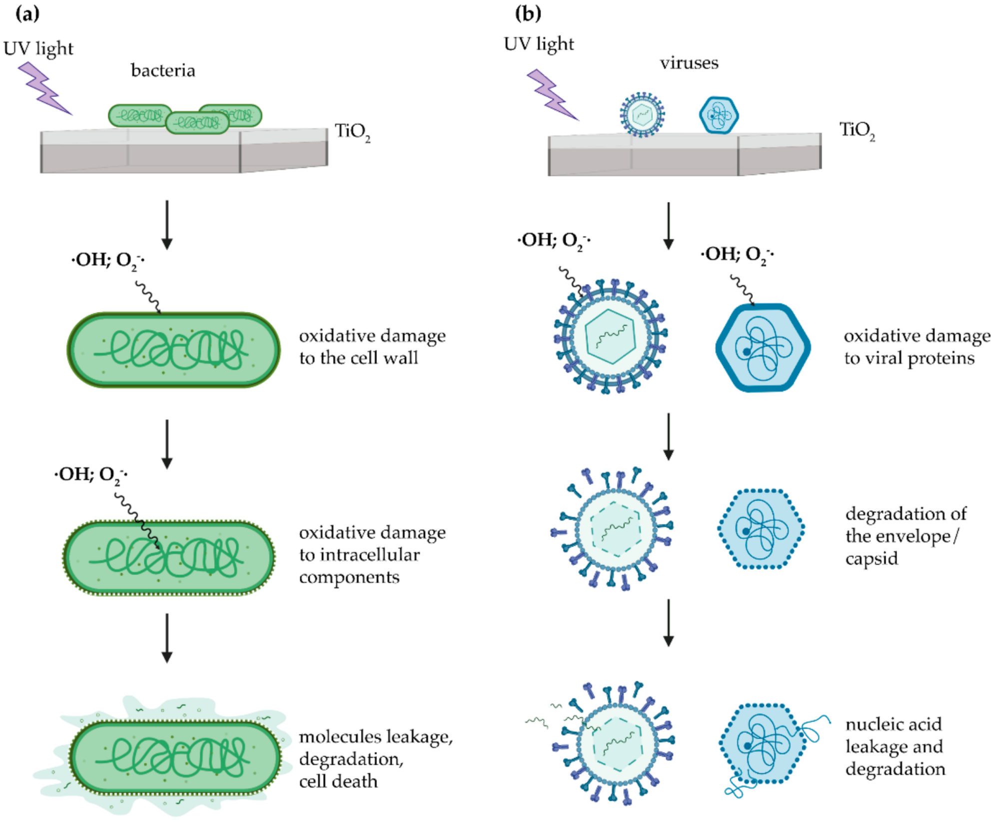

Figure 3: Effect of UV PCO on bacteria and viruses (Bono et al., 2021)

hydroxyl radicals into the environment.

6 Results of PCO Air Sanitization

When hydroxyl radicals react with organic compounds, the results are sometimes surprisingly innocuous. Viral bodies and bacterial cells are dramatically disrupted by oxidation with hydroxyl radicals, either causing ruptures in their exterior walls that allow their DNA and other cellular structures to leak out, or penetrating into the cell and destroying their DNA, preventing the organisms that are spared complete obliteration from replicating, and either way rendering these pathogens harmless (Bono et al.,2021, Poormohammadi et al.,2021, De Pasquale et al.,2021). Toxic gases such as ammonia, carbon monoxide, and formaldehyde, are converted into harmless water, carbon dioxide, and molecular oxygen. Other VOCs are similarly converted into water, carbon dioxide, and molecular oxygen, or in other words, clean air (Huang et al., 2016). (see figure 2) Laboratory testing has shown that a well-designed PCO air sanitizer can substantially reduce the concentration of these harmful pollutants in the air. In combination with germicidal UV-C, our products have been shown to reduce the concentration of some contaminants by 99.9% or more.

PCO has even been shown to be an effective tool against COVID-19. Matsuura and colleagues report in the journal Viruses "that TiO_2-mediated photocatalytic reaction inactivates SARS-CoV-2 in a time-dependent manner and decreases its infectivity by 99.9%", stating "the multi-antiviral effects of TiO_2-mediated photocatalytic reaction implies universal disinfection potential for different infectious agents. Notably, TiO_2 has no adverse effects on human health, and therefore, TiO_2-induced photocatalytic reaction is suitable for disinfection of SARS-CoV-2 and other emerging infectious disease-causing agents in human habitation."

Research studying the actual health benefits produced by using this kind of technology is still ongoing. Because of the relative novelty of the technology, and the challenging complexity and scale required to organize effective medical research on this kind of intervention, there is still little medical research on the health benefits of PCO air sanitization. However, given what we know about its ability to neutralize harmful pollutants, there is little doubt that PCO air sanitization offers real benefits.

7 Summary

Photocatalytic oxidation (PCO) is a process in which TiO_2 exposed to UV light produces hydroxyl radicals and other reactive forms of oxygen. By engineering an environment in which air can react with these oxidizers, harmful contaminants in the air can be neutralized. Pathogens are destroyed or rendered inert, and many other pollutants are converted into clean air. Although only continued medical research can definitively confirm the health benefits provided by this air sanitization technology, its operating principles are well understood, and its efficacy in neutralizing harmful contaminants has been repeatedly demonstrated. PCO is therefore considered a highly promising technology, and an important tool for improving indoor air quality.

8 Works Cited

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